Advances In High Harmonic Fast Wave Heating of NSTX H-mode Plasmas

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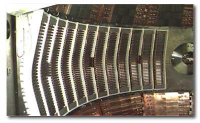
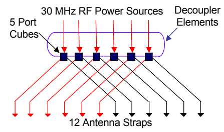
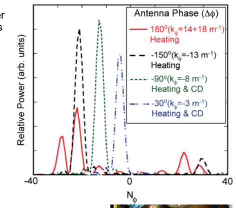
Antenna Upgraded To Reduce Peak Voltages on the Straps

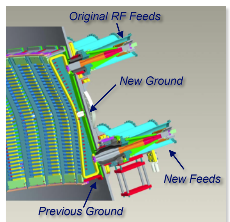


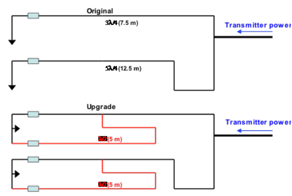
HHFW antenna extends toroidally 90º

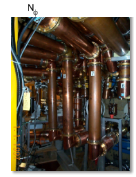




- 12 straps are connected to form two adjacent 6-element arrays, 180º out of phase with each other.
- For phase shifts of 30º, 90º, and 150º, it operates as a 12-element array with a single highly directional peak.

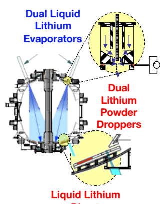






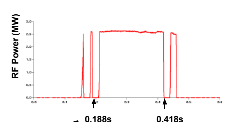
- Goal was to bring system voltage limit with plasma (~15 kV) up to its vacuum limit (~25 kV), thus increasing the power limit by a factor of ~2.8.
- For a given strap current
  - Peak strap voltage would be halved.
  - Peak voltage on vacuum side of feedthrough would be reduced by ~30%.
  - Peak system voltage in transmission line would remain unchanged.
- Tests whether electric fields in strap/Faraday shield region or the strap/antenna frame currents set the limit for plasma operation

Extensive Antenna Conditioning Needed For Li Operation

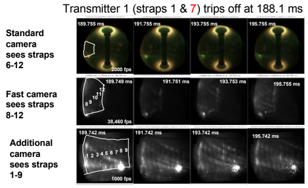


- Li deposited on antenna contributed to arcing and had to be cleaned by plasma conditioning
- Three visible light cameras (1000, 2000, and >30,000 fps) observing antenna during plasma condtioning in He, L-mode plasma.
- Shot 135242 had three transmitter trips during a 200 ms, 2.6 MW pulse at -90º phasing.

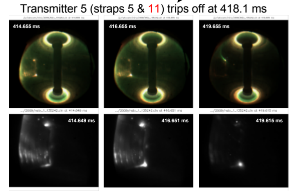
Observation of Arcs During Plasma Conditioning



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

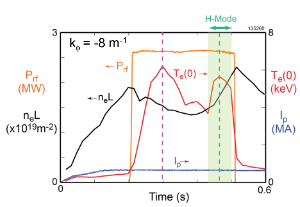


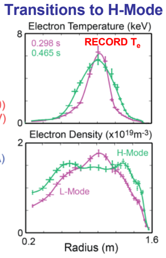
Transmitter 5 (straps 5 & 11) trips off at 418.1 ms

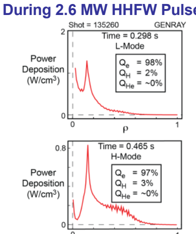


Li Operation Improves Power Coupling to the Core

Ohmically-Heated Helium Target Plasma Transitions to H-Mode During 2.6 MW HHFW Pulse



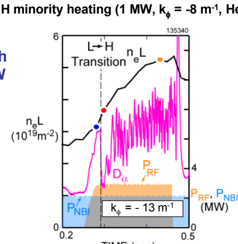


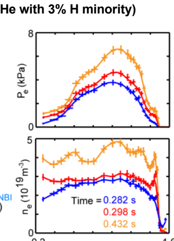


- **GENRAY ray tracing simulation predicts HHFW power deposited on electrons inside ρ ~ 0.5.**
- **Broader power deposition during H-mode.**
- **Negligible damping on He predicted, some H minority heating (1 MW, k_ϕ = -8 m^{-1}, He with 3% H minority)**

H-mode Initiated & Maintained Through ELMs with P_{RF} ~ 2.7 MW During ~ 2 MW D_2 NBI (Shot 135340)

- Transition to H-mode occurs after RF turn on and without RF arc.
- With reflection coefficient trip level set to 0.7, RF stays on during ELMing plasma.

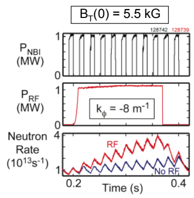


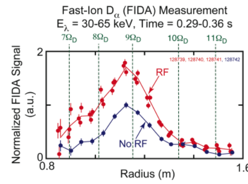


Results for HHFW Heating of NBI-driven H-modes

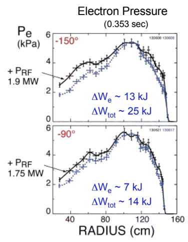
RF-acceleration of fast ions from NBI

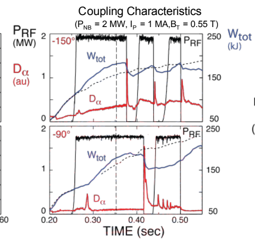
- Large increase in neutron rate when HHFW is applied to NBI plasmas (as predicted originally by CQL3D/GENRAY)
- Measured significant enhancement & broadening of NBI fast-ions profile over a range of ion cyclotron harmonics and

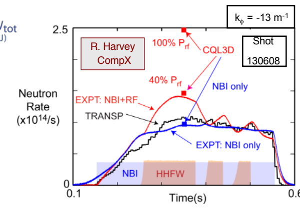




In NBI-driven H-mode, Power Coupling to Core Decreases ~20% Compared to L-mode

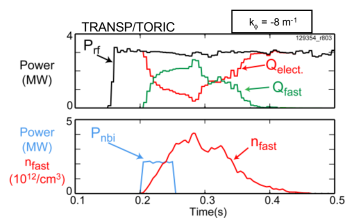


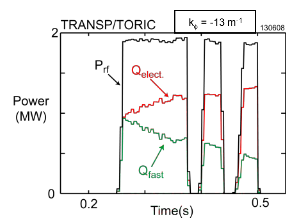




- $\tau_{\Delta Wtot}$ ~ 20 ms gives η_{eff} ~ 66%, 40% for -150°, -90° antenna phasings
- P_{RF} losses coupled to edge are ~ 0.7MW, 1.1 MW for -150°, -90°, out of 1.8 MW launched by antenna

- CQL3D simulation predicts ~ 40% of RF antenna power coupled to plasma for k_ϕ = -13 m^{-1} (-150°) Heating
- P_{rf} used in CQL3D modeling reduced to match simulated and measured neutron rate



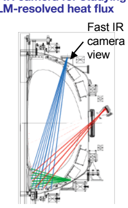


- TRANSP/TORIC modeling predicts RF absorption by NBI fast-ions lasts well after NBI turn off
- All rf power absorbed by electrons prior to NBI pulse
- After NBI turn-on, the fast-ion population absorbs HHFW power at the expense of the electrons
- Trend confirmed by single time point calculations with AORSA, GENRAY and TORIC

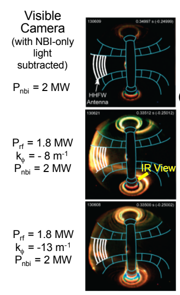
- RF Power Absorption by Fast-Ions Decreases as Fast-Ions Thermalize During RF-Heated NBI H-Mode
- Electron β increases with time as density rises, increasing RF heating on electrons

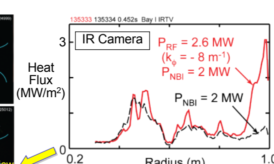
Visible & IR Images Show Significant RF Power Flows to Divertor, Particularly for Lower k_ϕ Heating

Fast IR camera for studying ELM-resolved heat flux



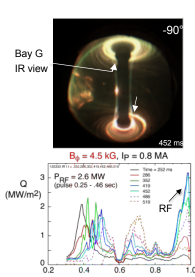
Three bolometer views for studying divertor radiation

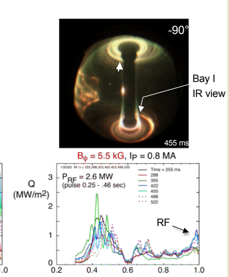




- "Hot" region in outboard divertor more pronounced at k_ϕ = –8 m^{-1} than –13 m^{-1}
- Linked along field lines to scrape-off plasma in front of antenna
- 3 MW/m^2 measured by IR camera during 2.6 MW of k_ϕ = –8 m^{-1} RF heating
- Time for "hot" spot to decay away is ~ 20 ms at –8 m^{-1} and ~ 8 ms at –13 m^{-1}

RF heated pattern on lower divertor plate follows the change in magnetic field pitch





Summary

- **Antenna grounds were moved and power feeds added to reduce voltage on the straps.**
- **Li wall conditioning, needed for improved power coupling through SOL, imposes additional antenna conditioning requirements.**
- **Achieved record T_e (>6 keV) in He.**
- **H-modes accessed with HHFW alone.**
- **Heating of core electrons in NBI-driven H-modes for k_ϕ of 3, 8, 13 m^{-1}.**
- **Significant damping on the fast ions from neutral beams.**
- **Increased edge plasma power losses in NBI-driven H-modes.**
- **Increased heating of outer divertor with HHFW.**