NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

[OV/4-5Rb] Recent NSTX-U theory, modeling and analysis results

Walter Guttenfelder for the NSTX-U team

IAEA Fusion Energy Conference 2020
Virtual
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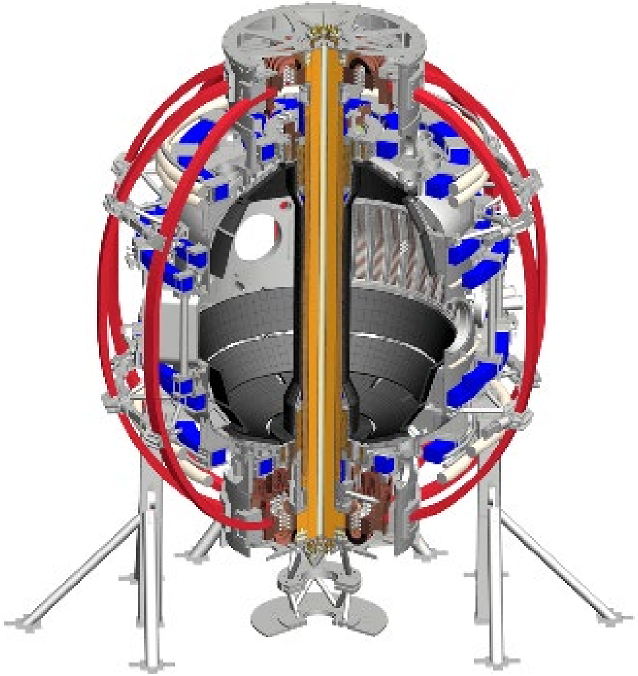
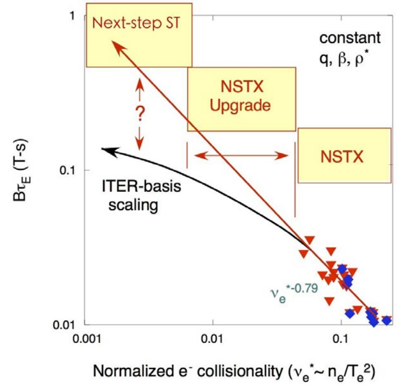
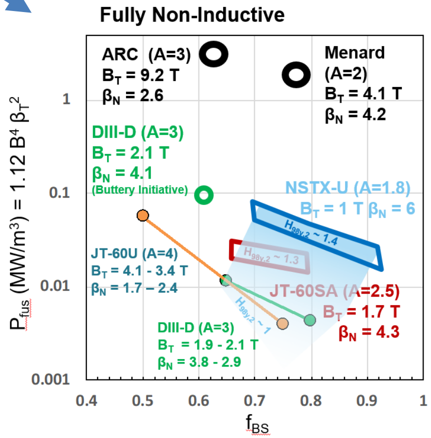


NSTX-U Mission: Advance low-A physics basis for configuration optimization, support ITER & critical fusion development needs

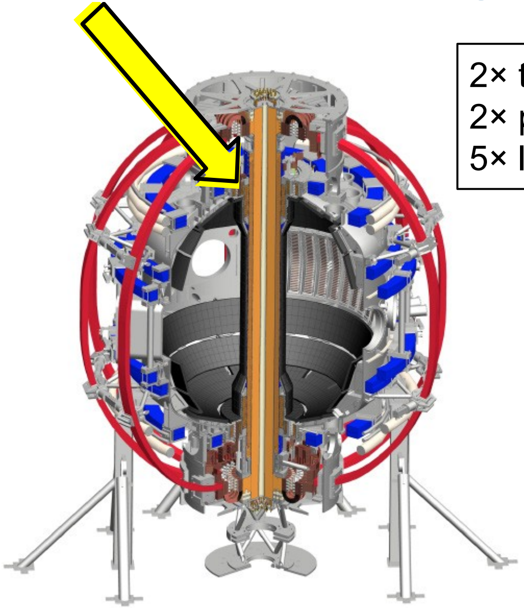
- Key objectives of NSTX-U research program:
  - Extend confinement and stability physics basis at low-A and high beta to lower collisionality relevant to burning plasma regimes
  - Develop operation at large bootstrap fraction and advance the physics basis required for non-inductive, high-performance and low-disruptivity operation of steady-state compact fusion devices
  - Develop and evaluate conventional and innovative power and particle handling techniques to optimize plasma exhaust in high performance scenarios
  - Support additional critical fusion science and technology development needs (e.g., ITER) utilizing the unique regimes accessible in NSTX-U





NSTX-U targeting major performance increase to explore new physics regimes

1. New Central Magnet

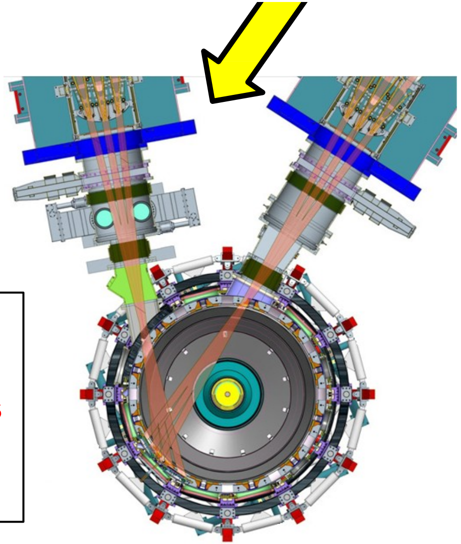


2× toroidal field (0.5 ➔ 1T)
2× plasma current (1 ➔ 2MA)
5× longer pulse (1 ➔ 5s)

Unique regime (high β, low ν_*)

Study new transport and stability physics

2. Tangential 2nd Neutral Beam



2× heating power (5 ➔ 10MW for 5s)

- Tangential NBI ➔ 2×η_{cd}
- Up to 15 MW NBI + 6 MW RF for 1-2s

Up to 10× higher $nT\tau_E$ (~MJ plasmas)
4× divertor heat flux (➔ ITER levels)

➔ Sustain plasma without transformer

Not yet achieved at high-β_T, low ν_*

Essential for any future steady-state ST/tokamak

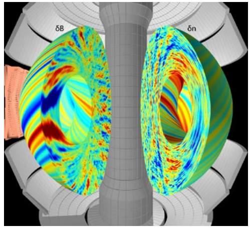
NSTX-U research addresses urgent issues for fusion science, ITER and next-step devices

- ST accesses unique regime of high β_T
  - Fundamental changes in nature of turbulence, MHD stability → Enhanced electromagnetic and super-Alfvénic effects
  - STs can more easily measure electron-scale turbulence

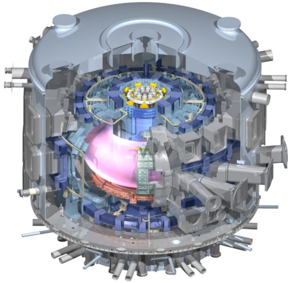
    → Important transport channel at all aspect ratio
  - Neutral beam fast-ions in present STs mimic DT α populations → Study burning plasma science
- ***Expanded parameter space crucial for model validation***
- If physics results favorable, STs could provide more economical fusion development & energy systems
  - Potentially reduced magnet and device size and cost

J.E. Menard, TECH/2-4 (FEC2021)

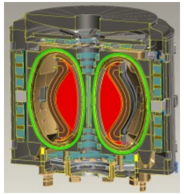
Electromagnetic turbulence



ITER



Pilot Plant



Significant progress made in analysis, theory and modeling in multiple areas addressing NSTX-U Mission

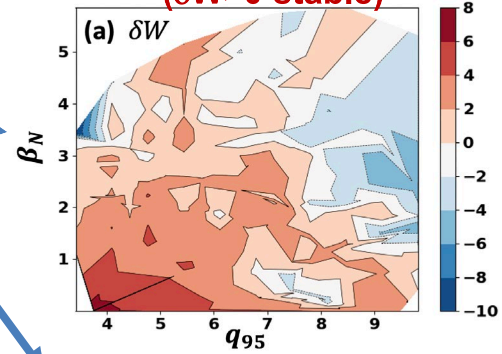
- Core MHD stability
- Energetic particle physics
- Transport and pedestal structure
- Boundary and divertor
- RF heating
- Scenarios and control

Core Stability: kink (n=1) + tearing (2/1) calculations identify stable (β_N, q_{95}) operating space

- Global kink and tearing modes often limited performance on NSTX, also cause disruptions
- Resistive DCON developed to identify scenarios stable to external kink (n=1) & NTM (2/1)
  - Benchmarked with MARS, PEST3 [Z. Wang, 2020]
  - For NTSX-U projection (B_T=1.0 T, I_p=2.0 MA, P_{NBI}=12 MW, $q_{min} \rightarrow 1^+$), both stable for $\beta_N \approx 3$, q_{95}=7.5 (regions in red are stable)
  - Can also be applied to optimize ramp-up

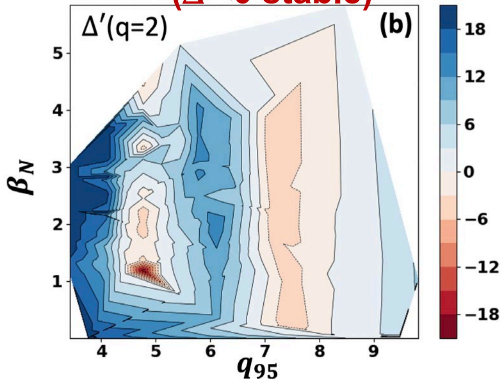
n/m=1/1 kink stability

(δW>0 stable)



n/m=2/1 NTM stability

(Δ'<0 stable)



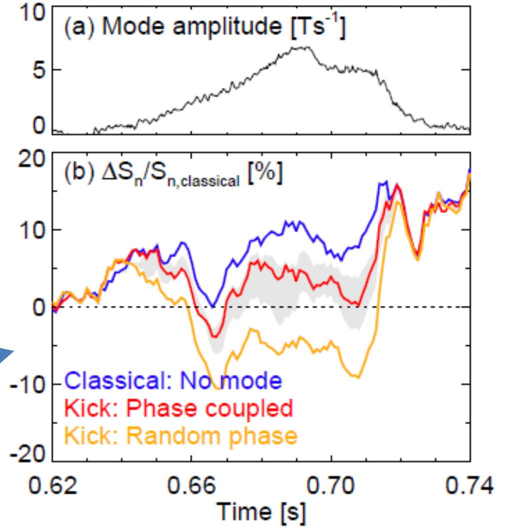
- 3D calculations (IPEC, M3D-C1) used to study sensitivity of plasma response & PFC strike-points to coil alignment
  - Tearing & locked-mode onset + PFC field line pitch used to guide engineering alignment tolerances [Ferraro, 2019]
  - Corresponding strike-point splitting & extended footprints contained to high-heat flux PFCs [Munaretto, 2019]

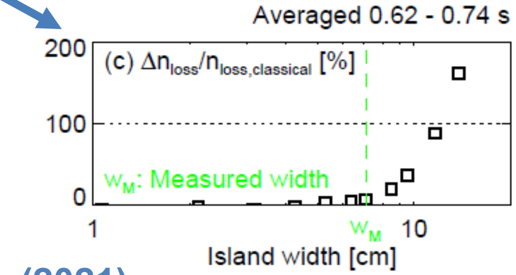
EP: Coupled low-frequency modes modify fast ion transport synergistically

- Alfvenic and low-frequency (MHD) modes can interact nonlinearly to influence fast ion transport
- “Kick” model for energetic particle (EP) transport has been extended to include low-f perturbations

M. Podesta (2019), TH/P1-26 (FEC2021)

- Predicted neutron rate deficit (ΔS_n) correlates with amplitude of coupled kink (n=1) + tearing (2/1) modes
  - Important to model phase-coupled, as inferred in experiment; different than sum of randomly-phased modes
- Possible experimental evidence of NTM saturation level clamped by "stochastization" of EP phase space
- Kinetic module of M3D-C1 recently developed to simulate coupled MHD-EP interactions (C. Liu)

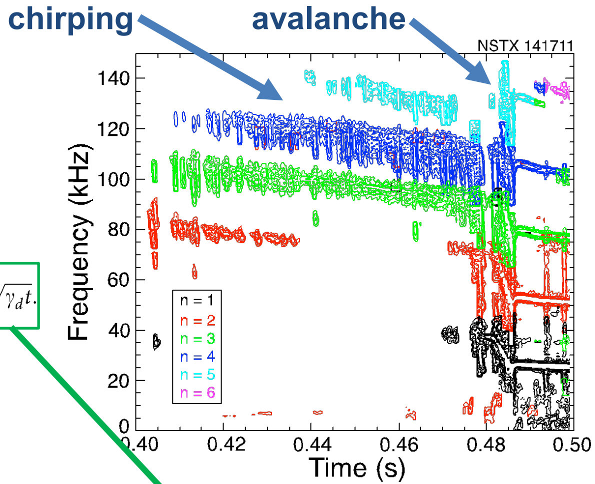


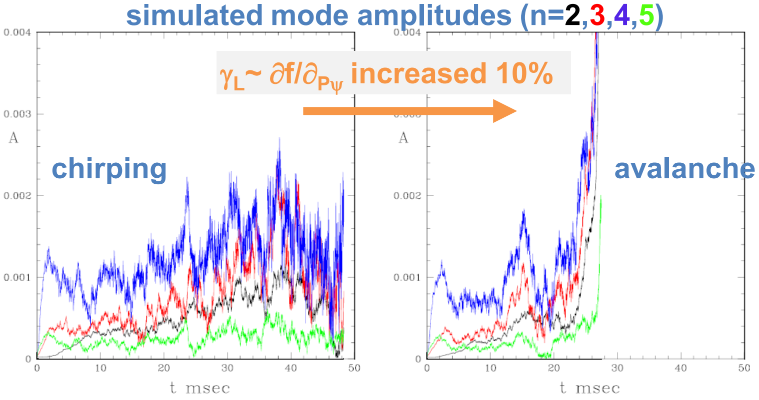


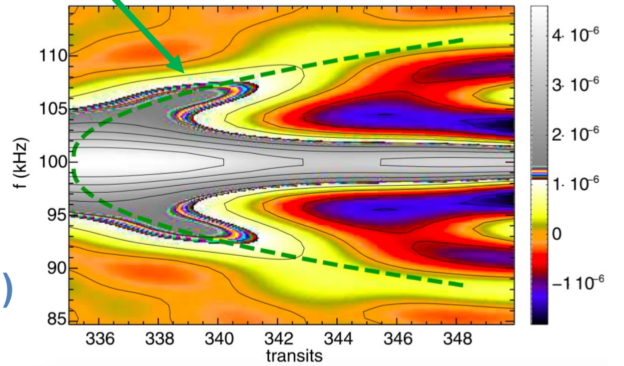
J. Yang (2021)

EP: Guiding center simulations (ORBIT) + delta-f formalism predict nonlinear chirping & avalanches due to AEs

- Chirping and avalanches are primary mechanisms of fast ion loss due to Alfvén eigenmodes (AEs)
  - Avalanches often observed in NSTX with super-Alfvénic beams ($V_{beam}/V_A>1$) → relevant to ITER α's
- Frequency chirping predicted by simulations, consistent with analytic theory based on wave-particle nonlinearity $\delta f = \pm \frac{16\sqrt{2}}{\pi^2 3\sqrt{3}} \gamma_L \sqrt{\gamma_d}\, t.$
- Avalanche onset requires multiple modes with sufficient resonance overlap, simulations predict threshold behavior







R.B. White (2019, 2020)
TH/P1-13 (FEC 2021)

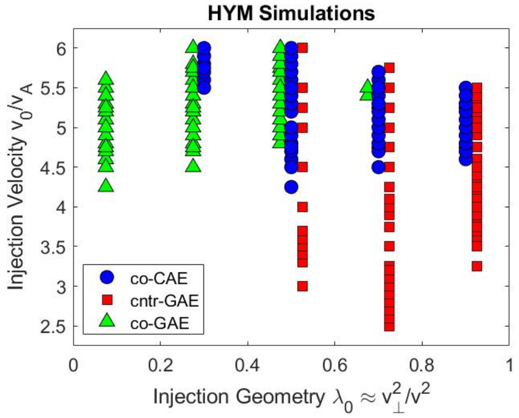
EP: Theory & simulation predict ways to stabilize high-frequency GAE/CAE, hypothesized to influence core T_e

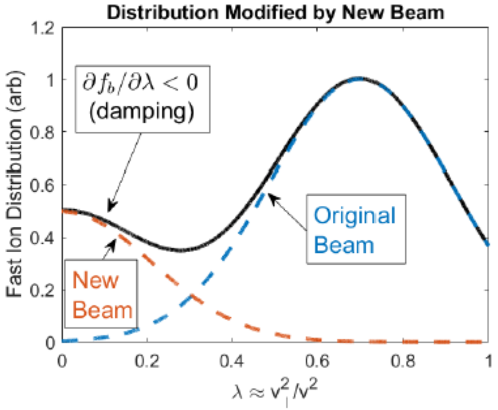
- GAE/CAE observed at high power, correlated to flattening of T_e
  - Possibly due to stochasticized electron orbits (χ_e) and/or energy channeling to edge via CAE-KAW mode conversion
- Hybrid MHD-kinetic simulations (HYM) predict sensitivity of GAE/CAE stability with beam injection geometry and velocity
- Local analytic theory gives insight on how to stabilize

$$\gamma \propto \int h(\lambda, v)\left[\left(\frac{\ell\omega_{ci}}{\omega}-\lambda\right)\underline{\frac{\partial}{\partial\lambda}}+\frac{v}{2}\frac{\partial}{\partial v}\right] f_b(\lambda, v)\, d^2\mathbf{v}$$

  - Counter-propagating GAE requires perpendicular injection (λ_0~0.5-0.7 in NSTX) → stabilized by more tangential NBI on NSTX-U (λ_0~0)
  - Co-propagating GAE predicted with more tangential NBI at low field (V_0/V_A>4) → testable on NSTX-U to further validate theory
  - Exp. and simulations for DIII-D suggest GAEs will be unstable in ITER, but much smaller growth rates & amplitudes than NSTX

J. Lestz (2020a,b, 2021); E. Belova, TH/P1-27 (FEC 2021)

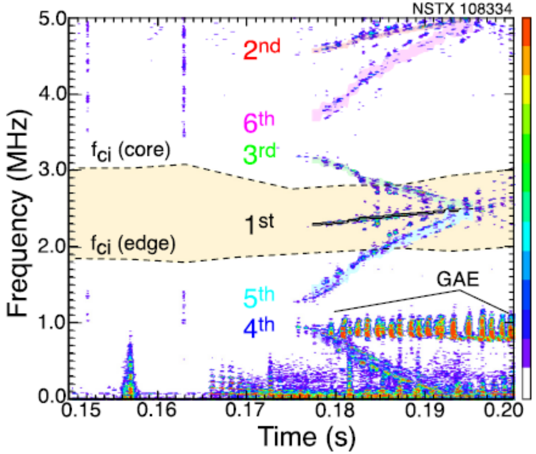




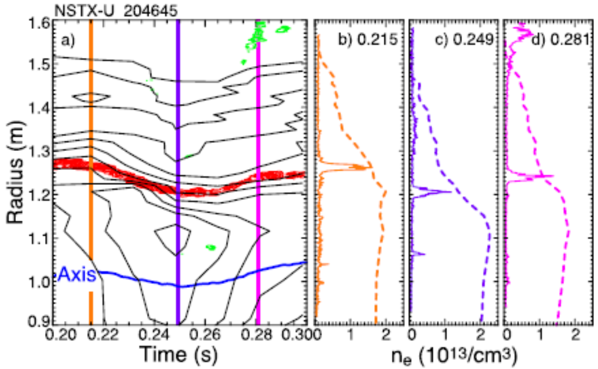
EP: Detailed analysis of ion cyclotron emission (ICE) challenges present theories

- ICE being considered as an additional α-particle diagnostic in ITER, measurable via external Mirnov coils

- ICE observed in NSTX(-U) with ω_{ICE} from 1st to 7th Ω_{ci} harmonics, distinct variations identified:
  1. ~100 μs bursts (γ/ω~1%)
  2. quasi-stationary, strong 3-wave coupling to GAE
  3. longer, stronger bursts (γ/ω~0.06%) with chirping



- ω_{ICE} scales with B (Ω_{ci}), not with density ($V_{Alfvén}$)
- ICE frequency, $\Omega_{ci}(R)=\omega_{ICE}/n$, often maps mid-radius (not core or edge), appears correlated with density gradient
- No correlation between neutron rate and ICE amplitude



E. Fredrickson (2019), EX/P7-6 (FEC2021)

Transport: Comprehensive validation of electron-scale (ETG) gyrokinetic simulations using high-k microwave scattering

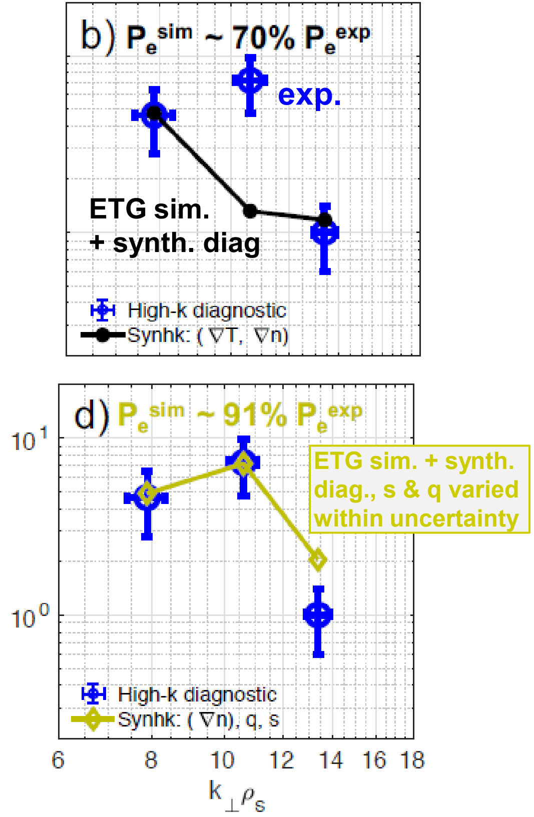
- Local high-k microwave scattering diagnostic + lower-field on NSTX enable detailed validation of electron-scale ETG turbulence

- Using novel synthetic diagnostic, nonlinear gyrokinetic simulations (GYRO) reproduce electron transport & high-k microwave scattering spectra for moderate-β NSTX H-mode
- Numerous parameter scans (∇n, ∇T, q, s) used to quantify sensitivity of predicted fluxes and synthetic high-k spectra

J. Ruiz Ruiz (2019, 2020a, 2020b)

- Global ion-scale simulations (GTS) consistent with negligible ion-scale transport ($\chi_i \approx \chi_{i,NC}$) in this discharge (Ren, 2020)
- Novel pseudolocal SXR tomography concept to measure high-k δT_e developed (X. Chen, 2021)

High-k microwave scattering

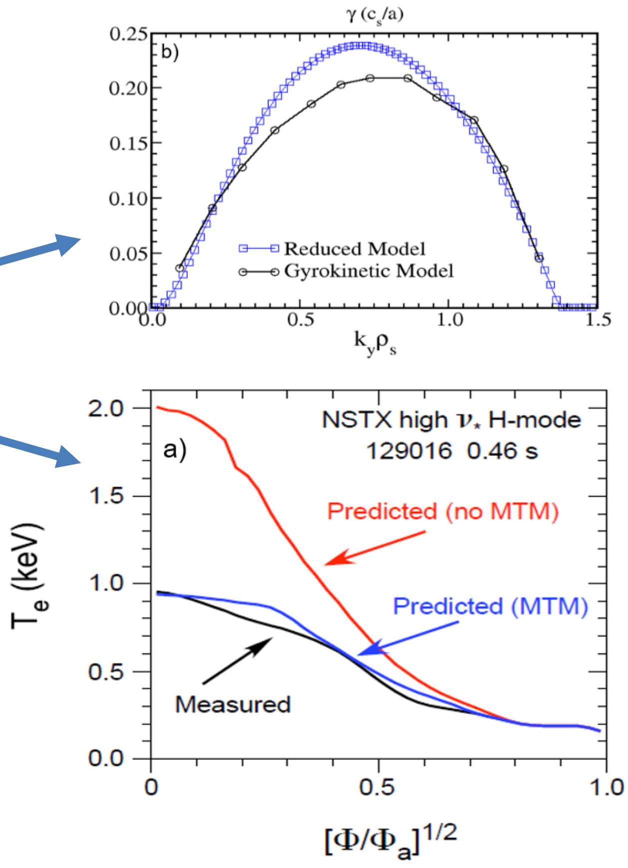


Transport: MTM reduced transport model qualified with gyrokinetics and validated via predictive modeling

- Significant microtearing mode (MTM) electron thermal transport predicted by gyrokinetics in high-β NSTX H-modes
- Hybrid fluid/kinetic MTM model developed to enable integrated predictive modeling
  - Recovers many linear gyrokinetic scalings ($k_\theta\rho_s$, β_e, a/L_{Te} and ν_e)
  - $\delta B/B_0$ saturation model (from nonlinear dispersion) recovers some scalings from nonlinear GYRO simulations
- Predicted T_e profiles using MTM model + Multi-Model Model recover experiment for higher ν_* discharges
  - Overpredicts transport at lower ν_* as $\delta B/B_0$ saturation model scales too weakly with collisionality; other modes may also contribute

T. Rafiq (2021)

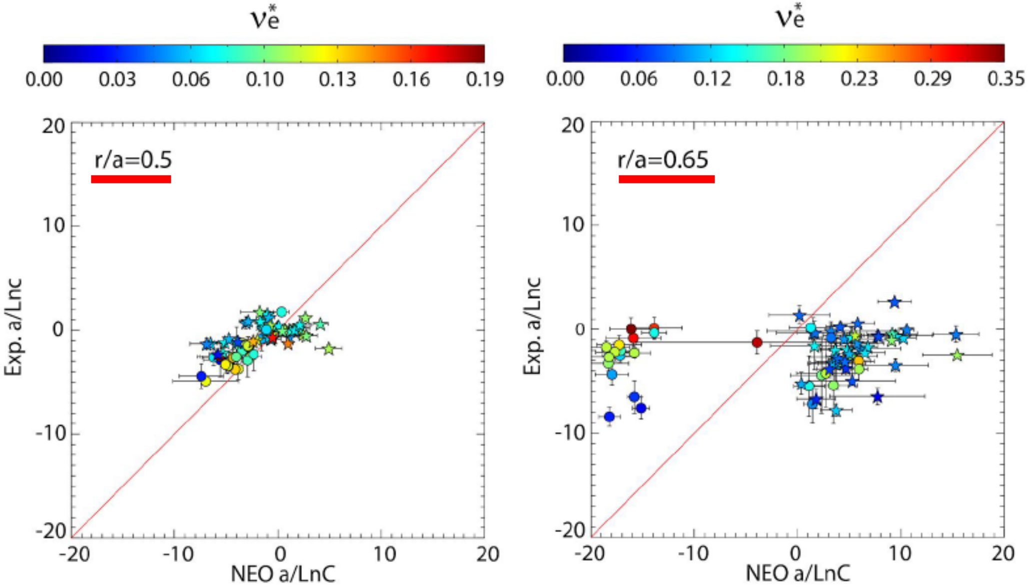
- Empirical χ_e model based on artificial neutral networks also recently developed and being tested (Y.-S. Na)



Transport: Carbon impurity peaking near midradius consistent with neoclassical theory in NSTX database

- Expanded database analysis finds $a/L_{n,C} \approx a/L_{nC,NEO} \sim (a/L_{n,D} - 0.5\ a/L_{Ti})$ at mid-radius

Exp. $a/L_{n,c}$ compared to neoclassical $a/L_{n,c}$ @ Γ_C=0 computed by NEO (w/ poloidal asymmetry from rotation)



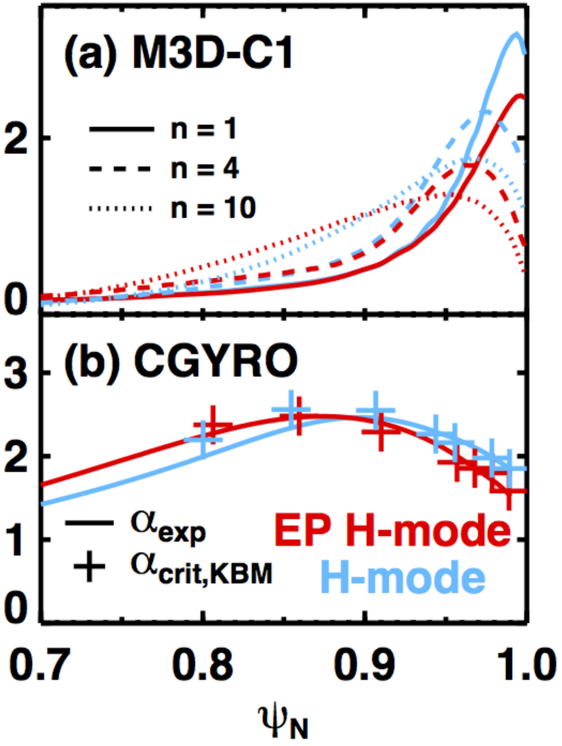
- Deviations further out (r/a=0.65) correlate most with wall conditioning
  - circles = boronization
  - stars = lithium wall conditioning
- Linear CGYRO predicts a mix of unstable modes, unable to account for the difference
  - MTM (Γ_C~0) at high ν_*
  - Ballooning modes at low ν_*, but Γ_C same direction as NEO

N. Howard, PD/1-1 (FEC 2021)

Pedestal: Kink/peeling and KBM instabilities may enable Enhanced Pedestal H-modes (EPH)

- EPH is an attractive wide-pedestal, ELM-free scenario for optimized core-edge performance
  - $H_{98}>1.3$ & $f_{BS}>0.7$ at $f_{GW}>0.7$
- Increased edge $\nabla T_i \approx \nabla T_{i,NC}$ typically accessed via transient reduction in ν_{*i} (e.g. low edge density following large ELM)
- Hypothesis: particle transport from edge instabilities "locks-in" new edge profile state
  - Changes in BES fluctuations observed
  - Kink/peeling linearly unstable (resistive MHD: M3D-C1)
  - Profiles broadly at linear KBM threshold (gyrokinetics: CGYRO)
- SOLPS analysis in NSTX typically finds $(D_e/\chi_e)<0.1$ → profile evolution likely dependent on other additional mechanisms predicted unstable (ETG, MTM, TEM)

Resistive MHD (M3D-C1) and gyrokinetic (CGYRO) KBM stability



D. Battaglia (2020)

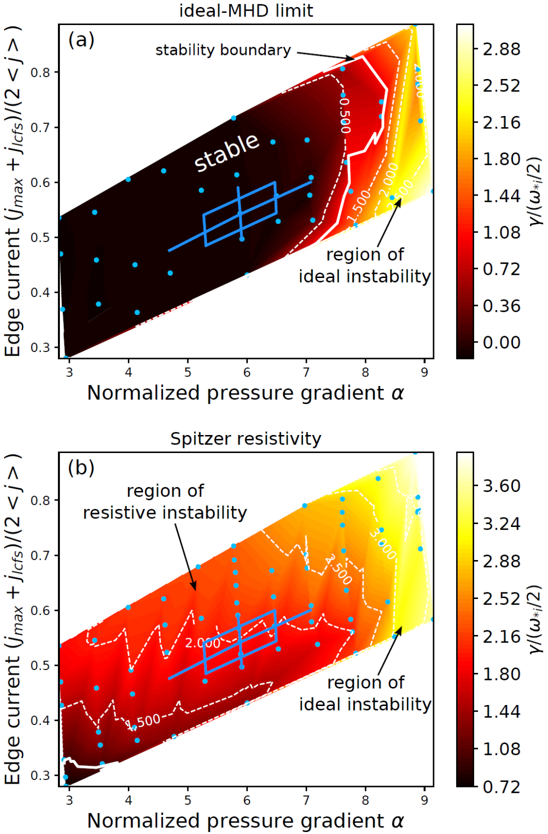
Pedestal: Resistive effects important for predicting MHD pedestal stability in NSTX H-modes

- Ideal MHD peeling-ballooning (P-B) growth rates in ELMy H-mode, $\gamma_{NSTX,ELMy\text{-}H} / (\omega_{*i}/2) \approx 0.1$, smaller than that for conventional tokamaks, $\gamma / (\omega_{*i}/2) = 1$

- Resistive MHD simulations (M3D-C1) predict larger P-B growth rates & change in stability boundary for NSTX ELMy H-modes
  - ELM stability boundary closer to $\gamma_{resistive} / (\omega_{*i}/2) = 2$

- Moving towards generalized pedestal structure model including non-ideal MHD + gyrokinetic KBM

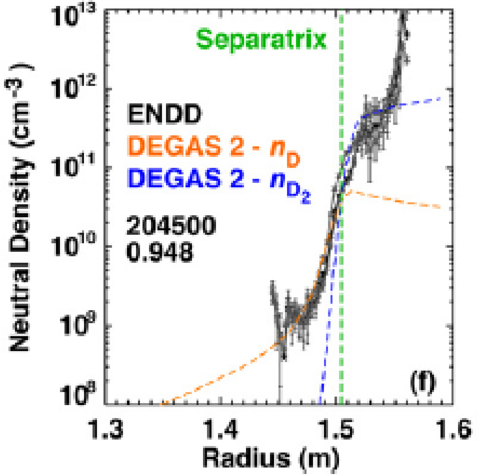
A. Kleiner (2021)



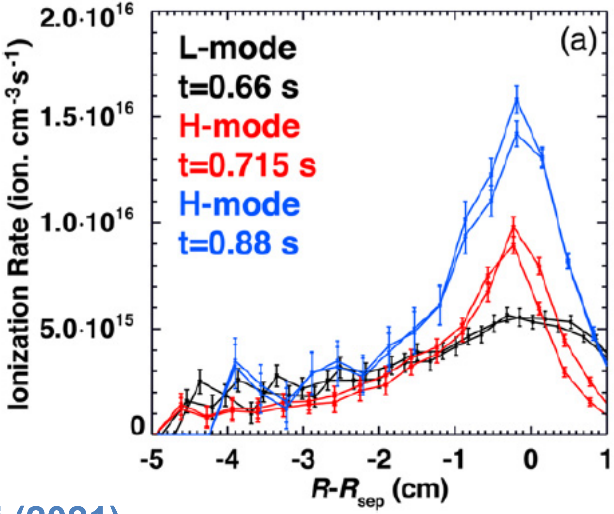
Pedestal: Neutral density & ionization measurements enable fueling and pedestal transport studies

- Neutral density and ionization rate inferred via inverting line-integrated 2D D_α (ENDD)
- Good agreement with DEGAS 2 over large database of NSTX / NSTX-U discharges
- n_D and ionization profiles narrow following L→H, widths remain similar as n_e pedestal grows

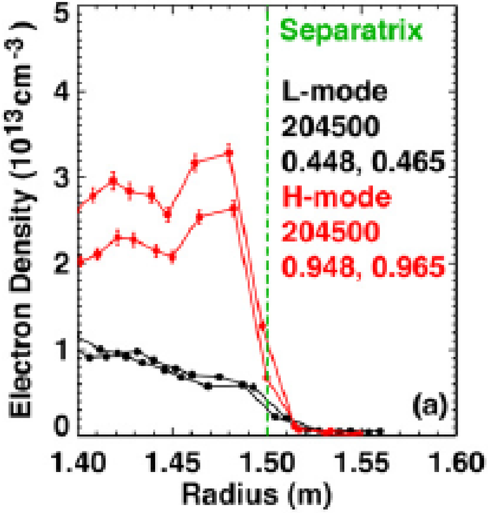
Neutral densities
exp. (ENDD), modeled (DEGAS 2)



Ionization rate (ENDD)



n_e pedestal formation

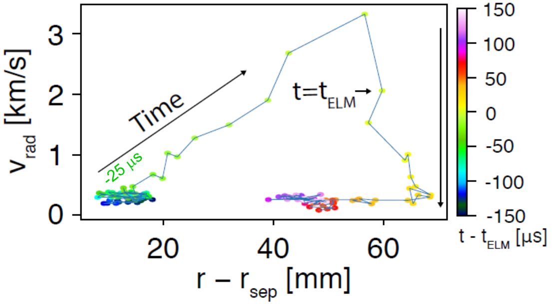


F. Scotti (2021)

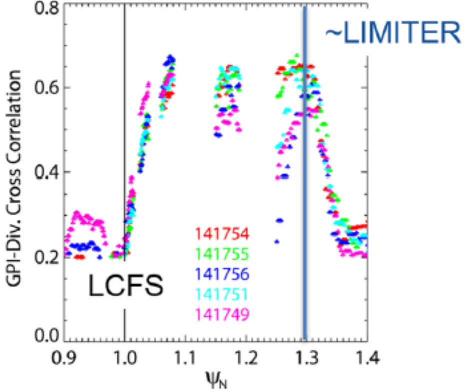
Boundary: Numerous turbulence observations challenge L/H, ELM and SOL theory

- 2D gas puff imaging (GPI) enables detailed edge turbulence studies
- **L/H**: No statistically significant change in average turbulence $\langle V_{pol} \rangle$ or gradient inside LCFS prior to L→H (S. Zweben, 2021)
- **ELM:** Several SOL filaments coalesce into a single, circular filament, accelerates away from separatrix until ELM crash (Lampert, 2021)
  - Current filament model (Myra, 2007) consistent with coalescence, circular shape, and poloidal acceleration, does not explain $V_{radial} \sim (r\text{-}r_{sep})$
  - Possibility of reconnection contributing to current transport (Ebrahimi, 2017)
- **Inter-ELM**: wakes observed trailing SOL filaments (Zweben, 2019)
  - Possibly drift-Alfven waves, not observed in earlier seeded blob turbulence simulations (Myra, 2013)
- **Upstream (GPI) / divertor target (Li I) correlation**: weak correlation measured near separatrix (Scotti, 2020)
  - Supports the role of X-point geometry and collisionality for disconnection of midplane instabilities from divertor target (Myra, 2006)

ELM filament radial velocity (V_{rad}) vs. distance from LCFS



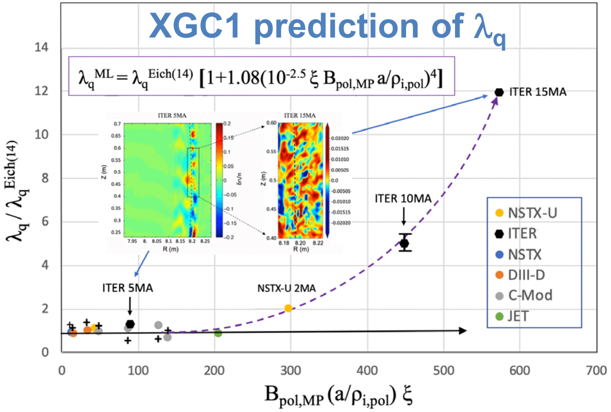
Correlation between upstream and divertor target



Boundary: Gyrokinetic simulations are approaching realism needed to simulate SOL dynamics

- XGC1 predictions of SOL λ_q for NSTX-U & ITER deviate from Eich scaling
- Due to emergence of TEM turbulence at large f_{trap} (low-A) and lower ν_{*e} → opportunity to validate on NSTX-U

Chang (2021), TH/P4-04 (FEC2021)



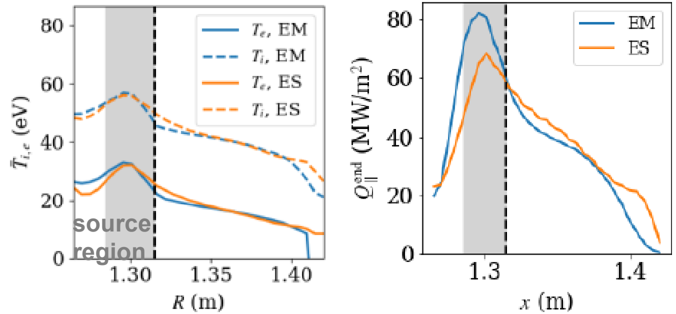
XGC1 prediction of λ_q

$$\lambda_q^{ML} = \lambda_q^{Eich(14)} \left[1+1.08\left(10^{-2.5}\,\xi\, B_{pol,MP}\, a/\rho_{i,pol}\right)^4\right]$$

- Electromagnetic effects incorporated into full-f gyrokinetic open-field line simulations for first time (GKEYLL)
- Used to model NSTX-like simple helical SOL
  - Does not yet include closed surfaces, shaping or X-point
- Predicts change in upstream gradients and target fluxes for scaled-up heating & fueling source rates (β↑)

Mandell (2020); Hakim (2021), TH/3-4 (FEC 2021)

Temperature and target heat fluxes predicted by GKEYLL (scaled sources)

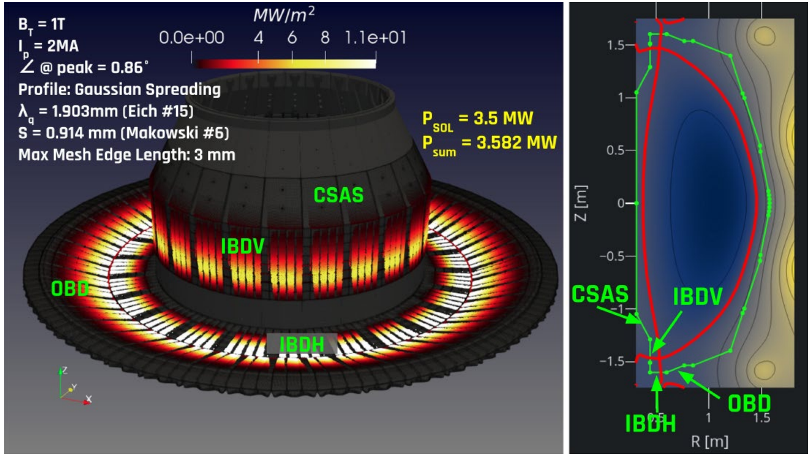


Boundary: New modeling developments to evaluate present PFC operational limits & future PFC concepts

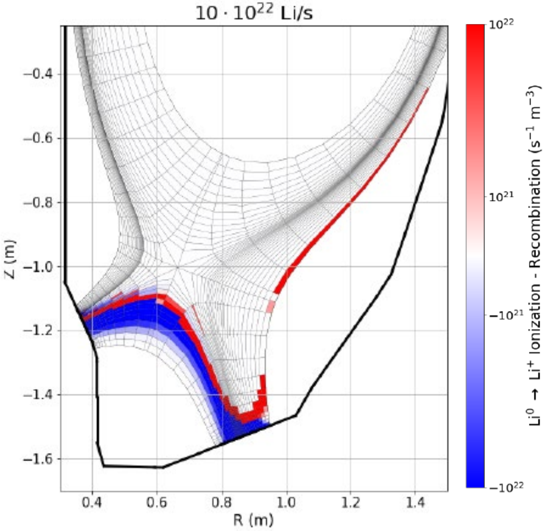
- Heat flux Engineering Analysis Toolkit (HEAT) couples physics, CAD, … to predict 3D heat flux & temp. on new castellated, fishscaled tiles
- Used to evaluate efficacy of strike-point sweeping to extend high power pulse lengths

- Lithium vapor box (LVB) predicted to reduce target $q_\perp$ while maintaining stable detachment
- For NSTX-U LVB concept, SOLPS-ITER predicts upstream n_{Li}/n_e can be minimized (<2%) with sufficient D_2 puffing while maintaining detachment

Predicted 3D distribution of PFC heat fluxes (HEAT)



T. Looby (2021)



Volumetric Li ionization (with D_2 puff)

E. Emdee (2021)

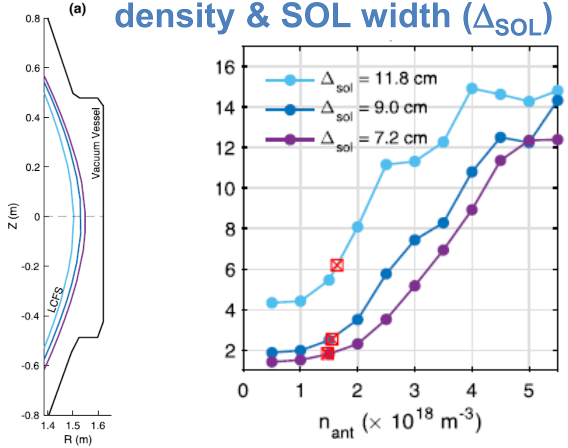
Additional concepts proposed (Ono, 2020; TECH/P7-11)

RF: 2D simulations used to investigate high harmonic fast wave (HHFW) coupling & SOL losses

- Significant HHFW power often lost to SOL in NSTX through cavity modes
- 2D full wave code (FW2D) updated to include realistic boundary → predicted SOL loss minimized for lower density near antenna (n_{ant} ~ fast wave cutoff)
  - Reduced at higher field (NSTX-U), smaller outer gap (Δ_{SOL})

E.-H. Kim (2019)

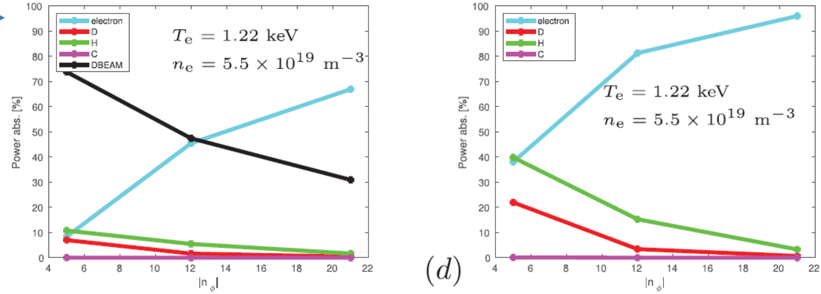
HHFW SOL power loss (%) vs. antenna density & SOL width (Δ_{SOL})



- Challenge to couple HHFW with NBI fast ions
- 2D full-wave simulations (AORSA, w/o SOL) predict competition between electron and fast ion absorption
  - Electron damping increases with phasing / toroidal wave number (n_φ), T_e/T_i and B_T
- Additional simulations show that a sufficient concentration of H+ minority species could enable new HHFW heating scenarios (without NBI)

N. Bertelli (2019)

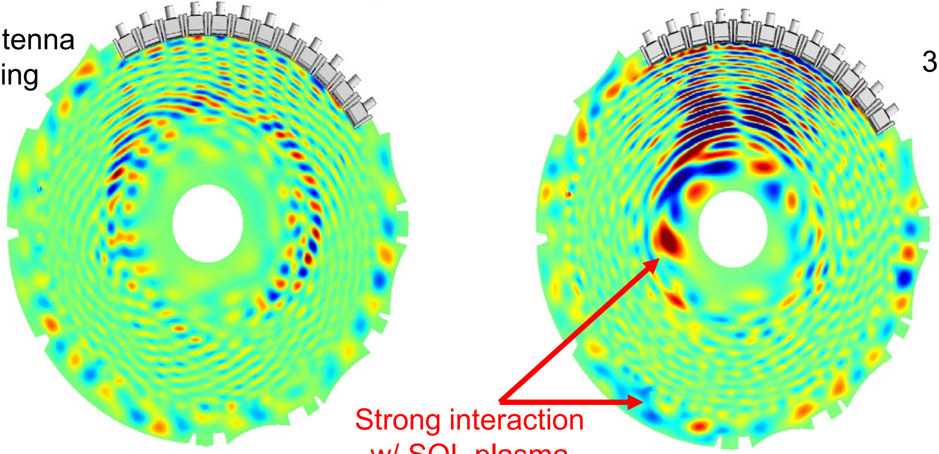
Predicted HHFW absorption w/ & w/0 NBI fast ions



<u>RF</u>: Realistic 3D simulations (Petra-M) applied to study NSTX-U HHFW heating and SOL losses

- Petra-M developed for 3D simulations including SOL
  - 3D CAD for vessel & 12-strap antenna, EFIT for magnetic equilibrium
- Predicts increased SOL loss with lower antenna phasing (lower n_φ)
  - Stronger interaction with SOL plasma, far away from plasma
  - Stronger surface |E|, important for understanding impurity generation & RF sheath effects

Ez component of wave field

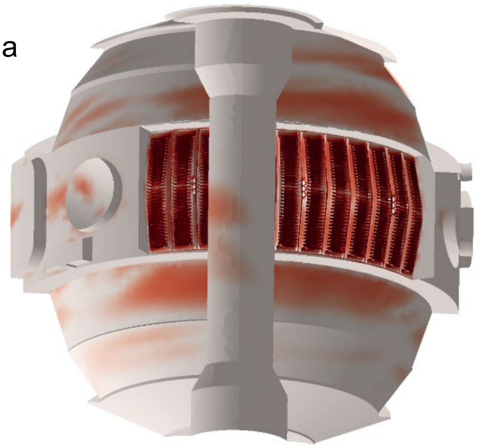


150° antenna phasing

30° antenna phasing

Strong interaction w/ SOL plasma

|E| on the surface



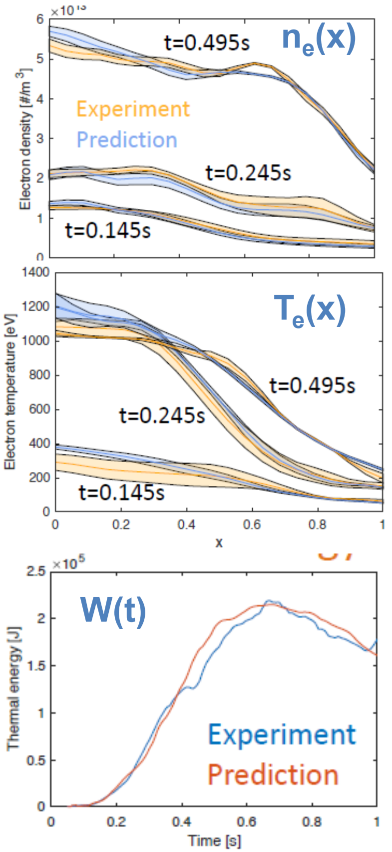
S. Shiraiwa, TH/7-2; N. Bertelli, TH/P2-16 (FEC2021)

Scenarios & Control: Many developments to establish, optimize and control high-performance discharges

- **Scenario optimization**: Optimizing steady-state scenario and actuator trajectories using ML acceleration integrated predictive modeling
  - Automated approach developed for optimizing scenarios & ramp-up trajectories (Wehner, 2019)
  - Accelerated (days → seconds) through reduced models & machine learning for NBI (Ilhan, 2019; Boyer, 2019) and electron transport (Boyer, 2021)

M.D. Boyer, EX/P7-5 (FEC 2021)

- **Realtime (RT) control developments**:
  - Physics-based closed-loop RT control algorithm of snowflake divertor (Vail, 2019)
  - Safety factor control algorithm (Ilhan, 2019), tested using improved TRANSP closed-loop control modeling (Boyer, 2020)
  - Scalable framework for RT Thomson scattering (<17ms latency) using dedicated server & parallel analysis (Laggner, 2019)
- **Startup**: Semi-empirical model for designing inductive startup scenarios developed (Battaglia, 2019) → used to help achieve MAST-U first plasma

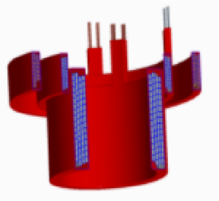


NSTX-U Recovery Project in construction & installation phase

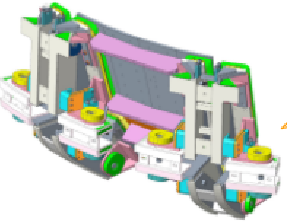
- Magnet fabrication is complete; strong progress in CS casing, PFCs, passive plates
- Due to COVID delays, early start date now August 2022

S. Gerhardt, TECH/P3-17

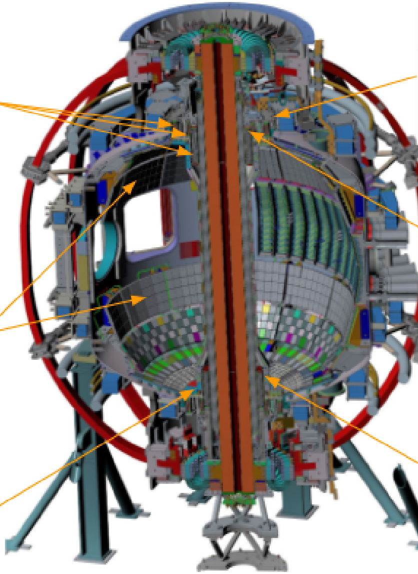
Six new inner-PF coils (PF-1a, -1b, -1c, upper and lower)



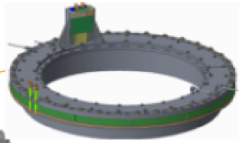
Repairs to passive plate bracketry to allow operation at full EM load

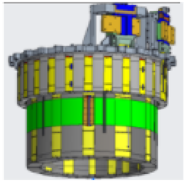


New graphite tiles with improved heat flux handling capabilities

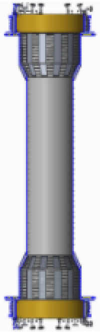


PF-1a, -1b, -1c support structures and double O-ring seals





New Center Stack Casing With **Improved Heating/Cooling Features**



Summary: NSTX-U research addresses urgent issues for fusion science, ITER and next-step devices

- Advances in core transport validation and model development
- Advances in modeling fast ion transport and energetic particle stability
- Expanded understanding of transport and stability mechanisms setting pedestal structure
- Boundary studies addressing SOL turbulence and PFC modeling
- 2D and 3D RF modeling of HHFW coupling and SOL losses
- Advances in scenario optimization using machine-learning accelerated integrated predictive modeling and in real time control algorithms