Operating The Upgraded NSTX HHFW Antenna Array In An Environment With Li-coated Surfaces

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Abstract. The single-feed, end-grounded straps of the NSTX 12-strap HHFW antenna array have been replaced with double-feed, center-grounded straps to reduce the voltages in the vicinity of the Faraday shield (FS) for a given strap current. The strap spacings to the FS and to the back plate were increased by 3 mm to decrease the electric fields for a given voltage. The electric fields near the FS have been roughly halved for the same strap currents, permitting a direct examination of the roles that internal fields play in determining antenna power limits in plasmas. Extensive RF/plasma conditioning of the antenna was required to remove enough of the evaporated Li deposits from prior wall conditioning to permit coupling in excess of 4 MW to L- and H-mode plasmas in 2009. Most arcs were associated with expulsion of Li from the FS/antenna frame surfaces. The center-grounded straps were less susceptible to arcing during ELMing H-mode plasmas. Reliable operation above 2 MW was difficult after the installation of the Liquid Lithium Divertor (LLD) in 2010. Li-compound "dust" was found in the antennas after this run and is believed to have contributed to the reduced power limit.

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INTRODUCTION

The High Harmonic Fast Wave (HHFW) system on NSTX is used for electron heating, current drive, current profile control, and plasma ramp up/sustainment. It is a 12-element, phased array operating at 30 MHz, driven by six transmitters (nominally 1 MW each) [1]. HHFW operation has benefitted from the deposition of lithium coatings on plasma facing surfaces, applied between shots from two heated evaporators (LiTERs) located at the top of the machine [2]. The resulting decrease in plasma density in the edge has allowed the position of the fast wave cutoff to move away from the first wall, reducing power losses to the edge and improving the core heating efficiency [3].

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THE UPGRADED ANTENNA GEOMETRY

The original, single end-fed, end-grounded current straps were replaced with double end-fed, center-grounded straps prior to the start of the 2009 experimental campaign [4]. The hypothesis was that the electric fields at the high voltage end of the straps, internal to the Faraday shield (FS) but in close proximity to the plasma, were primarily responsible for the arcs that were limiting reliable high power operation to about 3 MW in 2008. If the system voltage limit in plasma (~15-16 kV) could be increased to its limit in vacuum (~25 kV), the power delivery capability of the system could potentially more than double.

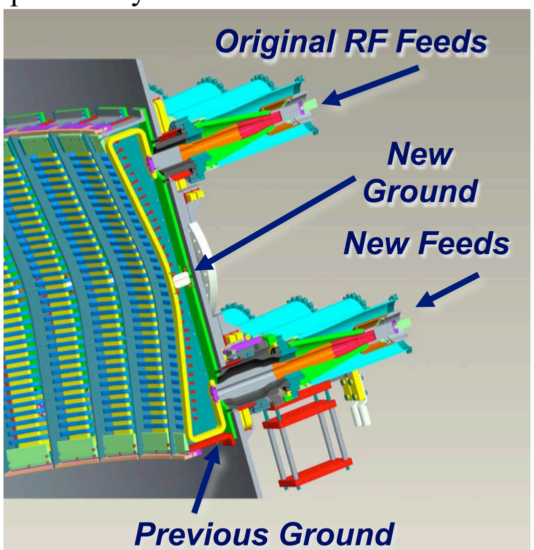
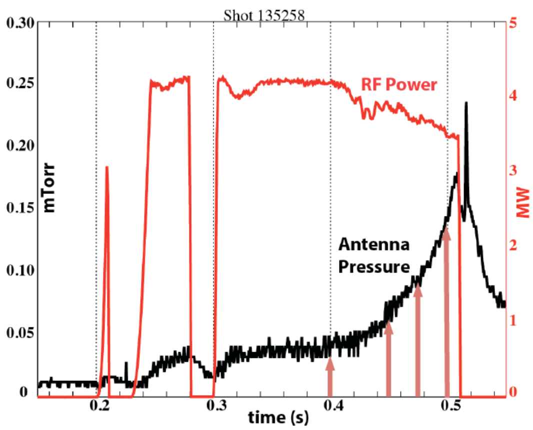


FIGURE 1. The new strap configuration moves the ground point from the end to the center of the strap and adds a second power port at the bottom, to be fed 180º with respect to the top port.

The new straps are similar in shape and dimensions to the originals, but the ground has been moved to the center of the strap, reducing the voltage extreme on the end of the strap. Moreover, 3 mm have been added to the gaps between the straps and grounded surfaces of the FS and antenna box, thus reducing the electric field for a given voltage. The new lower ports are driven out-of-phase with respect to the original upper ports by the addition of a half-wavelength (5 m) section of transmission line for each strap. Calculations by CST Microwave Studio indicate that the new geometry reduces the peak voltage on the straps by 40% for the same ground current in the strap and by 50% for the same strap power (the slightly higher effective loading is due to more uniform current distribution in the center-grounded strap). The maximum system voltage for each strap pair is located at the cube where the two legs of the resonant loops, the two connections for the mutual inductance decouplers, and the transmitter power feed all meet. These cube voltages are slightly higher (~9%) for the same power with the new straps, while the voltages at the vacuum feedthroughs are about the same as before. System peak voltages quoted are measured at the cubes; the peak voltage on the straps was about 80% of the cube voltage for the end-grounded straps and 38% for the center-grounded straps.

HHFW OPERATION WITH LITHIUM-COATED SURFACES

The upgraded antenna straps were installed in NSTX in April, 2009, prior to the machine bakeout and initial operation of the 2009 experimental campaign. However, the installation of the transmission lines was not completed until July, by which time approximately 300 g of Li had been deposited in the machine, much of it on the antenna itself. The new straps were subjected to high voltage vacuum conditioning and the maximum system voltage reached its previous limit of 22-25 kV rather rapidly.



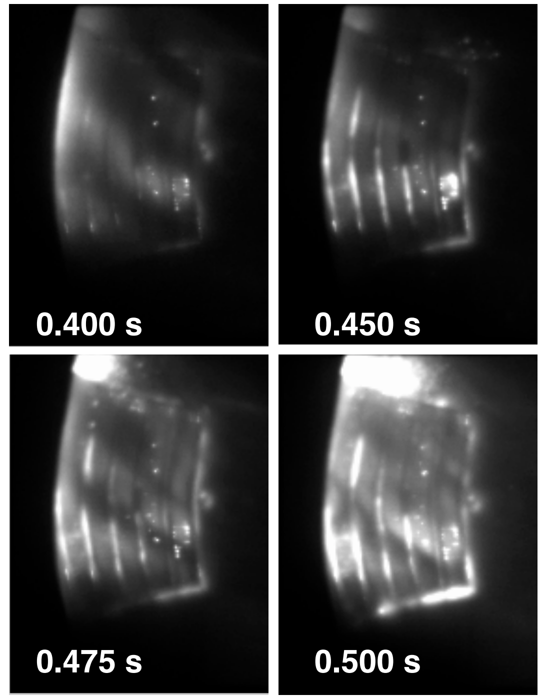


FIGURE 2. (a) RF power (red) and neutral pressure in antenna (black) as a function of time for shot 135258; the pressure rises during last 100 ms of HHFW pulse and the power falls due to an increasing load mismatch. (b) Camera images of straps 8-12 during last 100 ms of the HHFW pulse show increasing Li ablation from the top of the array before an arc shuts off power at 0.51 s.

Moreover, high frame-rate cameras recording the visible light from the antennas on a small fraction of the vacuum conditioning shots confirmed that the arcs were all located within the antenna box, usually on the high voltage ends of the straps. The introduction of 76mm transmission line in a few spatially constrained locations rather than the 152mm line used for the rest of the resonant loops did not compromise the maximum attainable system voltage in vacuum. Several days of plasma conditioning the antenna were needed to ablate lithium deposits on its surface by progressively increasing the power until reliable high power operation (~4 MW) was attained. An example of a 4 MW plasma conditioning pulse is shown in Fig. 2. Photos of the antenna taken at four times during the pulse show the increasing glow of Li coming off the top of the antenna, while the internal neutral pressure, measured with a fast ion gauge at the back of the antenna (calibrated for D_2), also increases until an arc terminates the pulse.

In 2010 some operational changes were made to accommodate the Liquid Lithium Divertor (LLD) that also affected the HHFW performance: no boronization of the machine, no glow discharge cleaning between shots, and increased LiTER evaporation rates (typically a factor of two compared to 2009). The LLD was prefilled before plasma operation was initiated, precluding any Li-free reference operation of the HHFW system.

Figure 3 shows the HHFW power per shot for the years 2008-10. In 2008 HHFW operation was in the 2-3 MW range, was spread out evenly over five months, and the majority of time was spent on experiments after the initial plasma conditioning. In 2009 the operation with the new center-grounded straps was concentrated in the last month of the campaign, with the majority of time spent on plasma conditioning. The achievable power increased compared to the end-grounded straps, with most shots in the 2.5-4 MW range, and improved with time as the antennas were cleaned of excessive Li deposits. In 2010 operation was widely spaced over four months; almost all the time was spent on plasma conditioning and power levels never exceeded 3 MW and deteriorated with time. Dust particles could be observed traveling toward the antenna during a disruption event, after which achievable power levels would be reduced for many subsequent shots. Dust particles and flakes, presumably Li_2CO_3, were found in the bottom of the antenna boxes after the campaign ended.

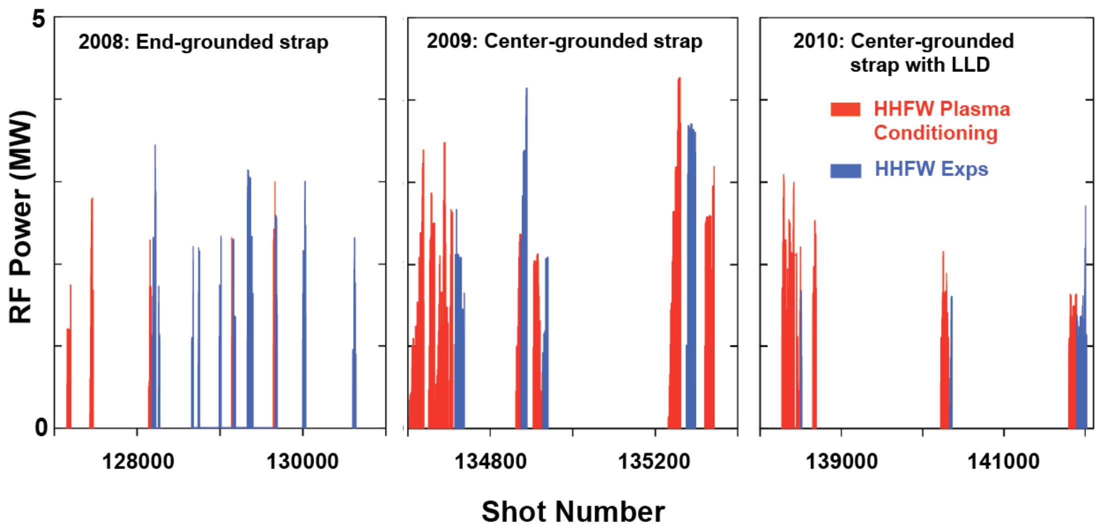


FIGURE 3. Comparison of the total RF power delivered per shot for the years 2008 (end-grounded strap), 2009 (center-grounded strap), and 2010 (center-grounded strap with LLD). The shots in red were primarily intended to condition the antennas in plasma; shots in blue were devoted to HHFW experiments. Operation improved with time in 2009, degraded with time in 2010.

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