Wave heating and current drive

R. Perkins & N. Bertelli

NSTX-U PAC-39
PPPL, Princeton, NJ
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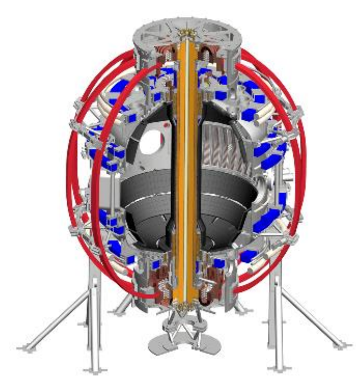
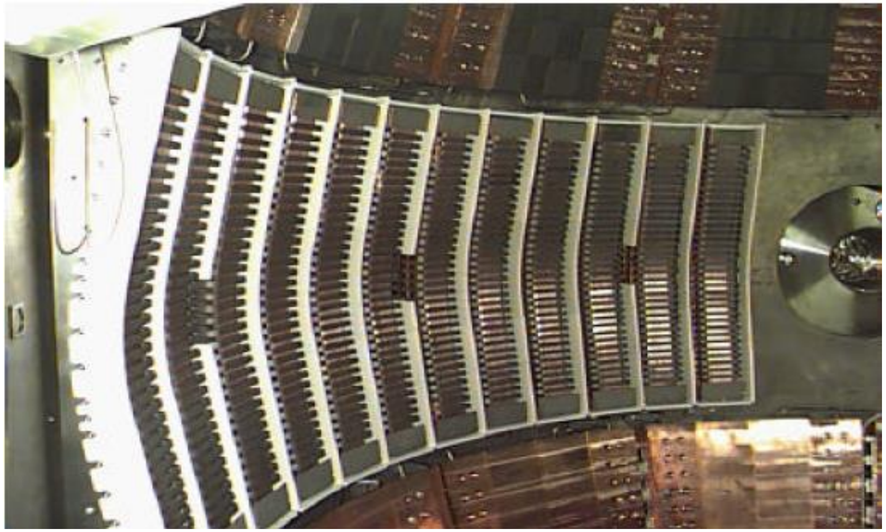
PPPL



High-harmonic fast-wave (HHFW) heating: 6 MW source power with flexible phasing

- 30 MHz: well above ion cyclotron frequency
  - Landau damps on electrons
  - Can be absorbed by beam-ions
- 12-strap phased array
  - Power-deposition control via phasing
- Complementary to NBI
  - Injects heat without particle or momentum input

12-Strap HHFW antenna at NSTX-U midplane



- Only ICRF on toroidal experiment in USA
- Unique system among STs

HHFW is envisioned as a tool that diversifies and enhances the following NSTX-U research:

- Transport studies
- Rotation effects on stability
- Interactions with fast-ion-driven modes
- Low-current non-inductive scenarios

Near- & mid-term

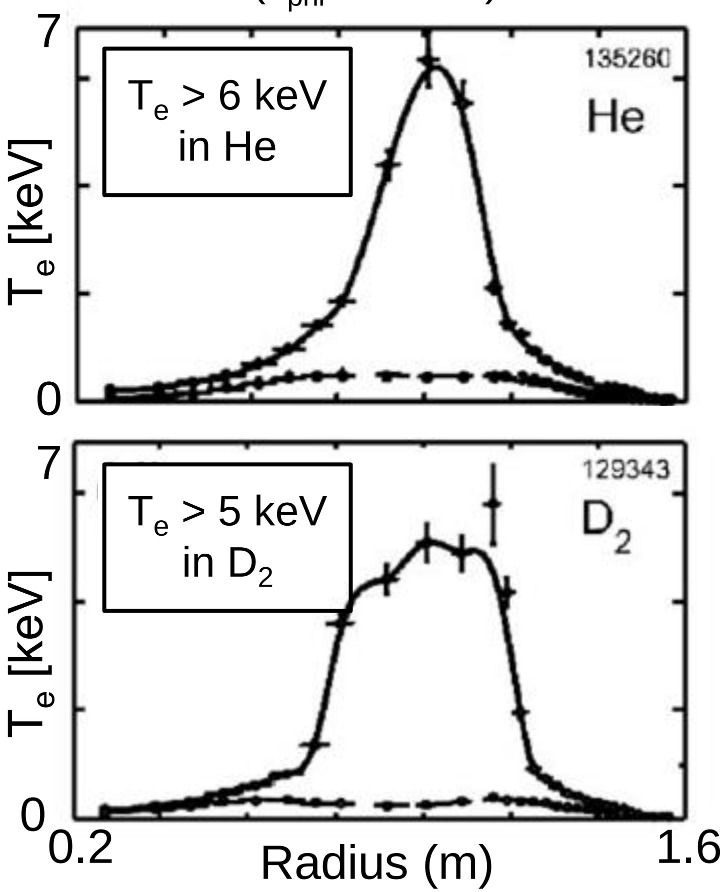
- High-Z impurity transport
- Solenoid-free start-up

Long-term

HHFW can support the investigation of ST confinement via significant e^- heating [T&T-TSG]

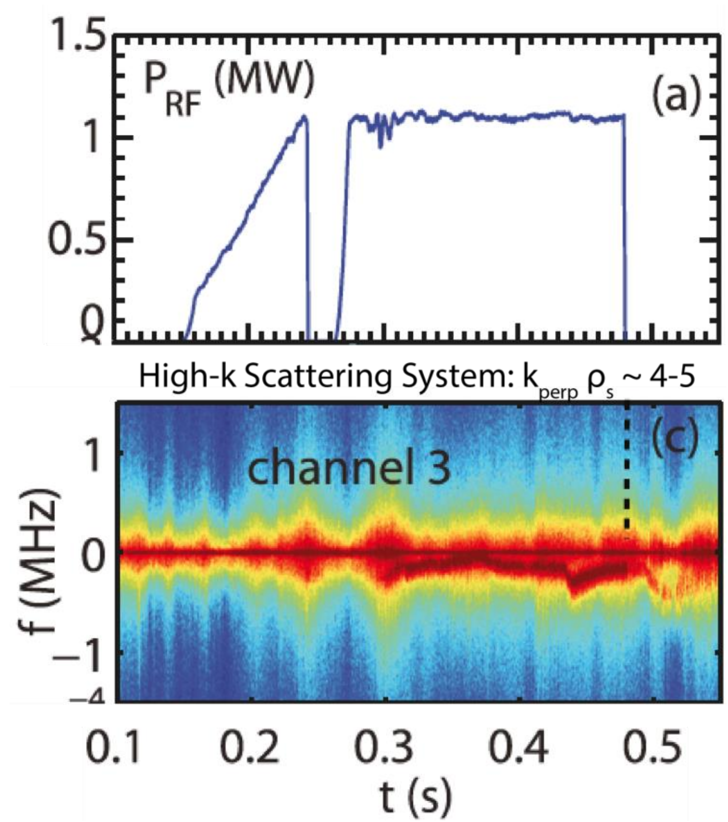
ST record high T_e achieved using 3 MW HHFW

(k_{phi} = -8 m^{-1})



G. Taylor *et al.*, *Phys. Plasma* **17** (2010) 056114

Steep T_e gradient enables transport studies

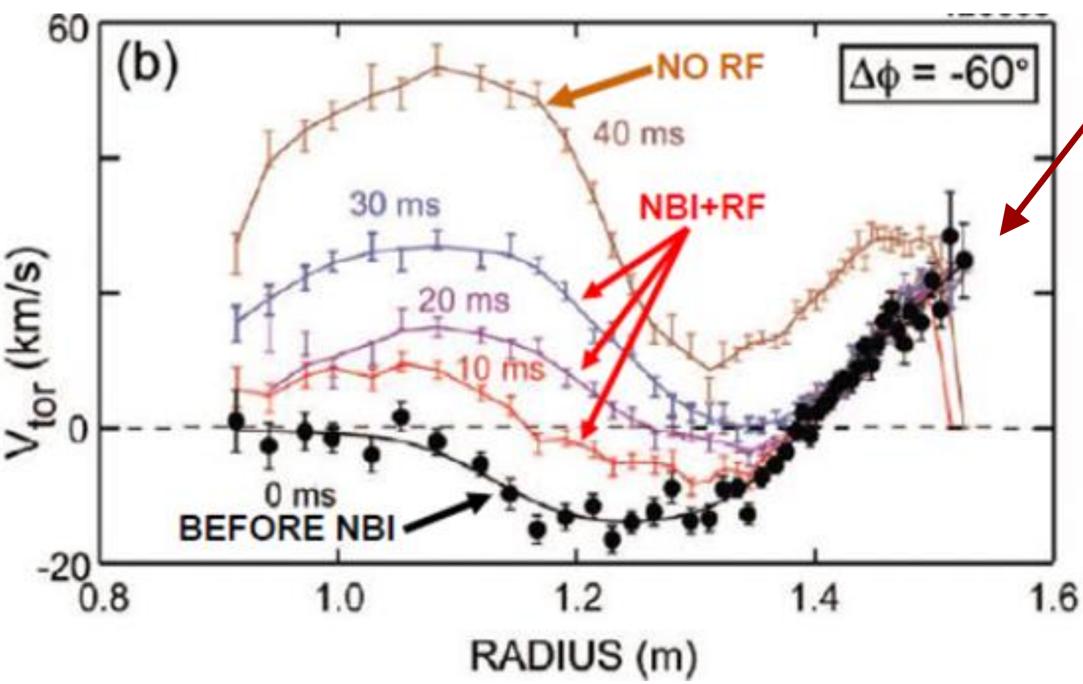


Perturbative electron transport studies investigating non-local transport ($k_\perp \rho_s$ ~ 4-5)

Y. Ren *et al.*, *Phys. Plasma* **22** (2015) 110701

HHFW can strongly change rotation profile; possible tool for transport & stability [T&T- & MS-TSGs]

Velocity profile evolution during diagnostic beam blip



1.1 MW of HHFW, 2 MW beam blip

G. Taylor *et al., Phys. Plasma* **17** (2010) 056114

HHFW influences rotation profile

- Clamps edge rotation to no-NBI level

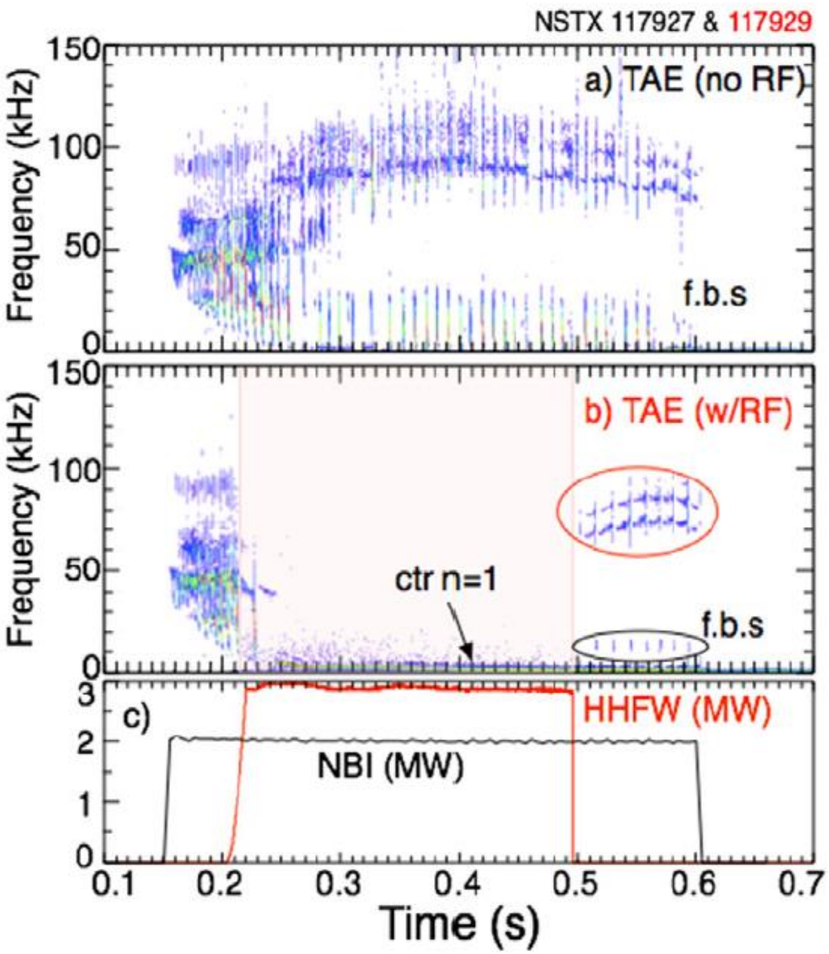
HHFW can produce low-torque H-modes

- Study e^--heated, low-torque discharges for ITER
- Useful for L-H transition studies
  - Important topic ITER
  - Compare to JET results
- Study NTV offset rotation
- Would benefit from x-ray crystal spectrometer (MIT)

HHFW can suppress EP/AE activity [EP-TSG]

- HHFW can significantly modify the fast ion phase space
  - D. Liu *et al., Plasma Phys. Control. Fusion* 52 (2010) 025006

- Significant interaction between HHFW and fast-ion driven modes
  - Possible suppression/excitation of EP/AE modes
  - ITER relevant:
    - ITER will have (super-Alfvénic) alpha particle & ICRF
    - NSTX-U beam injection is super-Alfvénic



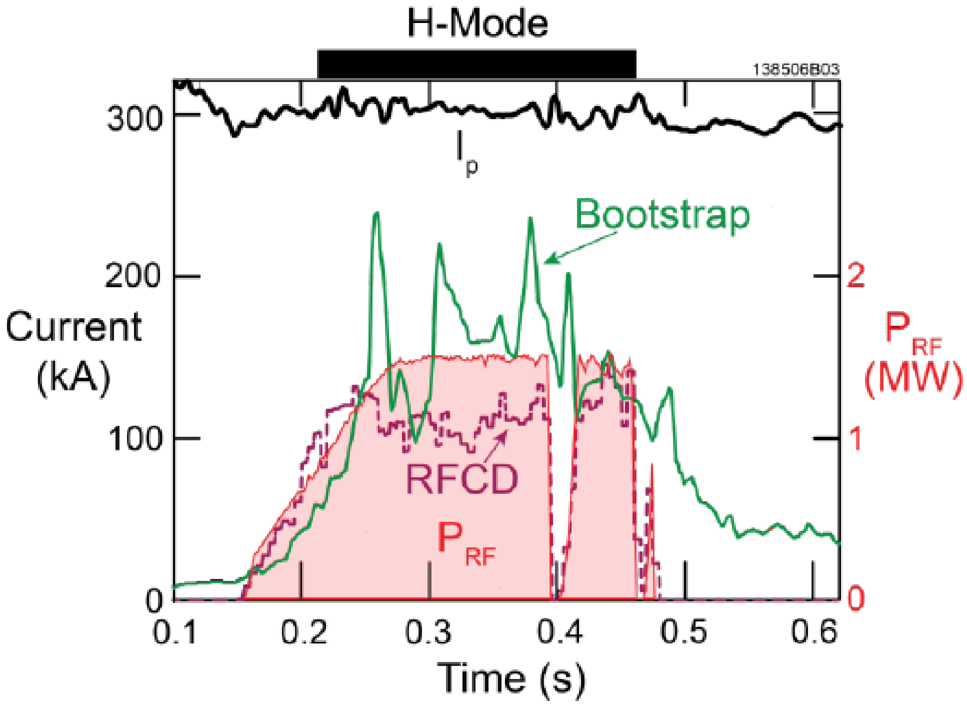
E. Fredrickson *et al., Nucl. Fusion* **55** (2014) 013012

Heating low-I_P plasmas: applications to solenoid-free ramp-up & high bootstrap fraction [SSR- & ASC-TSGs]

- HHFW can potentially bridge the gap between a solenoid-free start-up plasma and NBI
  - Bring cold low-current plasma up to suitable target for NBI

- NEAR TERM: target low-current (300 KA) Ohmic flattop
- MID/LONG TERM: target actual ramp-up phase
- See following Non-Inductive Start-up and Ramp-Up talk

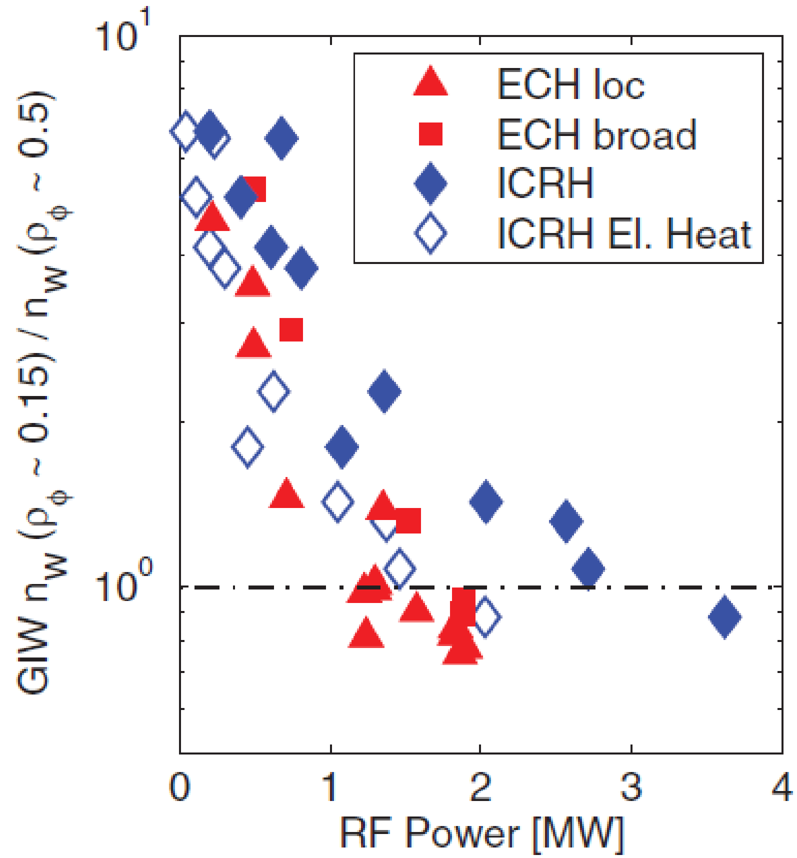
300 kA inductive NSTX target heated to 3keV using ~1 MW HHFW



Central RF heating mitigates high Z impurity accumulation in the plasma core [ASC- & M&PFCs-TSGs]

- High-Z impurity accumulation is a major issue for high-Z walls
  - STs can explore neoclassical vs turbulent effects
- NEAR TERM: HHFW can contribute in near term (before high-Z tiles)
- LONG TERM: HHFW may be an operational need if we transitior to a high-Z wall
  - Significant recommendation from PAC-37

ASDEX-U results showing reduced W concentration with RF



C. Angioni *et al.*, *Nucl. Fusion* **56** (2017) 056015

Charge Question 1: Research in 2016-17 in support of improved HHFW operation

- Modeling of SOL losses of HHFW power
  - AORSA simulations including SOL extended to different aspect ratios
    - N. Bertelli *et al., Nucl. Fusion* **56** (2016) 083004
  - FW2D incorporates realistic antenna & limiter geometry
    - E.-H. Kim *et al., EPJ Web of Conferences* **157** (2017) 02005
  - Cylindrical model calculates modes with enhanced fields in edge
    - R. J. Perkins *et al., Nucl. Fusion* **57** (2017) 116062
- Modeling of HHFW absorption by different ions
  - Self-consistent TORIC & NUBEAM coupling
    - N. Bertelli *et al.*, Nucl. Fusion **57** (2017) 056035
  - Impact of 2nd harmonic H absorption ~1 T
    - New heating scenario
- Collaborations to study far-field rectification
  - Experiments at LAPD on RF rectification and vessel-wide current paths
  - Analysis of EAST ICRF experiment: far vs near field rectification

Prospect of HHFW in NSTX-U (2020-25)

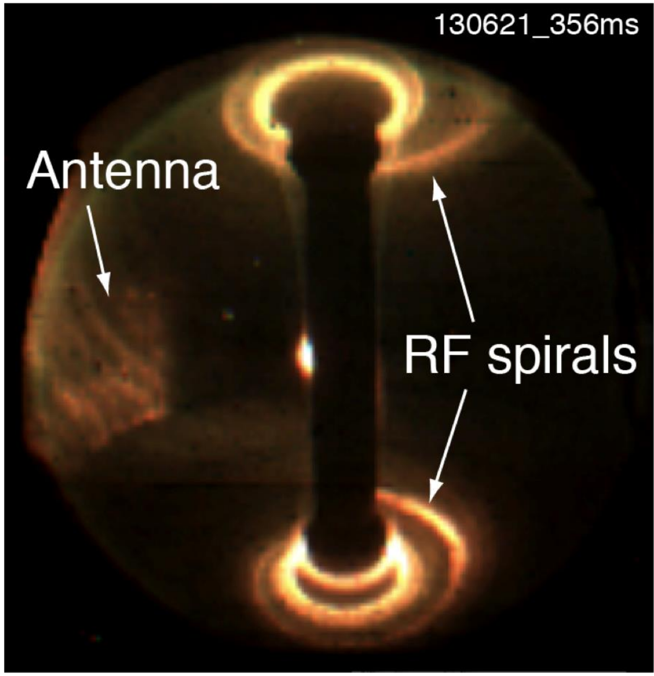
- Characterize SOL losses at higher toroidal field
  - Expected to improve based on operation experience & modeling
  - Quantify losses so users know power input to core

- Study HHFW absorption profiles
  - Assess absorption by 2nd beam ion vs 1st beam
  - Characterize e^- vs beam-ion absorption
    - Predicted to vary with antenna phases & Te/Ti ratio
  - Impact of H species on HHFW performance

- Continue collaboration with RF SciDAC research
  - RF core physics: TORIC + non-Maxw. effects + NUBEAM (w/ TRANSP group)
  - Possible synergy with Helicon research

Charge questions 2 & 3: Uniqueness of NSTX HHFW in view of global RF Research

- SOL losses: unique physics issues
  - Modeling of enhanced RF fields in SOL
  - Far-field rectification: dissipating wave power
- Impact of field misalignment of antenna at high pitch
  - Compare to results obtained from C-Mod field-aligned antenna
- HHFW on NSTX-U is a unique feature for spherical tokamaks



  - Highest power & flexible phasing
  - TST-II: 21 MHz HHFW system up to 30 kW
  - Globus-M: ICRH (~7-9 MHz), 2-strap antenna, 0.5 MW
- Will be the only ICRF system on a toroidal experiment in US
  - DIII-D 476 MHz helicon system: lower-hybrid range of frequencies

Summary

- HHFW system can provide up to 4 MW couple power
  - Complementary to NBI
- HHFW on NSTX-U would support and enhance a broad spectrum of applications:
  - High core T_e for transport studies
  - Interaction between HHFW & NBI
  - Heating of low-I_p targets for subsequent NBI ramp-up
  - Effect on rotation profile
  - High-Z impurity expulsion
- Theory Partnership through RF SciDAC project

THANK YOU

NSTX-U WH&CD research in line with ITPA activities 2017, 2015 PMI & Integrated simulations workshops

- ITPA Integrated Operation Scenarios:

  IOS-5.1 ICRH impurity generation

& 2015 PMI workshop:

[PRD-C] Understand, develop and demonstrate innovative boundary plasma solutions for main chamber wall components, including tools for controllable sustained operation, sufficient for extrapolation to steady-state reactor application

  - Interaction between HHFW and SOL plasma: HHFW SOL losses, antenna impurity sources

- 2015 Integrated simulations workshop:

  [PRD-Boundary-4] Integrate RF antenna/plasma-absorption simulations with SOL/pedestal plasma transport simulations, filling a notable gap in present capability

  - collaboration with the new RF SciDAC project on this task

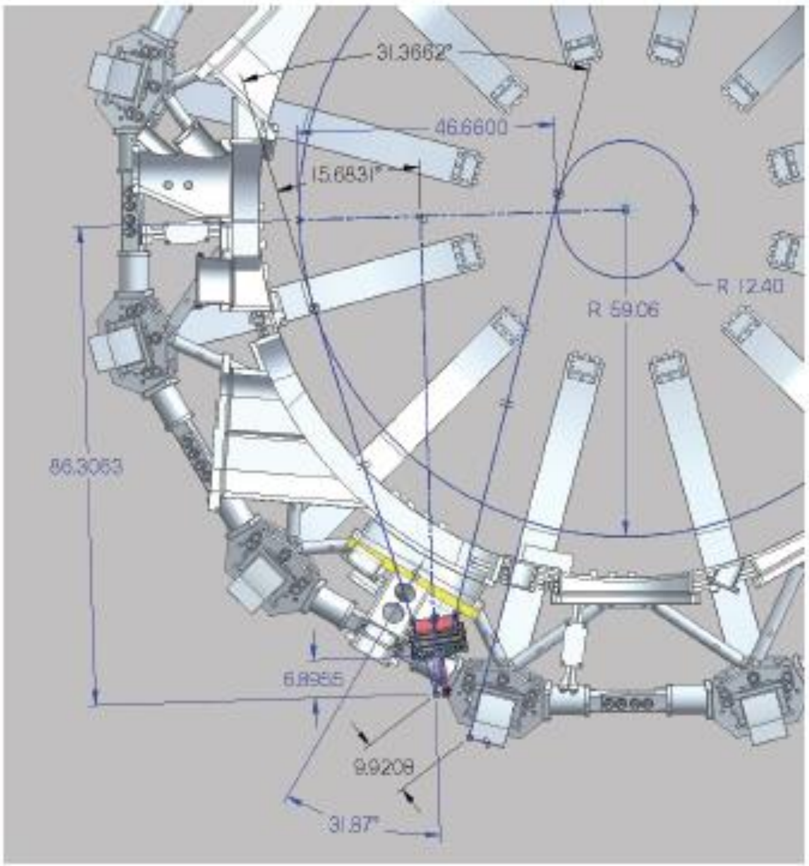
- ITPA ENERGETIC PARTICLES PHYSICS:

  EP-12 Identification of AE control actuators and preliminary assessment for ITER

  - Interaction HHFW + NBI: modification of fast ions phase space by RF
  - suppression of AE activity by HHFW

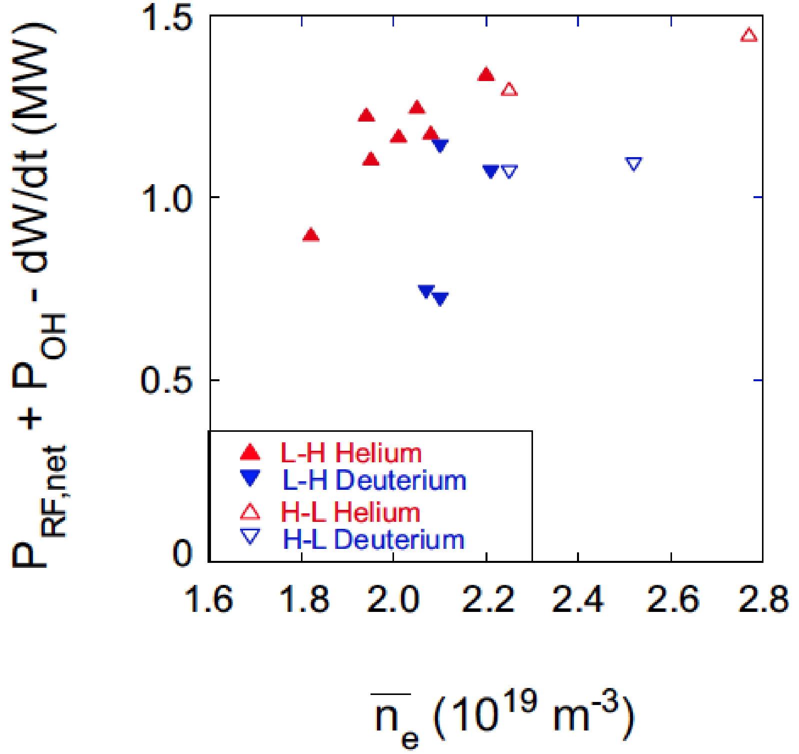
Proposed x-ray crystal spectrometer (MIT)

- Obtains rotation & T_i profiles without NBI "blips"
  - Uses argon seeding for Doppler measurements
  - Useful for HHFW-only discharges for which CHERS is unavailable without beam blips
- Conceptual design review completed
  - Covered redesign of port flange, spectrometer layout, test of analysis
- Not included in Recovery scope
  - Could be near-term capability if supported



Isotope-dependence in L-H transition studies are enabled by HHFW

- HHFW advantages for L-H transition studies
  - HHFW can heat discharges without momentum input
  - HHFW heats He discharge w/o injecting D
  - HHFW power level is arbitrary
    - NBI "discretized" to 2 MW steps
- Important for ITER
  - Marginal power for L-H transition in hydrogen phase?
  - Added ST data point to ITPA studies
  - Will compare future NSTX-U results to recent & upcoming results from JET



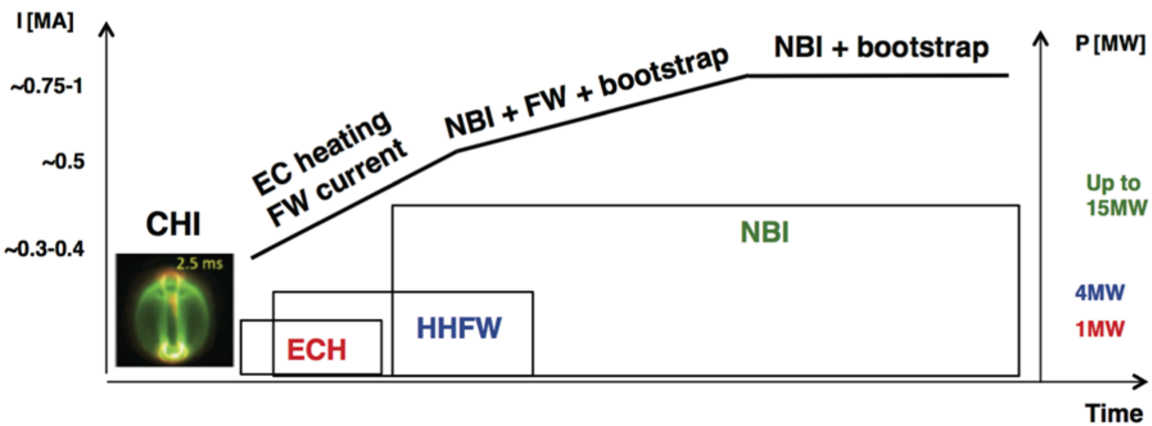
S. Kaye *et al.*, *Nucl. Fusion* **51** (2011) 113019

Developments in RF

- SOL losses determine to be field-aligned and occurring across entire width of SOL
- MIT field-aligned antenna demonstrates reduced impurity production and variations in reactive loading
- RF rectification shown to be a strong candidate mechanism for dissipating HHFW power
- Full-wave simulations show strong increase in RF amplitude in SOL when SOL density exceeds cutoff
- Cylindrical analytic model shows existence of modes with large edge amplitudes when a half-wavelength structure fits into edge region
- Self-consistent full-wave modeling and particle distribution function evolution

EC/EBW Motivations for NSTX-U

- 28 GHz gyrotron system can heat CHI plasma to enable HHFW heating and current drive, ramp-up to higher I_P with NBI heating
- 28 GHz gyrotron could also be used for EC/EBW plasma formation, H-mode heating and current drive (with launcher upgrade)
- Performed TRANSP simulations combining all heating schemes: EC+HHFW+NBI
  - F. Poli et al, Nucl. Fusion **55** (2015) 123011



See talk on Non-inductive start-up and ramp-up