Supported by Office of Fusion Energy Sciences — Excellent Science Attractive Energy; Office of Science

NSTX

NSTX Waves and Energetic Particles Research Plan for 2009-2013

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Gary Taylor

For the NSTX Research Team

National Tokamak Planning Workshop

MIT, Cambridge, Massachusetts

September 18, 2007

Culham Sci Ctr
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NSTX Parameters Important for Studying Wave-Particle Interactions Relevant to Burning Plasma and ST-CTF

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- High Harmonic Fast Wave (HHFW) system is studying surface wave & edge parametric decay physics relevant to ITER ICRF:
  - *Recent HHFW experiments show improved coupling; results support several proposed upgrades to existing antenna design*
- HHFW & Electron Bernstein Wave (EBW) heating & current drive (CD) can assist non-inductive ST-CTF plasma startup & sustainment:
  - *28 GHz heating system being installed on NSTX to test EBW coupling, heating and CD at up to 1 MW of RF power by 2013*
- NSTX NBI ions resonate strongly with Alfvén modes, providing test bed for studying reactor-relevant energetic particle (EP) physics:
  - *Discovery of CAE/GAE modes, multi-mode transport & new understanding of chirping modes are helping to advance theory*
  - *Install 1 MW CAE stochastic ion heating system*

Long-Term HHFW Research Objective: Assist Non-Inductive ST-CTF Startup & Sustain Reactor-Grade H-Mode

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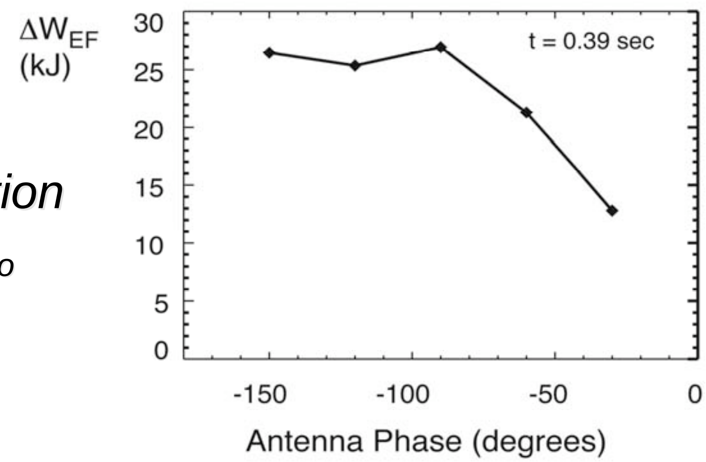
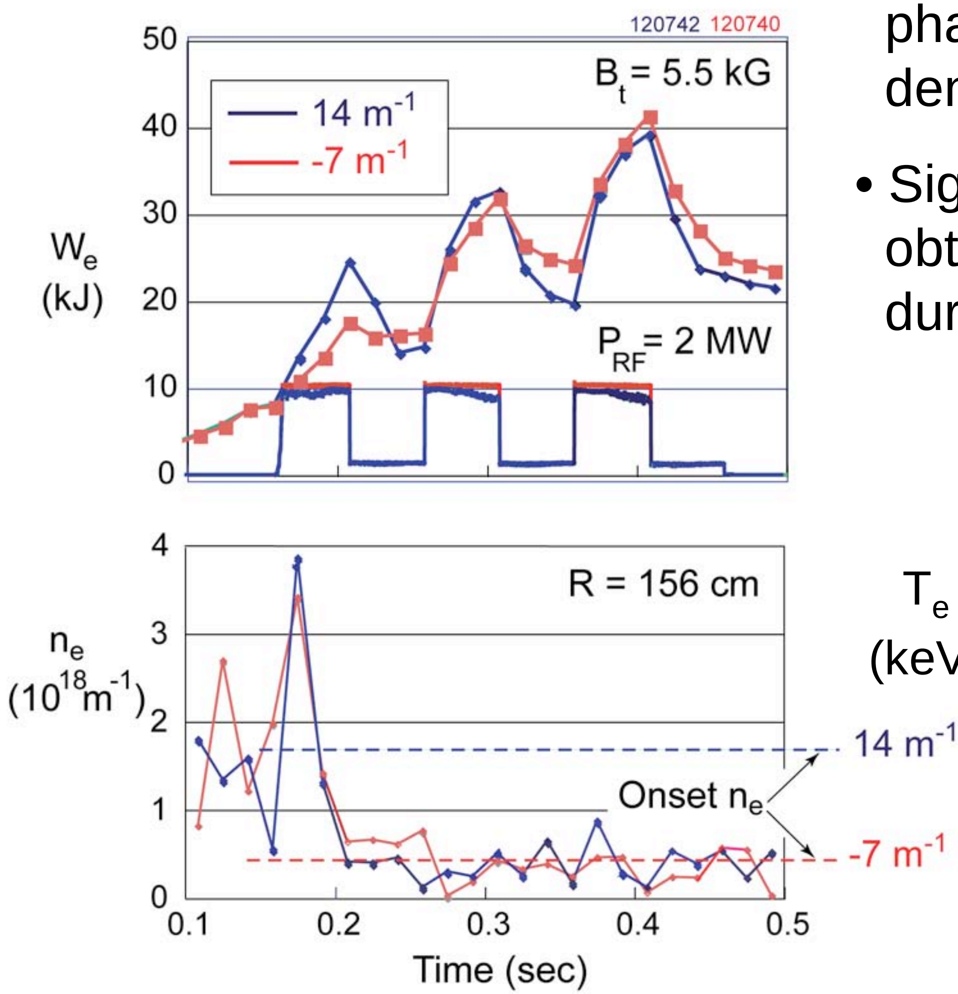
- ITER ICRF will operate at high RF power with large antenna-plasma gap, a scenario where even low levels of RF edge losses could be detrimental
- NSTX HHFW parameters provide an opportunity to quantify RF edge power loss mechanisms:
  - → *Core heating efficiency shows strong dependence on launched wavelength*
    - – *consistent with enhanced surface loss when edge densities exceed density for onset of perpendicular wave propagation*
    - – *perpendicular propagation begins at ~ 20^o to B field, even in ITER*



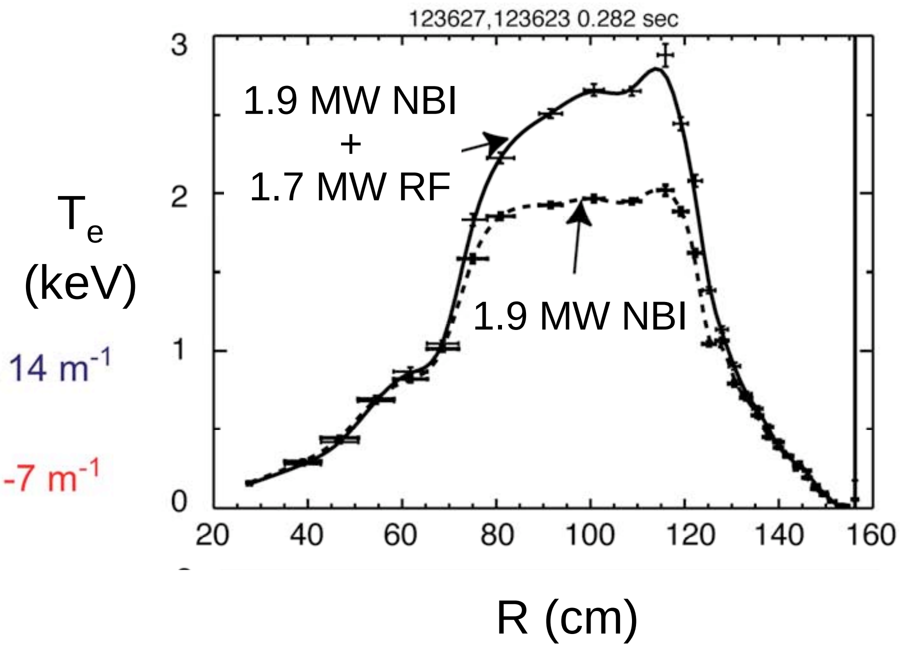
  - → *Other loss mechanisms, such as Parametric Decay Instability (PDI), RF sheaths, will be studied with RF probes and other edge diagnostics*

Substantially Improved HHFW Coupling by Keeping Density Near Antenna Below Level Needed to Generate Surface Waves

NSTX



- Improved HHFW coupling for CD phasing obtained by lowering edge density
- Significant core electron heating now obtained in L-mode for CD phasing during NBI at $B_t(0)$ = 5.5 kG



HHFW Antenna Upgrades Provide More Power to be Coupled Per Strap into H-mode and Provides Space for EBW Launcher

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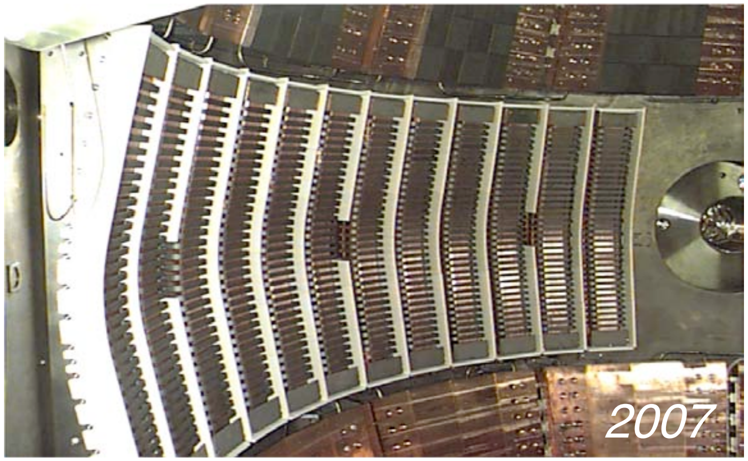
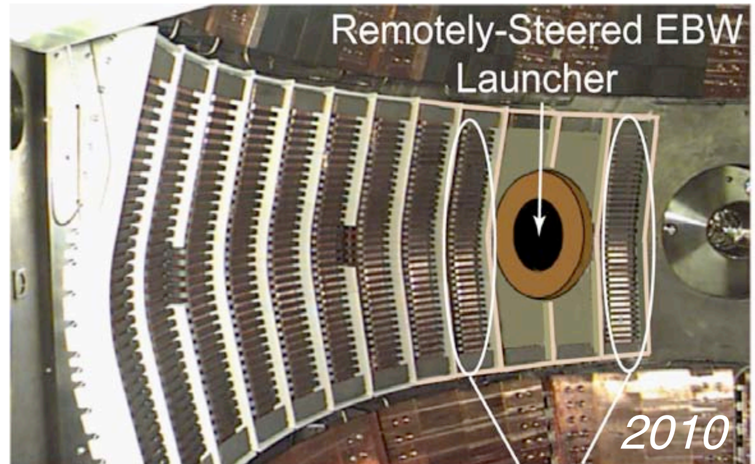
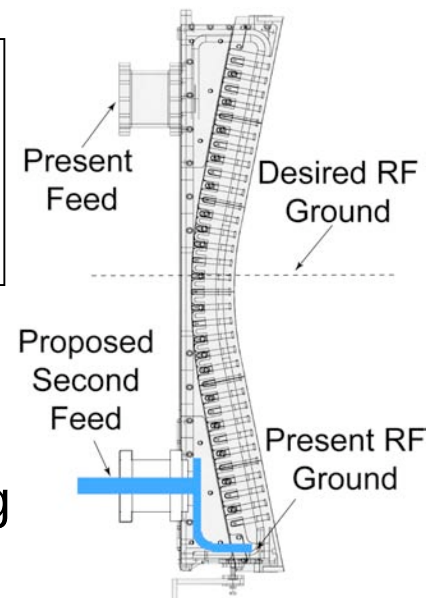




- Reduce HHFW antenna from 12 to 8 straps (2009)
- Add 3dB hybrid coupler for increased resilience to ELMs during H-mode (2010-11)
- Improved diagnostics to monitor arcing, plasma-antenna interaction and PDI (2008-10)
- Upgrade high-k scattering and FIReTIP for direct observation of RF wave structure in the core (2008)
- Leave two disconnected HHFW straps for CAE coupling

Double Feed Upgrade (2009)



2008-13 HHFW Research Plan

2008:

- Extend previous helium plasma coupling physics studies to deuterium plasma; improve operation with NBI, and optimize heating efficiency
- Begin heating & CD studies in deuterium H-mode plasmas

2009-10:

- Optimize heating and CD operation with NBI with upgraded antenna
  - *Larger plasma-antenna gap permitted with more stability and power (more antenna voltage standoff and greater power for same antenna voltage)*
- Begin HHFW coupling optimization into plasma startup/ramp-up

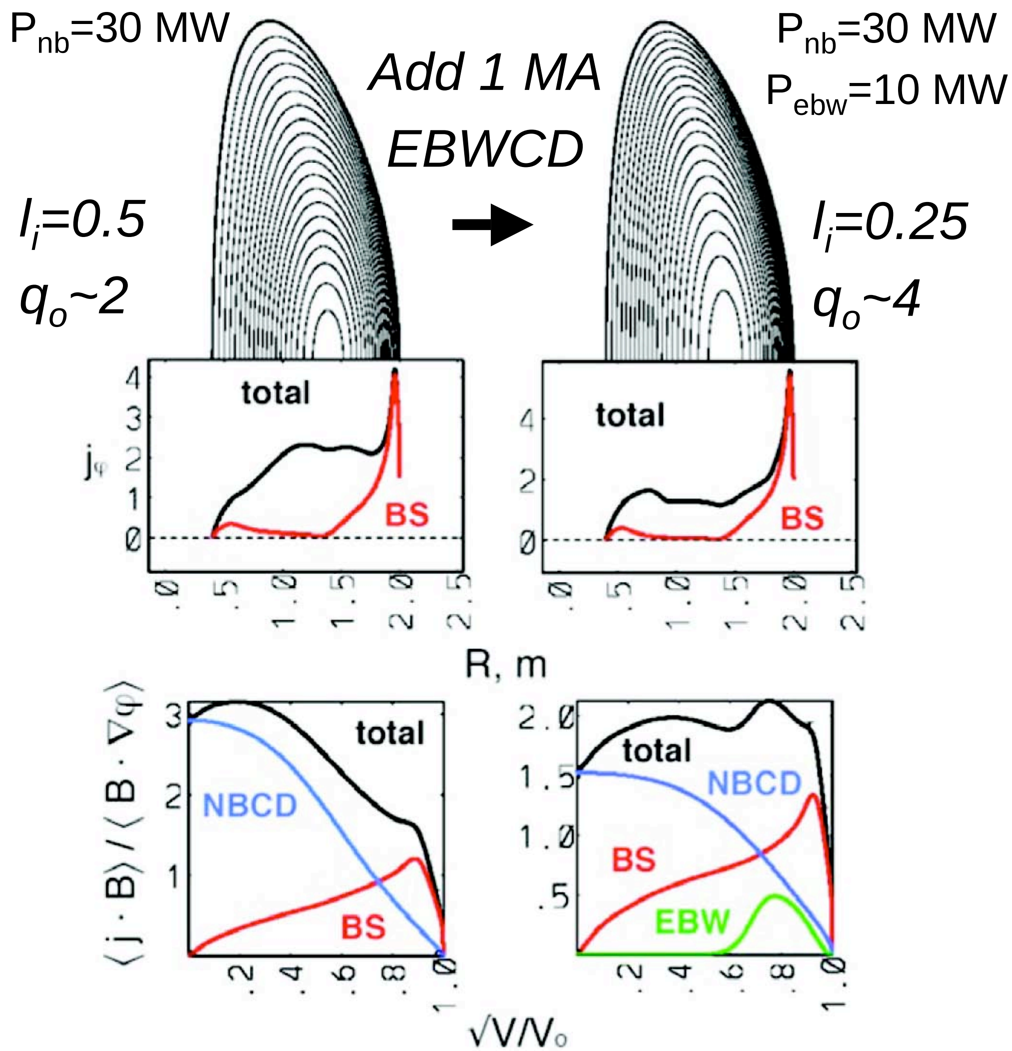
2011:

- Test HHFW coupling during ELMs using 3dB hybrid coupler to further optimize H-mode heating and CD operation

2012-13:

- Combine HHFW and ECH/EBW to provide fully non-inductive plasma startup and ramp-up

Long Term EBW Research Objective: Assess Ability of EBWCD to Generate Off-axis Stabilizing Current in ST-CTF



- JSOLVE modeling for steady state TSC simulation shows that adding 1 MA of off-axis EBWCD to ST-CTF plasma with wall loading of 1 MW/m^2 can decrease l_i from 0.5 to 0.25 & increase q_o from ~ 2 to ~ 4
- EBWH and/or ECH can also assist solenoid-free ST plasma startup

Y-K. M. Peng, et al., Plasma Phys. Control. Fusion, ***47*** *B263 (2005)*

80% EBW to O-Mode (B-X-O) Coupling Measured Via Thermal Emission from Axis of NSTX L-Mode

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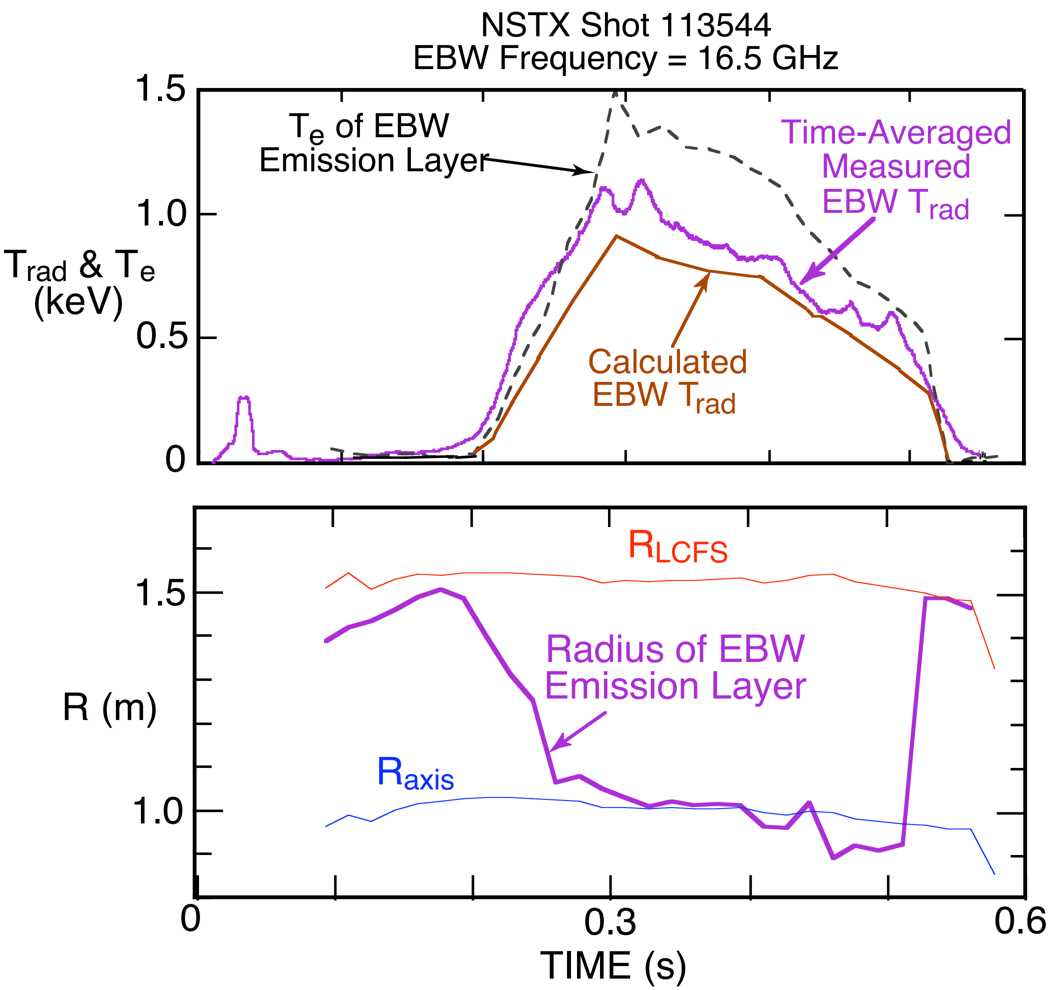
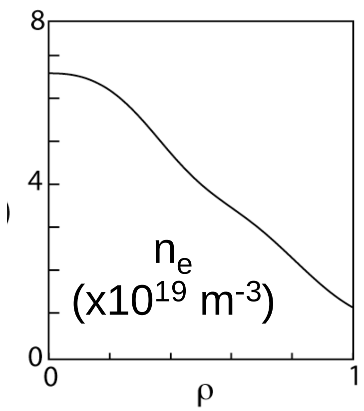
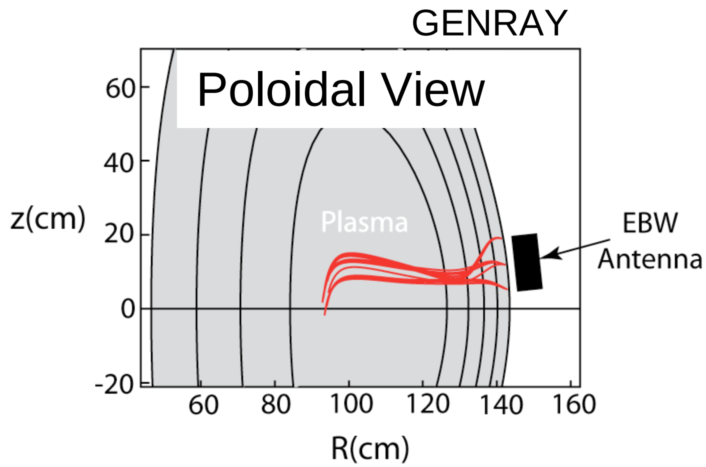


- Experimental results consistent with modeling
- Recent measurements show ~ 50% EBW coupling during H-mode
- Evidence for 50-60% EBW coupling during O-X-B heating on MAST and TCV during H-mode
- B-X-O coupling experiments in 2008, using thermal EBW emission, will seek H-mode regimes with > 80% coupling

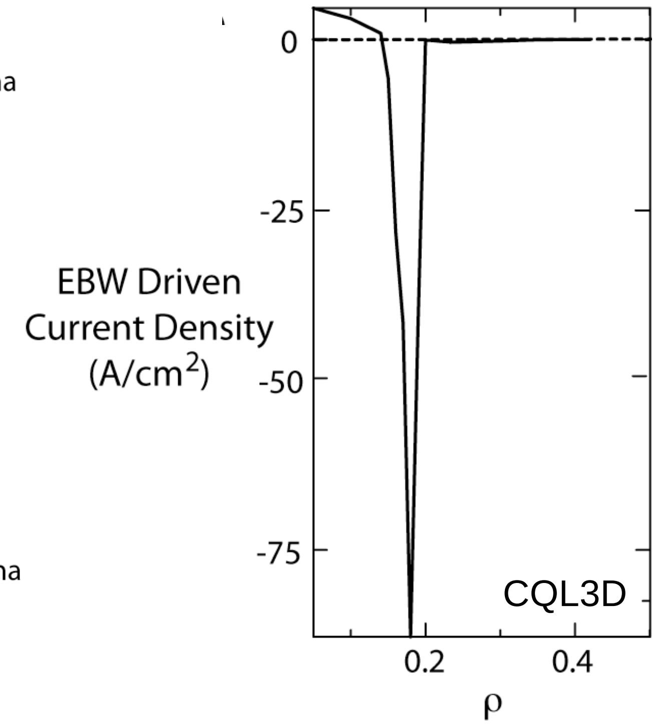
Modeling Predicts Localized Core Heating and ~ 40 kA/MW for On-Axis 28 GHz EBWCD in NSTX β = 20% Plasma

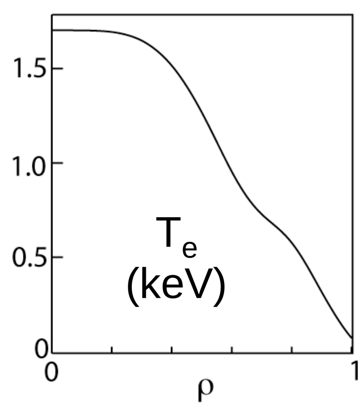


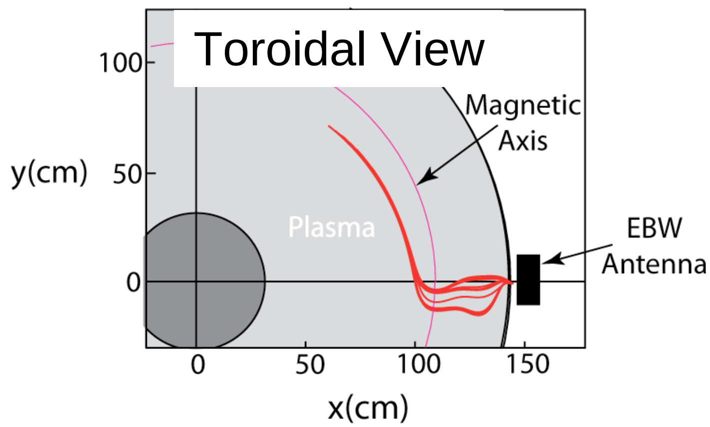


P_{ebw} = 750 kW

I_{EBWCD} = 29 kA







- Off-axis (ρ ~ 0.6) Ohkawa CD possible with similar CD efficiencies at higher T_e and lower n_e
- MSE can measure this level of CD, especially by using RF modulation

2008-13 EBW Research Plan

NSTX

2008:

- Continue coupling studies with EBW emission radiometers

2009:

- 350 kW 28 GHz gyrotron system operational
- ECH-assisted startup using fixed horn launcher:
  - *Heat CHI & PF-only startup plasma to ~ 300 eV for HHFW coupling*

2010:

- Install second 350 kW 28 GHz gyrotron & locally-steered O-X-B launcher next to HHFW antenna
- Coupling studies & core heating:
  - *Edge reflectometer at EBW launcher to measure local L_n*
  - *Lower hybrid antenna probe to measure PDI*

2011:

- Upgrade to remotely-steered O-X-B launcher
- 700 kW core & off-axis heating studies (benchmark deposition codes)

2012-13:

- Install third 350 kW 28 GHz gyrotron
- 1 MW heating & EBWCD (benchmark Fokker-Planck codes)

Long-Term EP Research Objective: Develop Ability to Predict EP Transport for ST and Tokamak Reactors

NSTX

- Capability to simulate EP transport by non-linear energetic particle driven modes required for future devices (ST-CTF, NHTX, ITER…):
  - *affects heating profiles, ignition thresholds and efficiency*
  - *affects beam driven current profiles (ST-CTF, NHTX)*
- Transport in small ρ^* devices will be through interaction of multiple modes and/or by global EP modes
- NSTX will study physics of EP instability-driven fast ion transport and confinement for:
  - *TAE avalanches*
  - *Energetic Particle Modes (EPMs) with q(0)>1*
- Measure EP mode structures, EP distributions and redistribution to benchmark codes and guide development of simulations

Fast Ion Loss on ITER Expected from Multiple Nonlinearly Interacting Modes, Studied on NSTX

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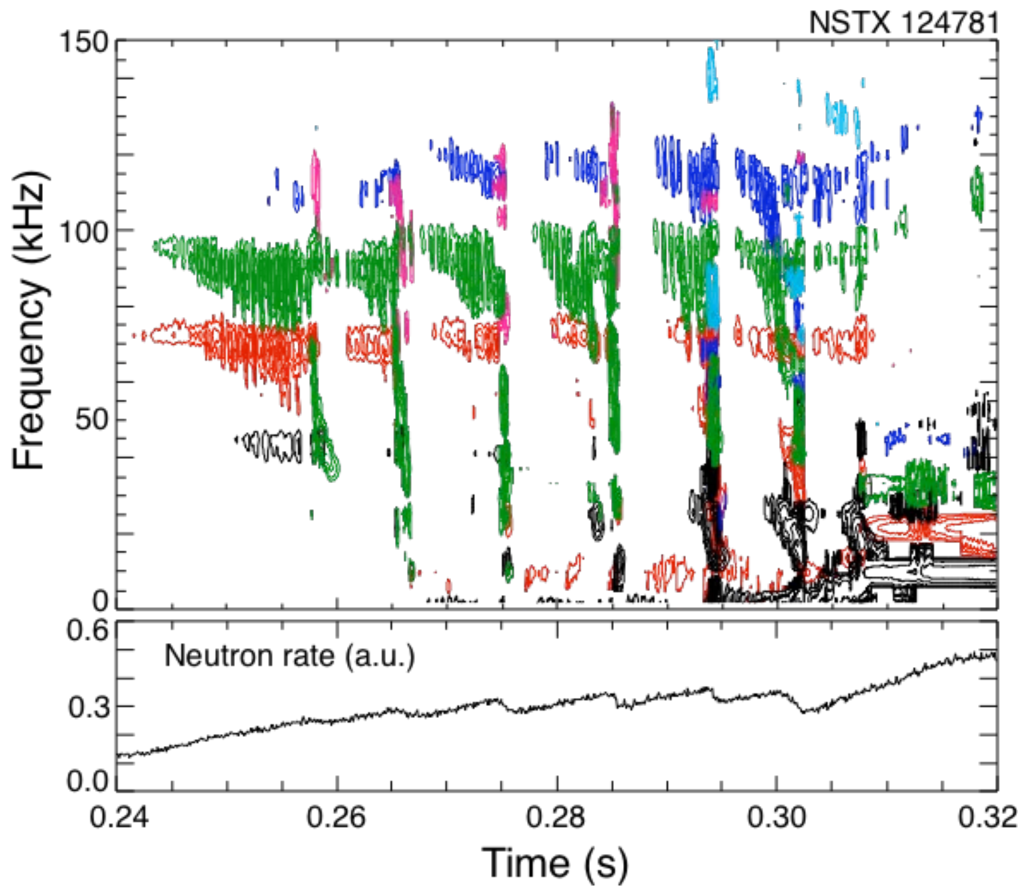
- Strong drops in neutron rate correlate with avalanche events
- Avalanches typically involve strong frequency chirping that may also be important for fast ion transport
- Goal is to develop ability to predict fast ion redistribution by multi-mode interactions



2008-13 Energetic Particle Research Plan

NSTX

2008:

- Studies of EPMs/TAE avalanches with extended reflectometer array
- Installation and check-out of FIDA

2009:

- Extensive documentation of fast ion redistribution with FIDA, NPA, FLIP and multi-channel reflectometers for TAE avalanches and fishbones
- Develop beatwave capability for TAE range of frequencies (in lieu of dedicated antenna for *AE spectroscopy)
- Extend polarization and toroidal Mirnov coil arrays
- Passive observation of CAE/GAE using HHFW antenna strap
- Use high-k scattering to document continuum damping

2008-13 Energetic Particle Research Plan (cont.)

NSTX

2010:

- Extend beatwave capability to CAE/GAE range of frequencies - measure mode damping rates
- Faster "scanning" reflectometer to measure TAE mode structure
- Use low power, low frequency amplifier to excite TAE/CAE using HHFW antenna strap

2011:

- Control mode chirping with HHFW
- Study ITER-relevant multi-mode (fishbones, TAE, CAE, …) driven energetic particle effects
- Determine stochastic ion heating thresholds
- Measure HHFW antenna strap loading at TAE/CAE frequencies

2008-13 Energetic Particle Research Plan (cont.)

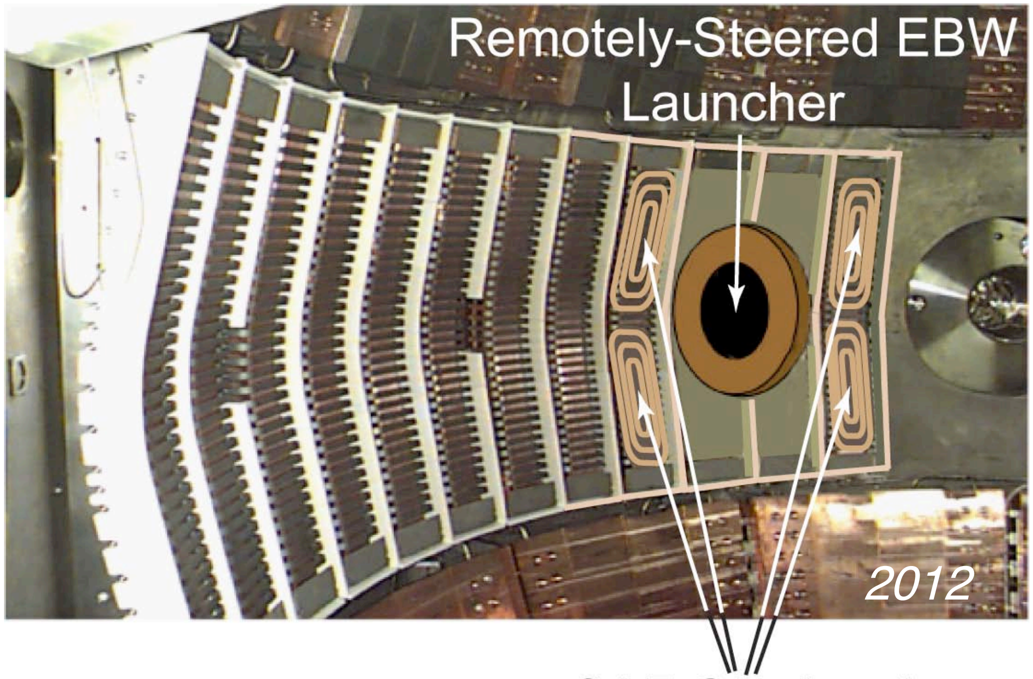
NSTX

2012-13:

- Add high power, low frequency source to excite CAE to stochastic heating threshold using new dedicated, multi-turn, antenna

- Continue studying multi-mode interactions with energetic particles

- Explore effects of fast ion distributions on mode stability with 2nd off-axis neutral beam.



Timeline for 2009-13 NSTX Plan for Waves and Energetic Particles Research