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Operation of the NSTX upgrade HHFW antenna array with the Liquid Lithium Divertor*

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Introduction

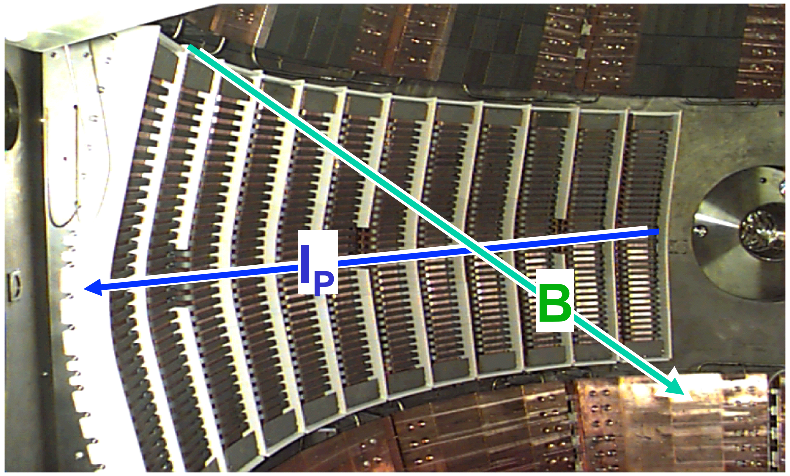
- Good RF physics results were obtained on NSTX in 2009 and 2010, and will be reported by Joel Hosea and Gary Taylor.
  - H-mode with HHFW alone
  - H-mode with NBI and HHFW
  - HHFW interaction with ELMs
  - Low current (I_p ~ 300 kA) HHFW H-mode operation

- This presentation will focus the difficulties the HHFW system had operating with the liquid lithium divertor (LLD) in 2010.

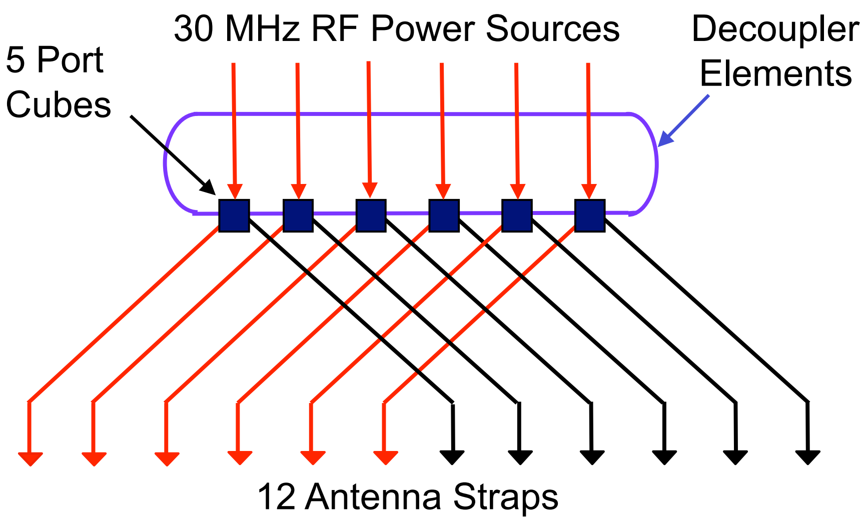
Outline

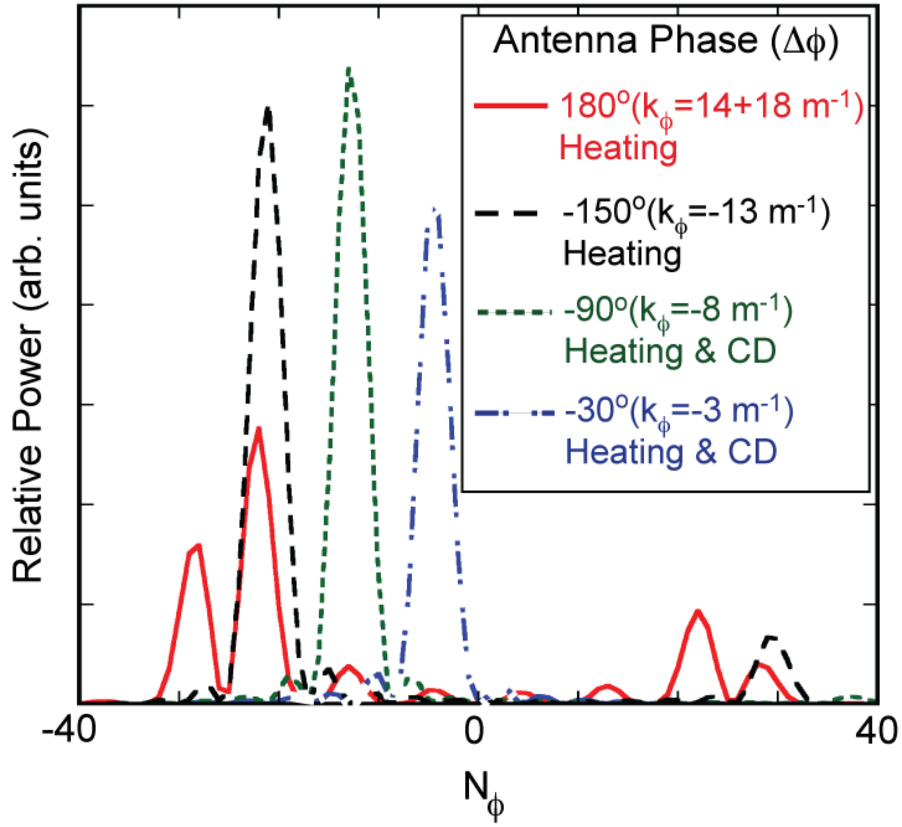
- The High Harmonic Fast Wave (HHFW) system on NSTX
- The lithium evaporators (LiTER) and liquid lithium divertor (LLD) on NSTX
- 2009 operation with the HHFW Upgraded Antenna in lithium environment.
- 2010 HHFW operation with LLD
- Future plans

NSTX HHFW System: Six (1 MW each) Transmitters Drive a 12-element Phased Array at 30 MHz



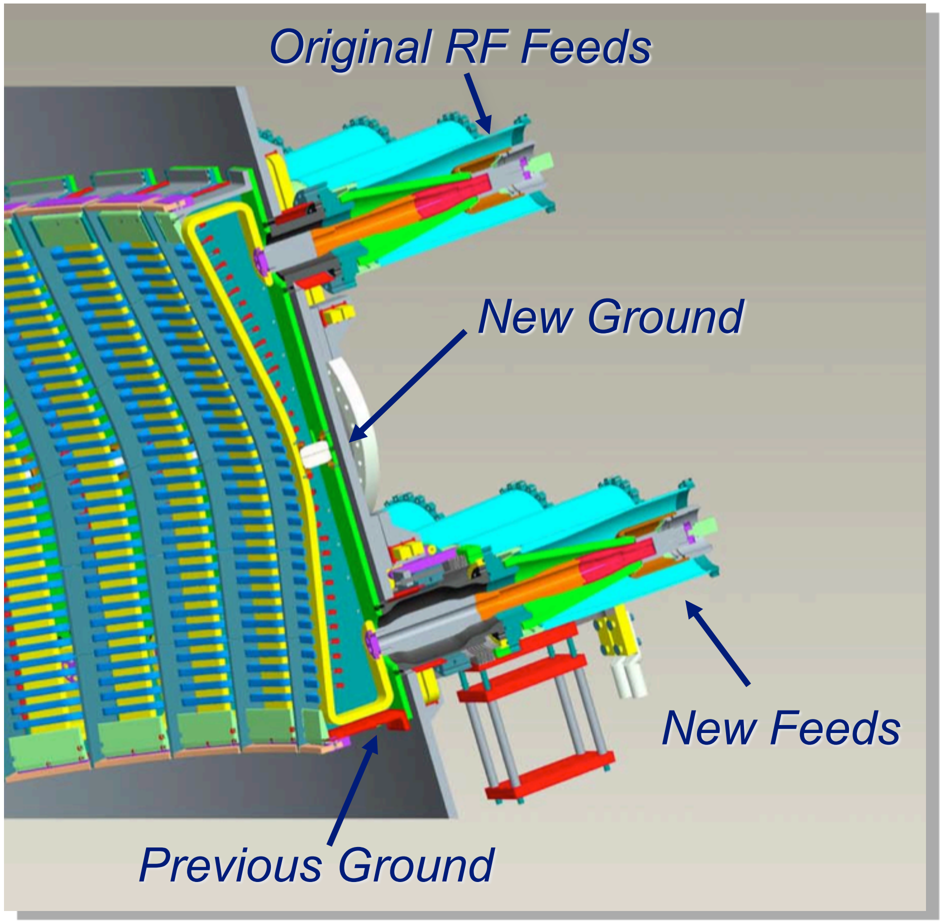
B-field makes ~45º angle at antenna





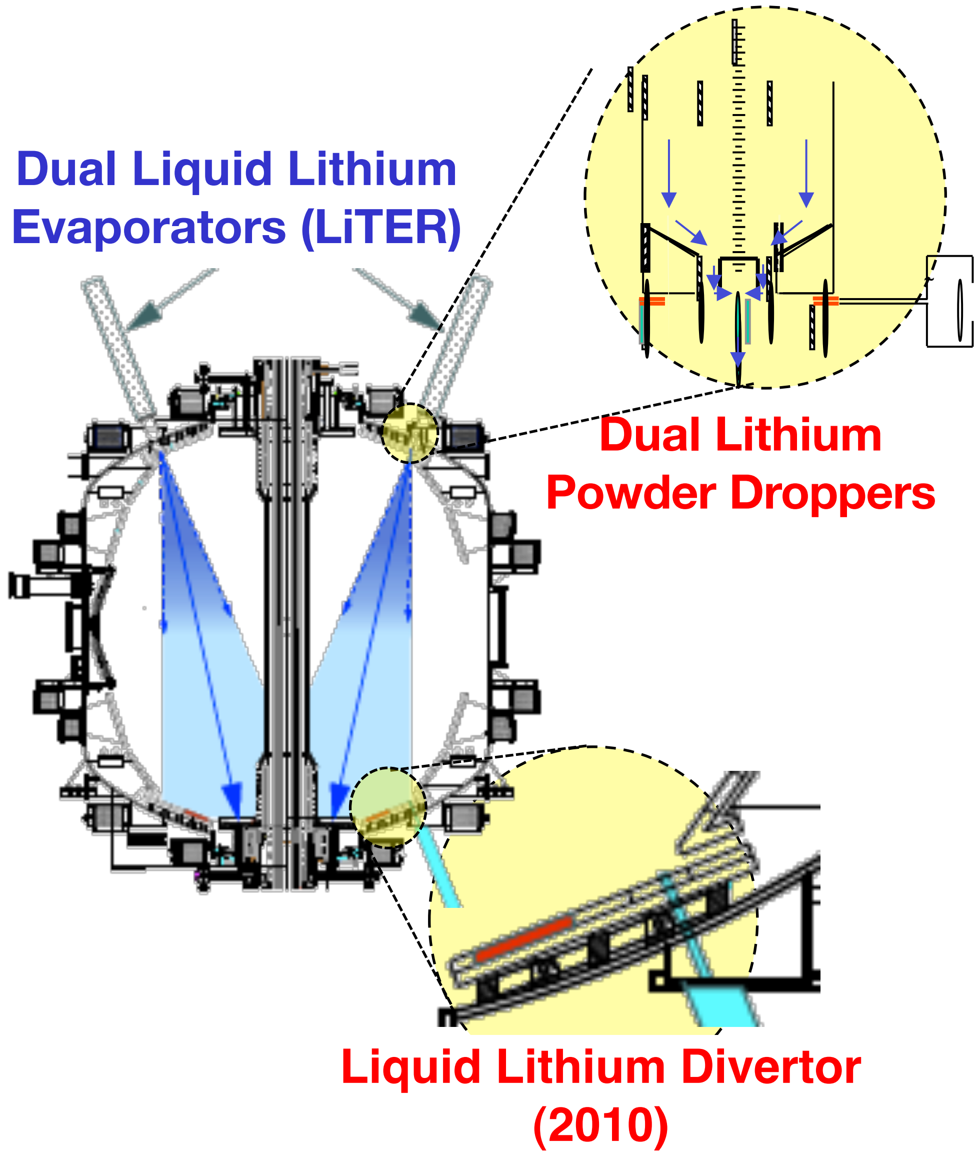
- **12 straps are connected to form two adjacent 6-element arrays, 180º out of phase with each other.**
- **For phase shifts of 30º, 90º, and 150º, it operates as a full 12-element array with a single highly directional peak (3, 8, 13 m^{-1}).**

Single end-fed, end-grounded straps vs. double-end fed, center-grounded straps

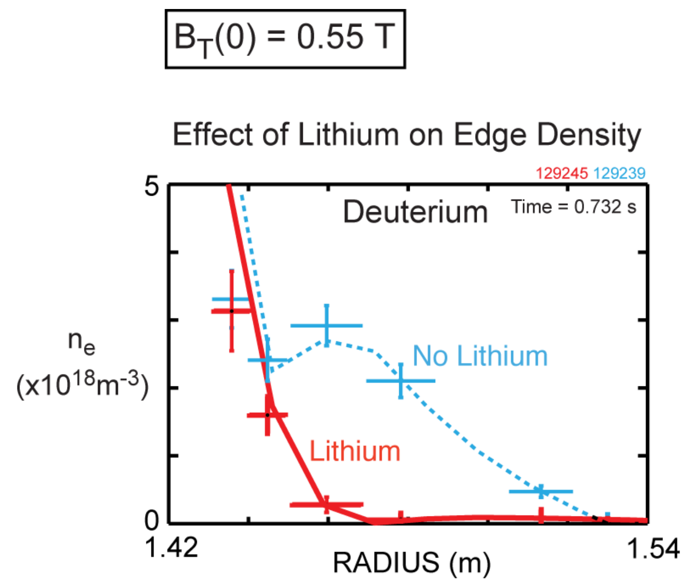


- In 2009 the strap ground was moved to the strap center.
  - Peak V and E on the strap reduced.
  - Peak V in system unchanged.
- The goal is to bring the system voltage limit with plasma (~15-17 kV) up to its vacuum limit (~23-25kV)
  - Would approximately double the power limit
- Tests whether electric field in strap/FS region sets the limit for plasma operation

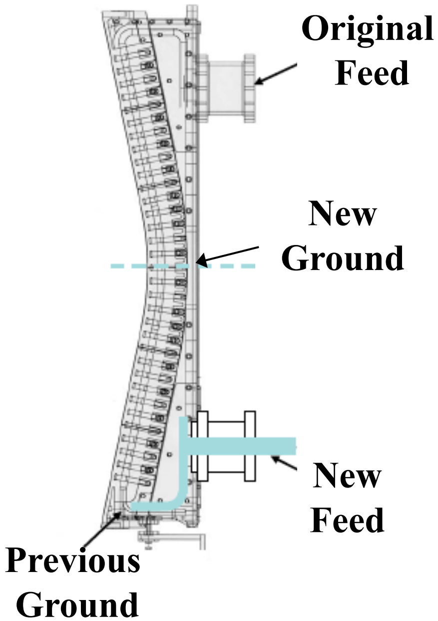
Li Evaporators (2006+), Li Droppers (2008+), Liquid Lithium Divertor (2010) improve HHFW coupling to core



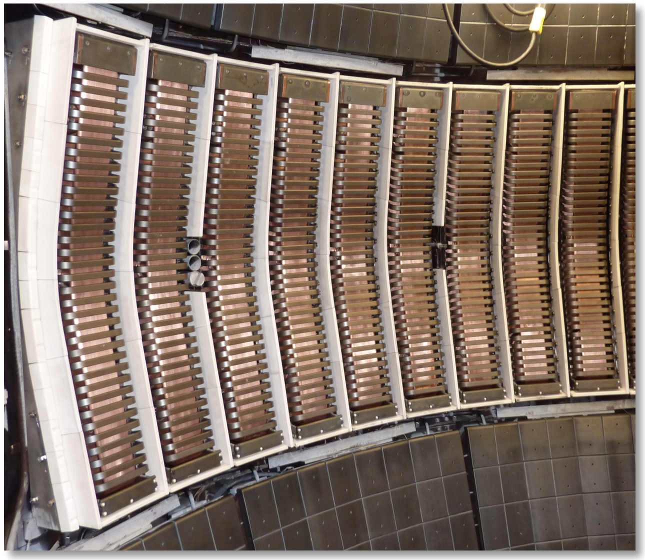
Decreased edge density moves fast wave cutoff away from first wall, lessening edge power losses.



RF Conditioning Li-coated Antennas in 2009 (If evenly coated, could be hot spot/power flux diagnostic)

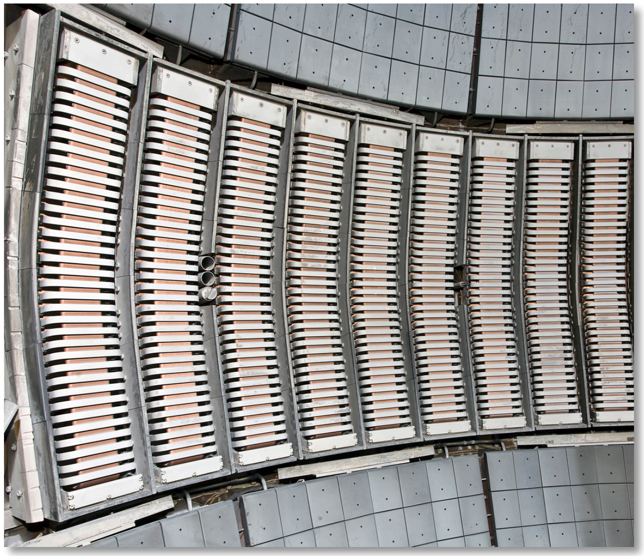


Clean antennas before 2009 campaign



~ 300 g of Li was deposited in NSTX before the HHFW array was operated in 2009.

Li-coated antennas after 2009 campaign



Bare straps being installed

Antenna Conditioning and Performance in 2009 After Extensive (3 months, ~300 g) Li Deposition

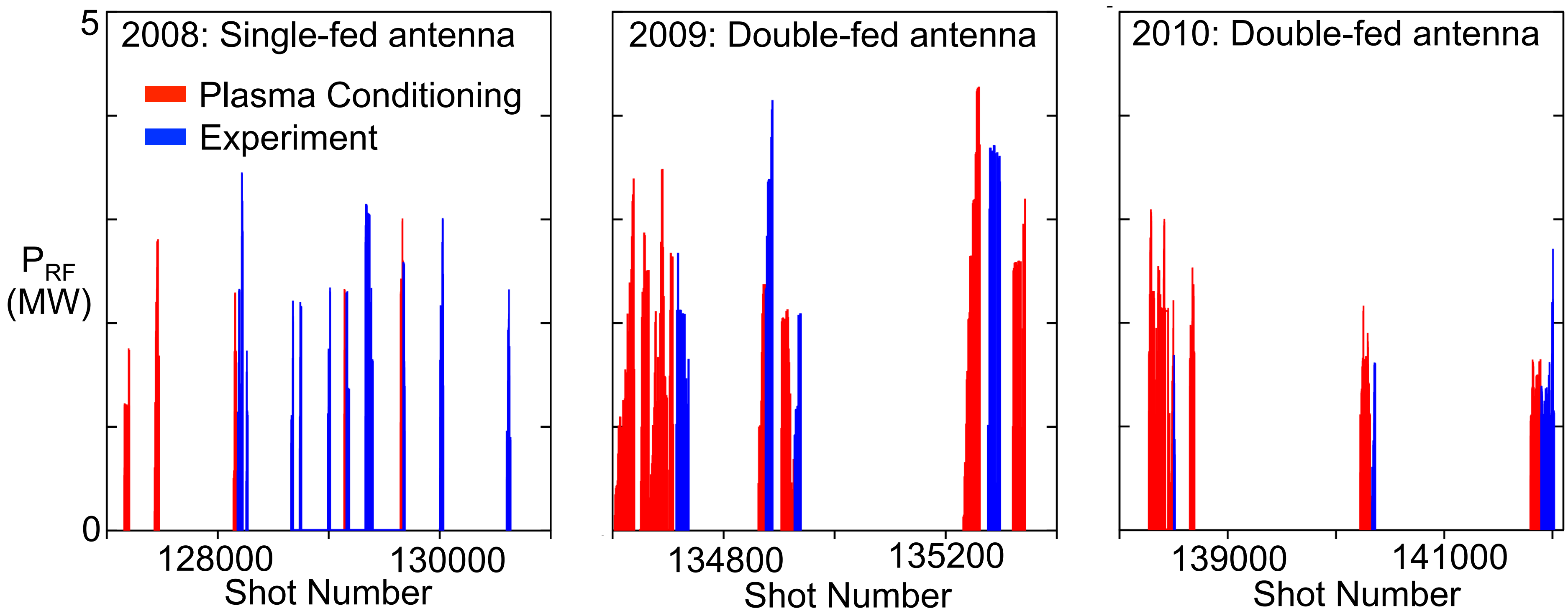
- **Vacuum conditioning**
  - Brand new current straps needed high voltage/current conditioning to remove surface irregularities.
  - System voltage limits after extensive Li operation were often below 10 kV, but quickly conditioned up to previous 22-25 kV limits.
  - Fast camera observation (July 22) indicated that breakdowns were occuring in the antenna box.

- **Plasma conditioning**
  - Brought brand new straps up to previous power levels (2-3 MW) more quickly than in the past.
  - Evidence that Li coating of antenna frame, FS, and BN limiters were contributing to antenna arcing.
  - HHFW power limits increased during RF/plasma operations.

Antenna Operation in 2010 with LLD

- **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 lithium in 2010 (up to 50-100 mg/min).
  - More than 1400 grams of Li deposited in machine in 2010
  - Several vents in Ar-air from shutter replacements compromised surface conditions
  - LiTER snout/apertures accumulated Li, dropped onto lower divertor (several day clean up)
- **Li evaporation began before HHFW was operated.**
- **Could vacuum condition the system to 25 kV at the beginning of the campaign, difficult to condition to 15 kV by end of campaign.**

Double-fed HHFW antenna power delivery improved with time in 2009, but degraded over time in 2010

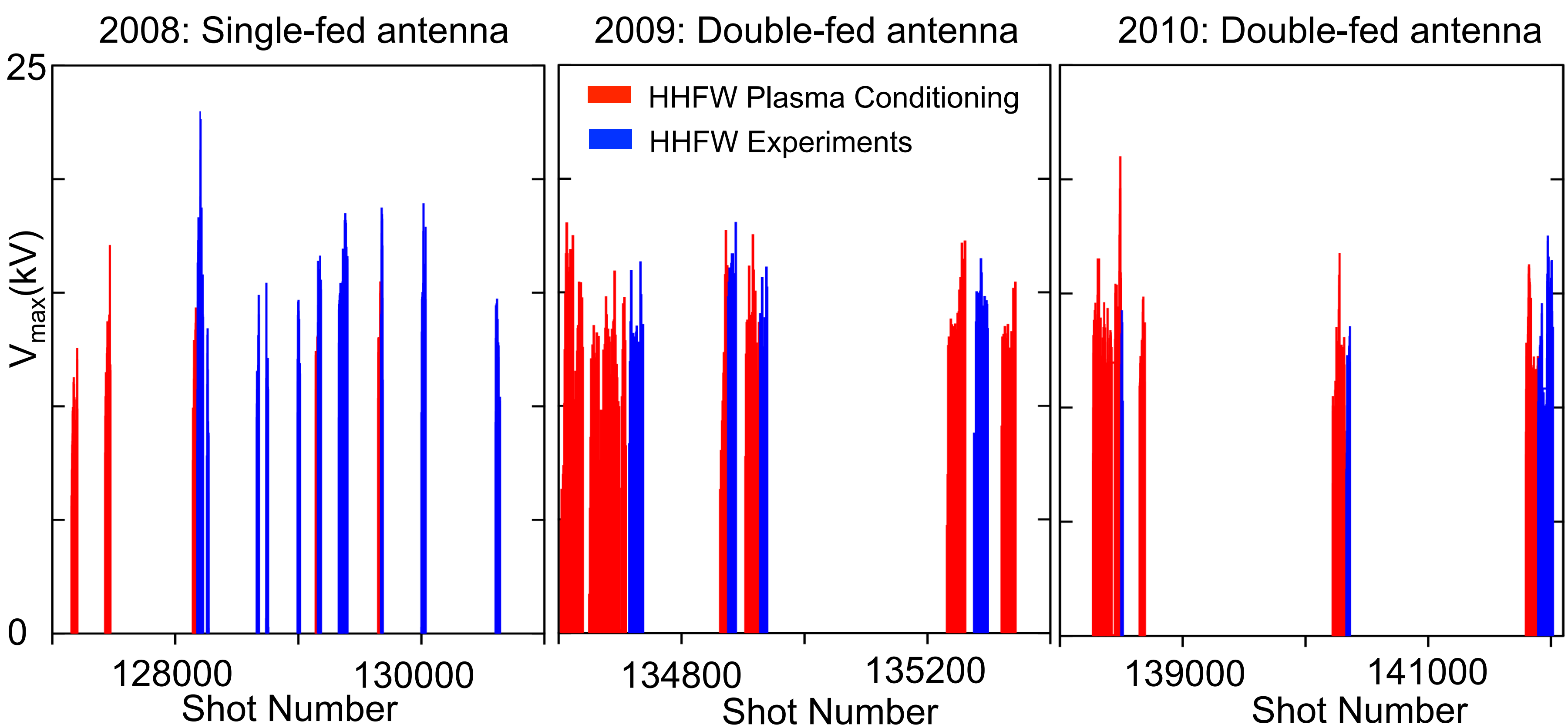


- Operation spread out evenly over ~5 months
- Initial plasma conditioning, then majority of time on experiments
- Most operation in 2-3 MW range throughout campaign

- 2009 operation concentrated in last 4 weeks
- Majority of time spent on plasma conditioning
- Operation in 2.5-4 MW range, improved with time

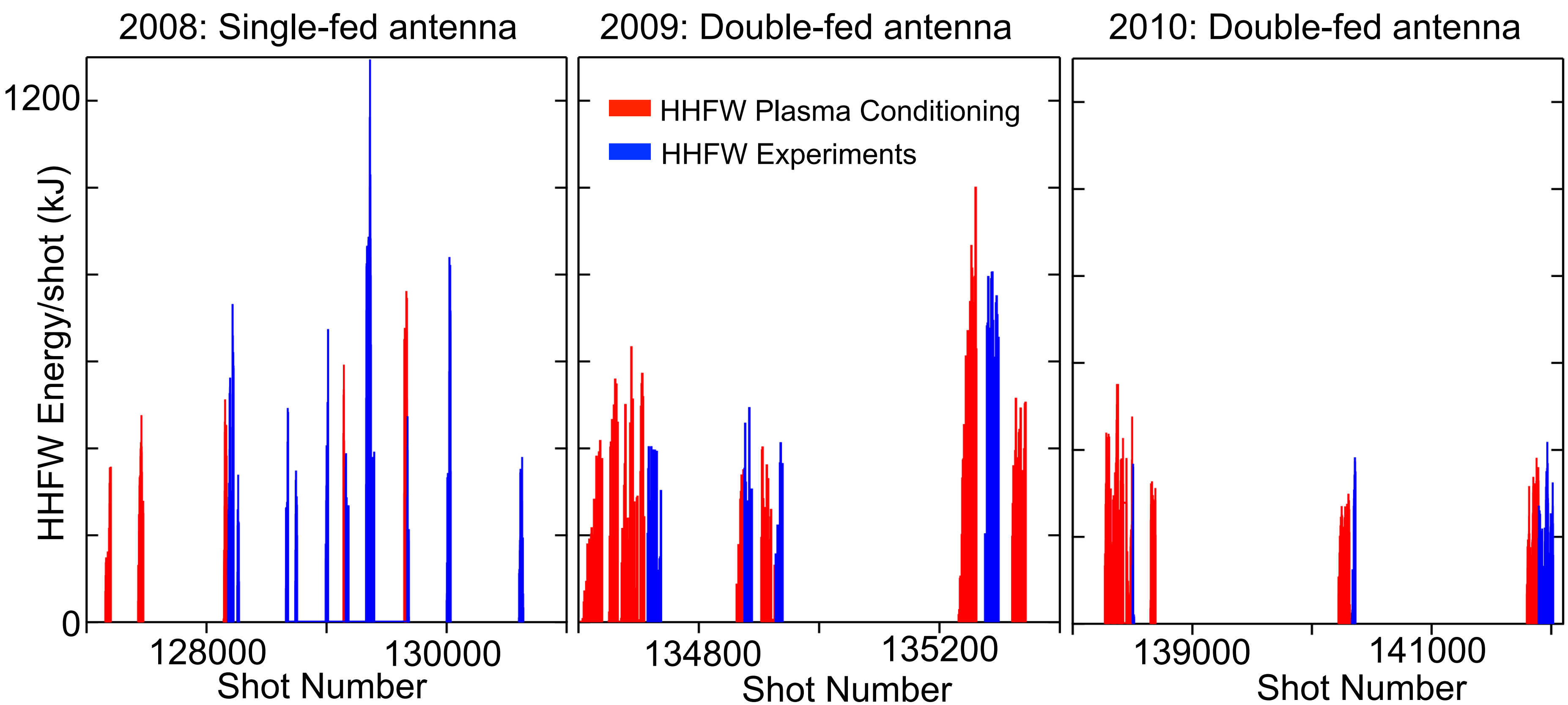
- 2010 operation widely separated over ~4 months
- Almost all time spent on plasma conditioning
- Operation < 3 MW, deteriorated with time

Expected improvement in maximum HHFW system voltage has not yet been achieved



- **Extensive vacuum conditioning was needed in 2010 just to maintain system voltage limits.**
- **Vacuum voltage holding would degrade when antennas were not in use.**
- **All vacuum arcs were observed to occur in the antenna box, not transmission lines.**
- **Vacuum arcs generally occur in the high voltage regions (top and bottom of strap).**

RF Energy/pulse decreased in 2010 due to lower power and more frequent arcs



- **In 2009 the RF energy per pulse grew as the power levels increased and the number of trips decreased. The pulse length was increased for later experiments.**
- **In 2010 the RF energy per pulse never improved, due to power limit and continual arcs and trips.**

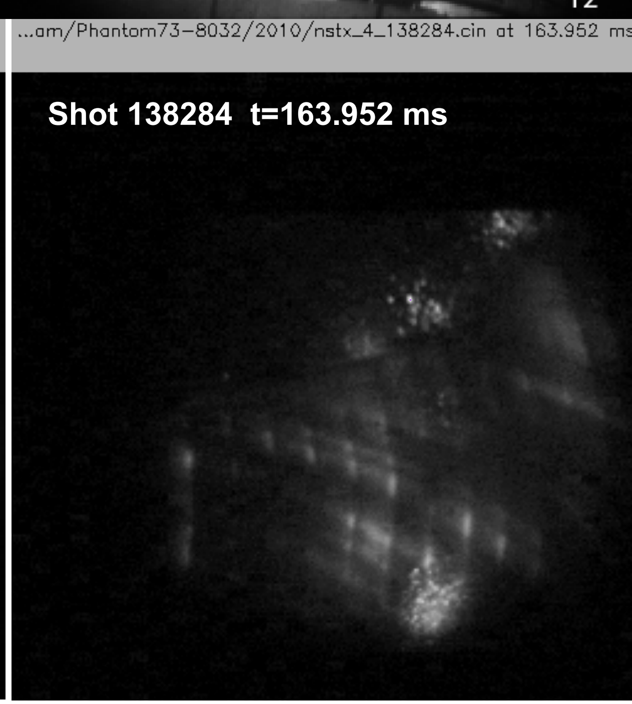
Li-I (excited neutrals) and Li-II (first stage ionization) filters confirm that Li coatings contribute to arcs

New Camera view in 2010

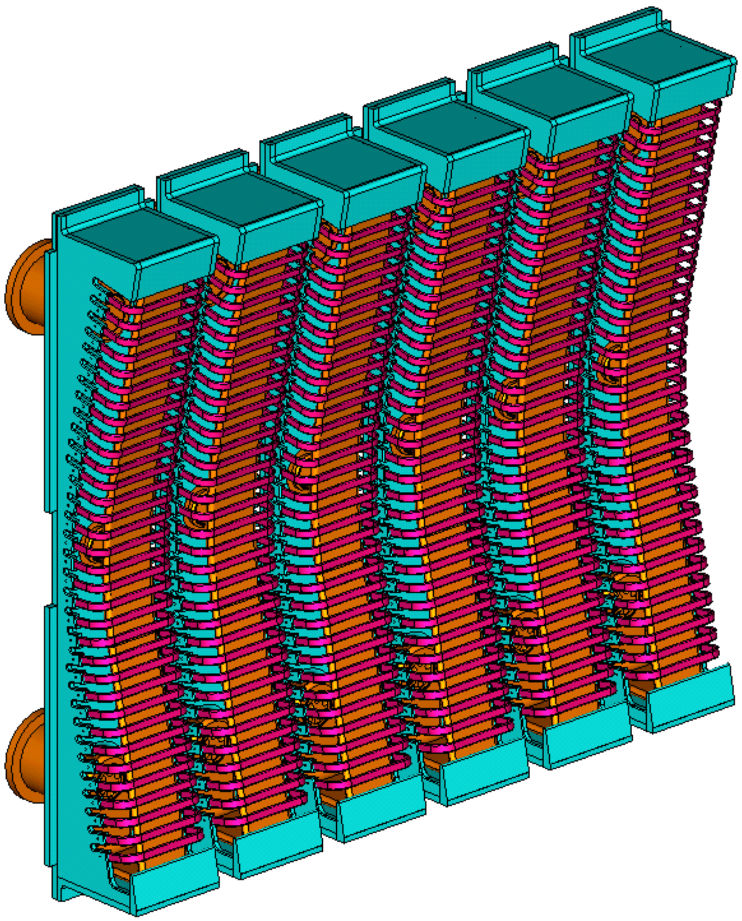
Majority of visible light data collected with no filters on the camera

Li-I filter (transmitter 2 arc)

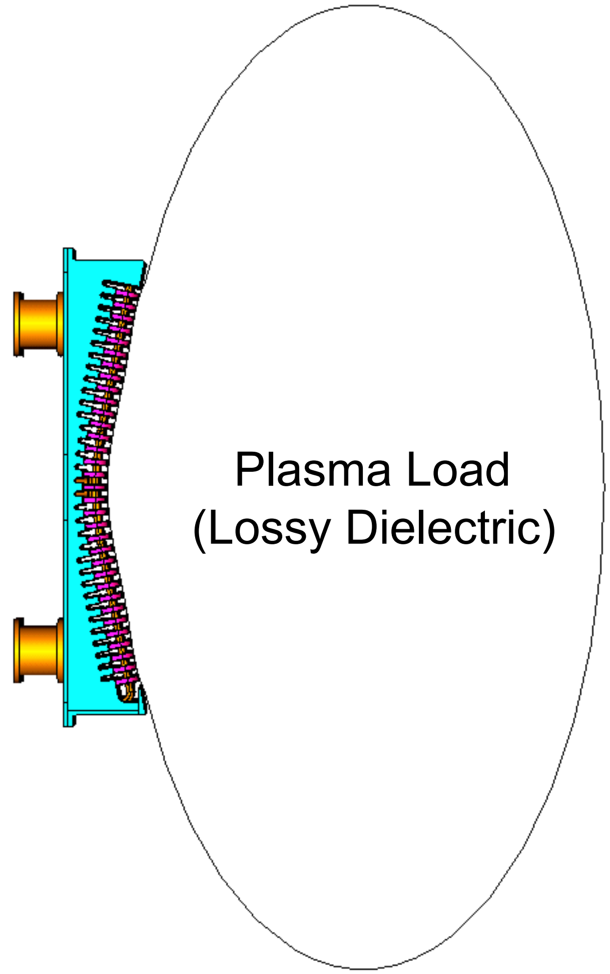
Li-II filter (transmitter 2 arc)



Model of 6-element section of HHFW array predicts location of HV rectified sheaths should depend on array phasing

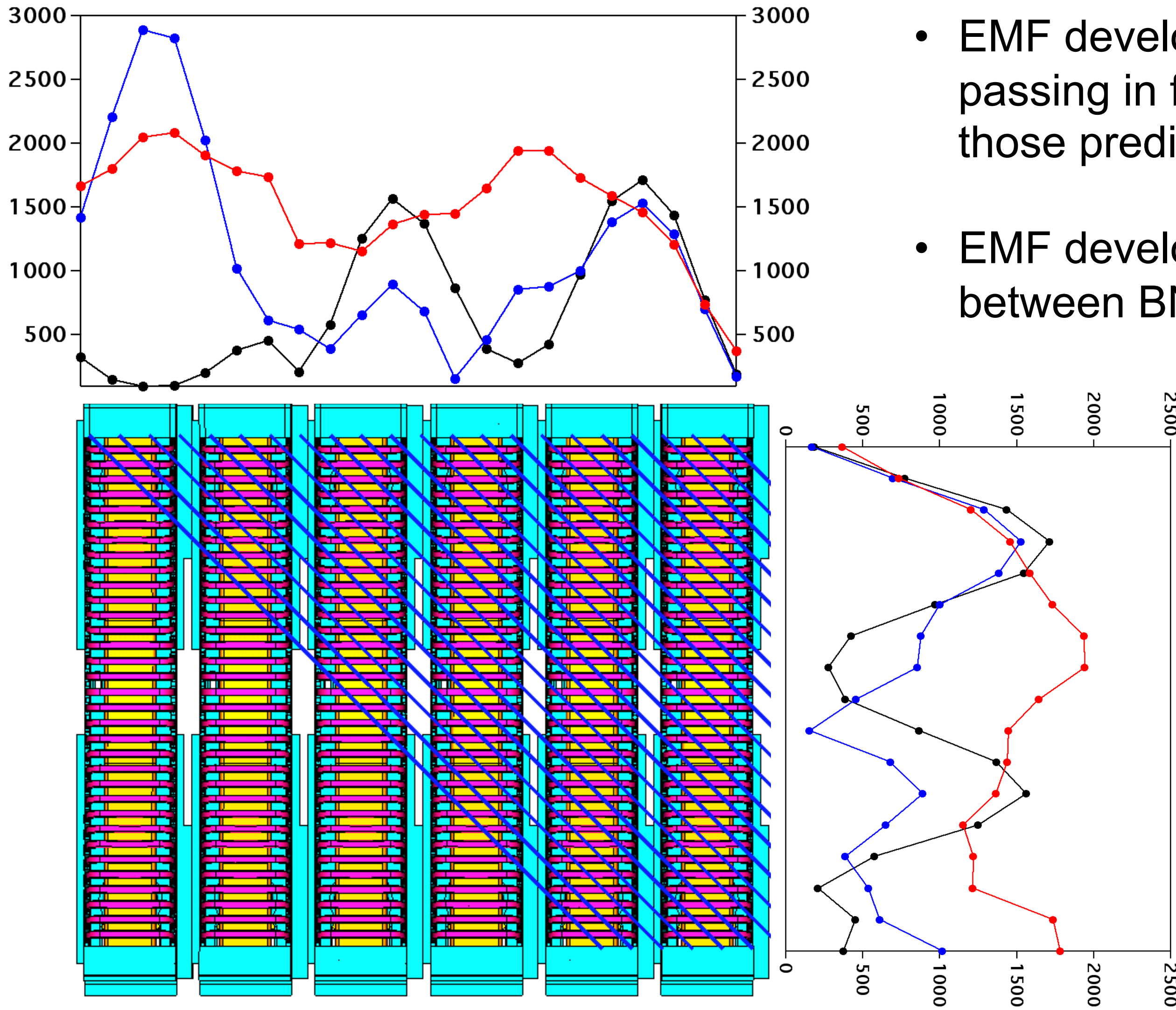


Detailed CAD model provided by C. Kung, PPPL
Model simplification by D. Smyth, Tech X.



CST Microwave Studio model uses lossy dielectric to represent the plasma

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



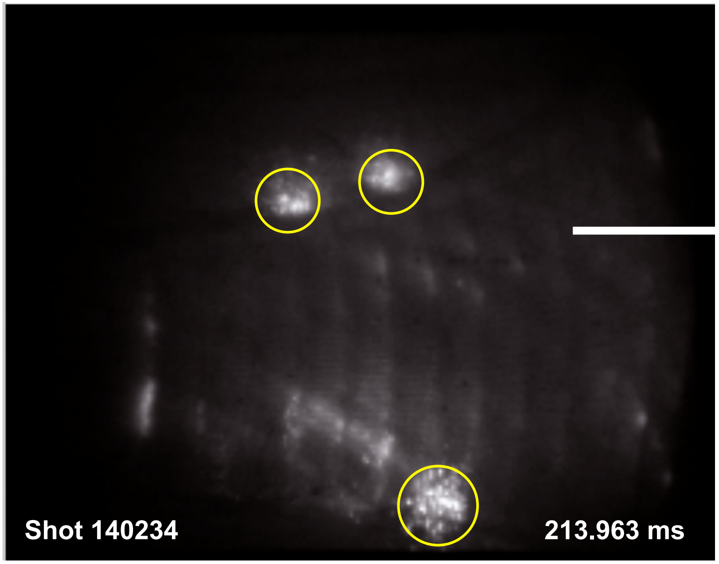
- EMF developed along field lines passing in front of array similar to those predicted for DIII-D upgrade.
- EMF developed along field lines between BN limiters ~ 1200-1700 V

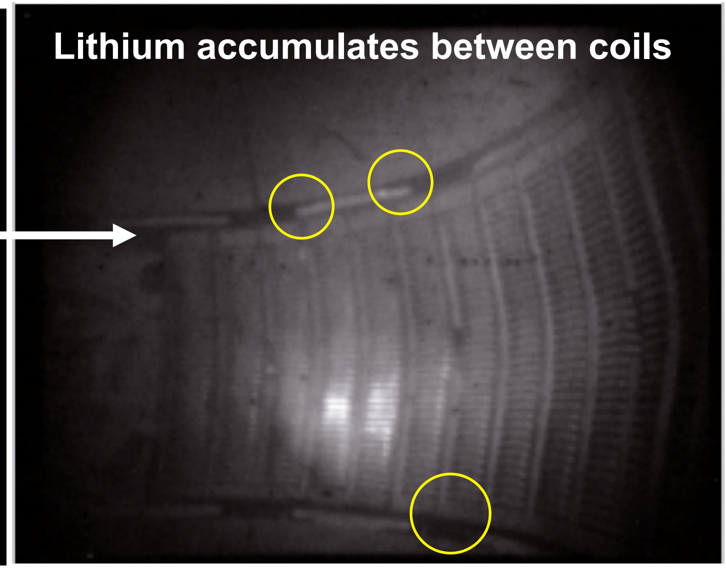
$\Delta\phi$ = 90º
$\Delta\phi$ = 150º
$\Delta\phi$ = 180º

Location of lithium ablation spots generally do not depend on array phasing, but on lithium accumulation sites

23 August 2010
I_p = 0.6 MA
B_T = 0.55 T
He discharge

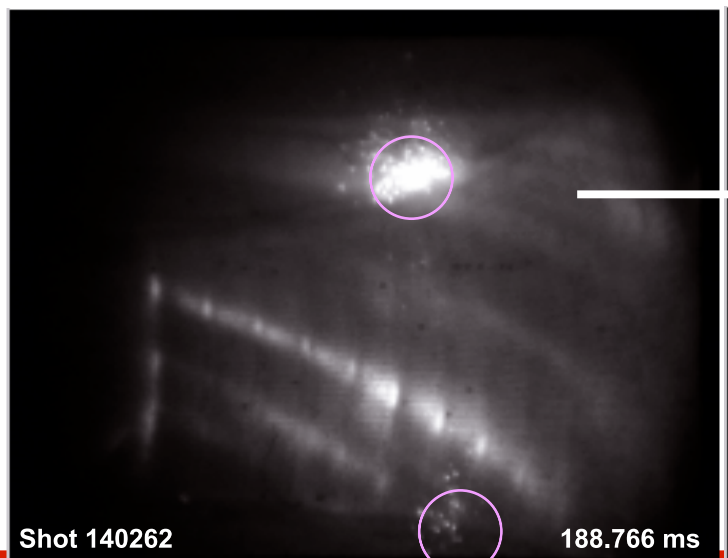
P_{RF} = 1.5 MW
$\Delta\phi$ = -90º

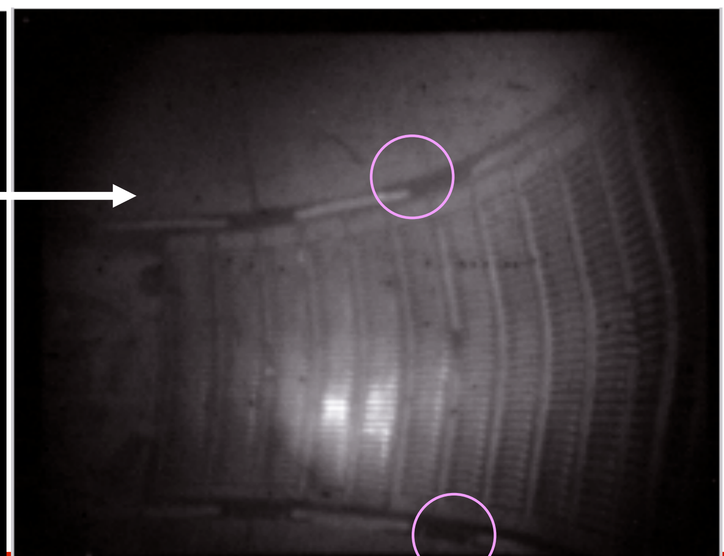




24 August 2010
I_p = 0.6 MA
B_T = 0.55 T
He discharge

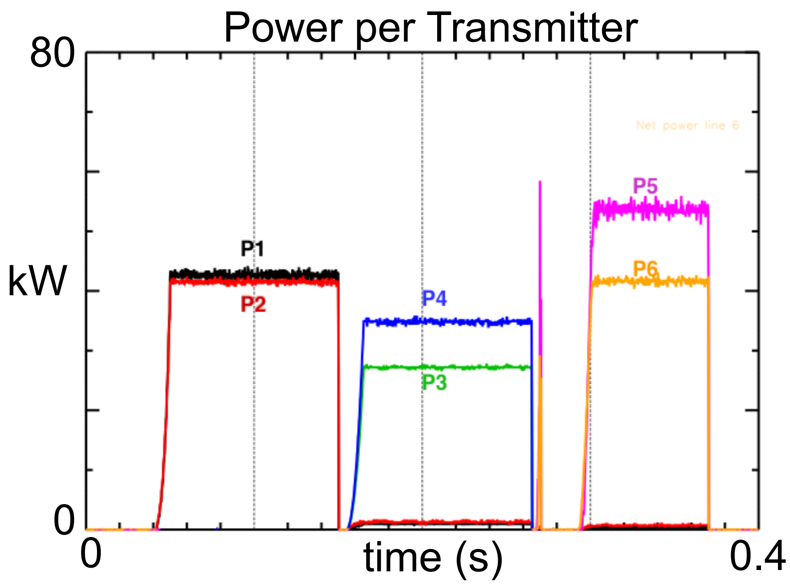
P_{RF} = 1.3 MW
$\Delta\phi$ = 180º

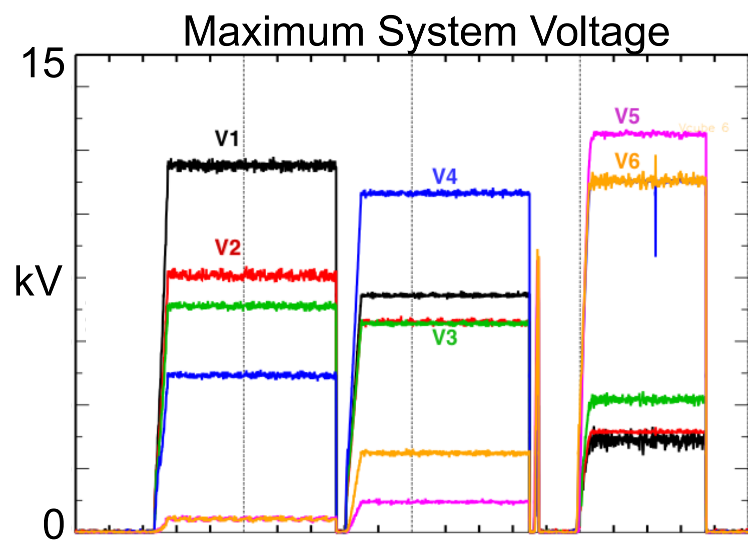




Develop More Efficient Antenna Cleaning/Conditioning Techniques

➡ Between-shot, sequential transmitter vacuum conditioning



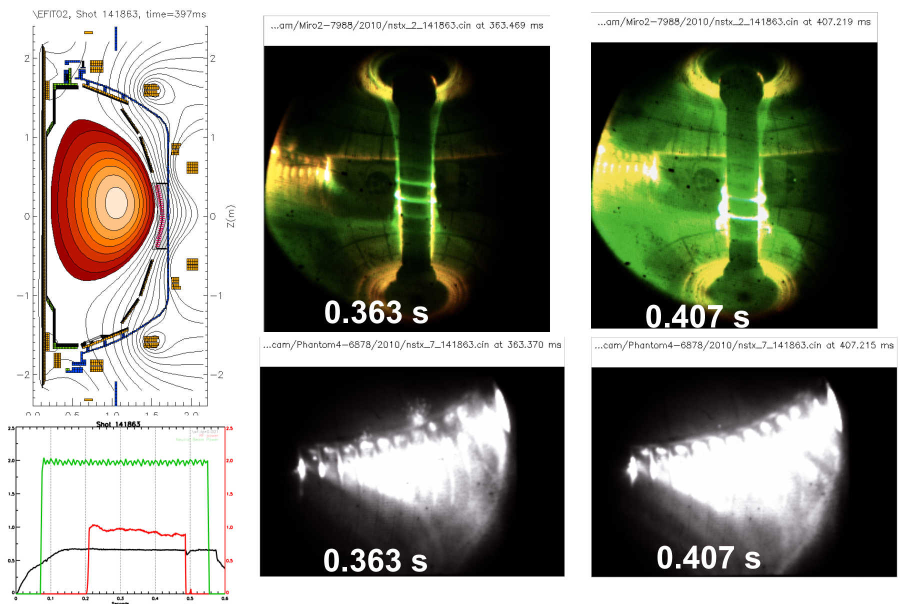


- **Transmitters were sequentially pulsed in pairs for vacuum conditioning between shots.**
- **3 x 0.1s/30 s for 300 s**
- **Advantages:**
  - Increases overall effective duty cycle.
  - Easier to match and to adjust power levels for each loop than for all six simultaneously.
  - Arcing on one loop wouldn’t trip all six transmitters. The other pairs get full conditioning pulse during their turns.
- **Disadvantages:**
  - Although de-couplers isolate nearest transmitters from one another, voltages still appear on unpowered loops due to uncompensated mutual inductances (next-to-nearest neighbors).
  - Need to switch the matching between vacuum and plasma loading each shot.

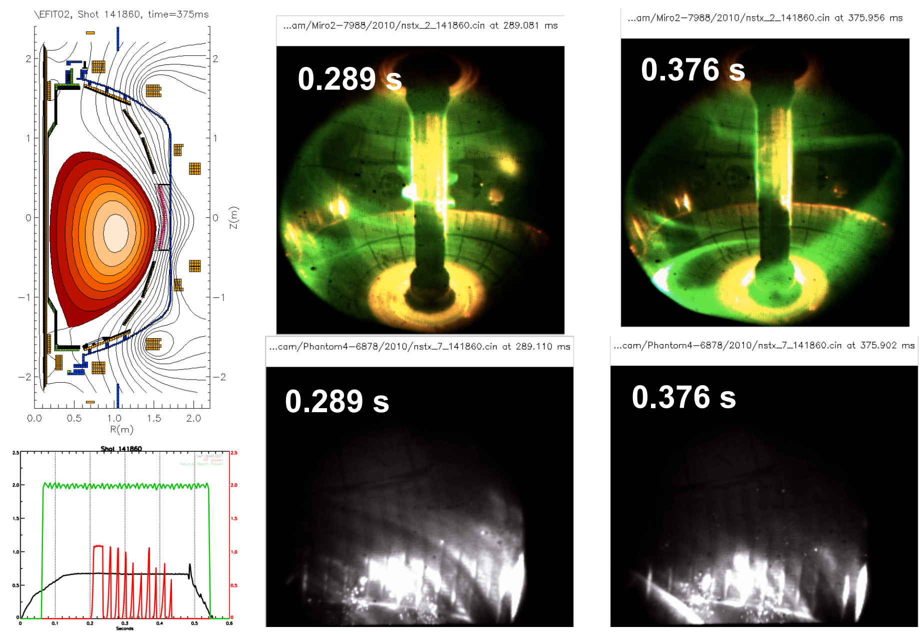
Develop More Efficient Antenna Cleaning/Conditioning Techniques

➡ Plasma Scrubbing of Antenna

Cleaning Top of Antenna



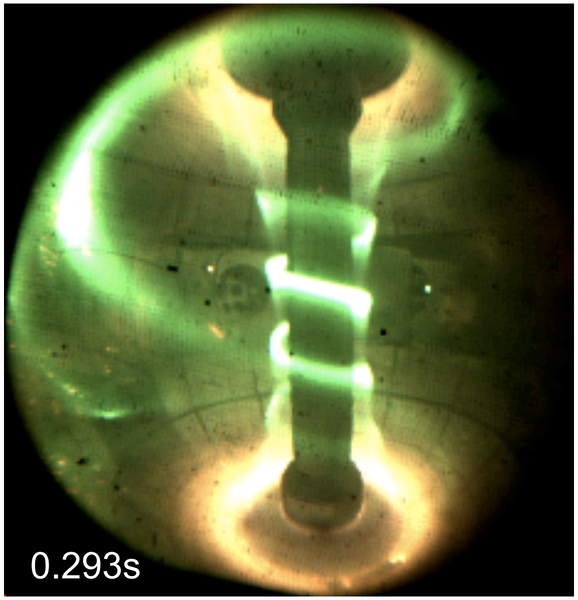
Cleaning Bottom of Antenna

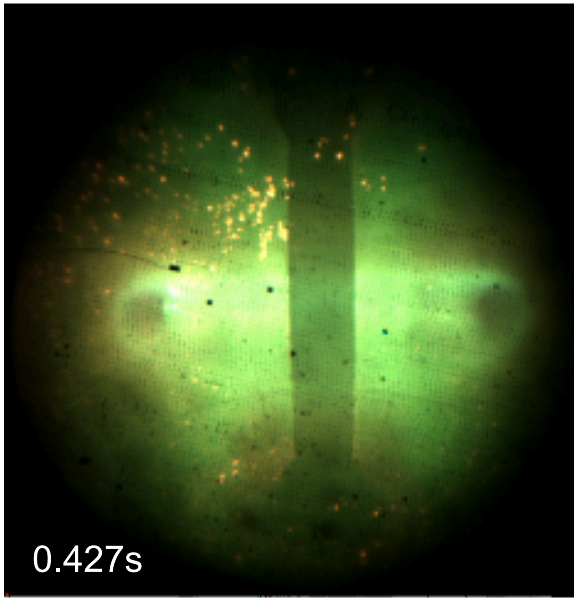


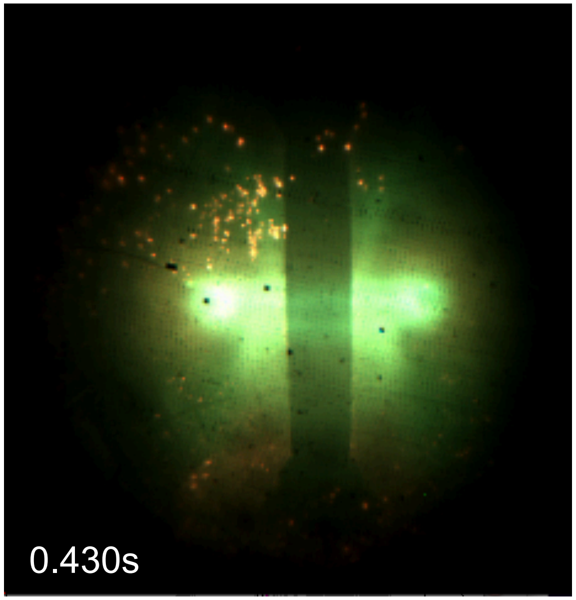
- Moved NBI-heated plasma ± 20 cm vertically from shot to shot to “plasma scour” top and bottom of antenna.
- Profuse lithium expulsion throughout, enhanced while RF is on.
- Observed no great improvement in power capability after limited testing (4 shots).

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 field line.

Lithium projectiles at end of shot, moving outward toward antenna

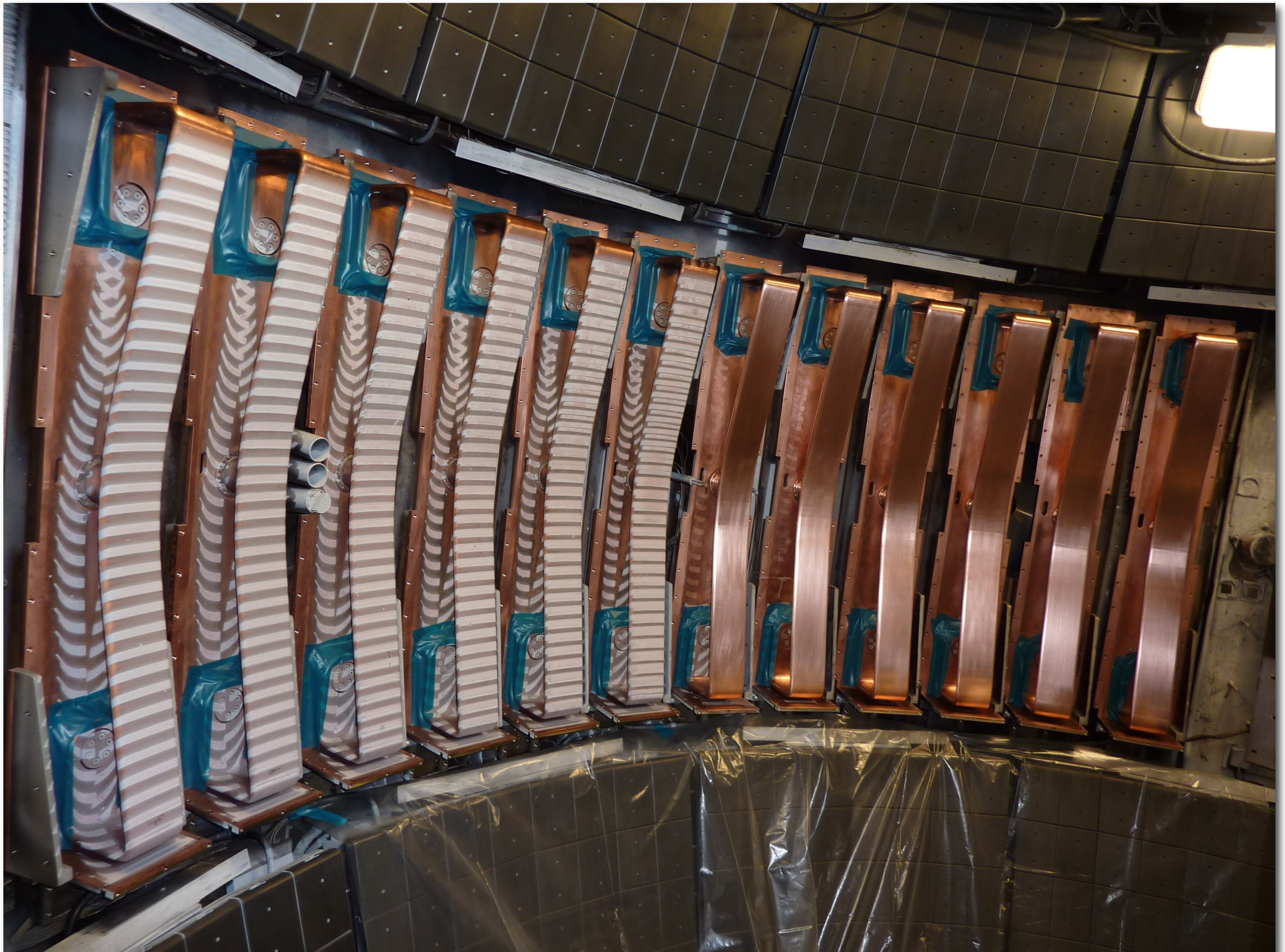
What is the primary cause of increased arcing in 2010?

- **Increased dust (Li_2CO_3)?**
- **Increased lithium deposition on the antenna?**
- **Changes in antenna surface properties?**

INSPECTING THE ANTENNA FOR CLUES

Interior Following 1.347 kg Li Deposition Applied During 2010
Indicates Extensive Li Coverage Due to Direct Evaporation and Plasma Transport

Pattern of Li stripes caused by Faraday shield indicates that some straps in the array were coated by both LiTERs



Thicker “zebra stripe” Li coating on straps after 2010 run

More Li and Li oxide deposits and “splashes” seen on straps after 2010 run.

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

More dust was found in the machine in 2010 than in previous years. May be due to chemical reactions during the Ar/air vents needed to replace LiTER shutters.

Summary of High Power HHFW Operation for 2010 and Future Plans

- Summary
  - 2010 HHFW operation had problems with the LLD filled by LITER applicators.
  - In 2009 the upgraded antennas conditioned fairly rapidly to 4 MW level in a lithium environment.
  - In 2010, reliable operation above 1.4 MW was unachievable even after aggressive antenna conditioning.
  - Li 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 Plans
  - LLD will not be used in 2011. LiTER use should return to 2009 levels.
  - Shields will be installed to keep Li from accumulating above and below antennas.
  - Operate antenna strap on test stand to increase standoff voltage in vacuum.
  - Automate between-shot, sequential vacuum conditioning of antennas (in conjunction with return to glow discharge cleaning).
  - Initial HHFW operation will be with no Li in machine to establish baseline.