High Power Operation of the Upgraded NSTX HHFW Antenna Array

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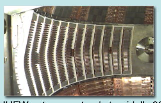
ORNL is managed by UT-Batelle, LLC, for the U.S. Dept. of Energy under contract DE-AC-05-00OR22725. Additional support by U.S. DoE contract DE-AC02-09CH11466.

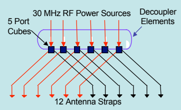
Abstract

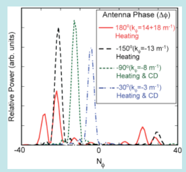
The single-feed, end-grounded straps of the NSTX 12-strap HHFW antenna array have been replaced with double-feed, center-grounded straps while keeping the remaining antenna geometry unchanged. The peak voltages and electric fields in the vicinity of the Faraday shield have been halved for the same strap currents, permitting a direct examination of the roles that strap voltages and currents play in determining antenna power limits in the presence of plasmas. Plasma operation cleaned enough Li deposits, accumulated during prior wall conditioning, from the antenna surfaces to reach coupled powers in excess of 4 MW in L-mode plasmas in 2009. The center-grounded straps were less susceptible to arcing during ELMing H-mode plasmas than the end-grounded straps had been. A fast framing, visible light camera monitors the full antenna array; an arc can usually be associated with expulsion of Li from the FS/antenna frame surfaces in its immediate vicinity. The voltage holding and power levels obtained during the 2010 campaign will be reported and the limiting mechanisms will be discussed.

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



HHFW antenna extends toroidally 90º



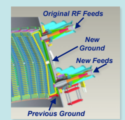


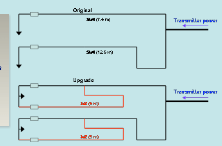
- 12 straps are connected to form two adjacent 6-element arrays, 180º out of phase with each other.
- For phase shifts of 30º, 90º, and 150º, it operates as a 12-element array with a single highly directional peak.
- A decoupler system isolates each transmitter from its two nearest neighbors under vacuum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

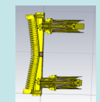
N. Greenough, PPPL

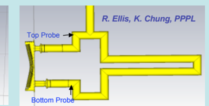
- Goal was to bring system voltage limit with plasma (~15 kV) up to its vacuum limit (~25 kV),
- For a given strap current
  - Peak strap voltages would be halved.
  - Peak voltage on vacuum side of feedthrough would be reduced
  - Peak system voltage in transmission line would remain unchanged.
- Power 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.



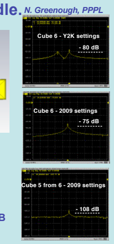


- 60 m of coax tranmission line was added to the system.
- Tight quarters required that some 3" sections be used in the 6" loops

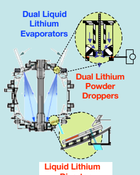




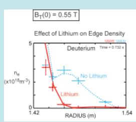
- Microwave Studio used to predict lengths
- Loops made resonant to within ~ 5 kHz to permit good decoupling between sources at cubes
- To cancel the mutual inductances of the straps, the decoupling capacitors were re-adjusted to provide ~33 dB isolation between adjacent transmitters



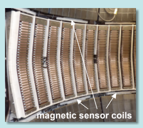
Li Evaporators (2006+), Li Droppers (2008+), Liquid Lithium Divertor (2010) improve HHFW coupling to core



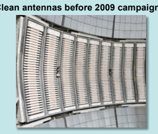
Decreased edge density moves fast wave cutoff away from first wall, lessening edge power losses.



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



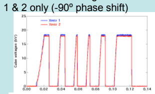
Clean antennas before 2009 campaign

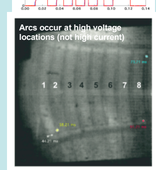


Li-coated antennas after 2009 campaign

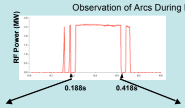
- External connections to antenna were not completed until June, near the end of the 2009 campaign.
- Li deposited on antenna over previous 3 months (~300 g) contributed to arcing and had to be cleaned by both vacuum and plasma conditioning
- Vacuum conditioning
  - Brand new current straps needed high 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 occuring 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)

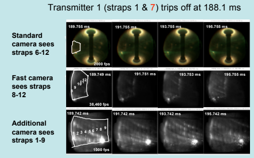




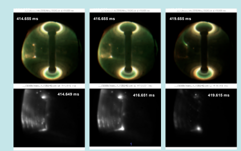
Observation of Arcs During Plasma Conditioning



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



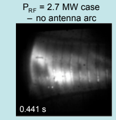
Transmitter 5 (straps 5 & 11) trips off at 418.1 ms



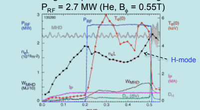
Summary of High Power Operation in 2009

- 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)



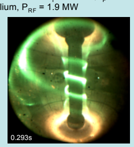
- Example shown above for P_{RF} = 2.7 MW ⇒ $T_e(0)$ up to 6.2 keV
- RF only H-mode produced near end of RF pulse

Liquid Lithium Divertor (LLD) operation in 2010

- Increased lithium deposition on antenna structures from LITER system
- Increased dust particles in antenna environment.
- Increased difficulty in cleaning/conditioning antennas

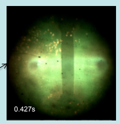
Lithium deposition affects HHFW antenna with coatings and dust projectiles

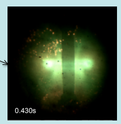
Shot 141988 B_T = 4.5 kG, I_P = 0.9 MA,
Helium, P_{RF} = 1.9 MW



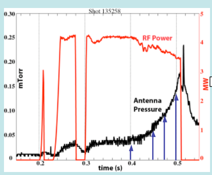
Lithium from top of antenna moving along magnetic field line

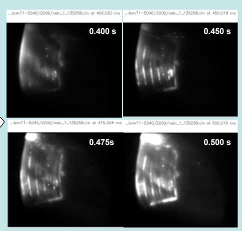
Lithium projectiles at end of shot
- Moving outward toward antenna





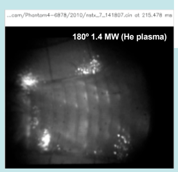
Pressure in the antenna rises during sustained lithium ablation/ejection



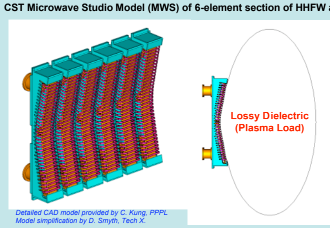


Sites of Lithium Ablation During Antenna Conditioning Appear To Be Dominated By Lithium Deposition Distribution

- 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.

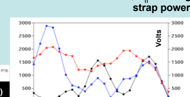


CST Microwave Studio Model (MWS) of 6-element section of HHFW array

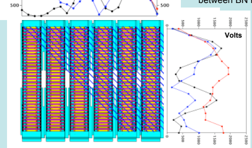


Detailed CAD model provided by C. Kung, PPPL
Model simplification by D. Smyth, Tech X.

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

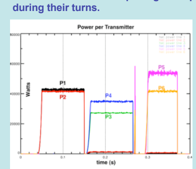


$\Delta\phi$ = 90º
$\Delta\phi$ = 150º
$\Delta\phi$ = 180º

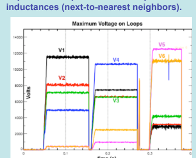
Developing Techniques For More Efficient Cleaning/Conditioning Antennas

Between-shot, sequential transmitter vacuum conditioning

- Transmitters were sequentially pulsed in pairs for vacuum conditioning between shots. (3 x 0.1s/30 s for 300 s)
- Increases overall effective duty cycle.
- Easier to match and to adjust power levels for each loop than for all six simultaneously.
- Arcing on one loop wouldn't trip all six transmitters. The other pairs get full pulse during their turns.



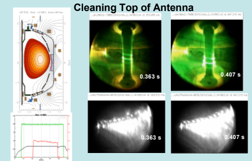
Although de-couplers isolate nearest transmitters from one another, voltages still appear on unpowered loops due to uncompensated mutual inductances (next-to-nearest neighbors).



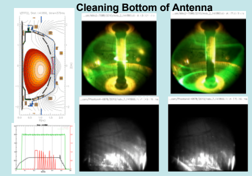
Plasma Scrubbing of Antenna

- Move NBI-heated plasma ± 20 cm vertically from shot to shot to "plasma scour" top and bottom of antenna.
- Profuse lithium expulsion throughout, enhanced while RF is on.
- Observed no great improvement in power capability after limited testing (4 shots).

Cleaning Top of Antenna



Cleaning Bottom of Antenna



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".

Future HHFW Operation Plans

Need to protect antennas from Li contamination

- Improve shielding/cleaning antenna arrays
  - Improve between-shot conditioning techniques
  - Evaluate effectiveness of plasma scrubbing
  - Modify BN limiters?
  - Shield above array?
- More directed method of filling LLD needed to keep antenna surfaces clean
  - Improved collimation on LITER closest to antenna?
  - More effective LLD filling technique?