***ASC***-170523-DB-01

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***Subject: impact of potential polar region modifications on research and scenarios for asc Topical Science group***

The NSTX-U Advanced Scenarios and Control (ASC) Topical Science Group (TSG) coordinates the development of control tools and integrated scenarios that enable research directed toward the design and optimization of next-step spherical tokamak (ST) devices, such as a Fusion Nuclear Science Facility (FNSF). For example, a major thrust within ASC is the realization of a steady-state scenario with large energy confinement at or approaching 100% non-inductive current drive. This task requires advances in the real-time control of the plasma parameters, as well as the integration of particle control, power handling, high confinement and MHD stability solutions developed in conjunction with other TSGs. Generally, ASC is also heavily invested in the development of control tools and scenarios that enable the scientific program contained within other TSG and Science Groups. For example, ASC coordinates the development and commissioning of active snowflake divertor control, enabling research within the Boundary Science Group.

The ASC TSG held a meeting on May 12, 2017 to solicit input on the impact the potential polar region modifications would have on the scientific goals of the TSG. The discussions are summarized below for each of the four research thrusts identified in the most recent 5-year plan.

**ASC-1: Scenario Development**

This thrust focuses on demonstrating long-pulse, high-performance discharges on NSTX-U. Broadly speaking, there are two types of scenarios considered in this thrust: 100% non-inductive current drive and high current partial inductive scenarios.

1.1 Full performance discharge development

This research thrust focuses on realizing the full-performance of NSTX-U, namely Ip = 2 MA, BT = 1T, tpulse = 5s, fGW ≤ 1 in a DN shape. Members of the ASC group are actively involved in defining the requirements for the polar region modifications based on this performance goal. Thus, the proposed changes are presumed to be compatible with this research activity. In our discussions, team members made suggestions on contributions the ASC group could make to inform the heat flux calculations that are being pursued, namely:

1.1.1) Is 10 MW of NBI heating achievable and sufficient for this scenario?

 Considering the requirement for beam heating in ramp up and controlled ramp down, what is the optimum choice for the beam voltages and modulation timing for each of the six beams that keeps the beams within the pulse-length and modulation limits and achieves a 5s flattop? Does this modulation allow for CHERs measurements of the carbon profiles? How much power is available for the 5s flattop period and can that power level support Ip = 2 MA within a range of reasonable assumptions?

Calculations with TRANSP [Gerhardt, NF 52 (2012) 083020] have shown the maximum Ip with 10 MW of NBI heating is strongly dependent on the energy confinement and the density profile shape. These calculations did not consider the constraints from beam heating in ramp up and ramp down, or the NBI modulation required for CHERS measurements.

1.1.2) What are the restrictions on the plasma shape for this scenario?

 These scenarios favor a large outer gap, small inner gap and high triangularity. The large outer gap leads to the requirement for vertical stability at large elongation. What li is expected for this scenario and how does it scale with shape or beam parameters? What is the minimum elongation that is credible for this scenario, considering a range of outer gaps and X-point Z-positions? What are the vertical stability limits to the elongation in these scenarios?

1.2 High current and heating power

Larger NBI voltages (> 80 kV) would access high temperatures compared to the case described in 1.1. The larger temperatures would result in longer current redistribution times, permitting stable non-stationary operation near Ip = 2 MA at fGW < 1 for shorter pulses (< 3 s).

The following parameters are taken from [Gerhardt, NF 52 (2012) 083020] assuming all six beams are injecting at the same voltage. These cases are calculated to evolve to stationary conditions with qmin > 1. The range of Ip values reflects a two-point scan in both confinement and profile peaking:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| NBI (kV) | Pinj (MW) | Max flattop (s) | fGW | Ip (MA) |
| 80 | 10.2 | 5 | 0.74 | 1.25 – 1.8 |
| 90 | 12.6 | 3 | 0.74 | 1.35 – 1.9 |
| 100 | 15.6 | 1.5 | 0.74 | 1.45 – 1.98 |
| 80 | 10.2 | 5 | 1.04 | 1.45 – 2.0 |

All cases shown in the table use BT = 1T and the same shape with a 15 cm outer gap (κ ~ 2.8). The limits to the shaping parameters raised in question 1.1.2 should be addressed for these proposed scenarios. Operations at reduced BT, Ip will be pursued, but it is anticipated that these scenarios would be less challenging to the first wall.

1.3 100% non-inductive current

One facility goal for NSTX-U is the demonstration of 100% non-inductive sustainment. As a result, ASC places high priority on developing the control tools and operational scenarios necessary for achieving this goal. These scenarios will operate at lower Ip than the partially inductive scenarios (1.1 and 1.2), thus it is anticipated that these scenarios are less challenging to the first wall. The table below comes from the NSTX-U five-year plan:



Experiments will have to be conducted to explore the impact (if any) of high flux expansion and snowflake configurations on obtaining 100% non-inductive scenarios. It was suggested that the elevated q95 in perfect snowflakes could be beneficial for non-inductive current drive. Therefore, the TSG feels any equilibria from section 1.1 and 1.2 that rely on large flux expansion are permitted in these scenarios.

1.4 Partially inductive long-pulse

 Experiments may desire H-mode pulses that have a flattop time longer than 5s at BT < 1 T and Ip < 2 MA. For example, the TF coil would support a 10s pulse at BT = 0.75 T. Long-pulse discharges would support studies in wall retention, particle control and disruption avoidance, which contributes to the ASC mission of advancing the understanding needed for next step devices.

Two scenarios studied in [Gerhardt, NF 52 (2012) 083020] at BT = 0.75 T used either all six beams at 65 kV injecting continuously or at 80 kV with 50% duty cycle:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| NBI (kV) | Pinj (MW) | Max flattop (s) | fGW | Ip (MA) |
| 65 | 6.6 | 8 | 0.73 | 1.0 – 1.25 |
| 80 | 5.1 | 10 | 0.73 | 0.85 – 1.1 |

Presumably, operation at lower Ip will not place a large constraint on the first wall surfaces in a DN shape.

**ASC-2: Axisymmetric Control**

This research thrust aims to develop the active feedback control solutions that enable the scientific program on NSTX-U and the requirements of future burning plasma devices. Many of the research topics within the thrust do not place strict requirements on the shape, heating or pulse length required to develop and test the feedback control. The following discussions focus on the control topics that could be impacted by the proposed changes to the polar region.

2.1 Snowflake and X-divertor control

 Fish scaling of the divertor tiles will most likely limit the range of snowflake divertor configurations that are permitted due to the introduction of reversed helicity field lines at the divertor surfaces. The impact this limitation has on experiments aimed at advancing the physics of the snowflake will be discussed in the DivSOL memo; this discussion focuses on the impact to developing snowflake control.

 The most significant concern from this TSG is that commissioning of the snowflake controller must be allowed a margin for error when first under development. This concern is reduced if there is active protection of the tile heat flux, which requires separate development. The snowflake controller is ready to test once reproducible H-mode scenarios are demonstrated. Thus, if NSTX-U comes back on-line without fish-scaled tiles, the controller commissioning could begin in the first campaign prior to commissioning a first wall protection system. Conversely, if NSTX-U resumes operation with fish-scaled tiles, the testing of the controller in conditions relevant for scientific experiments may require waiting for the tile protection system.

 The ASC members were in agreement that significant development and testing of the snowflake controller is needed, especially if tight tolerance on the strike point locations across a wide range of scenarios is required for safe operation of NSTX-U. Modeling efforts are planned to increase the efficiency of experimental time required to commission the controller.

 The X-divertor configuration shares similarities with the snowflake configuration whereby a second X-point in the SOL increases the flux expansion at the divertor target. Experiments directed at classifying the X-divertor would want to vary the distance between the two X-points (exploring a presumed transition from snowflake to X-divertor) by varying the primary X-point height. Provided the secondary X-point is not within the vacuum vessel, this configuration does not introduce reversed helicity issues. Again, development and testing the controller requires some margin for error and thus depends on the sequence of altering the tiles and introducing tile protection.

2.2 Integration of tile protection into active control

 The NSTX-U control group plans to incorporate the DCPS logic into the PCS in order to develop algorithms that avoid the DCPS limits, or at least initiate a soft shutdown if the limits are approached. In our discussion, the ASC group felt similar efforts could be undertaken to incorporate any tile protection logic into the PCS to avoid a hard shutdown from a protection system. The PCS could use the divertor configuration or NBI heating as potential actuators for avoiding the tile heating limits.

2.3 Active control of the current profile

 ASC aims to develop active control of the current profile using neutral beams and outer gap position as actuators. Initial experiments will want to access low-density operation where the beam current drive fraction is largest. The pulse lengths would need to be long enough that control is demonstrated over several current redistribution times. This would favor lower temperature regimes where the plasma is more resistive. Thus, it is expected that these desired regimes will not require conditions that challenge the first wall surfaces.

2.4 Active density control

 One concern raised in ASC discussions was that the requirement to have good pumping with a future cyro pump may place a limitation on the strike-point sweeps.

**ASC-3: Disruption avoidance by controlled discharge shutdown**

This research does not place any requirements on the ramp up and flattop discharge.  However, it is likely that controlled shutdown will act to reduce the plasma elongation quickly, potentially moving the strike-point locations to transient positions prior to becoming centerstack limited.  ASC members agreed that more work is needed to map out the sequence of a shutdown with the consideration of tile heating limits. Similar to ASC-2, some margin for error is required while developing the controller and the development timeline depends on when fish-scaled tiles and active tile protection are implemented.

**ASC-4: Scenario optimization for next-step devices**

 This research thrust encompasses topics that aim to push the boundaries of NSTX-U operations in terms of performance and scenario integration. In the view of ASC, the tile heating limits will inform the experiments within this thrust rather than the experiments restricting the tile design.