U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Full Wave Simulations of Fast Wave Scrape-off Layer Losses of NSTX/ NSTX-U and a Comparison with DIII-D/C-Mod/EAST

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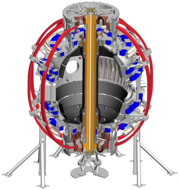
PPPL



Outline

- Motivations
- AORSA simulations including SOL plasma for NSTX and NSTX-U
  - Brief description of the full wave code AORSA
  - Computation of SOL power losses vs. edge density in NSTX with "collisional" damping as a proxy
  - NSTX-U case projections
- Extension to "conventional" tokamaks with higher aspect ratio
  - DIII-D (mid/high harmonic fast wave regime)
  - Alcator C-Mod and EAST (IC minority heating regime)
- Discussion
  - IC minority heating vs. HHFW regime
  - Magnetic pitch angle
- Conclusions and future plans

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Previous NSTX studies of heating efficiency showed large amounts of HHFW power missing from plasma core

- Interaction between the RF antennas and the SOL plasma is of crucial importance in determining the overall performance of RF in a tokamak
  - all frequencies: LH, IC, HHFW, . . ., and helicon waves
- In NSTX:
  - Strong interactions between HHFW and SOL plasma [Hosea PoP 2008, Perkins PRL 2011]
  - Up to 60% of the power possibly lost to SOL
  - Larger SOL losses for high density in front of the antenna
- Other machines (Alcator C-Mod, ASDEX-U, EAST, JET, Tore Supra, . . .)
  - Impurity contamination & transport
  - Impact of RF on SOL plasma
  - . . .

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Full wave code AORSA: wave field modeled with linear wave equation

- Full field wave equation: $\nabla \times \nabla \times \mathbf{E} - \frac{\omega^2}{c^2}\boldsymbol{\varepsilon} \cdot \mathbf{E} = 4\pi i \frac{\omega}{c^2}\mathbf{J}_{\rm ext}$
- AORSA includes the complete non-local, integral operator for $\boldsymbol{\varepsilon}$ that is valid for "all orders" ($k_\perp \rho_{\rm s} > 1$) [E. F. Jaeger et al, Phys. Plasmas 9 (2002) 1873]
- AORSA utilizes a Fourier decomposition in $k_{\rm x}$,$k_{\rm y}$ in the poloidal plane and a Fourier decomposition in the toroidal direction of symmetry:

$$\mathbf{E}(x, y, \phi) = \sum_{n_\phi} \sum_{n,m} \mathbf{E}_{n_\phi,n,m} e^{i n_\phi \phi} e^{i(k_n x + k_m y)}$$

where $x = R - R_0$ and y is the distance from the midplane

- Extended AORSA to include SOL plasma [D. Green PRL 2011]
  - Exponential decay for the SOL density to fit the experimental density data

$$n_{\rm e} = n_{\rm ant} + \left[n_{\rm e}(\rho = 1) - n_{\rm ant}\right] \exp\left[\frac{\rho - 1}{d_{\rm SOL}}\right], \quad \rho \geq 1$$

$n_{\rm ant}$ = density in front of the antenna

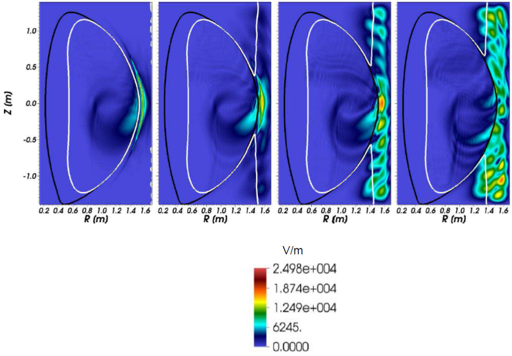
RF field amplitude in the SOL increases as soon as the FW cut-off is removed from in front of the antenna

- For very low density the RF field is strongly localized in front of the antenna
- Standing wave appears at higher density
- Note that $|E_{\rm tot}|$ in the SOL is much greater than $|E_{\rm tot}|$ inside the LCFS and spreads out with increasing density
- Direct correlation between SOL RF field and FW cut-off location

$|E_{\rm tot}|$ for $n_\phi = -21$ (# 130608)

$n_{\rm ant}[m^{-3}] =$

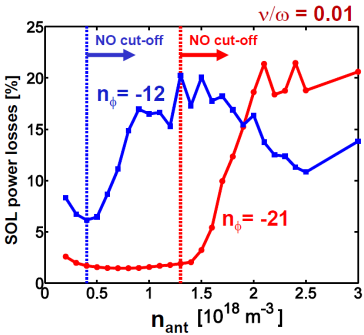
0.5×10^{18} 1.5×10^{18} 1.7×10^{18} 2.0×10^{18}



N. Bertelli *et al*, NF **54** 083004 (2014)

SOL power losses increase from the evanescent to propagating within SOL according to the FW cut-off location

- "Collisional" damping included in AORSA as a proxy to represent the real SOL damping processes (ν/ω is input into AORSA)
- FW cut-off condition: $n_{\mathrm{e,FW_{cut-off}}} \propto \frac{k_{\|}^2 B}{\omega}$
- Lower n_ϕ ($n_\phi/R = k_\phi \approx k_{\|}$) then transition at lower n_{ant}
- For given n_ϕ , SOL power losses increase if $n_{\mathrm{ant}} > n_{\mathrm{e,FWcut-off}}$
- Agreement with some indications from the NSTX experimental observations [Hosea PoP (2008) and Phillips NF (2009)]
  - Will be further validated in the upcoming NSTX-U campaign



N. Bertelli *et al*, NF **54** 083004 (2014)

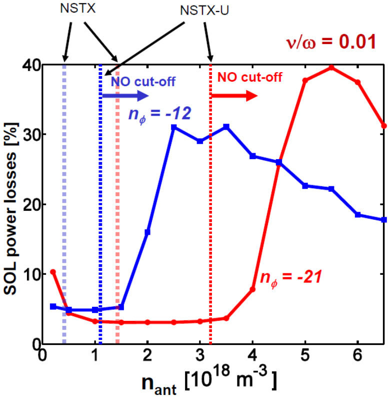
Larger evanescent region predicted at higher fields achievable in NSTX-U, favorable for future experiments

- H-mode scenario planned for NSTX-U, obtained by TRANSP simulations
  [S. P. Gerhardt, Nucl. Fusion **52**, 083020 (2012)]

- NSTX-U ($B_{\mathrm{T}} = 1$ T) vs. NSTX ($B_{\mathrm{T}} = 0.55$ T): transition occurs for $\sim$2x higher in n_{ant}

- Same relative behavior found for NSXT-U case with $B = 0.76$ T

- NSTX-U: optimization of edge density to minimize the SOL losses and maximize the coupling to the core



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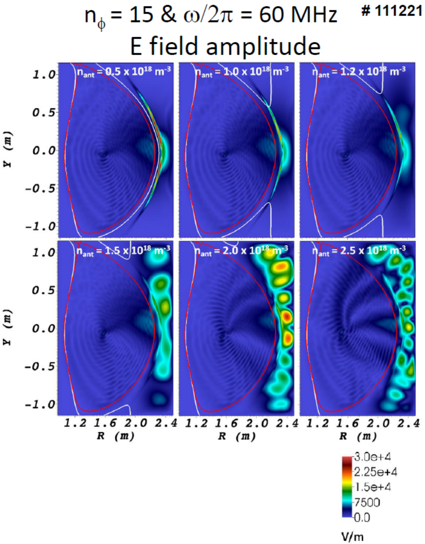
DIII-D results show similar E field behavior in the SOL found in NSTX and NSTX-U

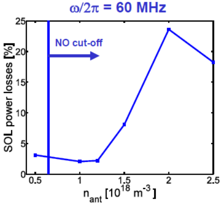
- FW heating used in DIII-D is similar to the regime adopted in NSTX/NSTX-U
- $\omega/2\pi = 60 - 120$ MHz & $B_{\mathrm{T}} = 1.3 - 2.1$ T: Mid/high harmonic regime ($\omega/\omega_{\mathrm{c,D}} = 4 - 12$)
- E field amplitude increases when wave propagates outside the LCFS
- Same trend of E field amplitude for $\omega/2\pi = 90$ MHz

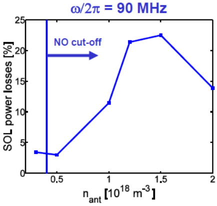


N. Bertelli *et al*, submitted to NF (2015)

Absorbed power in the SOL increases when the SOL density is above $n_{\mathrm{FW,cut-off}}$ in agreement with previous DIII-D experiments

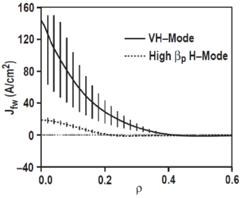
- From AORSA simulation including a damping as a proxy

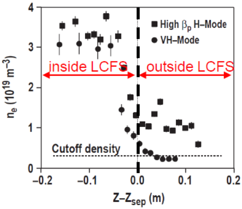




- FW cut-off condition: $n_{\mathrm{e,FWcut-off}} \propto \frac{k_{\parallel}^2 B}{\omega}$
- higher ω ➡ transition at lower n_{ant}

- DIII-D experiments shows large (small) FWCD in the core when SOL density is below (above) the FW cut-off density

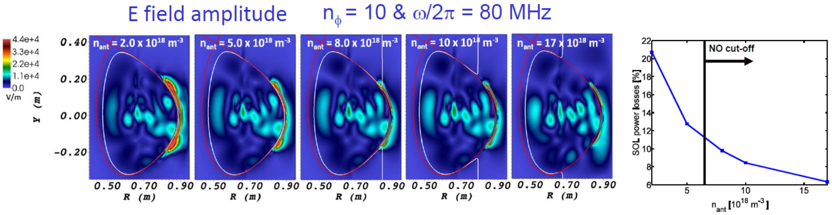




Petty et al
Nucl. Fusion 39 (1999) 1421

Unlike NSTX/NSTX-U/DIII-D, Alcator C-Mod results show a decreasing of E field amplitude outside LCFS with increasing $n_{\rm ant}$

- FW experiments in Alcator C-Mod operate in the ion cyclotron minority heating regime which differs from the mid/high harmonic regime adopted in DIII-D & NSTX/NSTX-U



- Transition to higher SOL power losses does not appear due to different E field amplitude behavior in the SOL w.r.t. NSTX/DIII-D
- Same behavior found for EAST case
- In Alcator C-Mod and EAST, results perhaps more intuitive w.r.t. the NSTX/NSTX-U/DIII-D:
  - increase SOL density ⇒ enhances antenna-plasma coupling ⇒ lower power lost to the SOL

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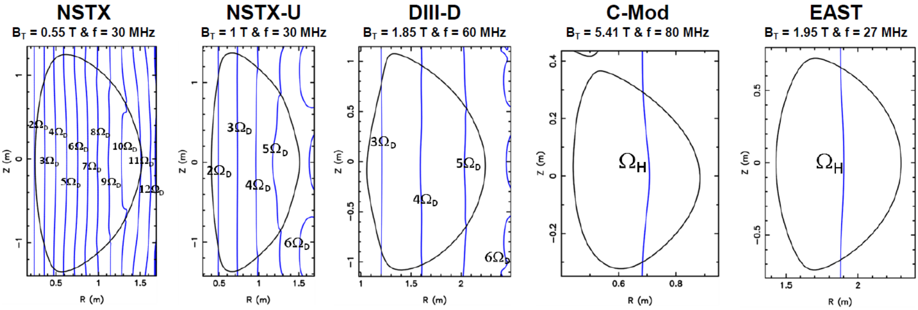
Hydrogen minority ICRH vs. mid/high harmonic ICRH regimes

Main difference: harmonic numbers $\omega/\omega_{\rm c,i}$ in the plasma and the interaction with the minority and majority ion species



No evidence in simulations of a specific role of the cyclotron resonances in the SOL plasma

Magnetic field pitch angle can play an important role in the E field behavior in the SOL

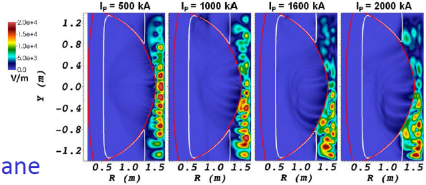
	NSTX	NSTX-U	DIII-D	C-Mod	EAST
$B_{T,0}$ [T]	0.55	1	1.85	5.41	1.95
I_p [MA]	1	1	1.2	1	0.49
$\langle B_p / B_t \rangle$ (ρ=1)	~0.34	~0.19	~0.12	~0.10	~0.08

NSTX-U magnetic equilibria

B_T = 1 T and I_p = 0.5, 1.0,1.6, and 2.0 MA

By free-boundary equilibrium ISOLVER

Large E amplitude still present but RF field moves down from the mid-plane

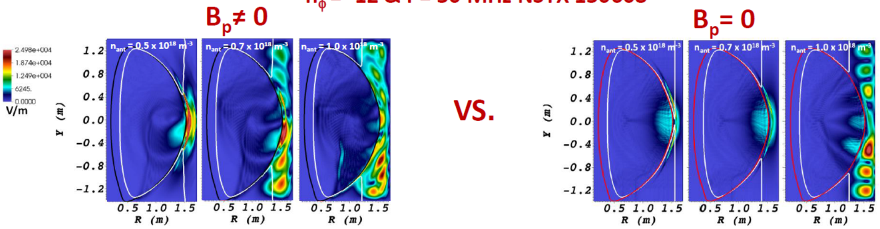


n_ϕ = -21

f = 30 MHz

n_{ant} = 5x10^{18}m^{-3}

n_ϕ = -12 & f = 30 MHz NSTX 130608



Conclusions & future plans

- AORSA simulations show a direct correlation between the large SOL RF field, the location of the FW cut-off, and the SOL losses in NSTX/NSTX-U & DIII-D
  - SOL losses increase significantly as the wave transitions from evanescent to propagating as the density in the SOL increases
  - Agreement with experimental observations
  - NSTX-U simulations predict a wider evanescent region with lower SOL losses relative to NSTX
- Alcator C-Mod & EAST results differ from NSTX/DIII-D results
  - SOL RF field amplitude decreases when SOL density above the FW cut-off
- Magnetic pitch angle can play an important role in the behavior of SOL RF field

- Estimate the impact of limiter boundary in the AORSA results
- Perform AORSA runs in a reduce domain area just in front of the NSTX-U antenna (in order to have higher resolution)