Evaluation of the High Power Performance of the Upgraded NSTX HHFW Antenna

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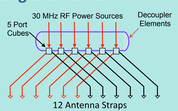
ORNL is managed by UT-Batelle, LLC, for the U.S. Dept. of Energy under contract DE-AC-05-00OR22725. Additional support by U.S. DoE contract DE-AC02-09CH11466.

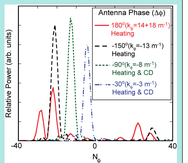
Abstract

The end-grounded straps of the NSTX HHFW antenna array were replaced in 2009 with center-grounded straps to reduce the interior voltages and electric fields in the plasma/Faraday shield region. After accumulated lithium deposits were removed from the antenna surface by plasma conditioning, reliable HHFW power was increased to 3-4 MW from the 2-3 MW levels of 2008. However, in 2010 reliable operation was limited to less than 2 MW, primarily due to changes in the antenna environment associated with the Liquid Li Divertor. The antennas have been cleaned of Li coatings and Li_2CO_3 dust in preparation for the 2011 campaign. The HHFW system will be operated early in the campaign to minimize the effects of Li accumulation in ascertaining the efficacy of reducing internal fields to increase reliability. A visible light camera covering the complete array will observe Li ablation from the powered antenna, and a newly installed IR camera covering ~40% of the array will monitor localized hot spot formation.

The NSTX HHFW system is a 12-element phased array driven by six 1 MW transmitters operating at 30 MHz.

HHFW antenna extends toroidally 90°

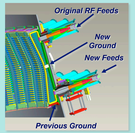


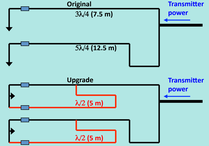


- 12 straps are connected to form two adjacent 6-element arrays, 180° out of phase with each other.
- For phase shifts of 30°, 90°, and 150°, it operates as a 12-element array with a single highly directional peak.
- A decoupler system isolates each transmitter from its two nearest neighbors under vacuum loading conditions.

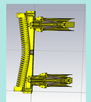
In 2009 the array was upgraded to reduce peak voltages on the straps. Ground was moved from the end of strap to the middle.

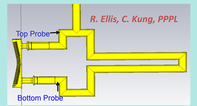
- Goal was to bring system voltage limit with plasma (~15 kV) up to its vacuum limit (~25 kV),
- Power capability expected to double.
- Tests whether electric fields in strap/Faraday shield region or the strap/antenna frame currents set the limit for plasma operation.

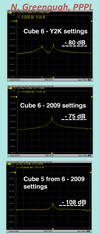




- 60 m of coax transmission line was added to the system.
- Tight quarters required that some 3″ sections be used in the 6″ loops



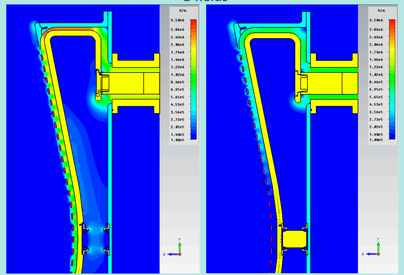




- Microwave Studio used to predict lengths
- Loops made resonant to within ~ 5 kHz to permit good decoupling between sources at cubes
- To cancel the mutual inductances of the straps, the decoupling capacitors were re-adjusted to provide ~33 dB isolation between adjacent transmitters

Electrical Improvements to the Antenna

E-fields

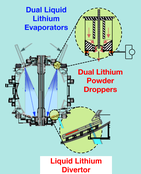


End-grounded | Center-grounded

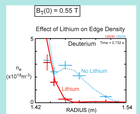
- By moving the ground point, the maximum strap voltage in the vicinity of the Faraday shield is reduced by **40%** for the same strap current (by **48%** for the same delivered power)
- By increasing all the strap to FS/ground gaps by 3 mm, the peak electric field near the plasma is reduced by a factor of roughly **2.5**.
- The maximum system voltage (located at the junction cubes) remains essentially unchanged for the new straps (less than **10%** change for equal powers)
- The ratio of strap voltage to cube voltage is ~**0.38** for the new center-grounded strap and ~**0.80** for the old end-grounded strap.

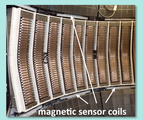
Extensive antenna conditioning needed for high power operation in 2009 after Li introduced into system

Li Evaporators (2006+), Li Droppers (2008+), Liquid Lithium Divertor (2010) improve HHFW coupling to core

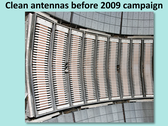


Decreased edge density moves fast wave cutoff away from first wall, lessening edge power losses.





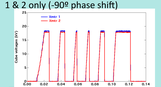
Clean antennas before 2009 campaign

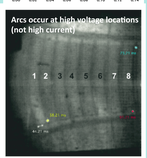


Li-coated antennas after 2009 campaign

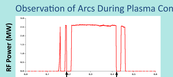
- External connections to antenna were not completed until June, near the end of the 2009 campaign.
- Li deposited on antenna over previous 3 months (~300 g) contributed to arcing and had to be cleaned by both vacuum and plasma conditioning
- Vacuum conditioning
  - Brand new current straps needed high voltage/ current conditioning to remove surface irregularities.
  - System voltage limits after extensive Li operation were often below 10 kV, but quickly conditioned up to previous 22-25 kV limits.
  - Fast camera observation indicated that breakdowns were occurring in the antenna box.
  - Conclusion: introduction of 3-inch line sections did not reduce previous system vacuum voltage limit.

Vacuum conditioning with transmitters 1 & 2 only (-90º phase shift)





Observation of Arcs During Plasma Conditioning



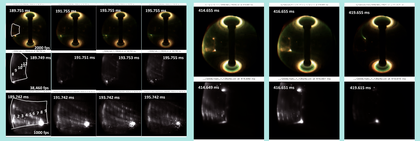
Transmitter 1 (straps 1 & 7) trips off at 188.1 ms

Transmitter 5 (straps 5 & 11) trips off at 418.1 ms

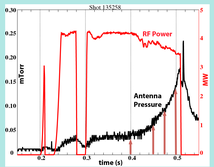
Standard camera sees straps 6-12

Fast camera sees straps 8-12

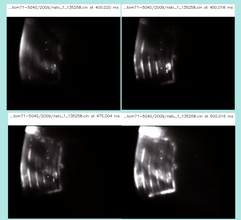
Additional camera sees straps 1-9



Pressure in the antenna rises during sustained lithium ablation/ejection



Observation of lithium ablation correlated with antenna pressure rise

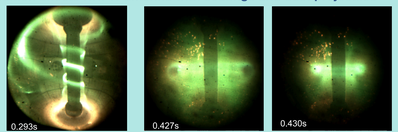


Liquid Lithium Divertor (LLD) operation in 2010

- Changes in the 2010 plasma environment adversely affected HHFW operation
  - Rapid start of Li operations with no boronization or He glow discharge cleaning.
  - Increased evaporation rates of Li (up to 50-100 mg/min in 2010 compared to typically 10-20 mg/min in 2009).
  - More than 1400 grams of Li deposited in machine in 2010.
- Increased dust particles in antenna environment.
  - Several vents in Ar-air from shutter replacements compromised surface conditions, may have contributed to dust generation.
- Increased difficulty in cleaning/conditioning antennas
  - Could vacuum condition the system to 25 kV at the beginning of the campaign, difficult to reach 15 kV by the end.

Lithium deposition affects HHFW antenna with coatings and dust projectiles

Shot 141988
B_T = 4.5 kG,
I_P = 0.9 MA,
Helium,
P_{RF} = 1.9 MW



Lithium from top of antenna moving along magnetic field line

Lithium projectiles at end of shot seen moving outward toward antenna

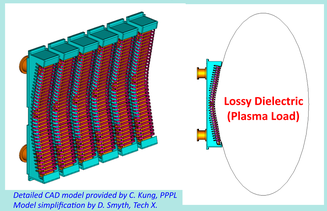
More lithium deposits and "splashes" seen on the straps after the 2010 run

White dust (Li_2CO_3?) was found on antenna straps and in the bottom of antenna boxes

Sites of Lithium Ablation During Antenna Conditioning Appear To Be Dominated By Lithium Deposition Distribution

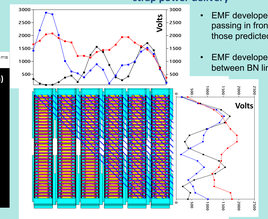
- Sites of lithium ablation depend on
  - lithium deposition distribution
  - plasma configuration (shape and position).
  - HHFW power level
  - Array phasing
- Spaces between magnetic sensor coils above HHFW array are prime sites for lithium accumulation
- Some evidence for periodic spacing of ablation sites for 180º phasing as predicted by Microwave Studio calculation of sheath potentials. Effect obscured by domination of lithium deposition distribution.
- Most rapid cleaning/conditioning occurs when RF power can be maintained for times >40 ms between arcs.

CST Microwave Studio Model (MWS) of 6-element section of HHFW array

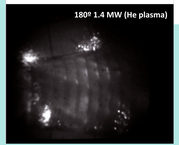


Detailed CAD model provided by C. Kung, PPPL
Model simplification by D. Smyth, Tech X.

MWS Calculation of $\int E_{||} \cdot dl$ along 45º field lines for 0.33 MW per strap power delivery

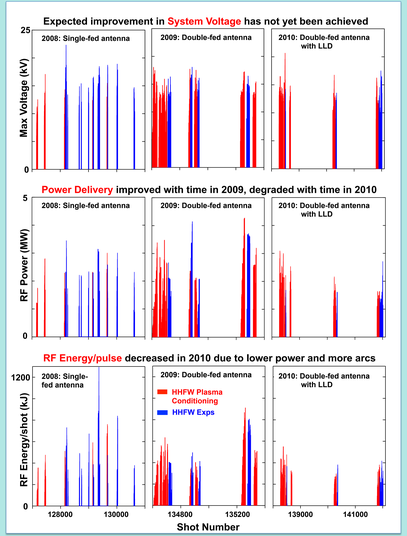


- EMF developed along field lines passing in front of array similar to those predicted for DIII-D upgrade.
- EMF developed along field lines between BN limiters ~ 1200-1700 V



$\Delta\phi$ = 90º
$\Delta\phi$ = 150º
$\Delta\phi$ = 180º

Comparison of HHFW Operation 2008-2010



2008: Single end-fed straps

- Operation spread out evenly over ~5 months.
- Initial plasma conditioning, then majority of time on experiments.
- Most operation in 2-3 MW range throughout campaign.

2009: Double end-fed straps

- Operation concentrated in last 4 weeks.
- Majority of time spent on plasma conditioning.
- Operation in the 2.5-4 MW range, improved with time.

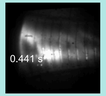
2010: Double end-fed straps with LLD

- Operation widely separated over ~4 months.
- Almost all time spent on plasma conditioning
- Operation < 3 MW, deteriorated with time.
  - Extensive vacuum conditioning needed to maintain system voltage limits.
  - Vacuum voltage holding would degrade when antennas not in use.
  - All vacuum arcs occurred in antenna box, not transmission line

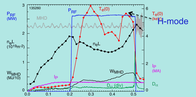
Summary of High Power Operation in 2009

- Antennas rapidly conditioned to previous system vacuum limits of ~25 kV.
- Plasma conditioning was needed to clean accumulated lithium deposits from antenna surfaces. Maximum powers of ~4 MW achieved during conditioning.
- Upgraded antenna allowed higher power operation and more robust heating of H-mode plasmas.
- H-mode regimes established with and without NB injection.

P_{RF} = 2.7 MW case – no antenna arc



Heating after plasma conditioning with P_{RF} = 2.7 MW (He, B_ϕ = 0.55T)



Example shown above for P_{RF} = 2.7 MW ⇒ $T_e(0)$ up to 6.2 keV
RF only H-mode produced near end of RF pulse

Summary of High Power Operation for 2010

- 2010 HHFW operation with the LLD filled by evaporated lithium from the LITER applicators was problematic.
- In 2009 the upgraded antennas conditioned rather rapidly to the 4 MW level in a lithium environment.
- In 2010, reliable operation above 1.2 MW was unachievable even after aggressive antenna conditioning.
- Lithium expulsion from antenna surfaces was greater than observed last year at similar power levels.
- Dust and granular particles were seen during HHFW operation that were largely absent in years past.
- Antenna conditioning can be set back significantly by one plasma "event".

Plans for 2011+

- HHFW experiments planned for 2011-12 were canceled due to the NSTX TF failure this summer.
- HHFW expected performance on NSTX-U will be modeled, including scenarios using a reduced number of straps in the array.
- High voltage vacuum testing of an antenna strap during the 2011-14 down period is being considered.