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NSTX Progress and Plans for Wave-Particle Interactions

From the
Mid-term Review of Major MFE Facilities
Gaithersburg, MD
September 21, 2006

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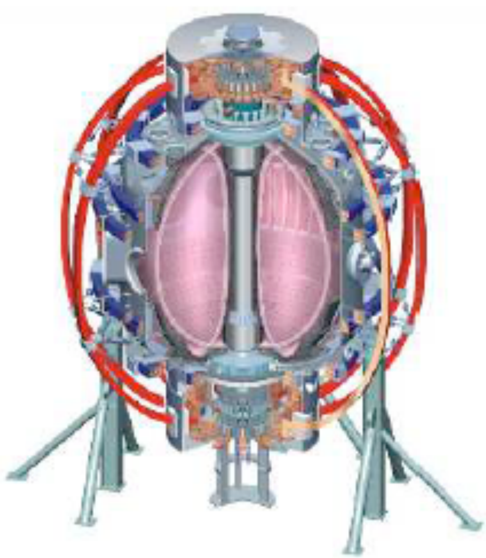

Culham Sci Ctr
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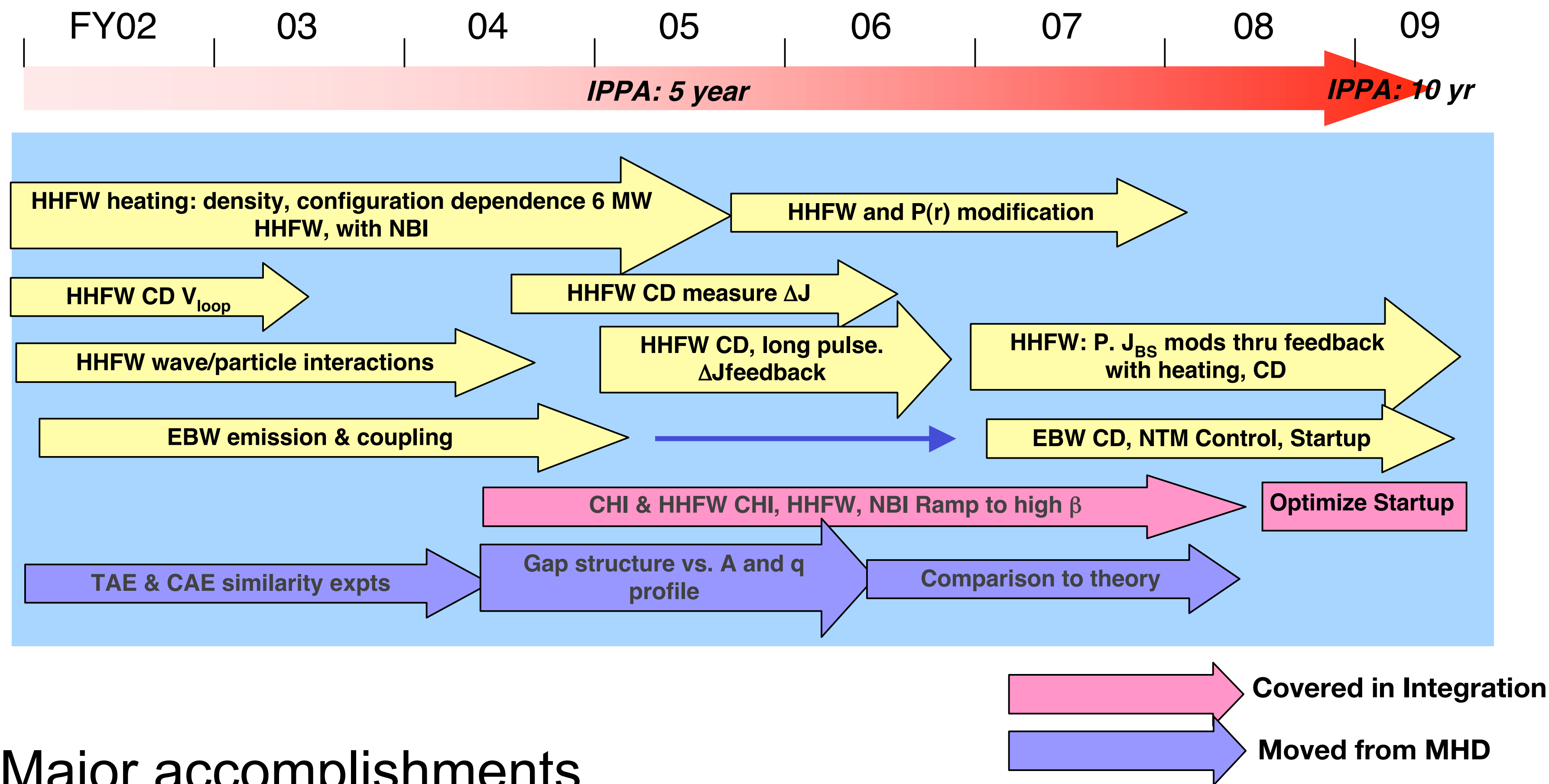
Wave-Particle Interaction Research

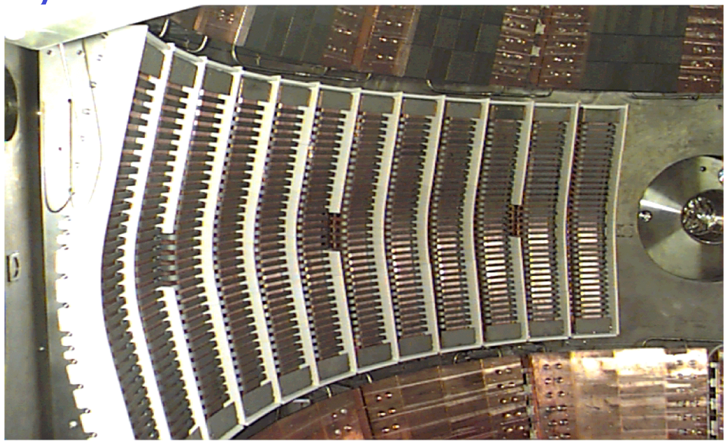


- Major accomplishments
  - Demonstration & understanding of HHFW core heating & current drive
  - Demonstrated possibility of high-power coupling to EBW
  - Discovered several new fast-ion-driven instabilities
  - Observe non-linear coupling of multiple fast-ion modes

NSTX is developing innovative wave heating and current drive techniques in a unique wave parameter regime

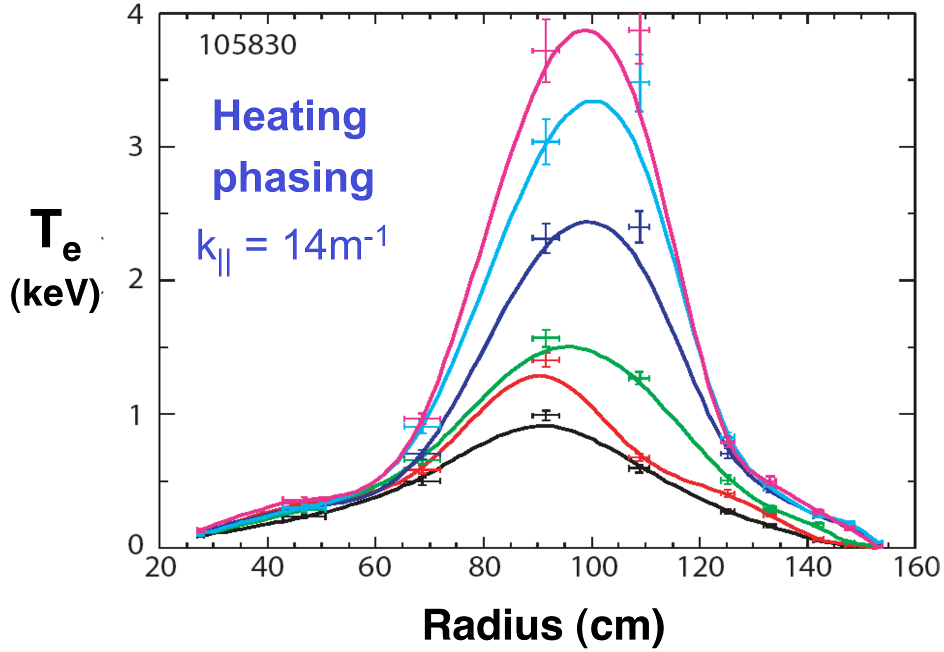
- High β → over-dense plasma ($\omega_{pe} > \Omega_{ce}$) with low v_A
  - Lower Hybrid and Electron Cyclotron (EC) waves do not propagate
  - Fast Alfvén Waves propagate with strong single-pass electron absorption
  - Electron Bernstein Wave (EBW)→ no n_e limit + localized absorption
    - EBW current drive 2-4 × more efficient than Electron Cyclotron current drive
- Complementary NSTX characteristics
  - Fast Wave also used for core current drive in AT plasmas of DIII-D
  - Efficient off-axis Ohkawa current drive physics relevant to AT

- ***NSTX High-Harmonic Fast Wave (HHFW) heating and current drive research utilizes world's most sophisticated ICRF launcher:***
- ***12 strap antenna, 6MW capability***
- ***6 independent transmitters***
- ***Real-time control of launched $k_{||}$ from 0 to $14m^{-1}$***



HHFW has successfully heated electrons and demonstrated core current drive in NSTX

Highest core electron temperatures on NSTX achieved with HHFW

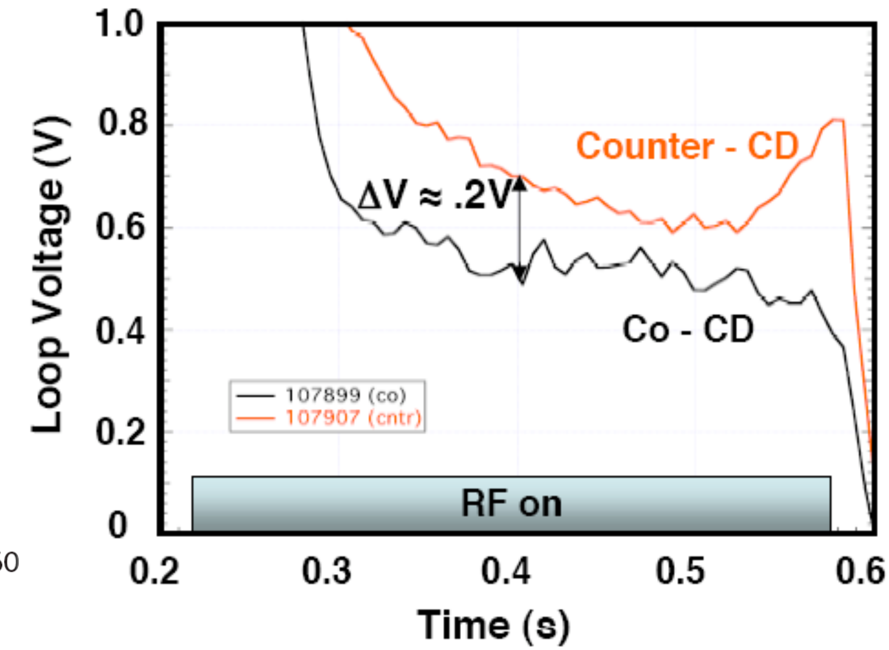


B. LeBlanc, Nucl. Fusion **44**, 513 (2004)

Co minus counter current drive

ΔI_{CD} = 180kA (I_P = 800kA)

Consistent with theory predictions

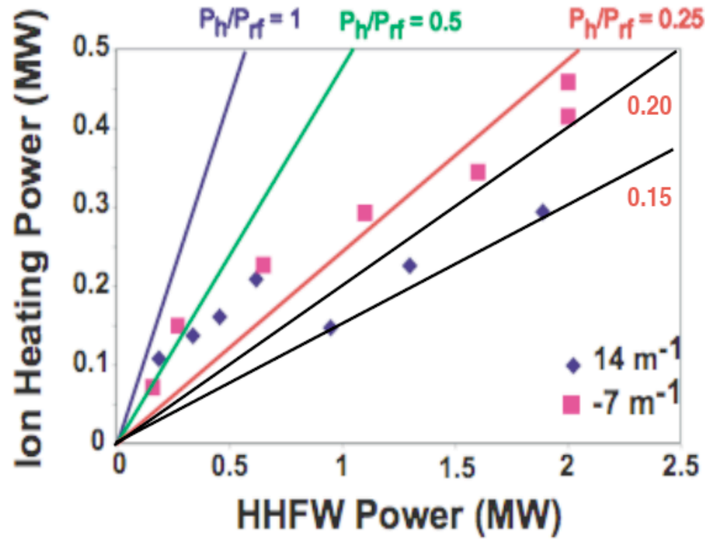


J.R. Wilson, Phys. Plasmas **10**, 1733 (2003)

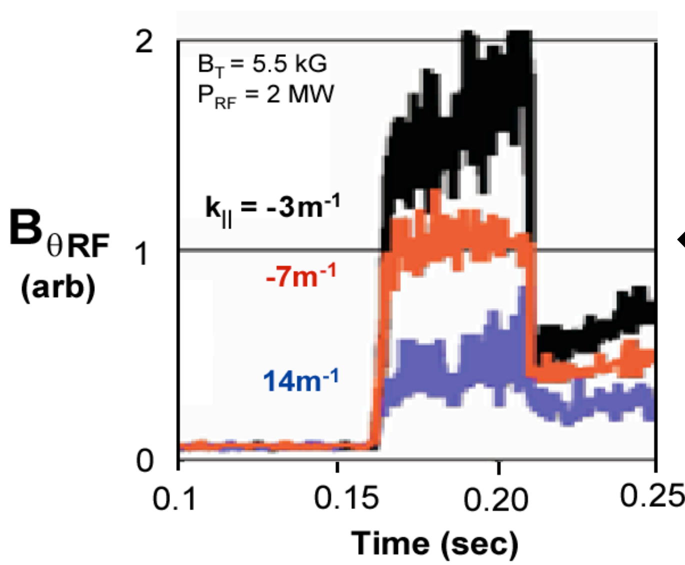
- **However, HHFW heating of core electrons is not always robust**
  - **Observe HHFW acceleration of NBI fast ions** A.L. Rosenberg, Phys. Plasmas **11**, 2441 (2004)

Improved understanding of HHFW edge interactions motivates changes to HHFW system for more efficient heating & CD

- Parametric Decay Instability (PDI) of HHFW → IBW → edge ion heating ➡
  - PDI increases with lower $k_{||}$ and/or B_T
    - Low $k_{||}$ used for HHFW current drive
    - Low B_T needed for high β



T. Biewer, Phys. Plasmas **12**, 056108 (2005)



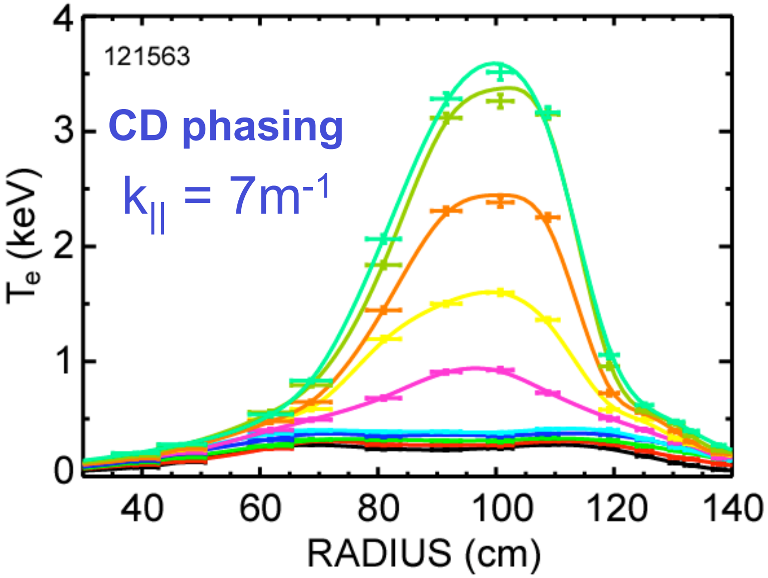
⬅ HHFW at low $k_{||}$ should begin propagating at much lower n_e → surface waves, wall interactions

- dB/dt probe data consistent with lower edge wave amplitude at high $k_{||}$

Both results imply higher $k_{||}$ should improve HHFW core electron heating

Key Research Results and Plans for HHFW

- Achieved high T_e=3.6keV in current drive phasing for first time using high B_T = 5.5kG
  - Improvement consistent with reduced PDI and surface waves expected at higher B_T
  - Expect similar improvements from **higher $k_{||}$**
    - Useful for HHFW-CD during ramp-up
    - Useful for HHFW heating at high-β



J. Menard, IAEA 2006

PLANS:

- Continue RF edge studies investigating causes of parasitic absorption (FY07-08)
  - Surface wave excitation damping + parametric decay instability ion heating
  - Additional RF probes to measure waves in plasma periphery
  - UCLA reflectometer upgrade to measure higher edge densities for RF studies
- HHFW antenna modification ⇒ directed spectra at 11m^{-1} for improved CD (FY-09)
  - High power operation capable of heating T_e ~ 50eV plasma with 28m^{-1}

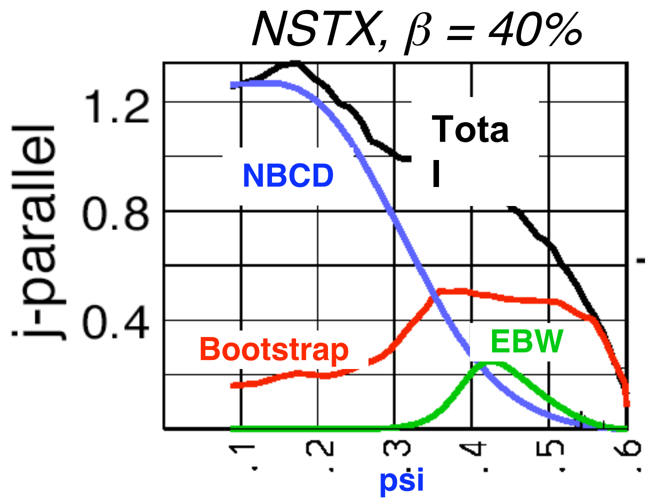
New physics understanding enabled by study of wave physics in over-dense plasmas

- Off-axis and efficient CD required for high β_T=40%, f_{NI} = 100% integrated scenarios.

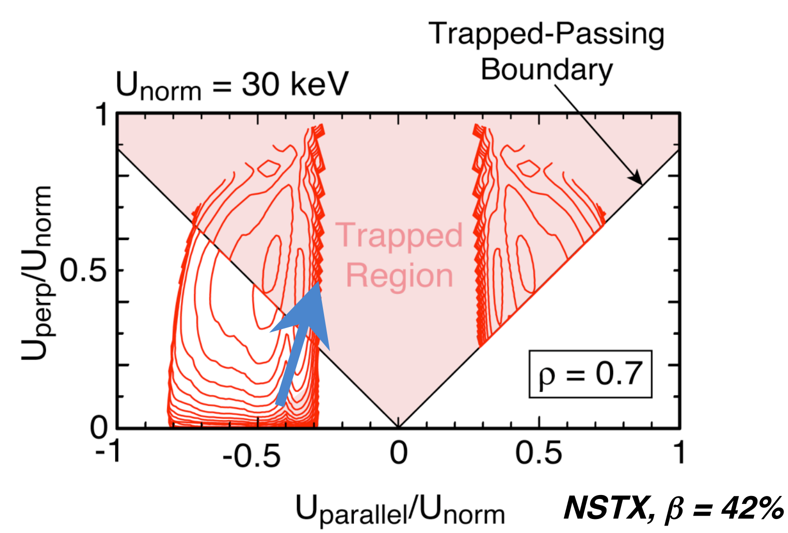
- EBW holds promise of taking advantage of unique, high trapping region: Ohkawa current drive:
  - **$0.4 < \rho < 0.7 \rightarrow \zeta_{EBW-CD} = 0.4$**
    - **2× more efficient than ECCD**
    - **8× more efficient than HHFW**

$$\zeta_{CD} \equiv 3.27 \times \frac{I_p(A) \times R(m) \times n_e\,(10^{19}m^{-3})}{P(W) \times T_e(keV)}$$

- For concept innovation: establish wave physics understanding for high beta fusion systems



C. Kessel, Nucl. Fusion **45** 814 (2005)

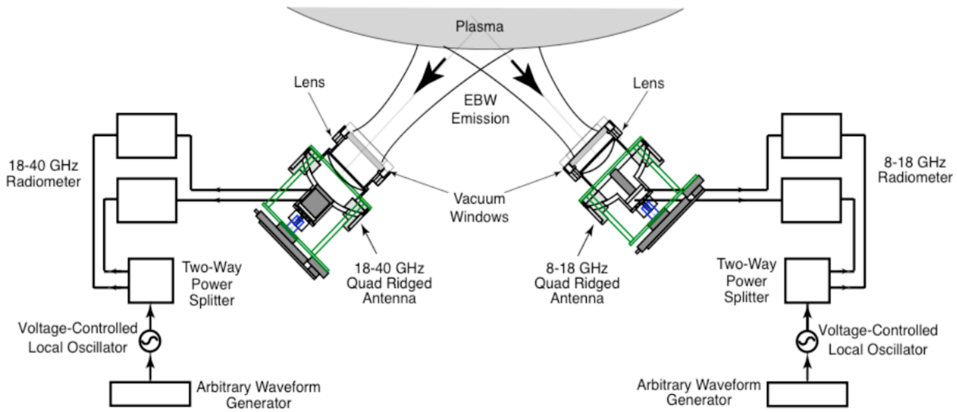


CompX

G. Taylor, Phys. Plasmas **11** 4733 (2004), R. Harvey, Phys. Plasmas **12** 052509 (2005)

Initial measurements of B-X-O emission on NSTX confirm possibility of high-power coupling to EBW

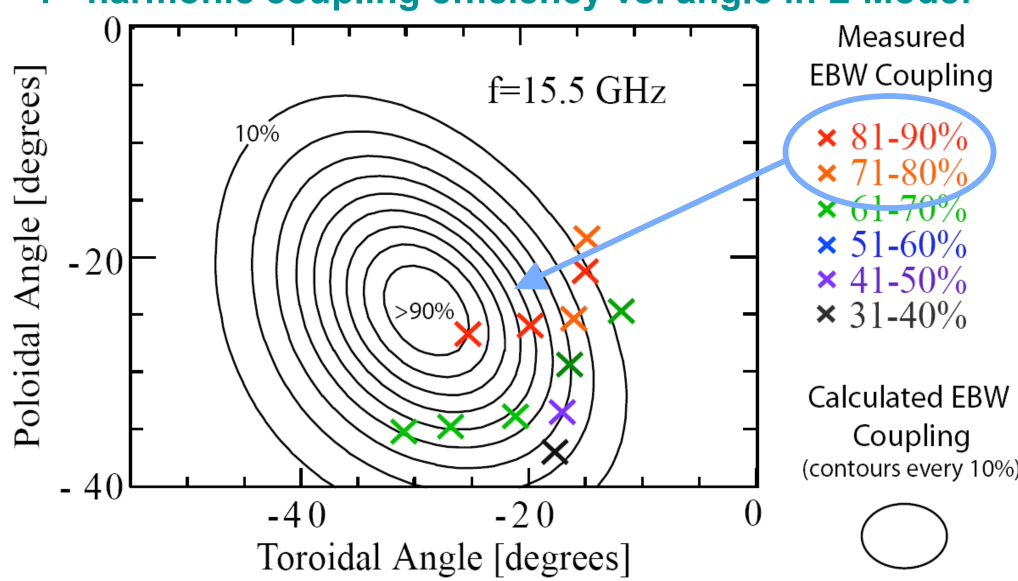
Dual-antenna remotely-steerable EBW radiometer system:



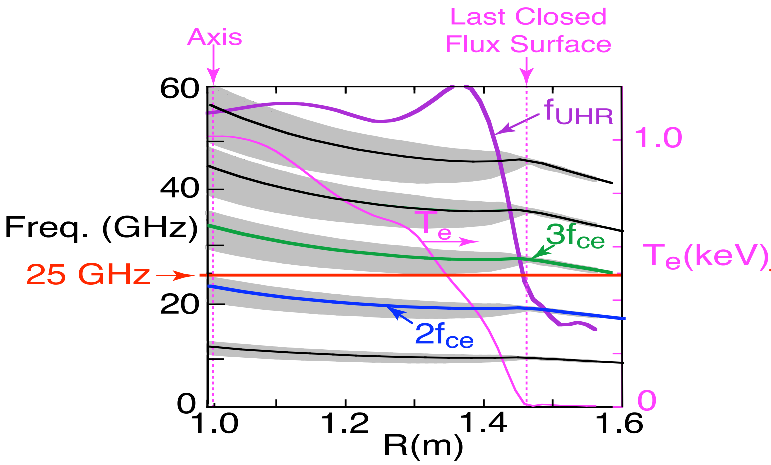
- Frequency range:
  - 1st & 2nd harmonic: 8-18GHz
  - 2nd & 3rd : 18-40 GHz
- Directionality:
  - ±10° steering in poloidal and toroidal directions
- Antenna acceptance angles:
  - 8-18GHz ~ 22°, 18-40GHz ~ 14°

- High EBW coupling efficiency for broad range of antenna pointing angles in L-mode:
  G. Taylor, Phys. Plasmas **12** 052511 (2005)
- But, poor apparent coupling efficiency (< 30%) observed in H-mode discharges

1st harmonic coupling efficiency vs. angle in L-Mode:



Key Research Results and Plans for EBW



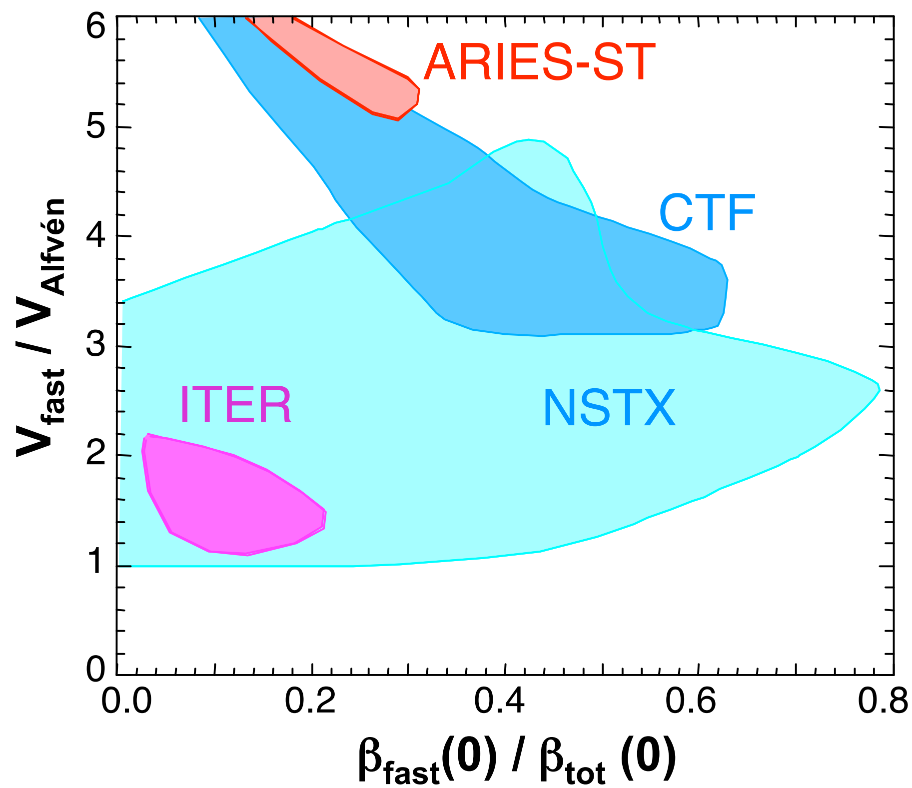
- 2005: Emission measurements in H-mode consistent with $3f_{ce}$ emission from large r/a
  - Evidence for collisional damping at f_{UHR} and possibility for $2f_{ce}$ overlap
- 2006: Angle/freq. scans confirm 2005 result:
  - Strong coupling in L-mode, poor in H-mode

PLANS:

- Implement 100-200kW 15.3-28GHz EBW system w/ ORNL gyrotrons (FY08)
  - **EC pre-ionization & heating for CHI & PF-only startup plasmas (low n_e, T_e)**
  - **EBW coupling studies + initial electron heating experiments**
- Test EBW coupling models for L & H-mode plasmas (FY07-08) **(Ph.D. Thesis)**
  - Experiments to understand cause of apparent poor coupling in H-modes
- Enhanced understanding & modeling through collaboration (FY07-08)
  - MAST collaboration: 28GHz startup/ramp-up (FY-07), B-X-O (FY07-08)
  - Include EBW mode conversion in GENRAY, optimize EBWCD scenarios [MIT]
  - Radial transport, Ohkawa anti-pinch effect on BS - CQL3D/GENRAY [Comp-X]
    - Also EBE from non-thermal electrons – same model used for ECE on ITER

NSTX is an excellent test-bed for simulation and validation of critical fast ion physics for burning plasmas

- NSTX uniquely able to mimic ITER in v_{fast} / v_{Alfven} and β_{fast} while maintaining full diagnostic capability, in particular MSE
  - ρ^*_{fast} does not overlap with ITER
- NSTX shows nonlinear physics of wave-particle resonance overlap, similar to ITER, due to large β_{fast}
- Can also study fast ion physics expected for ST-based CTF

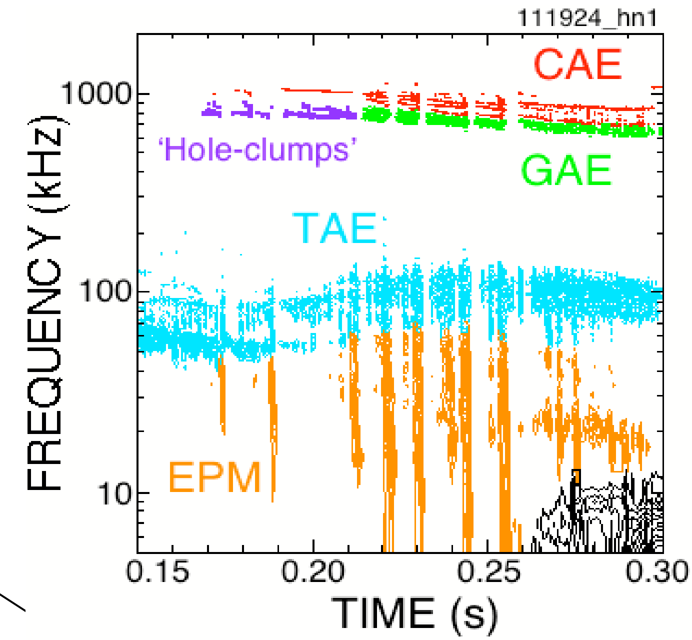


Many fast particle discoveries made on NSTX

- New discoveries a direct result of operating with $v_{fast} / v_{Alfven} > 1$ with full suite of diagnostics

References:

- NSTX fast particle mode physics:
  E. Fredrickson, Phys. Plasmas **13**, 056109 (2006) and references therein
- NSTX-motivated CAE work on DIII-D:
  W. Heidbrink, Nucl. Fusion 46 324 (2006)



High-f modes: energy transport

- Compressional Alfvén Eigenmode
- Global Alfvén Eigenmode
- Hole-clump pair

New modes discovered on NSTX - **predicted to be present on ITER**

Low-f modes: radial transport

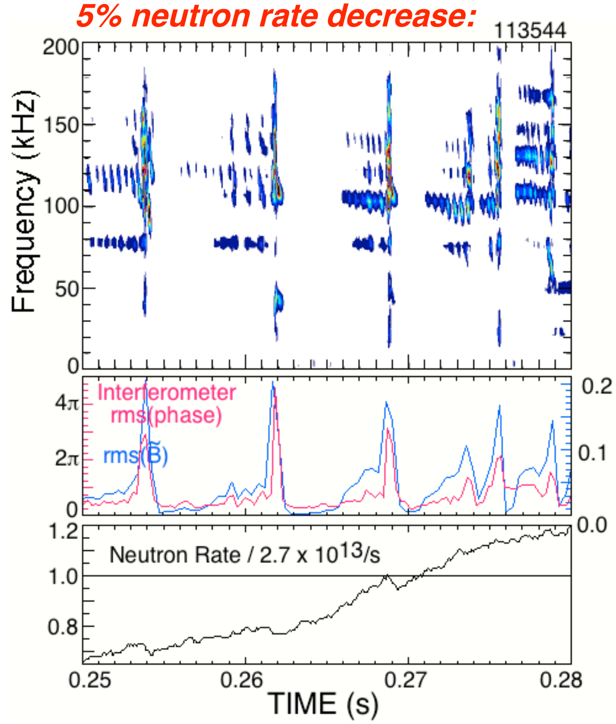
- TAE & EPM — Multi-mode regime ITER relevant
- Bounce resonance fishbone (not present in f-spectrum shown above) — New mode discovered - unique to NSTX

NSTX accesses ITER-relevant fast-ion phase-space island overlap regime with full diagnostic coverage

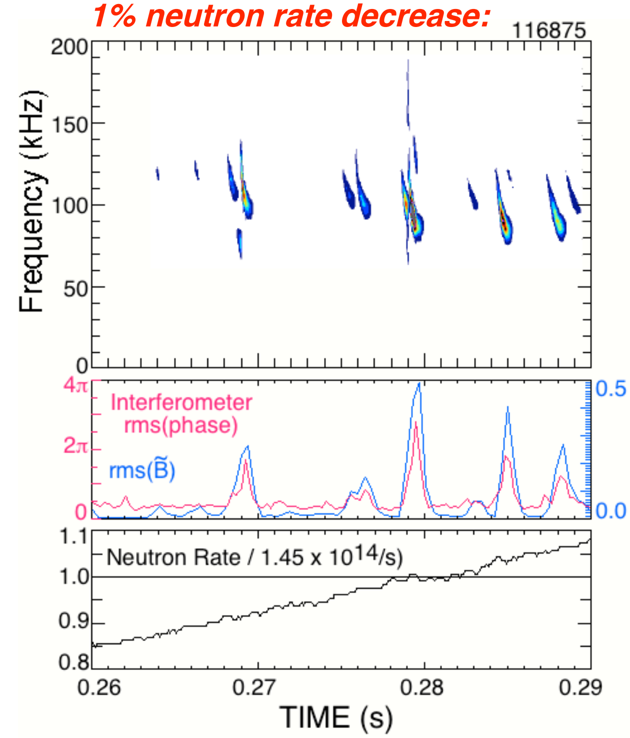
- **ITER** will operate in new, small ρ^* regime for fast ion transport
  - $k_\perp \rho \approx 1$ means "short" wavelength Alfvén modes
  - Fast ion transport expected from **interaction of many modes**
  - NSTX can study multi-mode regime while measuring MSE q profile

- **NSTX observes that multi-mode TAE bursts induce larger fast-ion losses than single-mode bursts:**

5% neutron rate decrease:

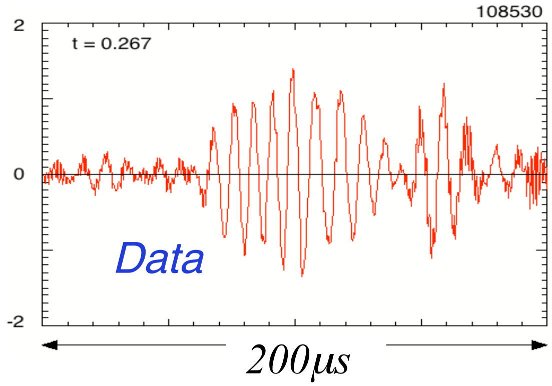


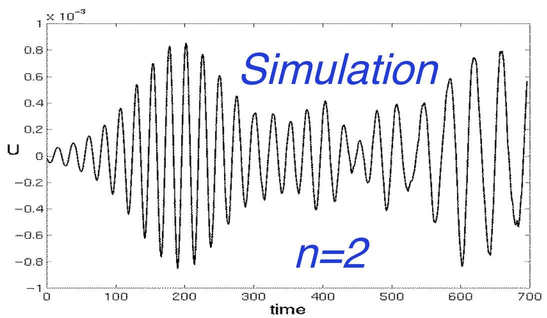
1% neutron rate decrease:



E. Fredrickson, Phys. Plasmas **13**, 056109 (2006)

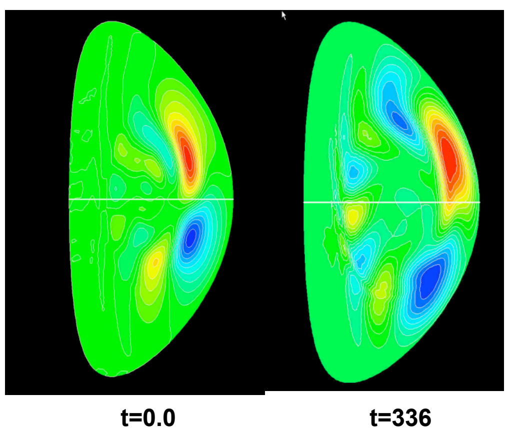
Non-linear TAE simulations (single-*n*) reproduce many features observed in NSTX data





- M3D Nonlinear Hybrid simulations:
  - Mode growth and decay times ≈ 50 - 100 μs
  - Bursting/chirping behavior results from:
    - Non-linear modification of fast-ion distribution
    - Change in mode structure
    - Predicted to be present on ITER

Simulations → Mode moves radially outward during amplitude saturation

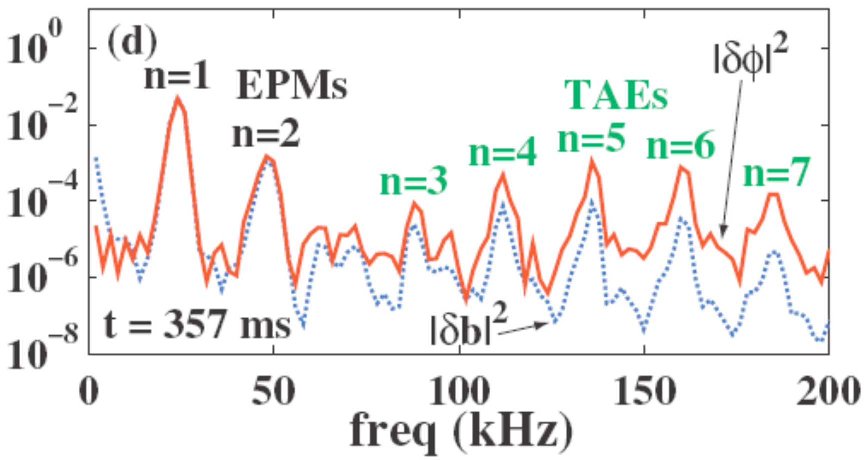


G.Y. Fu
IAEA FEC (2004)

- **New non-linear TAE simulations with multiple n's (not shown) predict:**
  - *n*=2 mode non-linearly saturates at higher amplitude than in single-*n* case
  - *n*=2 mode can be driven non-linearly by dominant *n*=1
  - Mode structure changes significantly due to non-linear evolution
- Comparisons to experiment just beginning…

Reflectometry data reveals 3-wave coupling of distinct fast-ion instabilities for first time

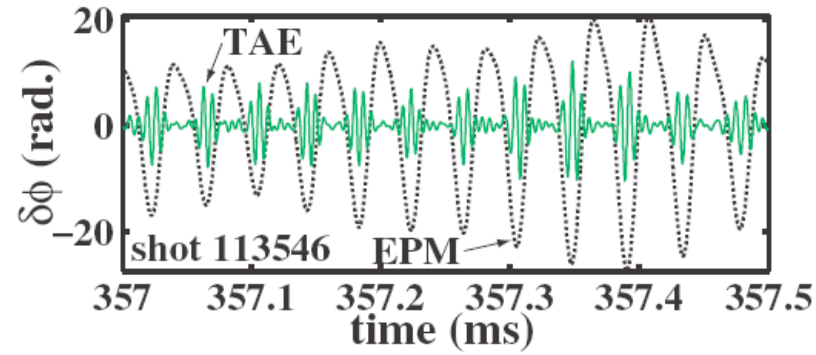
- *Low-f EPMs co-exist with mid-f TAE modes*



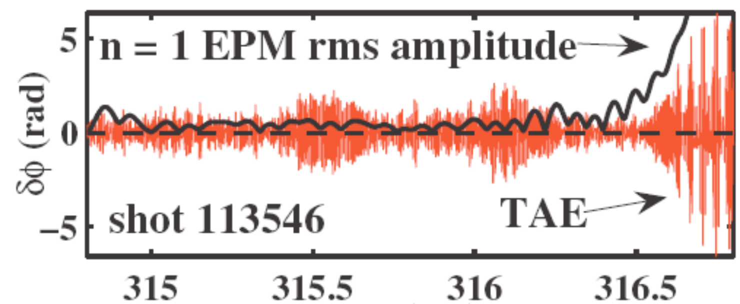
Bi-coherence analysis reveals 3-wave coupling between 1 EPM and 2 TAE modes

N. Crocker, Phys. Rev. Lett. **97**, 045002 (2006)

- *Large EPM ➔ TAE phase locks to EPM forming toroidally localized wave-packet*

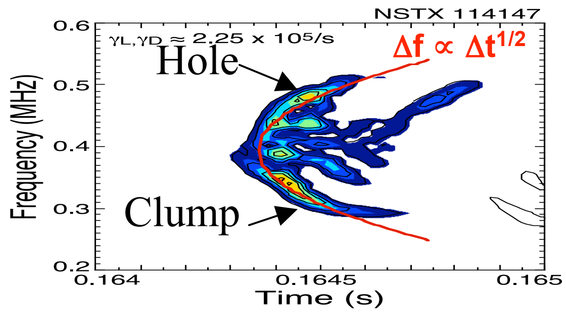


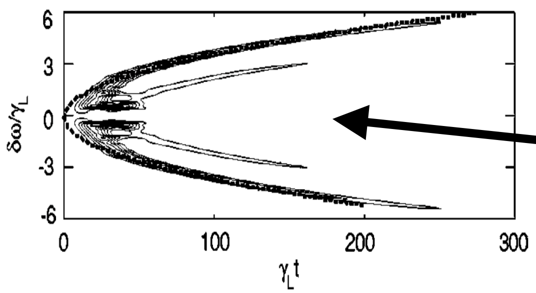
- *In absence of EPM, TAE modes do not form toroidally localized wave-packets*



Influence of toroidal localization of TAE mode energy on fast ion transport and EPM/TAE stability presently being investigated

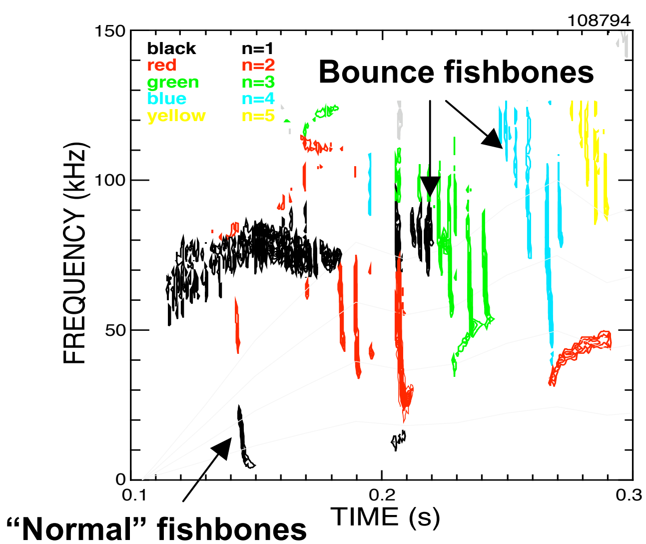
Hole-clump pair with GAE mode and bounce resonance fishbone discovered on NSTX





E. Fredrickson, Phys. Plasmas **13**, 056109 (2006)

- High frequency (GAE) hole-clump pair mode observed driven by energetically inverted velocity space distribution
  - Hole-clump behavior more commonly observed for TAE modes
- Hole-clump mode frequency evolution $\Delta f \propto \Delta t^{1/2}$ prediction by Berk et al., (PoP, '99)



E. Fredrickson, Nucl. Fusion **43,** 1258 (2003)

- Bounce fishbones present at low aspect ratio where bounce frequency is low
- Modes identified by calculating bounce and precession frequency ranges and comparing to Doppler shifted mode frequencies
- High-n modes are bounce resonance, n=1 are regular precession resonance fishbone

Research Plans for Energetic Particle Physics

- TAE avalanche threshold physics important for ITER (MDC-9)
  - Determine scaling of structure, stability, losses vs. *q* profile, v_{fast} / v_{Alfven} (FY07-08)
- Fast-ion MHD impact on NBICD important for ITER, CTF (SSO-2.2)
  - Validate/test bootstrap/beam-driven current models (TRANSP) (FY06-08)
    - Compare to J(r) evolution in plasmas with and w/o energetic particle MHD
- Comprehensive diagnosis of mode structure and fast-ion diffusion (MDC-9)
  - MSE measurement of current profile (FY07-08)
  - Mode structure: FIReTIP, reflectometer, δB polarization from Mirnovs (FY-07)
  - Fast ion loss: fast lost ion probe, solid-state & scanning E || B NPAs (FY06-08)
  - Fast ion $f(E,\rho)$: Fast Ion D-alpha (FIDA) diagnostic (FY-08)