Feasibility study of ECRH in NSTX-U startup plasma

N. A. Lopez[1], F. Poli[2], G. Taylor[2], R. Harvey[3], Yu. Petrov[3]
1. Princeton University, Princeton, NJ USA 2. PPPL, Princeton, NJ USA 3. CompX, Del Mar, CA USA

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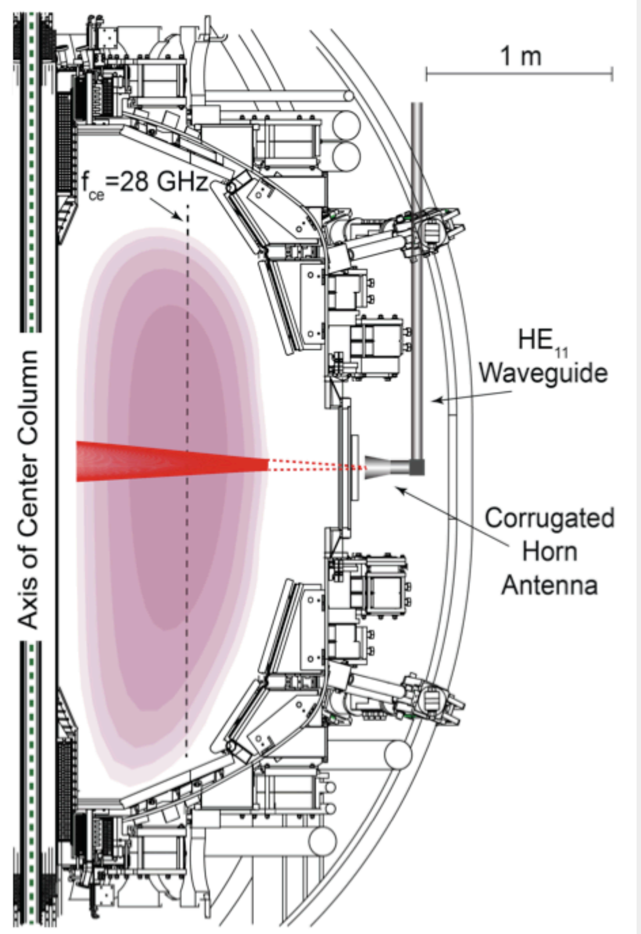
A key mission goal of the National Spherical Torus eXperiment Upgrade (NSTX-U) is the demonstration of fully non-inductive startup and operation. In part to accomplish this, a 1MW, 28 GHz ECRH system is presently being developed for implementation on NSTX-U in 2018. Like most spherical tokamaks, NSTX-U operates in the overdense regime ($f_{pe} > f_{ce}$), which limits traditional ECRH to the early startup phase. An extensive modelling effort of the propagation and absorption of EC waves in the evolving plasma is thus required to define the most effective window of operation, and to optimize the launcher geometry for maximal heating and for current drive during this window. In fact, the ECRH system will play an important role in preparing a target plasma for subsequent injection of IC waves and NBI. Here we assess the feasibility of O1-mode ECRH in NSTX-U startup plasma at full field of 1T through time-dependent simulations performed with the transport solver TRANSP. Linear ray-tracing calculations conducted by GENRAY are coupled into the TRANSP framework, allowing the plasma equilibrium and the temperature profiles to evolve self-consistently in response to the injected microwave power. Furthermore, we investigate additional possibilities of heating and current drive made available through coupling the injected O-mode power to the electrostatic EBW via the slow X-mode as an intermediary.

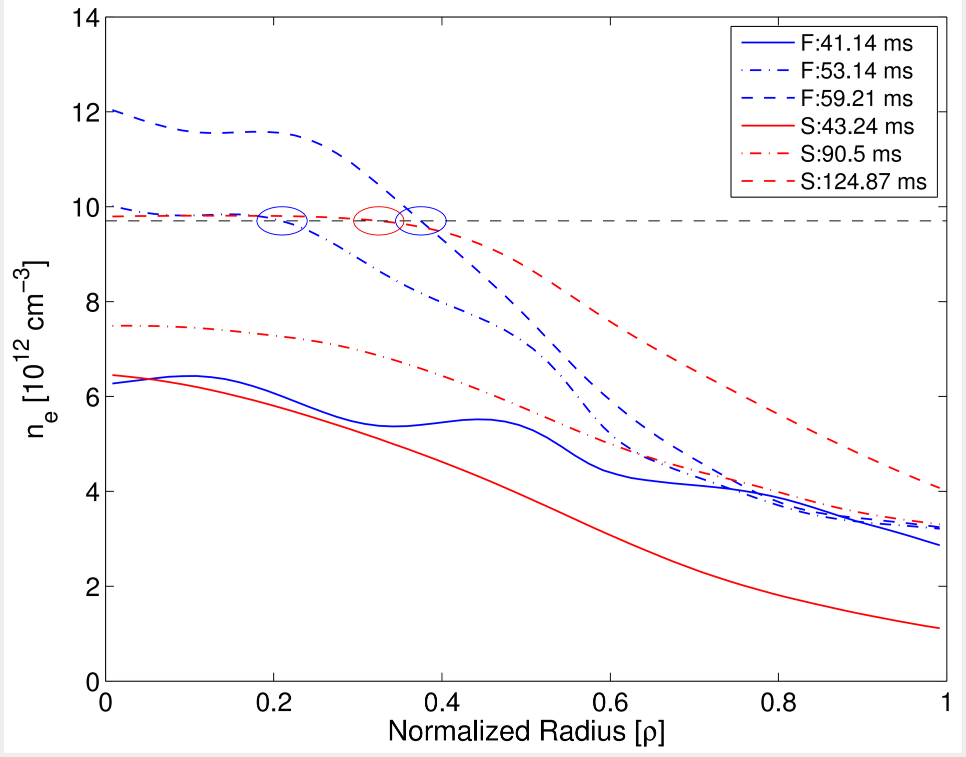
Motivation

- 28 GHz, 1 MW ECRH system planned for use on NSTX-U in 2018
  G. Taylor *et al* EPJ Web of Conferences **87** 02013 (2015)
  - Initial applications will focus on preparing target plasma for HHFW and NBI
    F.M. Poli *et al* Nucl. Fusion **55** 123011 (2015)
  - Further applications will explore EBW heating & current drive scenarios in the startup and later, I_p flattop phase
- Previous optimizations used static plasma profiles to optimize first pass absorption
  - Remains to assess robustness of proposed injection angle against plasma evolution at startup in response to injected EC power.



TRANSP Simulation Details

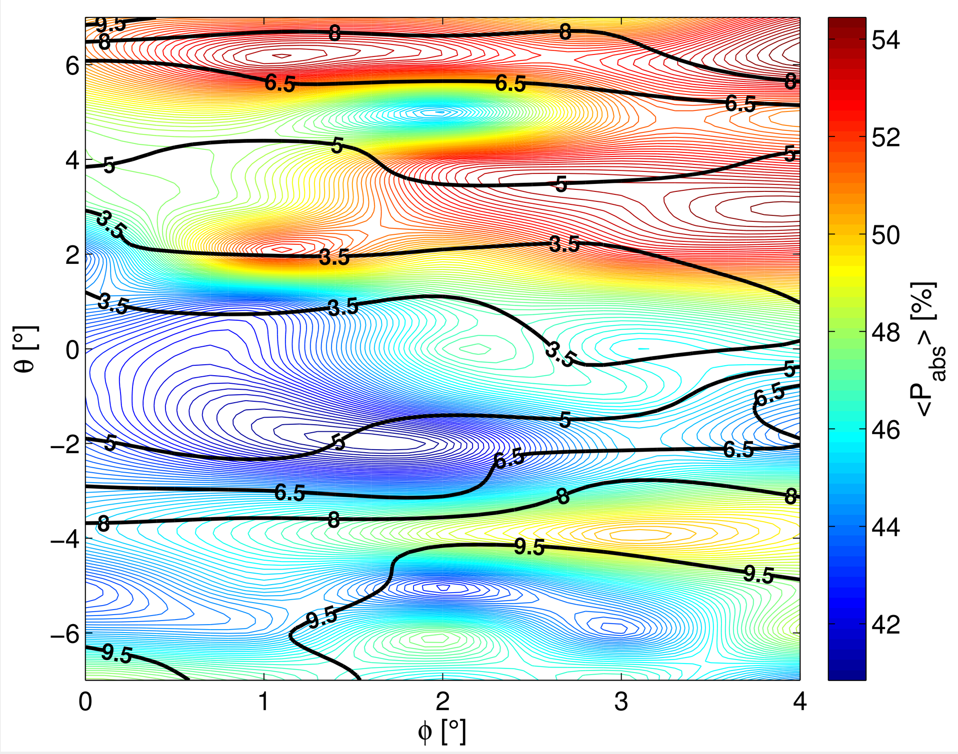
- TEQ inverse solver for fixed-boundary equilibrium calculation
  - reference equilibrium: NSTX-U shot #204202
- Predict electron/ion temperature with MMM 7.1
- Prescribe total I_p waveform from experiment; predict non-inductive component
- GENRAY for ECRH/ECCD calculations
  - Include momentum conservation effects in ECCD
  - Cold plasma dispersion
  - Absorption via Forest calculation



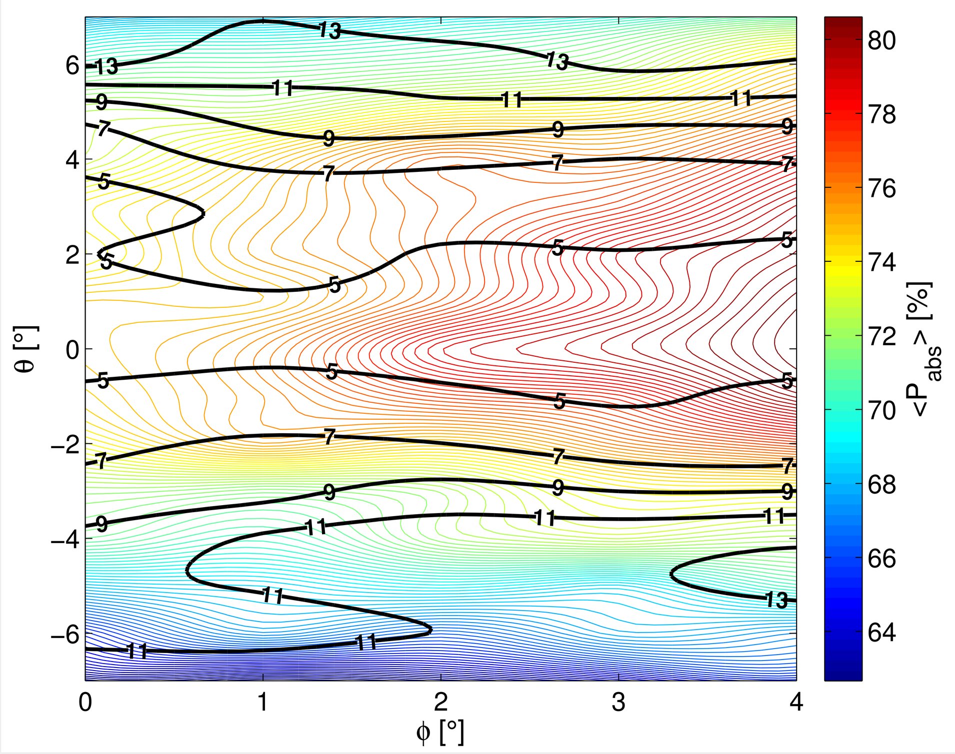
2 density rampup scenarios (above):
- 'Fast' rampup (NSTX-U #204202)
- 'Slow' rampup (NSTX #140358)

O1-Mode Optimization: Scan Over Injection Angles

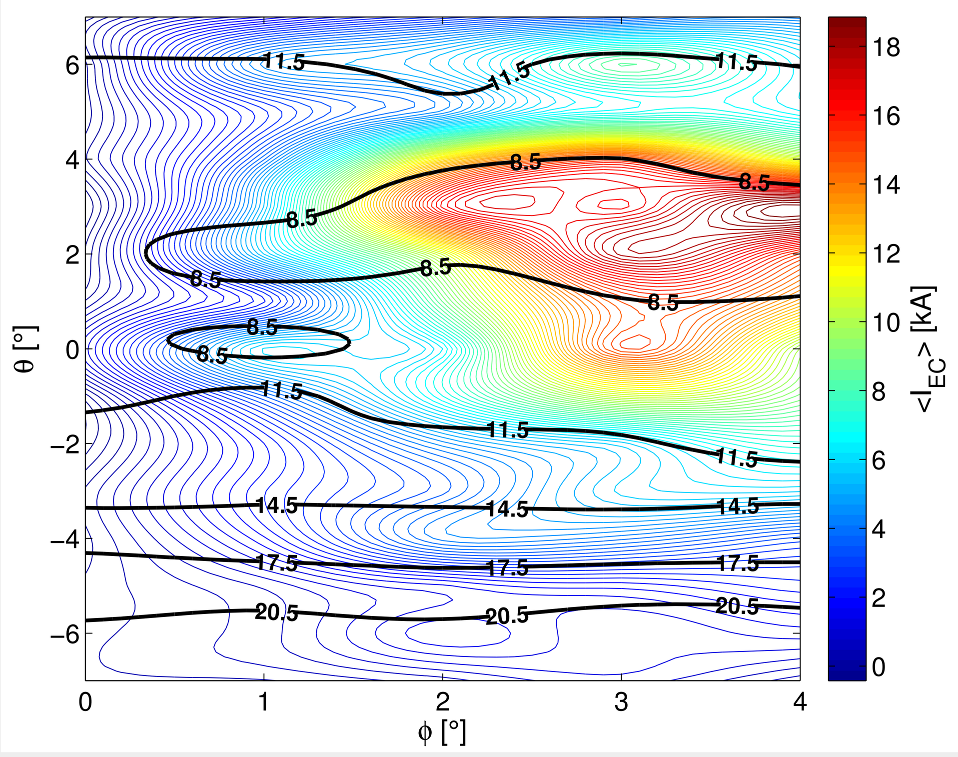
Angular scan: $\{(\phi°, \theta°) \mid \phi \in [0,4], \theta \in [-7,7]\}$

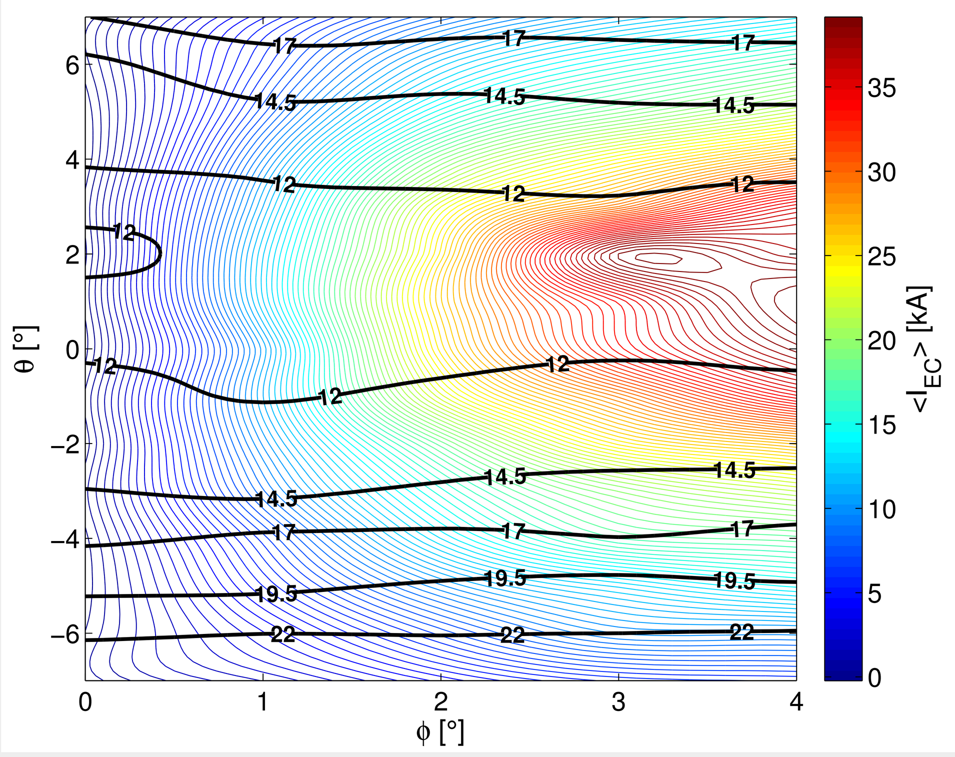


Fast Rampup



Slow Rampup





Black contours correspond to:
- Deposition width - <P_{Abs}> plot
- Deposition Location - <I_{EC}> plot

Injection angles: $\{(\phi°, \theta°) \mid \phi \geq 2, \theta \in [0,4]\}$ provide effective ECRH/ECCD on *both* rampup scenarios

Recommended Launch Angle: (4°, 3°)

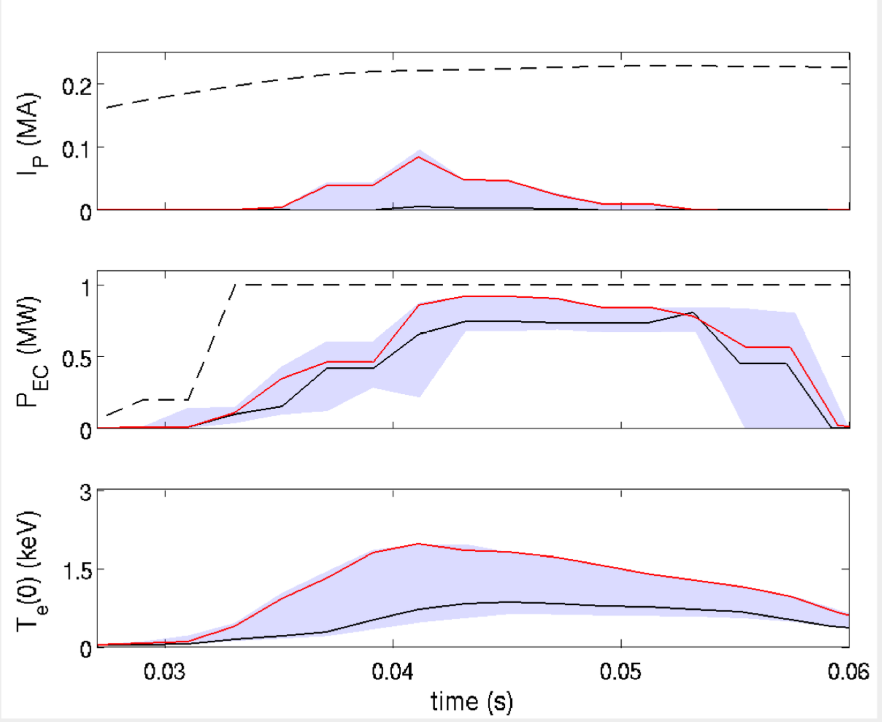
Injection angle recommendation from Figure of Merit:

$$\mathrm{FOM} = \frac{1}{6}\sum_{d=s,f}\left\{\langle\tilde{I}^d_{EC}\rangle + \langle\tilde{P}^d_{Abs}\rangle + \frac{1}{\sqrt{2}}\sqrt{\langle\tilde{\sigma}^d\rangle + 1} - 6\delta^d\right\}$$

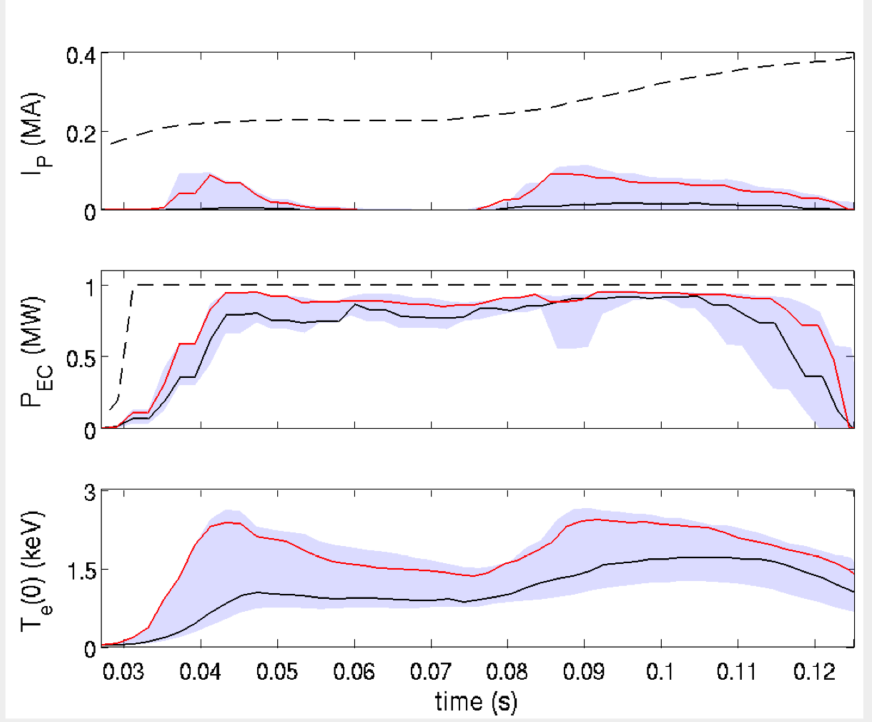
σ = width of deposition, δ = smoothing to deposition profile (if any)
<...> = time-averaging over EC duration, ~ = normalized to max value, summation is over the 2 rampups

	Angle	FOM
1.	(4°, 3°)	0.925
2.	(4°, 0°)	0.827
3.	(4°, -1°)	0.817
4.	(3°, -1°)	0.791

(4°, 3°) [red] improves ECRH & ECCD efficiency throughout EC duration compared to previously recommended angle (1°, -5°) [black]



Fast Rampup



Slow Rampup

Summary

- Time-dependent simulations with TRANSP are used to optimize O1-mode ECRH on NSTX-U during the startup phase
- We find EC waves injected 4° toroidal (co-directional) and 3° poloidal (above midplane) provide optimal ECRH/ECCD while remaining robust to modifications in the density rampup
  - T_e exceeding 1.9 keV and I_{EC} exceeding 80 kA achievable on both rampups

Work in Progress

- MHD stability analysis of resultant EC current profiles against ballooning modes
- Using GENRAY+CQL3D for quasilinear effects at low density
- Assess EBW startup feasibility – (somewhat) working case on slow rampup below