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Core fueling and edge particle flux analysis in NSTX spherical torus

Abstract

Boundary Physics program of the National Spherical Torus Experiment (NSTX) is focusing on optimization of the edge power and particle flows in $\beta \geq 25$ % long pulse L- and H-mode plasmas heated by up to 6 MW of high harmonic fast wave (HHFW) and up to 5 MW of neutral beam injection (NBI). Particle balance and core fueling efficiencies of low and high field side (HFS) gas fueling of L-mode ohmic and NBI heated plasmas have been compared using an analytical zero dimensional particle balance model and measured ion and neutral fluxes. Gas fueling efficiencies are in the range of 0.05 - 0.20 and do not depend on discharge magnetic configuration, density or poloidal location of the injector. The particle balance model indicates that the addition of HFS fueling results in a reversal of the wall loading rate, providing a particle control option towards achieving the improved plasma performance. Initial particle source estimates obtained from neutral pressure and spectroscopic measurements indicate that in diverted discharges ion flux into the divertor greatly exceeds midplane ion flux from the main plasma, suggesting that the main chamber recycling regime observed in other tokamaks has not been encountered in NSTX. Present analysis provides the basis for detailed fluid modeling of core and edge particle flows and the analysis of particle confinement properties of L- and H-mode plasmas. This research was supported by the U.S. Department of Energy under contracts No. DE-AC02-76CH03073 and DE-AC05-00OR22725.

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1 Introduction

The focus of the National Spherical Torus Experiment (NSTX) Boundary Physics program is the optimization of the edge power and particle flows in $\beta \geq 25$ % long pulse L- and H-mode plasmas heated by up to 6 MW of high harmonic fast wave (HHFW) power and up to 5 MW of neutral beam injection (NBI). It has been initially thought that spherical tori (ST) features, such as the compactness of the divertor and the scrape-off layer (SOL) width, resulting from the short connection length and high mirror ratio, would be challenging to power exhaust and particle handling techniques. NSTX has successfully achieved long NBI heated and HHFW heated H-mode plasmas of several τ_E duration and stored energy up to $E \leq 100$ kJ and plasmas with $\beta_t \leq 30$ thus demonstrating that conventional tokamak density control and wall conditioning techniques are adequate for high performing ST target plasma development. The purpose of this paper is to provide an initial analysis of global particle balance in NSTX and an assessment of the efficiency of the core fueling and divertor performance. Such global approach helps identify the pathways for further detailed analysis of particle confinement, scrape-off layer transport and core density limiting mechanisms involving multi-fluid numerical modeling of edge plasmas [1].

2 Experiment and diagnostics

External fueling of NSTX plasmas is achieved by neutral gas injectors and neutral beam injectors. Top and midplane fast piezoelectric valves are referred to as the low field side (LFS) injectors. The valves provide a well-controlled continuous gas flow at a rate $\Gamma_{gas} \leq 170$ torr·l / s per injector, and duration as low as $\tau_v \simeq 1$ ms. The high field side (HFS) gas injector was recently installed on NSTX following successful MAST demonstration of improved H-mode access with inner wall fueling. The gas injector provides a pseudo-constant flow at a rate $\Gamma_{gas} \leq 50$ torr·l / s. Three $E \leq 80$ keV deuterium beams injected co-directionally with plasma current at three radii of $r_1 = 48.7; r_2 = 59.2, r_3 = 64.9$ cm yield the fueling rate of $\Gamma_{NBI} \simeq 1.3$ torr·l / s per 1 MW of NBI power. Conventional wall conditioning techniques, including boronization and glow discharge cleaning (GDS), are used for wall particle inventory reduction and control [2]

Quantitative particle balance analysis utilizes the measurements of several diagnostics. These are fast neutral pressure gauges, including a calibrated ionization gauge at a midplane location, and a divertor Penning gauge. Plasma profiles are measured by a tangential Multipoint Thompson Scattering (MPTS) system. Various spectroscopic diagnostics include optically filtered detectors of impurity, visible bremsstrahlung, and the deuterium Balmer line emissions, and visible and VUV spectrometers. Especially useful for neutral recycling measurements are the photometrically and spatially calibrated 2048-pixel optically filtered CCD arrays, viewing the lower divertor neutralizer plates and the center stack tiles.

A database of about 100 center stack limited (CSL), lower single null (LSN) and double null (DN) diverted discharges has been used in the present analysis. The discharges included 0.8 - 1.0 MA ohmically and NBI heated fiducial L-mode deuterium plasmas, and the L-mode ohmic discharges obtained in a density scan experiment. Fueling efficiencies have been determined in the current ramp-up and flat-top phases of the discharge at $t \leq 0.25$ s as many plasmas experience violent MHD modes or reconnection events (RE's) altering plasma parameters.

3 Particle balance and fueling efficiency

A standard global particle balance model (PBM) [3] is applied to each discharge to analyze core plasma contribution of various particle sources and sinks:

$$\frac{d\,N_i}{d\,t} = \Gamma_{gas} + \Gamma_{wall} + \Gamma_{NBI} + \Gamma_{var} \tag{1}$$

The change in total particle inventory dN_p/dt is derived from the measured Z_{eff} and the volume-averaged density $N_e \simeq \bar{n}_e V_p$. Γ_{gas} and Γ_{NBI} are the gas injector and NBI fueling rates. Γ_{var} term includes the neutral gas build-up rate dN_n/dt, estimated from the neutral pressure measurements, vacuum vessel and NBI duct pumping rates Γ_{pump}, and the NBI line neutral gas fueling rate $\Gamma_{NBI-cold} \simeq 0.25 \times \Gamma_{NBI}$. The neutral gas build-up rate is dominant in Γ_{var}, and the fluxes due to pumping and NBI duct gas are on the order of 5 torr·l / s. The wall loading rate Γ_{wall} is derived from the balance equation. Integrating the equation yields the cumulative particle inventories. Fueling efficiency is defined as $\eta = N_p/N_{ext}$, where N_p is the total number of particles enclosed by the last closed flux surface (LCFS), and N_{ext} is the total number of particles introduced externally into the vacuum vessel. Fueling efficiency η characterizes individual source contribution to the global particle inventory, as thermal and fast particle transport and confinement properties are different, and core fueling is achieved not only by neutral but also by plasma fueling. Instantaneous fueling efficiency may be defined as $\eta_\tau = (dN_i/dt)\Gamma_{gas}^{-1}$. The instantaneous fueling efficiency η_τ is determined by the transitory particle balance and is lower than η. Shown in Figure 1 are the PBM results for a LFS (top injector) fueled 1 MA DN discharge with the following parameters:

P_{NBI} = 1.6 MW, line density 3.5×10^{15} cm^{-2}, stored energy $E_{stored} \simeq 120$ J. The wall loading rate is positive during the gas pulse duration indicating strong pumping by the walls. After the gas shut-off, the balance is dominated by the dN_p/dt term, which slowly falls to 10 - 20 torr·l / s, exceeding the NBI fueling rate of $\Gamma_{NBI} \leq 2$ torr·l / s. The wall loading rate becomes negative indicating the that wall starts degassing. This behavior is characteristic for most L-mode discharges fueled from the top and side gas injectors. Shown in Figure 2 are the PBM quantities derived for an otherwise similar discharge with additional fueling from HFS injector at $\Gamma \leq 30$ torr·l / s. The HFS injection starts at $t = -0.26$ s and produces a fueling rate burst at 0.09 s when it reaches the plasma. A pseudo-constant rate of 20 torr·l/s is maintained from HFS injector through a discharge. This rate is sufficient to change the wall state from outgassing to weakly pumping. The plasma reaches higher line density of 5×10^{15} cm^{-2} and the stored energy of $E_{stored} \simeq 150$ J. Improved plasma controllability and a higher central plasma density limit due to fueling have been achieved with LFS injectors and the HFS fueling rates from 10 to 60 torr·l/s. This suggests that with proper HFS timing and injector plenum pressure, better L-mode plasma performance can be achieved by particle balance modification. More importantly, the change in the boundary state allows for greater reproduceability of H-mode discharges and edge localized modes. No significant differences between HFS and LFS (top and midplane) fueling has been found in ohmic and NBI heated discharges: average fueling efficiencies are in the range 0.05 - 0.20. Higher density plasmas are produced in NSTX by increasing gas injection rate and duration, as shown in Figure 3. Densities as high as $\bar{n}_e \simeq \ timesn_G$ have been produced, limited by an onset of large MHD events or a density limiting mechanism. Higher densities have been produces with lower average fueling rates using LFS + HFS fueling. Also evident from the figure is that the diverted plasmas tend to sustain higher densities. No dependence of the fueling efficiency on the fueling rate has been found. The fueling efficiency is also independent of line density for IWL discharges, as shown in Figure 4. Diverted discharges, however, tend to achieve higher density with higher fueling efficiency. The SOL width determines whether thermal neutrals ionize inside or outside of the LCFS thus thinner SOL in diverted discharges may result in higher penetration efficiency of the fueling particles. This subject will be further addressed in future measurements of SOL temperature, density and the deuterium ionization profile.

NBI fueling efficiency Because of relatively low fueling rate of the NBI it is not possible to determine its fueling efficiency by global particle balance. The ionization profile of NBI is localized well within the core at $r/a \leq 0.5$, where a is the minor radius. The estimated beam shine-through for NSTX plasmas is less than 1 %.

Impurity fueling Main impurities are boron, carbon, and oxygen. Their typical core concentrations after boronization are 0.25 - 0.5 %, 1 - 1.5 %, and 0.1 - 0.3 %, respectively [4] This produces the $1.2 \leq Z_{eff} \leq 2.5$ in ohmically heated discharges and $2 \leq Z_{eff} \leq 3.5$ in NBI and HHFW heated plasmas. Impurities, therefore, contribute less than 10 % to electron density in NSTX.

4 Comments on edge particle fluxes

Internal particle source in NSTX is by far dominated by neutral recycling from the wall. The recycling occurs on carbon fiber composite (CFC)-tiled surface of the center column of area $A_{CS} \leq 3.2$ m^2 and the divertor and passive plates of area $A \leq 7$ m^2. This section describes observations and estimates of edge particle fluxes and their origins.

NSTX divertor has an "open" geometry. Whereas the advantages and disadvantages of the geometry over the narrow throat divertors are debatable, it provides only two channels of particle flows: direct particle flow to the divertor plate and direct internal leakage into the main chamber. Detailed characterization of divertor performance will commence at NSTX with commissioning of divertor probes, a bolometer array and a Penning gauge. Present assessment of divertor performance is limited to impurity and ion flux estimates obtained from spectroscopic observations.

Neutral and ion fluxes Balmer-α brightness is measured by two 2048-pixel filtered photometrically calibrated CCD arrays, and the ion flux is estimated from the measured brightness using the calculated factor of 40 ionization events per D_α photon for NSTX edge parameters $T_e \simeq 20 - 40$ eV, $n_e \leq 5 \times 10^{12}$ cm^{-3}. As follows from the global PBM the wall outgassing rate and gas fueling rate may be comparable. When a lower divertor null is formed, the brightness profile evolution profile indicated indicates large increase in recycling, whereas brightness across the center stack falls. The center stack profile frequently shows large toroidal asymmetries, presumably due to emitting neutrals trapped in high m, n MHD modes localized close to the surface. The flux from these "bright spots" may exceed the average surface flux by a factor of 100. It is of interest to compare the magnitude of ion and neutral fluxes at the midplane and on the divertor plates. Based on a limited database of calibrated measurements it is concluded that ion and neutral flux at the midplane are on the order of 5×10^{21} s^{-1}, whereas the divertor ion flux is $\leq 10^{23}$ s^{-1}. Shown in Figure 5 are the average particle fluxes for the HFS+LFS fueled discharge analyses for particle balance. The HFS gas injection is seen at 0.08 s and its flux is in good agreement with the neutral gas injection rate shown in Figure 2. This result suggests that the radial transport near the separatrix and in the SOL is fairly low and the particle flow along the field lines to the divertor plate is larger than the cross-field flow. The opposite situation has been observed recently in several tokamaks and termed "main chamber recycling" [5], [6], [7]. It has been suggested that strong SOL microturbulence results in a highly non-diffusive particle transport and plasma "blob" propagation radially outward [7].

Finally, we briefly discuss the transient particle flux phenomena that affect the particle balance in NSTX plasmas.

Observations in HHFW heated plasmas The injection of HHFW power broads plasma profiles and effectively increases the edge electron temperature and density by about 10 % as evident from the MPTS measurements. However, both edge intensity of D_α emission and neutral pressure increase by up to a factor of 4, from $\simeq XXX$ to $\simeq XXX$ and 0.1 - 0.3 mTorr to 0.5 - 0.8 mTorr respectively. Since HHFW power couples to electrons, the increase in edge neutral pressure suggest two possibilities - modification of edge ionization profile or direct neutral influx from the antenna surface. As follows from edge D_α intensity measurement the ion flux from the plasma does not scale with HHFW power, whereas there is a weak dependence of neutral pressure on the coupled HHFW power. No dependence of D_α emission and neutral pressure on the distance between antenna and plasma (outer gap) is found. Wall conditioning techniques and antenna surface conditioning generally reduce the HHFW induced neutral flux however do not eliminate it completely.

Reconnection events Reconnection events cause toroidally and poloidally asymmetric plasma flows that result in intense plasma wall interaction. RE is a global MHD instability that demonstrate itself as a fast collapse of the plasma pressure and magnetic flux surfaces and the loss of particle confinement. Although PBM predictions for these events lack accuracy, plasma inventory is observed to reduce up to a factor of 10, and the wall loading rate rise accordingly (Figure 1. The increase in wall loading results in wall conditioning or deconditioning effects as the plasma facing surfaces are bombarded by deconfined energetic ions and neutrals.

5 Summary

Particle balance and core fueling efficiencies of low and high field side gas fueling of L-mode ohmic and NBI heated plasmas have been compared using an analytical zero dimensional particle balance model and measured ion and neutral fluxes. Gas fueling efficiencies are in the range of 0.05 - 0.20 and do not depend on discharge magnetic configuration or poloidal location of the injector. Higher densities are achieved using LFS with HFS fueling with lower average injection rates. The particle balance model indicates that the addition of HFS fueling results in a reversal of the wall loading rate, providing a particle control option towards achieving the improved plasma performance. Initial particle source estimates obtained from neutral pressure and spectroscopic measurements indicate that in diverted discharges ion flux into the divertor greatly exceeds midplane ion flux from the main plasma. This suggests that the main chamber recycling regime observed in other tokamaks has not been encountered in NSTX. Present analysis provides the basis for detailed fluid modeling of core and edge particle flows and the analysis of particle confinement properties of L- and H-mode plasmas.

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Figures

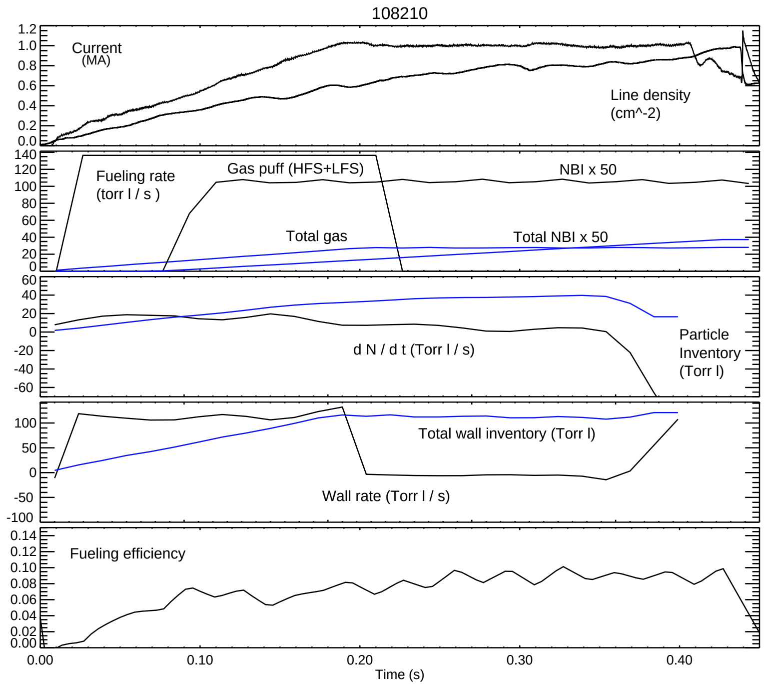

Fig. 1. Particle balance model for a LFS fueled plasma

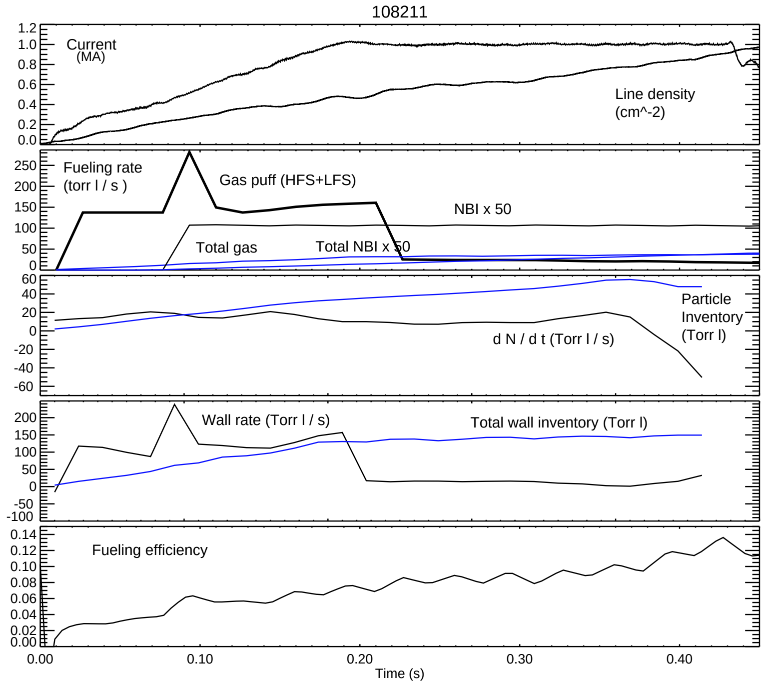

Fig. 2. Particle balance model for a LFS + HFS fueled plasma

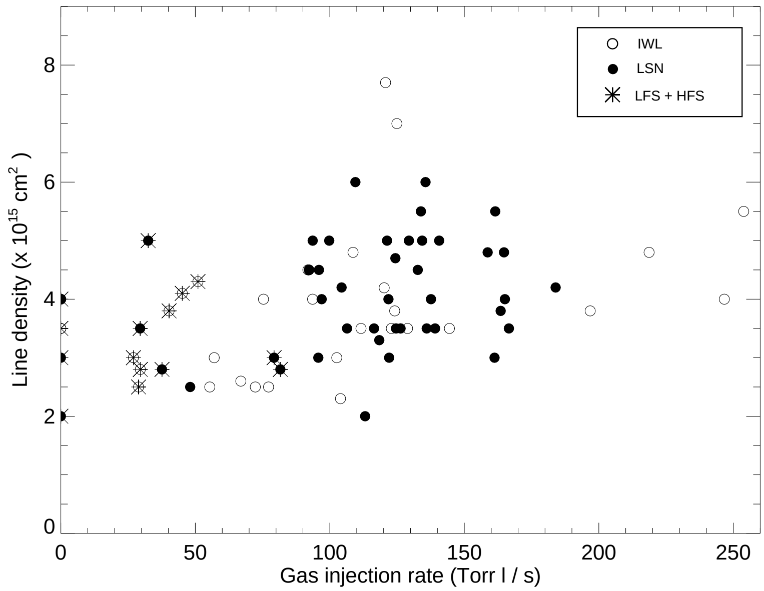

Fig. 3. Line density dependence on gas injection rate

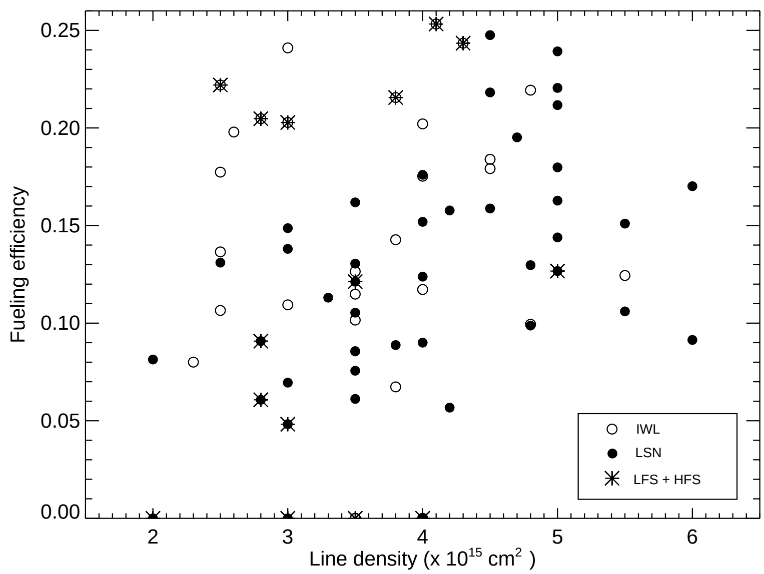

Fig. 4. Gas injection fueling efficiency dependence on line density

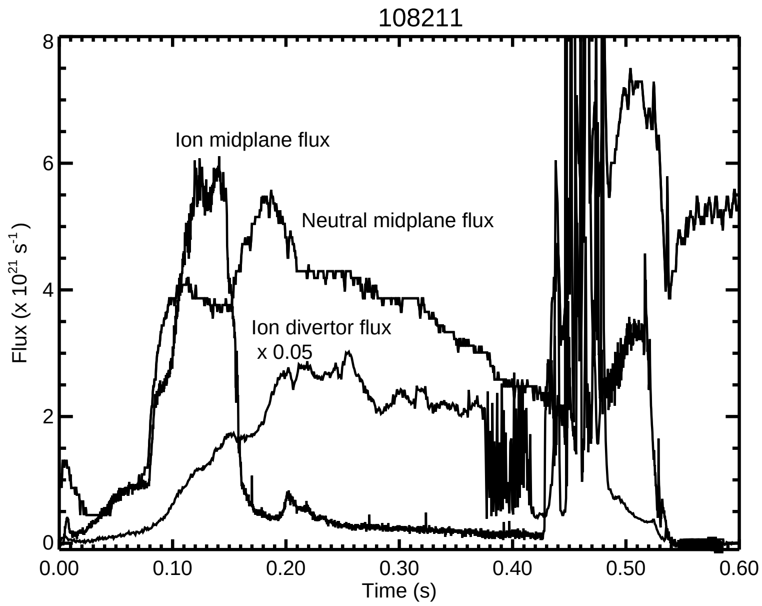

Fig. 5. Estimated ion and neutral fluxes for the discharge shown in Figure 2