Diagnostic options for radiative divertor feedback control on NSTX-U.[a)]

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A radiative divertor technique is used in tokamak experiments and planned for ITER to mitigate high heat loads on divertor plasma-facing components (PFCs) to prevent excessive material erosion and thermal damage. In NSTX, a large spherical tokamak with lithium-coated graphite PFCs and high divertor heat flux ($q_{peak} \leq 15$ MW/m^2), radiative divertor experiments have demonstrated a significant reduction of divertor peak heat flux simultaneously with good core H-mode confinement using pre-programmed D_2 or CD_4 gas injections. In this work diagnostic options for a new real-time feedback control system for active radiative divertor detachment control in NSTX-U, where steady-state peak divertor heat fluxes are projected to reach 20-30 MW/m^2, are discussed. Based on the NSTX divertor detachment measurements and analysis, the control diagnostic signals available for NSTX-U include divertor radiated power, neutral pressure, spectroscopic deuterium recombination signatures, infrared thermography of PFC surfaces, and thermoelectric scrape-off layer current. In addition, spectroscopic "security" monitoring of possible confinement or pedestal degradation are recommended. These signals would be implemented in a digital plasma control system to manage the divertor detachment process via an actuator (impurity gas seeding rate).

I. INTRODUCTION

A radiative (partially detached) divertor technique is used in tokamak experiments and planned for ITER to mitigate high divertor heat loads and material erosion of divertor plasma-facing components (PFCs) to prevent their thermal and structural damage[1,2]. The radiative divertor uses induced divertor volumetric power and momentum losses to reduce heat and particle fluxes on divertor target plates. Deuterium and/or impurity gas seeding has been employed to control the radiative divertor plasma parameters in several tokamak experiments via a real-time feedback control of the gas injection rate[3–11].

In the National Spherical Torus Experiment (NSTX), a large spherical tokamak with lithium-coated graphite PFCs and high divertor heat flux ($q_{peak} \leq 15$ MW/m^2 (Ref.[12])), radiative divertor experiments employed D_2, CD_4, or Ne gas injections that were controlled by pre-programmed waveforms[13,14]. At present, the NSTX facility is being upgraded to new capabilities that are expected to extend physics studies of the spherical tokamak (ST) to advance the ST as a candidate for the Fusion Nuclear Science Facility. In the NSTX-U device[15], discharges with $I_p \leq 2$ MA and $P_{NBI} \leq 12.3$ MW and up to 5 s duration are projected to produce steady-state peak divertor heat fluxes in the range 20-30 MW/m^2, thereby challenging thermal limits of divertor PFCs[12]. In this work we discuss the diagnostic development plan in preparation for real-time feedback control of divertor conditions in the NSTX Upgrade facility. Based on the NSTX experiments, the control diagnostic signals recommended for NSTX-U include divertor radiated power, neutral pressure, spectroscopic deuterium recombination signatures, infrared thermography of PFC surfaces, and thermoelectric scrape-off layer current, as well as spectroscopic "security" monitoring of possible confinement or pedestal degradation.

II. CONCEPTUAL DESIGN OF CONTROL SYSTEM

The divertor detachment process is tokamak-specific with respect to divertor PFC material, seeding gas species, radiating impurity, onset parameters and their relation to the core plasma. The radiative detachment of the divertor SOL is achieved when heat conduction can no longer be sustained as a result of high SOL collisionality and high volumetric power and momentum losses. The detachment signatures universally measured in present-day tokamak experiments include 1) the loss of plasma pressure $T_e n_e$ along the SOL (field line) from upstream locations to the target, increased divertor $n_e \leq 10^{15}$ m^{-3} and decreased $T_e \leq 1-2$ eV; 2) the reduction of divertor heat flux (esp. q_{peak}) and increase in P_{rad}; and 3) reduction of ion flux density to the plate, accompanied by an increased volumetric recombination rate[1,2]. In order to control radiative detachment, a diagnostic control signal should unambiguously reflect one of the detachment characteristics. The control signals that have been used in tokamak experiments included the divertor radiated power[3,5,7], direct T_e or n_e measurements[6,10], or a surrogate for the T_e measurement[11]; and neutral pressure[4].

The feedback control of divertor conditions can be accomplished using a commonly used proportional, integral, derivative (PID) controller algorithm in the digital plasma control system (PCS) implemented in NSTX[16]. The control signal S_c is compared in real-time to the reference signal S_{ref}: $\Delta S = S_c - S_{ref}$. The actuator signal V is calculated in real-time according to: $V = K_0 + K_p \Delta S + K_i \int_{t_1}^{t_2} \Delta S dt + K_d d\Delta S/dt$ where the

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control gains corresponding to the constant (K_0), proportional (K_p), integral (K_i), and derivative (K_d) parts are usually estimated or modeled off-line and verified in the experiment. If a calibrated valve that controls impurity seeding is the actuator, then the actuator V is a real-time voltage proportional to a gas flow rate. In this regard, the system is quite similar to many quantities, e.g. divertor strike point positions, controlled via PID-based algorithms in NSTX PCS[17].

In previous NSTX experiments, a single-channel divertor gas injector was used. For NSTX-U, an upgrade to the system is proposed. The upgraded system would include four outlets placed axi-symmetrically in the lower and upper divertor regions in the physical gaps between divertor plates. To control the gas inventory, existing turbo-molecular pumps and a divertor cryogenic panel (which is presently under consideration), would be used. The seeding impurity gas is selected based on operational and atomic physics (radiated power at low T_e) considerations. In the initial period of NSTX-U operations[15], all graphite PFCs conditioned via lithium and boron coatings are planned, and the seeding gas options are D_2, CD_4, and Ar. Nitrogen is excluded at this stage due to its chemical reactivity with lithium coatings and its adsorbtivity into graphite. If NSTX-U is upgraded with molybdenum and/or tungsten PFCs, then D_2, N_2 and Ar would be used.

III. DIAGNOSTIC OPTIONS FOR NSTX-U

It is expected that the same diagnostics used in NSTX[13,14] would be available for NSTX-U divertor characterization in the initial operations period. In NSTX radiative divertor experiments, a significant reduction of divertor heat flux from peak values of 4-10 MW/m^2 to 0.5-2 MW/m^2, simultaneously with good core H-mode confinement characterized by H98(y,2) up to 1, has been demonstrated in 1.0-1.3 s discharges[13,14]. A partial divertor strike point detachment was characterized in NSTX using a number of divertor plasma measurements: divertor plate PFC temperature (heat flux), radiated power using bolometry and impurity emission spectroscopy, neutral gas pressure measurements, ion flux using Langmuir probes, and divertor recombination using UV or NIR spectroscopy. Shown in Fig. 1 are divertor time traces in two 0.8 MA 4 MW NBI-heated H-mode discharges, a reference discharge and a radiative divertor discharge with CD_4 seeding. In the radiative divertor discharge, peak divertor heat flux was reduced from 4-5 to 1-2 MW/m^2 in the detachment phase that started at about 0.7 s. These time traces will be used to illustrate the control signal options for NSTX-U. On the basis of these experiments, we identify two categories of diagnostics: (1) divertor plasma and PFC diagnostics; and (2) the diagnostics characterizing the pedestal or core plasma that can be used as "security" measures to insure the radiative divertor compatibility with H-mode confinement. Initial considerations for spatial and temporal requirements to the control signal are as follows. The characteristic detachment onset time in NSTX was 5-20 ms, and it is expected to be similar in NSTX-U. The control signal spatial resolution should be better than 1 cm, and the ability to distinguish between inner and outer divertor leg parameters is important. One concern with spatially (both poloidally and toroidally) localized divertor signals is that they can be affected by changes in plasma shaping, strike-point locations, and toroidal asymmetries in heat and particle fluxes during the application of 3D fields. This could limit the operating space of the control system if it is based on a single spatially localized diagnostic.

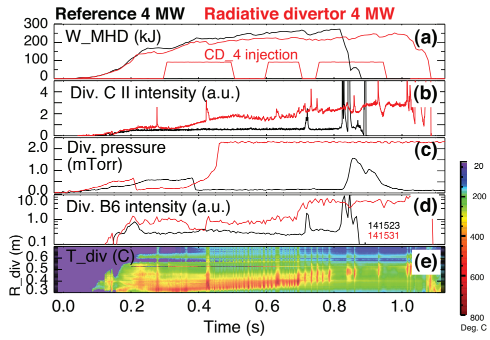

FIG. 1. Time traces of a reference (black) and a radiative divertor (red) H-mode discharges: (a) Plasma stored energy W_{MHD} and CD_4 injection waveforms, (b) divertor C II (λ658.5 nm) intensity, (c) divertor neutral pressure, (d) divertor Balmer $n = 2 - 6$ line intensity in the strike point region, (e) divertor PFC temperature from IR thermography.

Radiated power A signal representing spectrally integrated radiation as well as spectrally resolved impurity emission can be used to monitor divertor radiated power. In NSTX, bolometer signals showed a 50-75 % increase during detachment[13], as would impurity spectroscopy, as shown in Fig. 1. A number of spectroscopic options are available for NSTX-U. A major fraction of the power radiated by C, N, or Ar impurities at typical divertor conditions is in the 8-30 eV photon energy range. A divertor radiometer based on a single AXUV diode or an AXUV array (similar to the previously implemented on NSTX[18]) could be used. The AXUV diodes are widely used for plasma bolometry (despite the non-uniformity of the AXUV diode spectral response). Another option is impurity vacuum ultraviolet (VUV) line emission spectroscopy[19], e.g., a dedicated VUV instrument aimed at certain strong impurity emission lines as discussed in Ref[19,20].

Neutral pressure A divertor Penning gauge[21] showed an order of magnitude increase (or even saturation, Fig. 1) in neutral pressure during gas-induced detachment[14], suggesting that seeded impurity pressure measurements could be used in NSTX-U for radiative divertor feedback control as well. Another option under development for NSTX-U is a spectroscopically-monitored Penning gauge[22] calibrated for impurity gas pressure measurements in the range 0.1-5 mTorr.

Electron-ion recombination Divertor observations in NSTX[13,23–25] showed that hydrogenic Balmer or Paschen

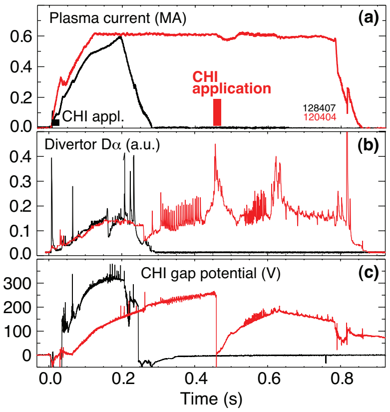

FIG. 2. Time traces of (a) I_p, (b) divertor D_α intensity, (c) V_{io} in CHI H-mode discharge (black traces) and an inductive discharge with CHI (black traces).

series emission lines are good indicators of volumetric recombination that always accompanies the detachment (Fig. 1), and a very sensitive diagnostic of divertor $T_e \leq 1-2$ eV and $n_e \geq 5 \times 10^{19}$ m^{-3}. Intensity of the high-n series lines is proportional to the volumetric recombination rate[26], and can increase up to 1-2 orders of magnitude during detachment[14]. A dedicated filtered spectroscopic detector or an imaging UV spectrometer (as implemented in NSTX[18]) could be used.

Surface temperature In NSTX, PFC temperature and divertor heat fluxes were routinely monitored using IR thermography[27] and slow thermocouples. Divertor PFC temperature in the strike point region was reduced from 600-1000 to 150-250 deg. C during detachment (Fig. 1). A simple robust solution for NSTX-U could thus include medium (3-5 μm) and/or long-wavelength (5-15 μm) IR thermography: dedicated one- or two-dimensional IR arrays or a single-channel collimated IR diode.

Thermoelectric SOL current One attractive option for NSTX-U could be a real-time thermoelectric SOL current measurement. Due to thermoelectric effects, i.e. because of the T_e difference between inner and outer (or upper and lower) divertors, currents can flow in the SOL[28]. The measured current can be related to divertor T_e[11,29]. In NSTX, the inner and outer parts of the vacuum vessel (and PFCs) were electrically isolated to enable non-inductive plasma start-up via coaxial helicity injection (CHI)[30]. In CHI experiments, the outer vessel (divertor) was connected to the ground, whereas the inner vessel (divertor) was floating. The electric potential V_{io} between inner and outer strike point regions was monitored. This is illustrated in Fig. 2 where time traces of two CHI discharges are shown. The black traces illustrate a discharge with CHI start-up that eventually went into an H-mode at about 0.17 s, with a steady-state $V_{io} \simeq 300$ volts[30]. The red traces illustrate a steady-state inductive discharge, with CHI voltage applied at about 0.450 s. The application of the CHI current reduced V_{io} from about 250 V to nearly zero. In NSTX-U, electrical insulation between the inner and outer vessel will be improved. Further developments of this capability aimed at better understanding of SOL thermoelectric currents, as well as active biasing experiments, are planned for NSTX-U.

Integration with core plasma Unchanged core H-mode confinement with high-pressure pedestal is one of the goals of real-time radiative divertor control. Reduced pedestal temperature and X-point MARFE formation are main concerns if too much impurity gas is requested by the PCS for control of divertor conditions. Signals that reflect these parameters can provide "security" monitoring (as in e.g. Ref.[6,10]) and will be needed in long-pulse NSTX-U discharges utilizing the radiative divertor. The implementation of these security signals would involve multi-variate controllers in PCS. A number of NSTX diagnostics can provide these security signals, e.g., pedestal region soft X-ray arrays and divertor recombination monitors aimed at the divertor X-point region.

In conclusion, we considered the diagnostic options for radiative divertor feedback control signals in the initial NSTX-U operation period. Further work will focus on developing and testing diagnostic prototypes, developing time-dependent models of the control diagnostic performance, and implementing the control algorithms.

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