Active Control of Rotating Edge Modes using HHFW Antenna in NSTX

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Motivation (I)

• A problem with impurity control in NSTX
  – Lithium is effective at holding the deuterium density constant
  – But the carbon density keeps rising [Maingi, PRL 103, 075001 (2009)]
  – Core radiation rises
  – This is not good, but it is not because the lithium is not pumping deuterium
  – In the absence of ELMs the plasma does not unload impurities

• Are EHOs the answer?
  – DIII-D has found QH modes both for counter and co-injected cases
  – The density does not rise in these plasmas, despite absence of ELMs
  – It is believed that the Edge Harmonic Oscillations (EHOs) are the reason
Motivation (II)

- EHOs have been observed in NSTX ELM-free periods
  - 2-8kHz and n=4-6 EHOs have been observed (PEST and ELITE codes showed n=3 is most unstable in NSTX)
  - EHOs were weak in amplitudes and did not pump density out

- Direct coupling to EHOs to increase amplitudes has been discussed, by utilizing HHFW antenna as 3D coils
  - Present Error Field Correction (EFC) coils are not effective for n>3
  - HHFW antenna straps are localized within $\Delta \phi < 90$ and perhaps would be effective for n>3

- This will be proposed for NSTX-U again in the future, but study showed the possibility of HHFW straps for 3D coils
EHOs were seen on NSTX Mirnov coils

- n=4-6 EHOs were observed in the edge by Mirnov coils tuned for low frequency and low amplitude
- EHOs are clearest in some optimal operating regimes
  – 4MW, 0.8MA, 0.4T
- Generally amplitudes of EHOs are very low, without reduction of density increase
- Amplitudes may be able to be increased by active driving for EHOs
EHOs were also seen on UFSXR

• n=4-6 EHOs were observed in the edge by Ultra-Fast Soft X-Ray (UFSXR) diagnostics
• Such clear signals were not seen without EHOs
EHOs in NSTX were however found in only limited operational domains (I)

- \( I_P = 0.8 \text{MA}, \; B_T = 0.4 \text{T}, \; P_{\text{NBI}} = 4 \text{MW} \)
- \( I_P = 0.8 \text{MA}, \; B_T = 0.4 \text{T}, \; P_{\text{NBI}} = 6 \text{MW} \)
EHOs in NSTX were however found in only limited operational domains (II)

- \(I_p=1.0\,\text{MA}, B_T=0.45\,\text{T}, P_{\text{NBI}}=4\,\text{MW}\)
- \(I_p=0.8\,\text{MA}, B_T=0.33\,\text{T}, P_{\text{NBI}}=4\,\text{MW}\)
Edge rotational shear is strong in NSTX, perhaps in a consistent way as expected for EHOs.

- Edge rotational shear is often strong in NSTX, and perhaps there may be a correlation between rotation shear and NSTX EHOs’ amplitudes.
Active control of EHOs using HHFW antenna has been proposed by R. Goldston

- Maybe we can use HHFW to drive EHOs and even control impurity influx
- Easy to modulate HHFW amplitude in high frequency 2-8kHz
NSTX HHFW antenna system can be used to produce high-n magnetic perturbations

- NSTX HHFW antenna system has 12x2 straps covering 90 toroidal angles at the midplane
  - Each strap is modeled with an open filament (model can be improved)
- HHFW can produce n=1-6 (spatially tangential) perturbations
High-n perturbations from HHFW may be able to excite dominant fields in NSTX plasmas

- Dominant fields for high-n’s in NSTX are localized at the midplane, and so may be well coupled with HHFW driven perturbations
  - Dominant field is defined as the field maximizing total resonant field at $\psi_N = 0.8\sim0.95$ for each $n$
  - As known, wavelength of dominant field becomes shorter for higher $n$

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**Figures:**

- NSTX_g138239.00595_nsxt_lrdfit4_n3
- NSTX_g138239.00595_nsxt_lrdfit4_n6
- NSTX_g138239.00595_nsxt_lrdfit4
- NSTX_g138239.00595_nsxt_lrdfit4

**Graphs:**

- Sensative field for edge
- Cosine
- Sine
- HHFW
Overlap with dominant field and Chirikov (I)

- All same currents for 24 straps give maximum power, but only to low n’s
Overlap with dominant field and Chirikov (II)

- Up-down asymmetry for 24 straps can maximize middle n’s (n=3-4)

**HHFW**

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**Overlap with dominant field**

- **n**: 1 2 3 4 5 6
- **Overlapping field [Gauss/(10kA)]**

**Chirikov for each n**

- **Chirikov [by 10kA]**
- **Ψₙ**: 0.0 0.2 0.4 0.6 0.8 1.0
Overlap with dominant field and Chirikov (III)

- The half of the straps can give the similar efficiency in this configuration.
Overlap with dominant field and Chirikov (IV)

- This configuration can maximize \( n \geq 5 \), while minimizing \( n \leq 4 \)

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HHFW
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\[
\begin{array}{cccccc}
+ & + & + & + & + & + \\
- & - & - & - & - & - \\
\end{array}
\]

\[
\begin{array}{cccccccc}
\text{n=1} & \text{n=2} & \text{n=3} & \text{n=4} & \text{n=5} & \text{n=6} \\
\end{array}
\]
Overlap with dominant field and Chirikov (V)

- This configuration may be the best by gradual weighting for higher $n$
Comparison with EFC coils for $n=6$ (I)

- HHFW is more efficient than EFC coils for higher $n>3$, even with same currents
Comparison with EFC coils for n=6 (II)

- HHFW antennas are effective 3D coils with various combinations, and can be combined with EFC coils to maximize only higher n’s.
Summary and Future work

• EHOs with n=4-6, 2-8kHz have been observed in NSTX by Mirnov and UFSXR
  – Amplitudes are however low and density pumping was not observed
• EHOs were however found in limited operating regime
  – Edge rotational shear may be also the key to EHOs
• HHFW antennas can produce such harmonic perturbations and so perhaps can be used for active control of EHOs
• Dominant field, and Chirikov analysis showed HHFW antennas are indeed effective to produce high n>3, unlikely to EFC coils
• HHFW antennas are effectively 3D coils, and can be combined with EFC coils to control various n’s
• This study will be extended and tested in NSTX-U
• We are open to the idea and to the collaboration in other tokamaks for active AC control of EHOs