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SUBJECT: IMPACT OF POTENTIAL POLAR REGION MODIFICATIONS ON RESEARCH AND SCENARIOS FOR SOLENOID FREE PLASMA START-UP AND RAMP-UP TOPICAL SCIENCE GROUP (SFPS)

While many fusion experiments are studying non-inductive current drive and current ramp-up, NSTX-U is the only machine in the world that has a program, and hardware capabilities, capable of demonstrating full solenoid-free plasma start-up and current ramp-up to the needed sustainment levels. This experimental demonstration would fundamentally alter future tokamak/ST designs, and would represent a major and unique NSTX-U contribution to world fusion energy development.

This unique capability on NSTX-U was developed over more than a decade and half of important progress with transient coaxial helicity injection (CHI).

Compared to other methods for solenoid-free-plasma start-up, many of which are presently being studied in existing experiments, transient CHI is the only method for which the scaling is well understood. The scaling is simple. The current generated is proportional to the injected flux. The conversion factor from open flux to closed flux is quite large in NSTX, about 70%. NIMROD simulations also now support this.

The NSTX-U experiment is equipped with all the tools, and more, to develop transient CHI capability to the extent that the next machine could be built without a solenoid.

NSTX-U's capabilities for transient CHI development are:

1) ***High Injector Flux Capability***: Over 300 mWb of injector flux are available on NSTX-U. On NSTX, 50 mWb of injector flux resulted in the generation of 160 kA of closed flux current. While only 400 kA of start-up current is needed for the present planned non-inductive start-up and ramp-up scenario, the over 300 mWb of injector flux capability means that start-up plasma currents in the range of 1 MA could be explored on NSTX-U. With start-up currents over 800 kA, the intermediate step of non-inductive current ramp-up could be bypassed on NSTX-U; then one needs to only do the current sustainment work, which would be easier on NSTX-U. Such a demonstration would lead to the consideration of new high-field ST designs that could use the space eliminated by the solenoid for a much higher field TF, possibly using new

high temperature super conductor technology, leading to simpler and lower cost reactor systems in which a large fraction of the current needed for sustained operation could be generated by transient CHI. Whether or not all of the current needed for sustained operation in a reactor could be generated by transient CHI is an exciting possibility that research on NSTX-U would help answer.

2) ***High Toroidal Field***: NSTX-U is also equipped with high 1 T toroidal field capability, to allow high levels of magnetic flux to be injected with acceptable levels of injector current.
3) ***Flexible Current Drive****:* The second more tangential neutral beam system is projected to be capable of current sustainment, and provide the current overdrive for the ramp-up scenario.
4) ***Capability for ECH***: NSTX-U at this time does not have an ECH system, but this is an external system that can be easily added since providing this capability does not require internal vessel modifications.
5) ***Strong Coupling to MHD Theory*****:** During the past few years, the modeling work using NIMROD has generated a PRL, and identified the potential for studying leading-edge reconnection physics based on the plasmoid instability. NSTX-U plasmas, through improved diagnosis of the reconnection region, will provide access to new parameter regimes not possible on any basic reconnection studies experiment, because these experiments do not produce plasmas with the confinement and heating parameters possible on NSTX-U. It is only through experimental measurements that these important simulations, that are also of considerable interest to basic reconnection studies, can be validated.

The CHI insulator and the CHI system, although novel to tokamak work, have been integrated into the NSTX design and operations. They have not adversely impacted the efficiency of the facility, while providing key research capabilities.

The NSTX-U engineering team has identified changes to the polar region of NSTX-U that protects the PF1C casing and allows high power divertor plasma operation, while retaining the unique CHI capability.

The revised polar region now uses a double O-ring configuration for all seals, including those for the ceramic break. This reduces the leaks from the polar region O-rings to virtually zero. The dominant O-ring leaks will now be from other locations, such as from the NBI pumping duct and diagnostic O-rings. In addition, the CHI ceramic assembly is assembled separately and leak checked, before the assembly is installed on NSTX-U. So the possibility of a leak from the CHI insulator is virtually zero.

During extensive Lithium deposition experiments on NSTX during the 2010 campaign, in support of a liquid lithium divertor experiment, there was no evidence for lithium interactions with the CHI insulator. This is because, the insulator is located on the vertical portion on the vessel, and recessed to be away from the vessel wall, so it is not possible for lithium to be deposited on the insulator. If the lithium is in liquid form, gravity would cause the lithium to settle down at a level lower than the physical location of the insulator. Based on the FY2010 experience, it is unlikely that lithium deposition levels similar to that used in 2010 would be used on NSTX-U.

Given the enormous positive impact transient CHI would have on the NSTX-U physics program, and with no demonstrable negative impact to machine operations, it would clearly represent a large loss to world fusion research if the transient CHI system were to be removed from NSTX-U.

It is also important to note that if the CHI insulator were to be removed, NSTX-U would need to rely on oscillating AC currents in the TF coil or in the OH coil for baking the vacuum vessel.

The present bake-out system has also operated reliably both on NSTX and NSTX-U, and there is considerable risk in implementing a new, unproven on NSTX, bake out system that relies on driving AC currents in these important coils. NSTX has had both OH and TF coil failure issues in the past, and some of the coil failures were related to the coil insulation material failing after a few years of routine operations. In general, the coil insulation experiences more stress when subjected to many oscillating current pulses, than when they are driven at constant current.
Driving AC currents in these coils and subjecting them to increased duty cycle clearly puts these coils at additional risk, and we do not have data on how some of these coils (the TF outer leg, the PF4, PF5, PF3 and PF2 coils) that are now over 20 years old would behave. Further any component inside the TF could suffer damage from eddy current heating; identifying which components or diagnostics might be damaged may prove more difficult than imagined.

It is only by taking the bold step to test and implement new tools and hardware capabilities that new ground breaking developments occur on a faster time-scale. Transient CHI is one such tool, and NSTX-U is already equipped with it. What remains is few years for the experimental work.

In summary, on NSTX-U, we have a wealth of proven capabilities to conduct game-changing research that would reduce the cost and simplify the tokamak/ST systems and help fusion power be economically competitive. The capabilities are: (a) Well-understood transient CHI scaling, (b) the tools needed for the experimental demonstration of high-current solenoid-free plasma start-up and ramp-up, and (3) simulation capability that benefits not only plasma start-up research, but contributes to the basic work on magnetic reconnection. Note that this basic physics research aspect requires an experimental system for model validation, as evidenced by the construction of new experiments solely to study magnetic reconnection physics.

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