NEUTRAL BEAM ARMOR FOR NSTX UPGRADE

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The National Spherical Torus Experiment (NSTX) is a low aspect ratio, spherical torus (ST) configuration device which is located at Princeton Plasma Physics Laboratory (PPPL). This device is presently being upgraded to enhance its operations by adding a second Neutral Beamline (NBL). This change will nearly double the power available to the plasma but necessitate improvements to other design aspects of NSTX. Included in these upgrades are the relocation and upgrade of the NSTX Neutral Beam Armor to capture both sets of beamline source profiles while maintaining the same level of vacuum vessel wall protection.

In order to minimize the space required to accomplish this, it has been proposed to relocate and reuse the existing armor array, improving the design so that two overlapping sets of beam profiles both fit completely. This beamline overlap could possibly cause the armor tiles to experience higher heat fluxes which translate into higher internal mechanical stresses. This would be mitigated by changing the isotropic graphite (ATJ) tiles in the overlap areas to a rugged 3D carbon-fiber composite (CFC) material, capable of handling thermally-induced stresses. Additional benefits to this recycling design proposal include opportunities to reduce project cost, increase diagnostic port access, and improve an awkward and difficult mounting scheme.

I. INTRODUCTION & BACKGROUND

At the present time, NSTX uses one Neutral Beam Injection (NBI) beamline, injecting a total power up to 7.4 MW into NSTX plasmas. This beam injection has provided numerous benefits in heating, fueling, and adding rotation to NSTX plasmas, and has provided diagnostic information intrinsic to the operation of the Charge Exchange Recombination Spectroscopy (CHERS) and the Motional Stark Effect (MSE) diagnostics.

It has been proposed to upgrade the Neutral Beam Injection System (NBIS) by adding an additional beamline (BL). This will double the power output, add additional fuelling, rotation, and diagnostics data, and allow for wider tangency radii aiming options. The NSTX upgrade (NSTX-U) NBIS configuration will consist of two BLs in a co-injecting arrangement in the NSTX Test Cell (NTC). Each BL has three positive ion sources and associated components to form a neutral beam and to inject it into NSTX-U. Each source can fire separately or in concert and the two BLs can be operated together or separately. With this upgrade, the NBIS will be capable of over 15 MW injected neutral power in support of the NSTX-U experimental program (Table I). With this increase in power, the safety systems also need to be evaluated and upgraded to meet requirements.

The purpose of the Neutral Beam Armor is to provide sacrificial vacuum vessel protection against NB misfiring or "faults". This paper will provide a general description of the upgrade design for the re-use of the NSTX Neutral Beam Armor and will elaborate on the analytical processes used to define the BL source profiles, their maximum heat fluxes, the probable resultant material temperatures and stresses of the armor tiles, as well as propose a tile material upgrade from ATJ to 3D CFC. Finally, the paper will elaborate on the changes to the mounting scheme in order to maximize port accessibility and to withstand larger disruption forces in the vessel. [2]

II. NEUTRAL BEAM ARMOR UPGRADE

The current plan for the NSTX NBI In-Vessel Armor Upgrade is to recycle the existing armor array. The armor

TABLE I. NSTX-U Neutral Beam Power (Reproduced from Ref. 1)

NB Shot type	Pulse Length (s)	Power (MW)	Heat flux/source (MW/m^2)	Flux to armor per NB source (MW/m^2)	Overlap Flux Peak for 2 NBs (MW/m^2)
80 kV	5	5	31.60	7.70	43.01
90 kV	3	6	37.88	9.24	28.67
110 kV	1	9	56.82	13.86	23.89

will be moved counterclockwise and centered on the Bay H vacuum port, allowing it to catch all six BL source profiles (Figure 1).

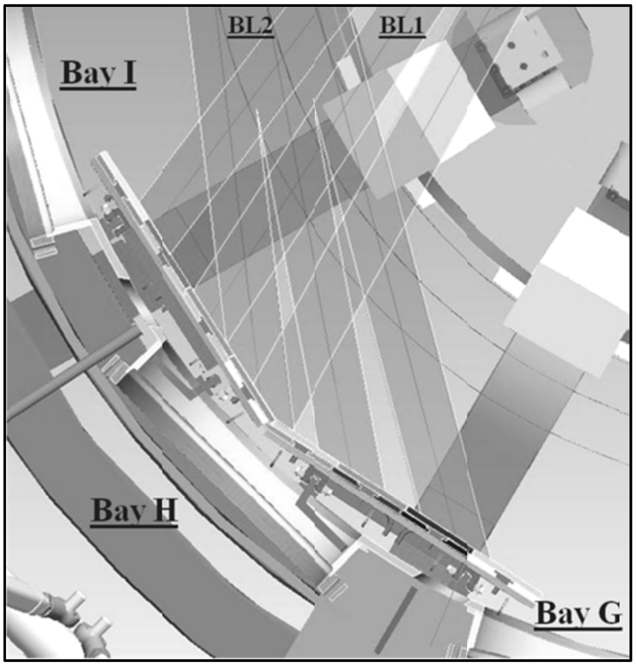

Fig. 1. Vacuum ports and BL alignment[3]

Some of the major benefits of moving the armor, rather than physically extending it on either side include preserving the space for diagnostic access on the mid-plane, utilizing Bays G, H, and I as mechanical access-points to the armor mounts, and major cost savings to the upgrade through the use of fewer materials. Because this proposed design exceeded the original operational limits of the armor, both the thermal and mechanical aspects of the design needed evaluation.

II.A. Thermal Evaluation

The following was considered and analyzed: BL source “footprint” fit on the armor, tile material suitability with respect to the increase in surface heat flux during “fault” conditions, and the efficiency of between-shot cooling during normal operations using the existing armor cooling system.

It should be noted that a “fault” is not a common event and the material evaluation of the armor is as a sacrificial surface. The primary purpose of the NB Armor is to protect the NSTX Vacuum Vessel in the highly unlikely event that the plasma-current interlocks fail and the NBs are fired without the presence of plasma.

II.A.1. Beamline Source Fit on Armor Face

To establish the fit of the beamline source profiles, their divergence was calculated. The spread of the source profiles or “footprints” is well-behaved, obeying an elliptical edge-divergence of about 0.5 degrees horizontally and 1.5 degrees vertically. This has been empirically confirmed by observation of armor striping on the present array (Figure 2). This image shows the lack of white lithium deposition due to the high surface temperature of the tiles where they are being struck by neutral beam sources during aiming and MSE calibrations.

Fig. 2. Beamline source “footprints” show as evaporated zones on the lithium-covered armor face
(Tiles are roughly 6.5” x 6.5”)

Taking this dispersion behavior into account, all six sources were plotted on a model of the armor to confirm their fit. For analysis purposes, the beam profiles were modeled as two distinct areas: the core beam which represents the area with the highest power concentration (80% of total source power), and the divergent beam which represents the area of high beam scatter (20% total source power) (Figure 3).

II.A.2. Armor Material Evaluation for Fault Conditions

The specifications for the present NSTX armor were designed for a single BL, three sources, with a worst case “fault” condition of 28 MW/m^2 for 0.75 seconds.[4] This was based upon an old Tokamak Fusion Test Reactor (TFTR) specification and was deemed acceptable for ATJ graphite armor tiles.

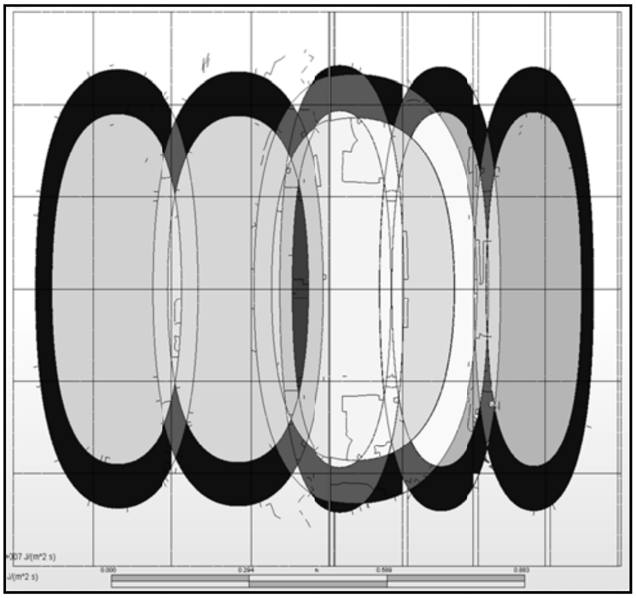

Fig. 3. NSTX-U source profile placement upon armor[3]

For the NSTX-U, in addition to the second BL, NB shot duration has been increased to the values shown in Table I. Therefore, an NSTX-U "fault" condition would be the maximum heat flux for the full duration possible. For example, during an 80 kV shot with a single NB, the armor might see sustained heat flux of 7.70 MW/m^2 for five seconds. For an 80 kV shot with two NBs, the heat flux could be up to 43 MW/m^2 for five seconds. The shots cannot last longer than described or the system risks damage to the NBL ion dumps, so this is a hard time-limit for the "fault".

TABLE II. Single BL Analysis Results

	Run Description	T (°C)	Time (s)	Stress (MPa)
1 Beamline	**MSE, 90 kV, 400 ms, 9.24 MW/m^2**	545	0.433	8.91
	80 kV, 5 s, 7.70 MW/m^2	1894	5.5	16.16
	90 kV, 3 s, 9.23 MW/m^2	1611	3.08	16.76
	110 kV, 1 s, 13.86 MW/m^2			
	max Temp	1220	1.05	16.42
	max Stress	956	1.2	17.78

The present thermal tiles on the armor are made of ATJ, a nuclear-grade, isotropic graphite. An initial thermal analysis using ALGOR[5] found this particular material to be suitable for a single BL "fault" (Table II). The max surface temperatures and subsequent max internal stresses were within the capabilities of the material: 2600 ºC and 26 MPa tensile, respectively. 2600 ºC is the temperature used for the point at which sublimation begins to rapidly accelerate. In the case of NSTX-U, the carbon in the armor array will only be near this temperature for a fraction of the full run time of 20 minutes, reducing material loss due this phenomenon to an acceptable level. Any wear to the armor tiles will be observed and repaired during yearly maintenance.

However, when the "double fault" condition was analyzed, a different result was found. With the addition of the second BL, areas of overlap are created on the armor (Figure 3). These lead to larger power densities up to three times that of a single source which cause large tensile stresses within the armor tiles, surpassing the limits of ATJ (Table III).

TABLE III. Double BL Analysis Results

	Run Description	T (°C)	Time (s)	Stress (MPa)
2 Beamlines	**80 kV, max q: 23.9 MW/m^2**			
	@ approx 2600C	2694	1.68	36.6
	@ ATJ limits	1965	0.96	25.6
	90 kV, max q: 35.8 MW/m^2			
	@ approx 2600C	2643	1.08	37.88
	@ ATJ limits	1906	0.6	26.1
	110 kV, max q: 35.84 MW/m^2			
	@ approx 2600C	2649	0.675	38.68
	@ ATJ limits	1880	0.375	26.86

These preliminary analyses of the overlap zones show that the max temperatures and related internal stresses make ATJ graphite an insufficient shielding material. It is proposed to replace the tiles within the overlap zones with a multi-dimensional carbon-fiber composite, a material better-equipped to handle the thermo-mechanical requirements of the armor. Research was done to investigate sources for a suitable 3D CFC and the following were approached for information: SAFRAN Group, Carbon Composites INC., Fiber Materials INC., HITCO Carbon Composites INC. (member of the SGL Group), and Meggitt Aircraft. Due to the International Trade and Arms Regulations (ITAR) and proprietary restrictions, it is not possible to discuss material properties from all of these companies, but all had promising products, suitable for the needs of the NSTX-U armor.

The impact of the additional BL is significant but does not impair the primary function of the NB armor. In the event of a “double fault” where two BLs fire for the duration of a full shot into the armor, the first priority is ensuring the tiles do not crack. 3D CFC has excellent thermal shock resistance as well as suitable tensile strengths. The next step is recognizing that after 2600 ºC, the carbon will begin to accelerate sublimation, but that the thickness of the tiles as well as the presence of thick stainless steel backing plates will provide enough material to protect the vacuum vessel wall. Therefore, if a “double fault” occurs, the armor will need inspection, evaluation, and maintenance, but will adequately perform its duty as a sacrificial protective surface.

II.A.3. Between-Shot Cooling

The armor is presently equipped with a cooling system which runs through channels in the stainless steel backing plates (Figure 4). A preliminary thermal analysis was performed to confirm that the concept to reuse this system was viable. A simple, “back of the envelope” analysis with a slice of armor and backing plate was used to determine the time constant for cooling. The analysis was run in ALGOR[5] with a 3”x1” armor “slice”, complete with a 3/8” cooling tube section running through a stainless steel backing plate. After applying the flow rate of the cooling system to the tube section, a worst-case heat load was applied and the system was allowed to cool for 20 minutes. Initial results produced a time constant of about 70 seconds, (Figure 5) which, since the between shot time for the upgrade was increased from 900 to 1200 seconds, suggests that the present cooling system is adequate to handle the increased heat loading from the upgrade.

II.B. Mechanical Evaluation

Mechanically, the following was considered and evaluated: the placement of the armor mount points in terms of accessibility, the mechanical loading of the armor mounting system, and the thermal growth of the armor backing plates during bake out.

II.B.1. Armor Mounting and Accessibility

With the relocation of the armor, there is an opportunity of improving the existing armor design for accessibility and the increasing mechanical loads. After the move, the armor will be almost centered on Bay H, allowing access to all of the center mounting points via that port. However, as an added improvement, all of the side mounting points on the array can also be accessed via Bays G and I (Figure 4). This modification makes installation and repairs considerably easier to accomplish and allows an increased number of mount points, if needed, to overcome any increase in the mechanical loading due to electromagnetic forces.

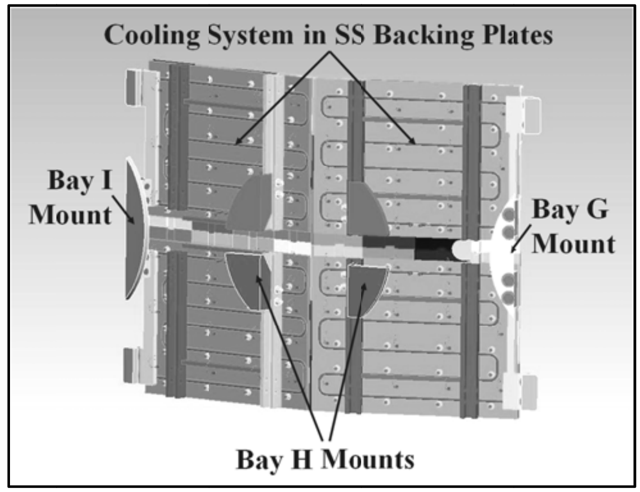

Fig. 4. Back of the armor showing cooling line layout and armor mounting points[3]

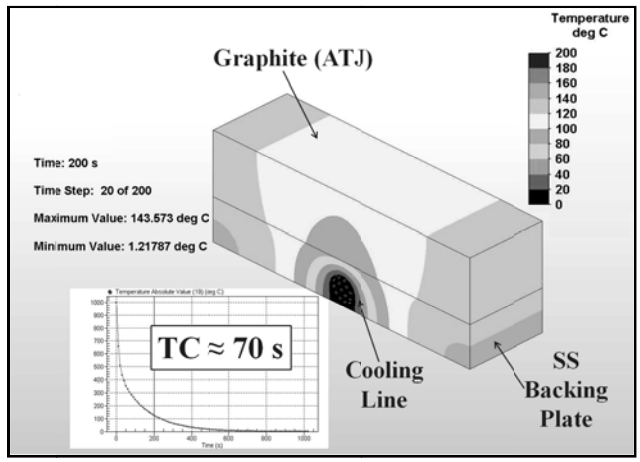

Fig. 5. Cooling time constant for a “slice” of armor[3]

II.B.2. Mechanical Loading of Armor System

An ANSYS[6] study was done to the Armor System in order to qualify it for disruption loading. Since the armor is symmetric about two planes (Figure 6), only $1/4^{th}$ was needed for this study. After applying the disruption loading and running a transient dynamic analysis, the max transient equivalent stress was found to be less than 68.95 MPa, well within the material strength capacity of the 304 stainless steel (Yield Strength = 215 MPa) used in the design. However, these results are based on merged solids, meaning the model was exceedingly stiff for a dynamic simulation, possibly obscuring areas of concern. This was adequate for a preliminary FE analysis, but additional qualification is underway with more realistic models.

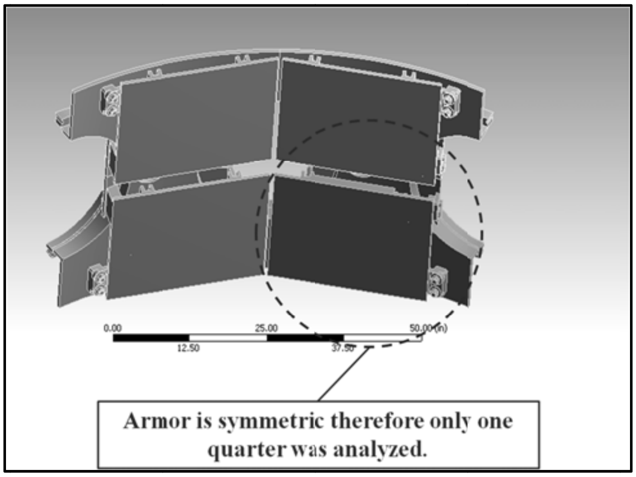

Fig. 6. Armor model used for mechanical analysis[3]

II.B.3. Thermal Growth in Backing Plates

The armor is assembled in four quadrants with the tiles mounted to stainless steel backing plates which also serve to house the cooling lines. During normal operation in the upgrade regime, the highest temperatures the backing plates should see would be during bake out, when the cooling lines are pumped with hot helium in order to heat the vacuum vessel and drive off water and impurities from the internal components of NSTX-U. During this time, the armor assembly will reach 150 ºC. With the changes to the armor mounting scheme, the thermal growth of these plates needed to be re-evaluated for possible infringement between carbon tiles. A model of the SS plate/cooling line assembly was imported into ALGOR[5] and the bake out conditions simulated. Results show that the plates grow "up and out"[3] away from each other, posing no threat to the carbon tiles.

III. CONCLUSIONS

The design plan to reuse the armor array to accommodate the second NBL is viable. The sources fit appropriately on the armor, the material change from ATJ graphite to 3D CFC will adequately handle the increased heat flux, and during normal operation, the cooling system will be able to remove the residual heat from the armor between shots. The changes to the mounting scheme will help with the difficulty of armor installation, removal, and maintenance, and handle the increase of mechanical loading due to electromagnetic disruption forces. Thermal growth of the large stainless steel backing plates will not cause any issues with clearances between armor quadrants or tiles. To further augment the design, other improvements will be implemented, such as adding more material to the backing plates between quadrants and increasing engineering and administrative control via an additional plasma interlock to guard against fault cases. Above all, it has been shown that the NBI Armor design is well-suited to be adapted to handle the increased loading from two NBLs, and should provide adequate protection for the NSTX-U vacuum vessel.

ACKNOWLEDGMENTS

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