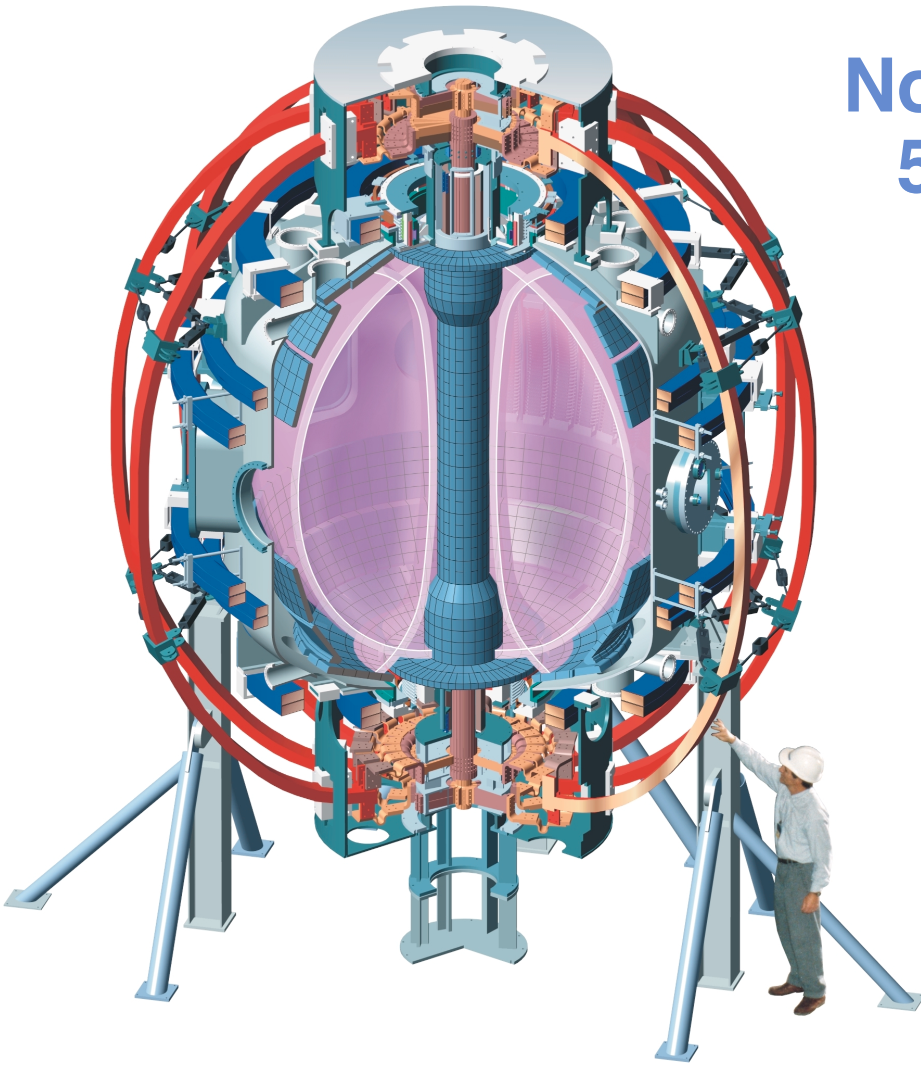


Non-Inductive Operation 5-Year Research Plan

Gary Taylor

presented on behalf of the

NSTX Research Team

NSTX Program Advisory Committee Meeting
(PAC-14)
January 21-22, 2003

NSTX
National Spherical Torus Experiment

Solenoid-Free Initiation & Non-Inductive Plasma Sustainment for $\tau_{pulse} > \tau_{skin}$ are Major Goals for the NSTX Program

- Spherical torus (ST) plasmas need auxiliary current drive (CD)

- Solenoid-free ST operation may be achieved by a diverse combination of CD tools

- This talk reviews the status & proposed 5-year research plans for three of these tools:

  - *High Harmonic Fast Waves (HHFW)*

  - *Electron Bernstein Waves (EBW)*

  - *Coaxial Helicity Injection (CHI)*

NSTX
NATIONAL SPHERICAL TORUS EXPERIMENT

HHFW, EBW, and CHI Science All Contribute to Solenoid-Free Startup Strategy

FY02 | 03 | 04 | 05 | 06 | 07 | 08 | 09

β_T = 30%, $\Delta t > \tau_E$
β_N = 5: > no wall limit
HH = 1

Highest performance

β_T = 40%, β_N = 8
$\Delta t >> \tau_E$, HH = 1.4

J_{NI} > 60%, $\Delta t \sim \tau_{skin}$
Non-solenoid startup demo

Solenoid-free

J_{NI} ~ 100%, $\Delta t > \tau_{skin}$

Solenoid-free up to high β_p

40% β_T
$\Delta t >> \tau_{skin}$
β_N = 8
HH = 1.4
70% J_{BS}

HHFW heating & CD → HHFW CD - local J, ΔJ → Real-time HHFW heating & phasing

EBW emissions ⟶ EBW CD 1 MW ⟶ 3 MW

CHI ⟶ Couple to ohmic ⟶ CHI + Non-inductive ramp up

Optimize non-solenoid operations

Non-inductive Current Ramp Up Has Three Phases, Each Requiring Different Current Drive Tools

- **Startup: 0 -> 150 kA**
  - *CHI the primary tool at present (maybe EBW later)*
- **Initial ramp up: 150 -> 500 kA:**
  - *HHFW, EBW, bootstrap*
  - *Research can be performed with an ohmic startup*
  - *PF induction - scenarios also being assessed*
- **Final ramp to flattop:**
  - 500 -> 800+ kA: NBI CD, bootstrap current overdrive
- Each phase can be studied separately; combining all three will be a control challenge

NSTX National Spherical Torus Experiment

HHFW
Research

HHFW Provide a Tool for Electron Heating and CD in High β, ST Plasmas

- High β scenarios demand on- and off-axis current drive to complement bootstrap and neutral beams
- A form of RF-driven current is also required for solenoid-free ramp-up
- Lower hybrid and conventional electron cyclotron CD (ECCD) cannot be used in high β plasmas
- HHFW in high β plasmas has strong single pass absorption on electrons that potentially results in desired off-axis deposition

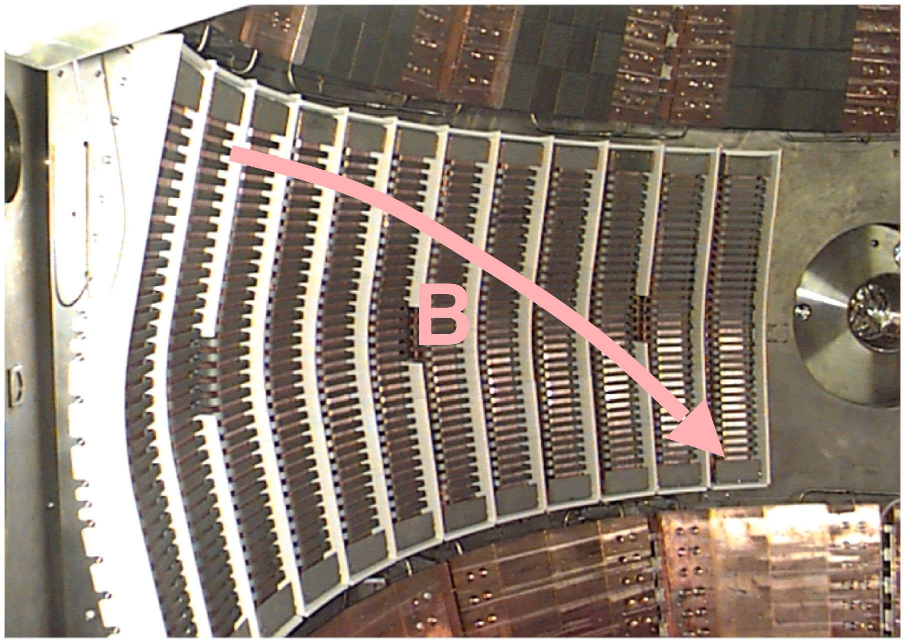
NSTX NATIONAL SPHERICAL TORUS EXPERIMENT

HHFW 5-Year Research Goals

- HHFW-assisted startup
- Pressure profile modification
- HHFW CD-assisted discharge sustainment
- Use HHFW, with other tools, for $\tau_{pulse} > \tau_{skin}$ operation

Status of HHFW Research

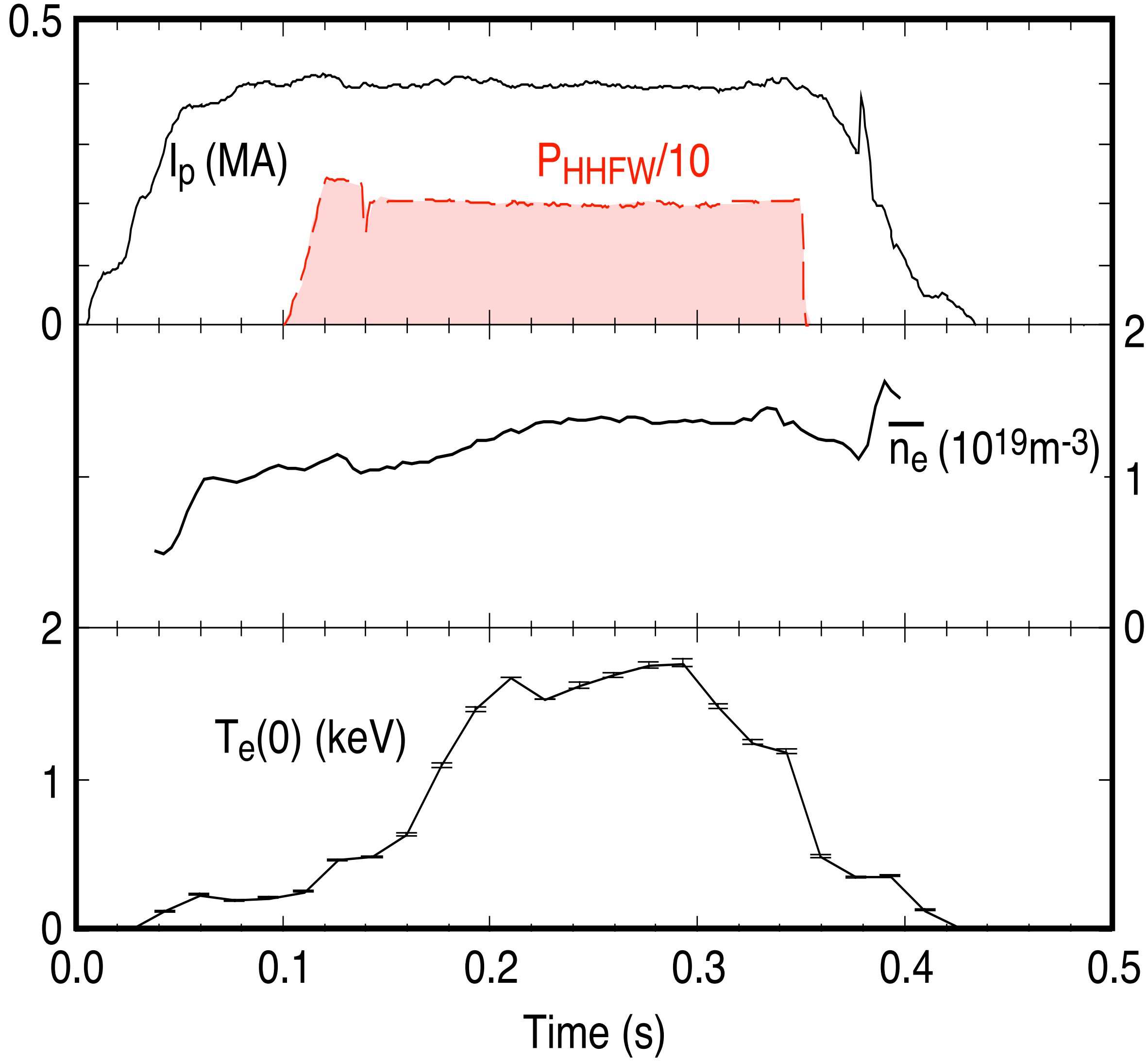
Flexible System for High Power HHFW Heating and CD System Operational on NSTX



- Uses TFTR ICRF hardware
- f = 30 MHz, ω/Ω_D = 9-13
- 6 MW from 6 transmitters
- Pulse length up to 5 s
- 12 Element antenna
- Active phase control
- Wide range of wave spectra
  - $k_T = \pm (3\text{-}14)\ m^{-1}$
  - *variable during shot*

- Digital phase feedback system sets phase between straps
- Antenna utilizes BN insulators to minimize RF sheaths

HHFW Primarily Heats Electrons, as Expected from Theory

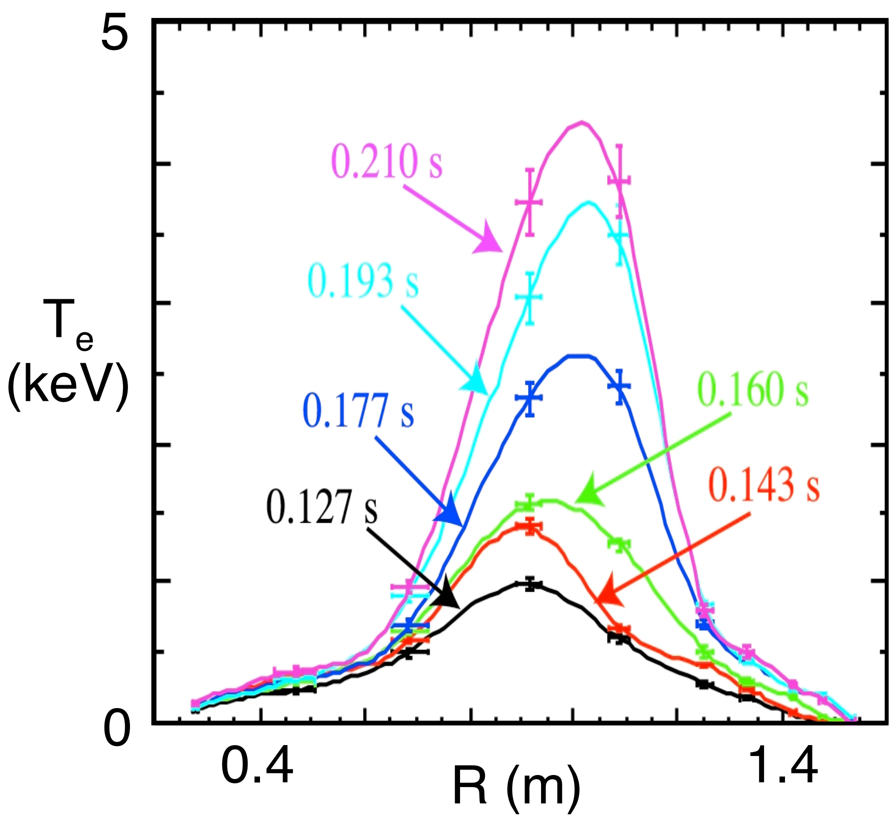


- No evidence for direct thermal ion heating; heats NBI ions
- Confinement consistent with ITER scalings:

L-Mode: ITER97L

H-Mode ITER98Pby2

Some HHFW-Heated Discharges Exhibit Behavior of Internal Transport Barrier

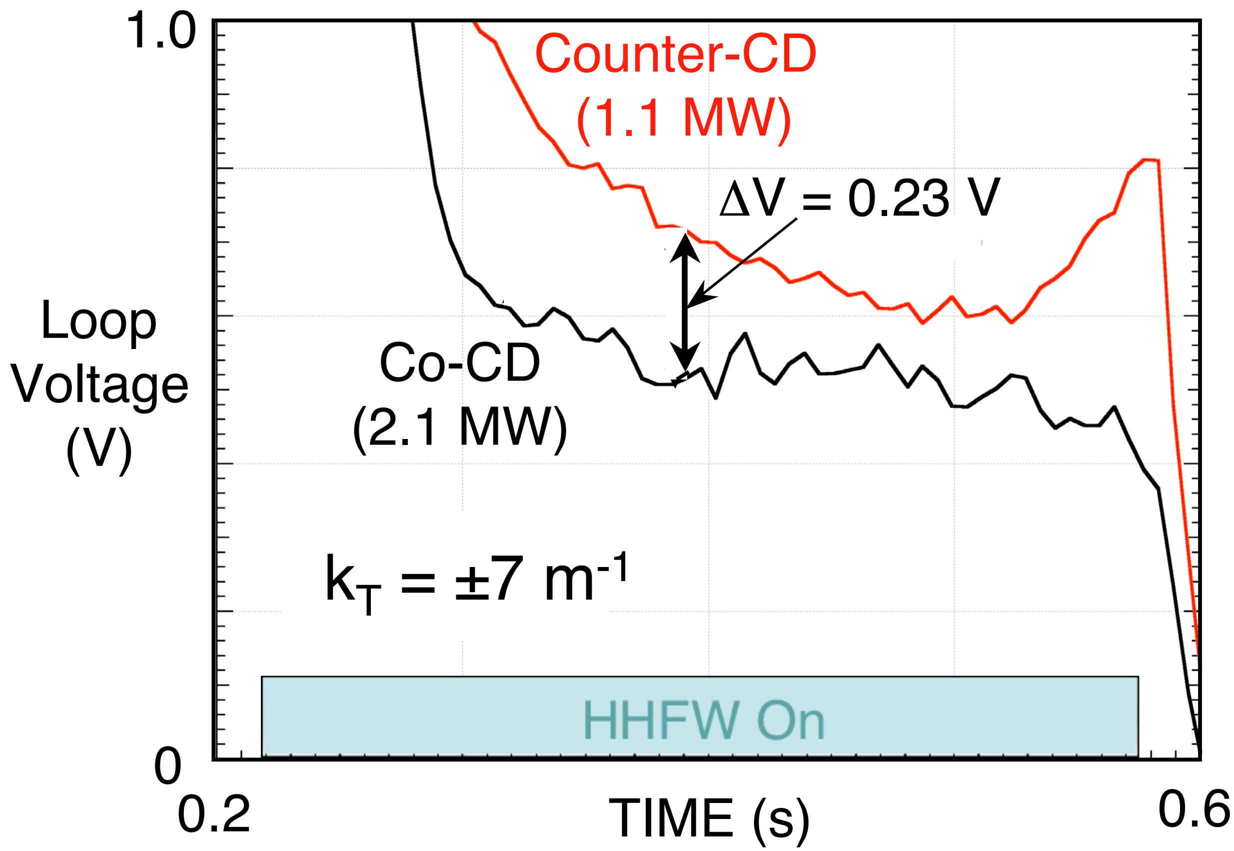


P_{rf} = 2.5 MW

I_p = 800 kA

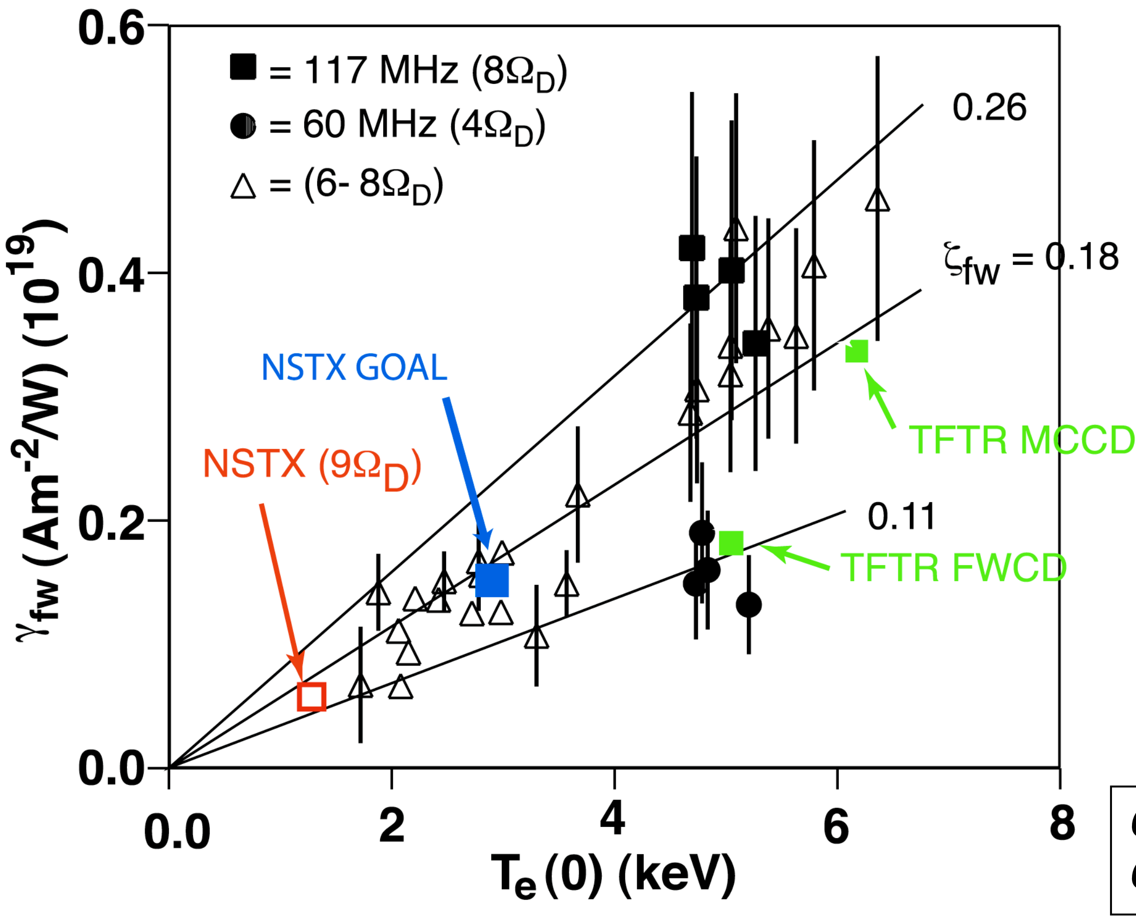
- T_e increases strongly inside half radius
- Density profile doesn't show change
- T_i (0) rises with T_e(0)
- χ_e progressively decreases with time in the central region

Less Loop Voltage to Maintain I_P With Co Phasing; Magnetic Signal Analysis Estimates I_{cd} = 110 kA (0.05 A/W)



- TORIC I_{cd} = 95 kA (0.05 A/W) *(Bonoli, MIT)*
- CURRAY I_{cd} = 162 kA (0.08 A/W) *(T.K. Mau, UCSD)*

CD Efficiency Consistent with DIII-D & TFTR CD Experiments

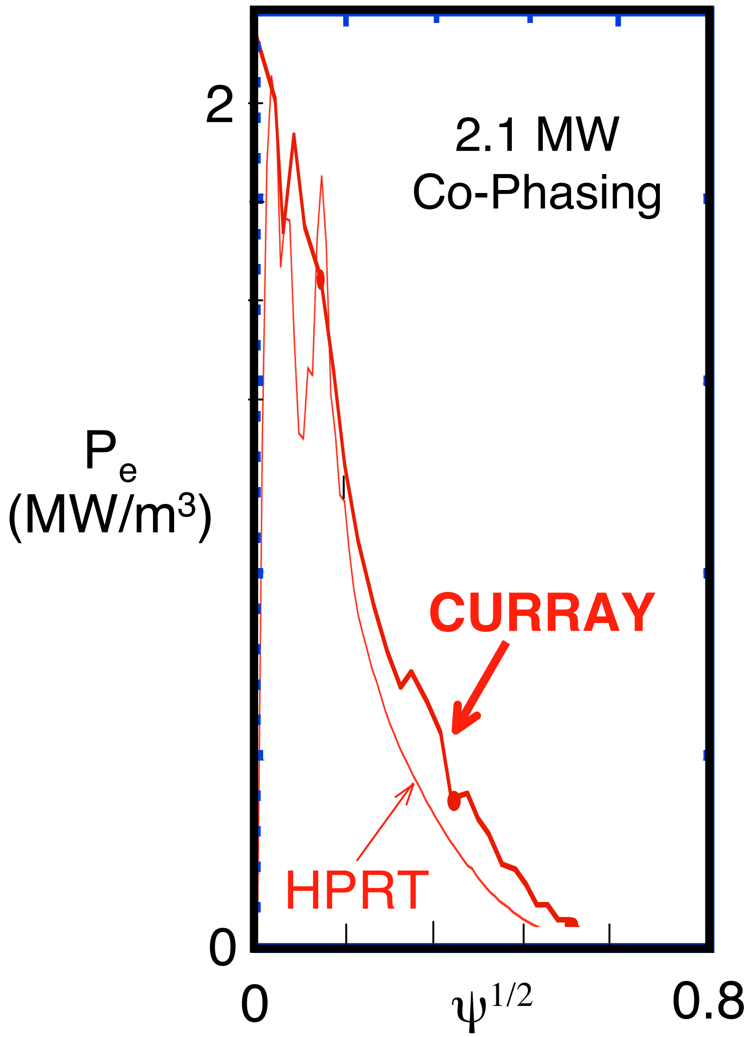


- Operation at increased T_e required to meet NSTX goals:
  - *More RF power and improved confinement regime should allow this*

C. Petty et al., Plasma Physics and Controlled Fusion ***43*** *(2001) 1747*

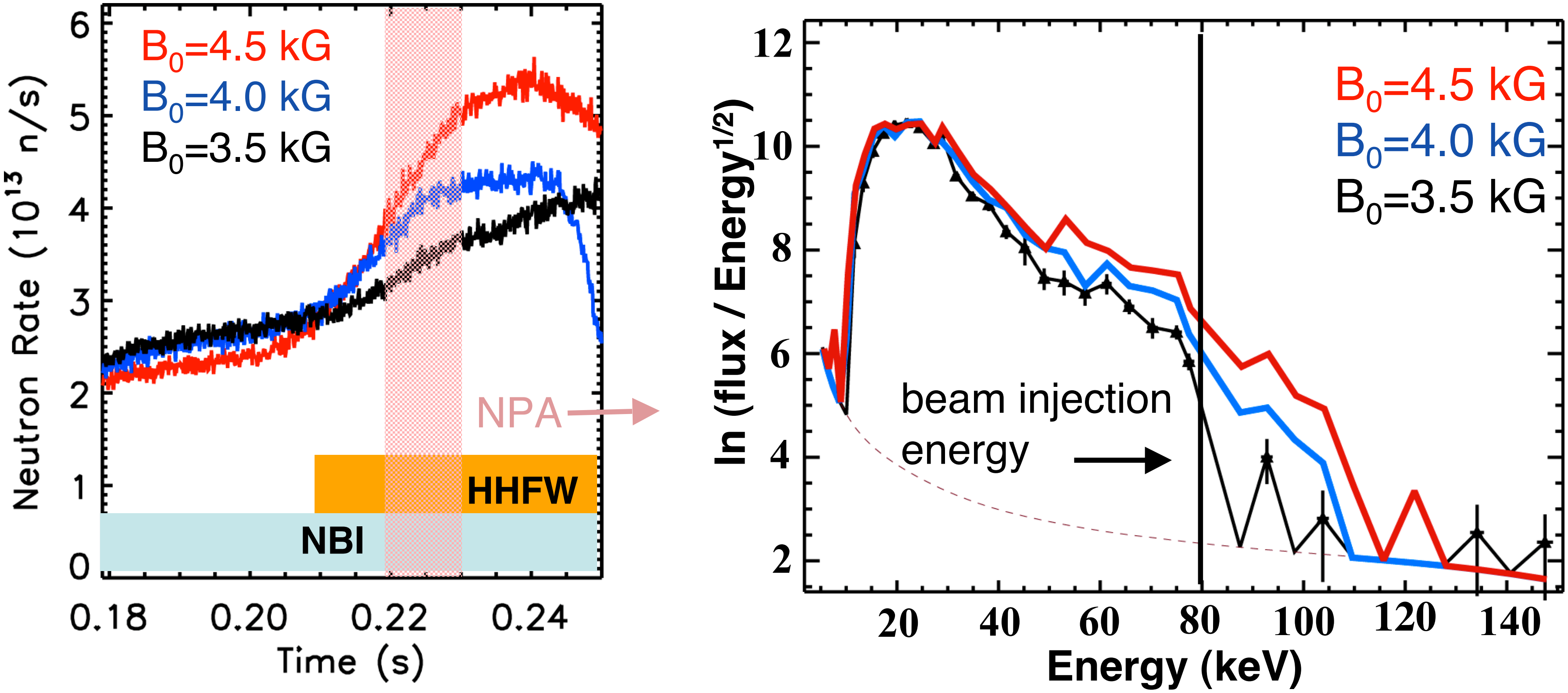
- Trapping significantly reduces HHFW-driven current:
  - *Diamagnetic effects at high β may reduce trapping*

Codes Predict Strong Electron Damping, as Seen in Experiments



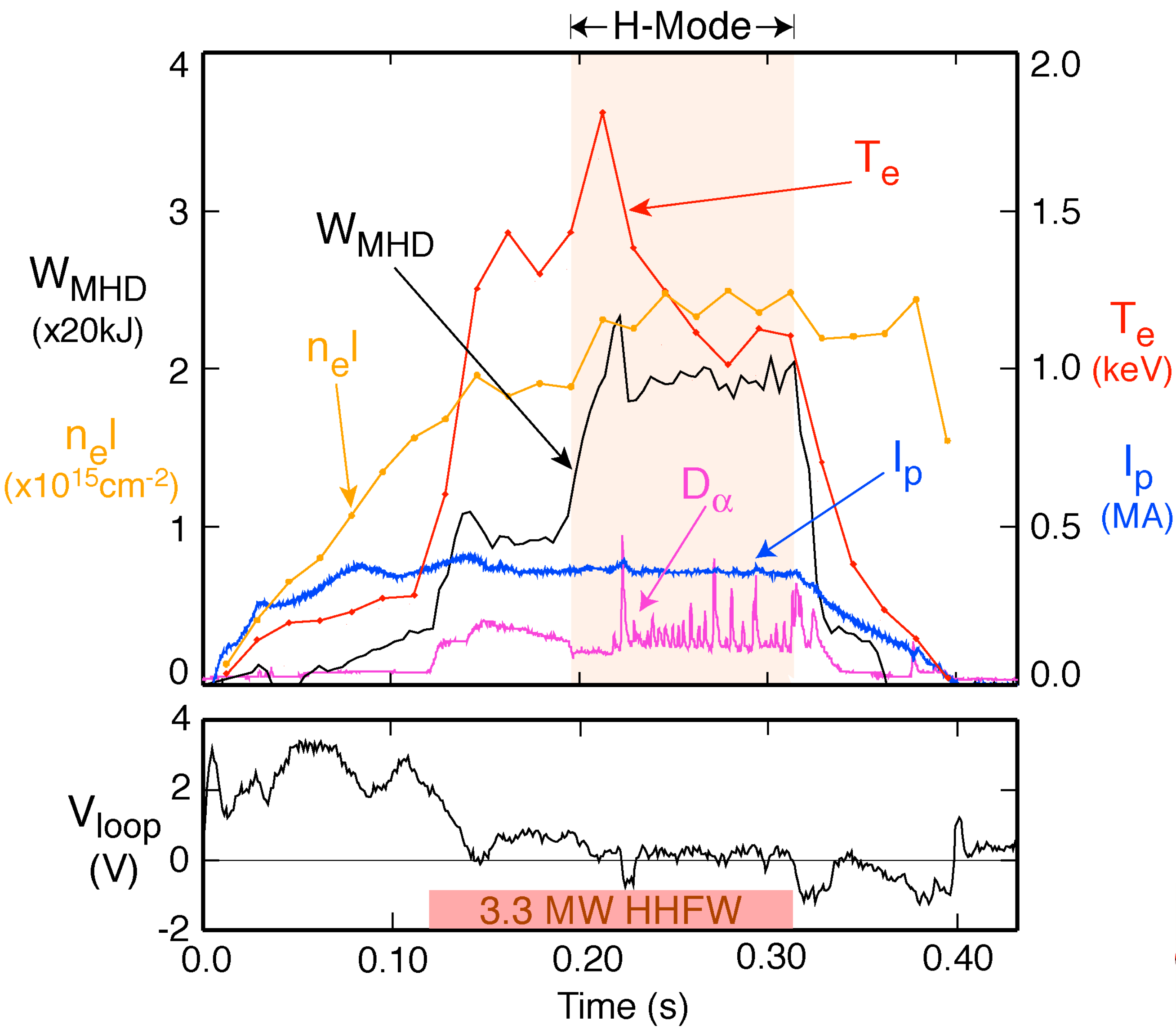
- Excellent agreement between ray tracing codes for HHFW CD experiments
- Full-wave codes predict similar deposition to ray tracing codes
- Full-wave kinetic models predict no significant IBW mode conversion
- More numerical studies to determine if IBW conversion is important at higher B and/or ion β

Evidence Seen for HHFW Interactions with Energetic Beam Ions, as Predicted



- Tail reduced at lower B, higher β:
  - *Larger β_e promotes greater off-axis electron absorption reducing power available to centralized fast ion population*

High β Poloidal H-Mode Plasmas Provide Excellent Candidate for Long Pulse Sustainment



- $V_{loop} \sim 0$
- ~ 40% bootstrap fraction

HHFW 5-Year Research Plan

2003-4: Test Physics of HHFW Heating & CD

- *Couple HHFW into double null; so far studied limiter and single null, but highest β achieved in double null*
- *Study effect of density on HHFW heating; wider range of densities due to improved fueling & wall conditioning*
- *HHFW-only H-mode access & couple HHFW into NBI H-mode*
- *Early HHFW heating; modify internal inductance, reduce volt-sec consumption and increase q(0)*
- *HHFW heating efficiency with strong NBI; study dependence on target β and density*
- *Measure J(R) with CIF MSE during HHFW CD*

2005-6: HHFW & CHI, Long Pulse HHFW & ΔJ Feedback

- *Couple HHFW into CHI startup*
- *HHFW heating with CHI to develop bootstrap current*
- *HHFW CD with CHI*
- *HHFW handoff to NBI*
- *Feedback control HHFW heating to maintain J(R) & P(R)*
- *Dependence of CD efficiency on power, n_e,T_e and phasing*
- *Study reduction in off-axis CD efficiency due to trapping and increase in CD efficiency at high β*
- *Feedback antenna phasing on MSE J(R) & rtEFIT*
- *Test fully non-inductive steady state operation*

2005-6: HHFW System Technical Improvements

2005:

- *Possibly modify HHFW antenna to be double-end fed to reduce voltage for same power*

2006:

- *If asymmetry in launch spectrum remains a problem for CD, may tilt antenna straps*

2007-8: HHFW Heating & CD Control of P(R) & J(R) and Flux Consumption Optimization

- *HHFW with full feedback control of phase using MSE LIF diagnostic to obtain real time J(R) & P(R)*

- *HHFW-assisted ramp to high* β_{pol}

- *Use HHFW to optimize flux consumption in high performance plasmas*

EBW Research

EBWs May Enable Local Heating, CD and $T_e(R,t)$ Measurements on ST Plasmas

- EBWs propagate when $\omega_{pe} >> \omega_{ce}$ and strongly absorb at EC resonances, allowing local EBW heating, CD and $T_e(R,t)$ radiometry

- Local EBW heating and CD may be important for non-inductive startup and MHD suppression in an ST

- EBWs can couple to electromagnetic waves near the upper hybrid resonance (UHR) that surrounds ST plasmas

EBW 5-Year Research Goals

- Efficient coupling of X- and/or O-mode to EBWs
- Control spatial location where EBW heats electrons
- Demonstrate EBW-assisted non-inductive startup, alone or in combination with HHFW and/or CHI
- Suppress neoclassical tearing modes with EBW heating and/or CD
- Install ~ 1 MW by 2006, ~ 3 MW by 2007

Status of EBW Research

EBW Experiments on CDX-U and NSTX Have Focused on Maximizing EBW Conversion to X-Mode (B-X)

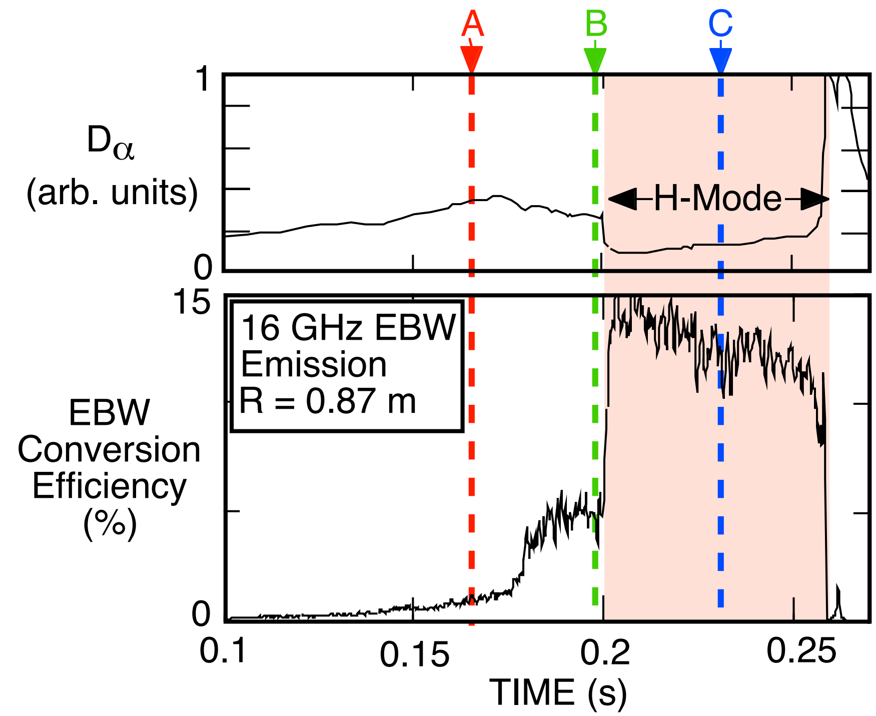
- Measurement of B-X emission evaluates the efficiency of the X-B process for heating and CD

- If L_n is short at the UHR, EBW can tunnel to the fast X-mode:
  - *EBW to X-mode conversion efficiency (C_{BX}) very sensitive to L_n*

- Mode conversion to the O-mode (B-X-O) also possible; studied on W7-AS and MAST

Need C_{BX}> 80% for Viable EBW Heating and CD System on NSTX

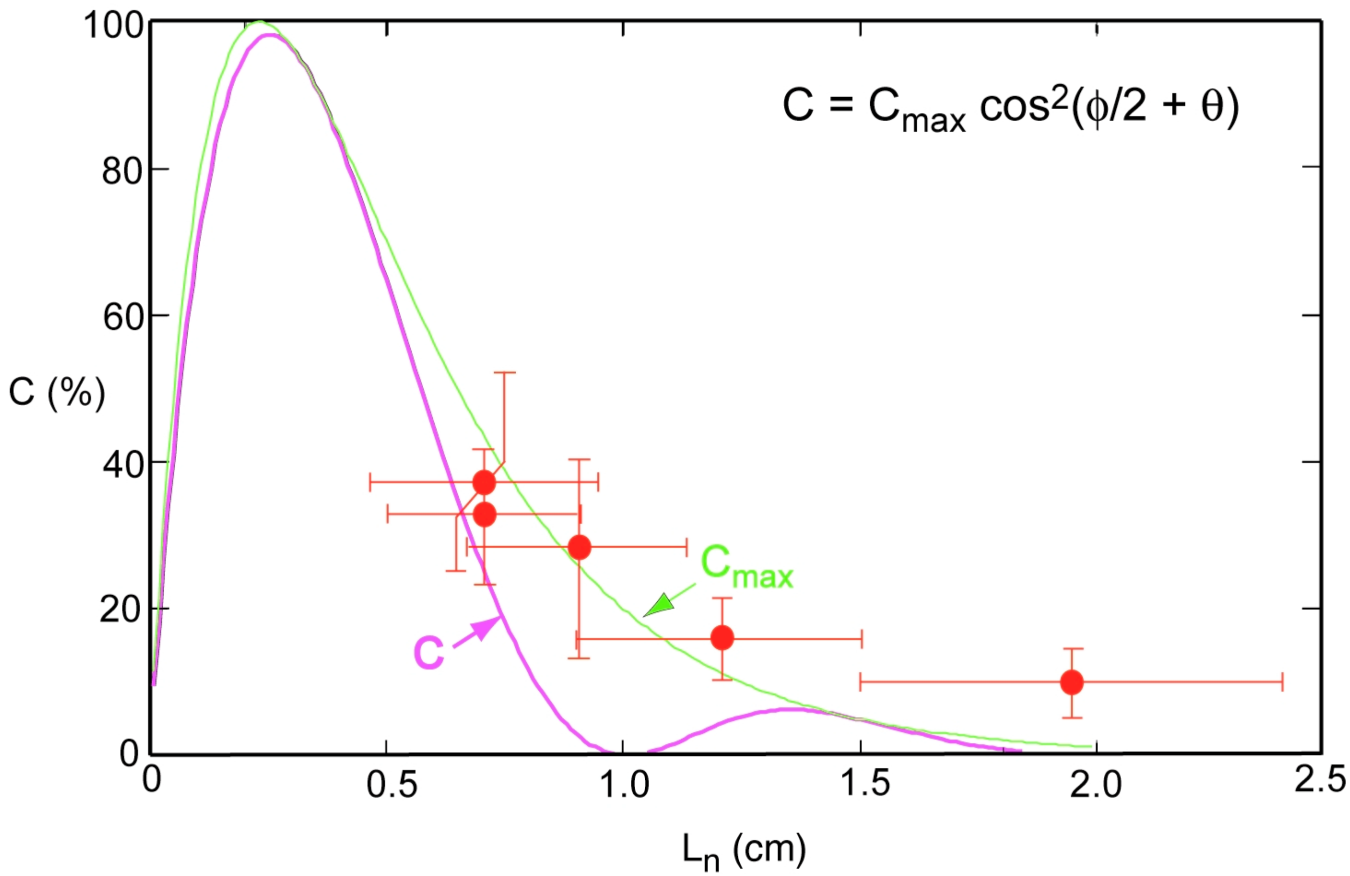
- Measured C_{BX} < 5% for NSTX L-Mode plasmas, 10-15% during H-Modes



- On CDX-U, local limiter shortened L_n to 0.7cm, increasing C_{BX} to > 95%, in agreement with theory
- Reproduce CDX-U experiments with local limiter on NSTX this year, for both B-X and B-X-O conversion

Experiment on NSTX Using HHFW Antenna Tiles to Shorten L_n Increases C_{BX} from 10% to ~ 50%

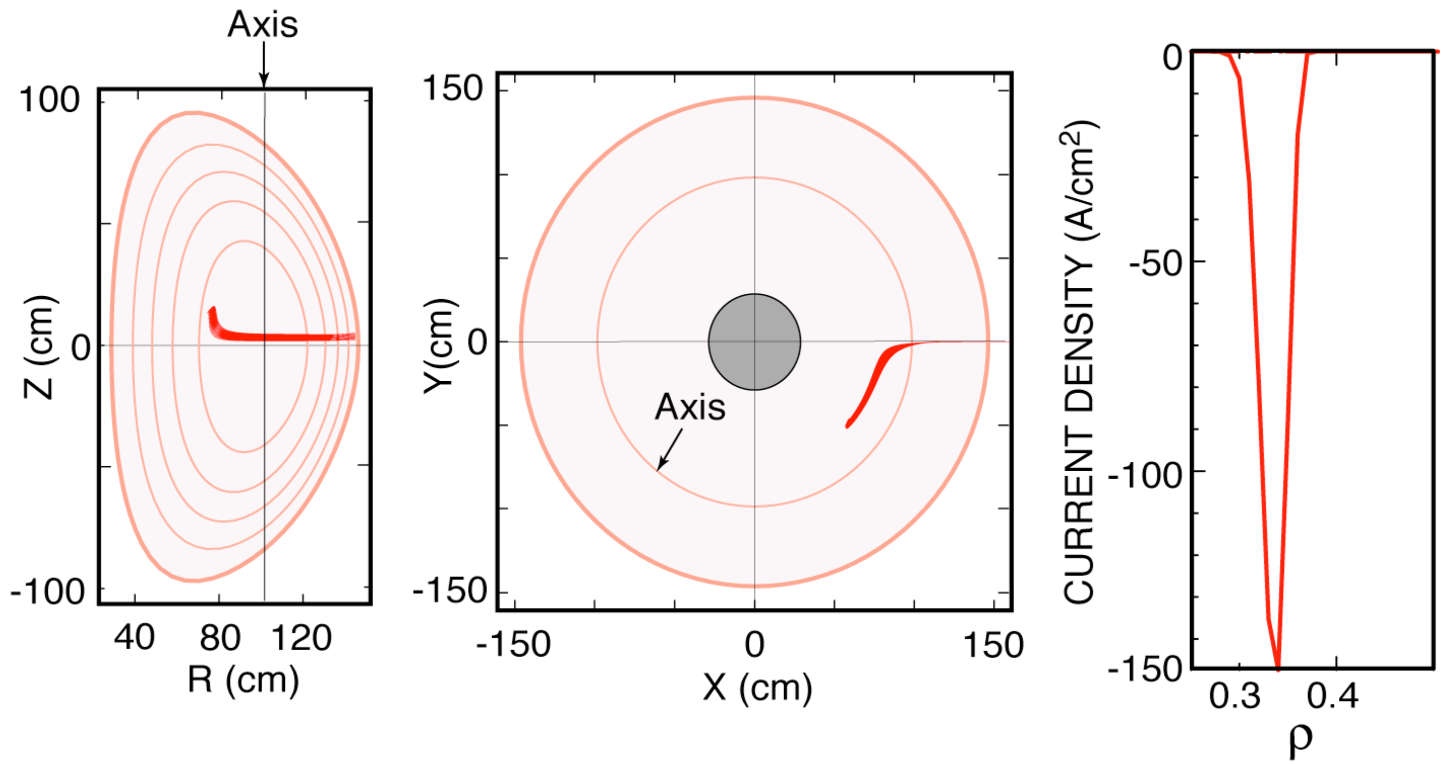
EBW Emission Frequency = 11.6 GHz



- Will attempt similar experiment with O-Mode antenna next year

Modeling Indicates Highly Localized EBW CD

- Use GENRAY ray tracing and CQL3D Fokker-Planck codes
- Greatest radial access for fundamental EBW



1 MW, 14.5 GHz RF at 5º above mid-plane, -0.1 < $n_{//}$ < 0.1, β = 20%

CD efficiency = 0.065 A/W, n_{eo} = 3x10^{19} m^{-3}, T_{eo} = 1keV

NSTX NATIONAL SPHERICAL TORUS EXPERIMENT

Status of EBW RF Source Technology

- B_o ~ 0.4-0.5 T NSTX plasma operation requires fundamental EBW RF source at ~ 15 GHz
- No long pulse, high power ~ 15 GHz sources available
- Develop new megawatt level ~ 15 GHz tube:
  - *MIT proposed 800 kW tube with ~ 50% efficiency, estimates 18-24 month development*
  - *Need request for cost & schedule quote in 2003*

EBW Launcher Design Presently Undefined

- Need well defined $n_{//}$ spectrum, good focusing and some beam steering
- Use either focusing mirrors or phased 4-8 element array
- Polarization control by external waveguide or grooved mirrors
- Use local limiter to steepen L_n at the mode conversion layer for both X-B and O-X-B launch

EBW 5-Year Research Plan

2003-5: Establish Conditions for Efficient Coupling to EBWs and Model EBW CD

2003: *Complete GENRAY/CQL3D scoping study for NSTX*

- *Include relativistic effects in EBW propagation & damping*
- *Are edge parametric instabilities for EBW heating?*
- *Request quote for ~ 1 MW, 15 GHz tube*
- *MAST to test O-X-B heating*

2004-5: *Obtain ≥ 80% B-X and/or B-X-O conversion on NSTX*

- *Complete 1-3 MW, 15 GHz EBW system design*
- *Include radial transport in CQL3D CD modeling*
- *Begin to install of 1 MW, 15 GHz system*

2006-8: Demonstrate Local EBW Heating, CD, Startup & NTM Suppression with 3 MW EBW System

2006: *Complete 1MW, 15 GHz EBW system*

- *Demonstrate EBW coupling with ~ 1 MW, 15 GHz*
- *Study spatial control of EBW electron heating*

2007-8: *Begin experiments with 1-3 MW, 15 GHz*

- *Demonstrate radial control of local EBW CD*
- *EBW plasma startup*
- *NTM suppression by EBW heating and/or CD*

CHI Research

CHI May Enable Non-Inductive ST Plasma Startup

- CHI creates plasma current without a solenoid and drives it to a level where other tools can take over
- CHI has potential to control edge current profile during the sustained discharge phase
- May induce edge plasma rotation to sustain an edge transport barrier
- May control scrape off layer flows
- High power density presents technical challenges

CHI 5-Year Research Goals

- Demonstrate transfer of a CHI produced plasma to the central solenoid:

  - *Handoff CHI startup initially to inductive and later to non-inductive CD system*

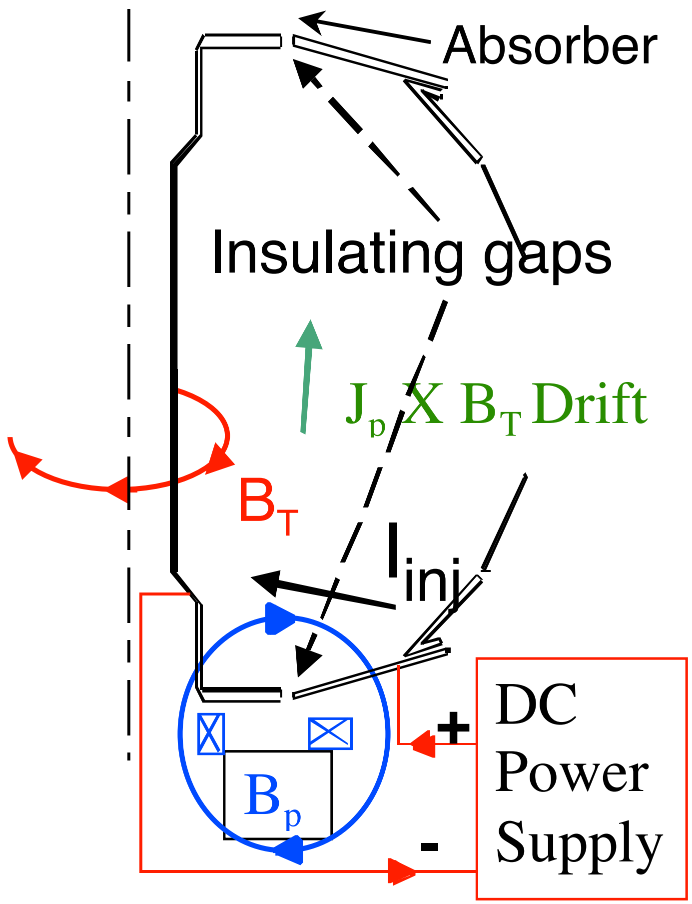
- Provide edge current during sustained non-inductive operation

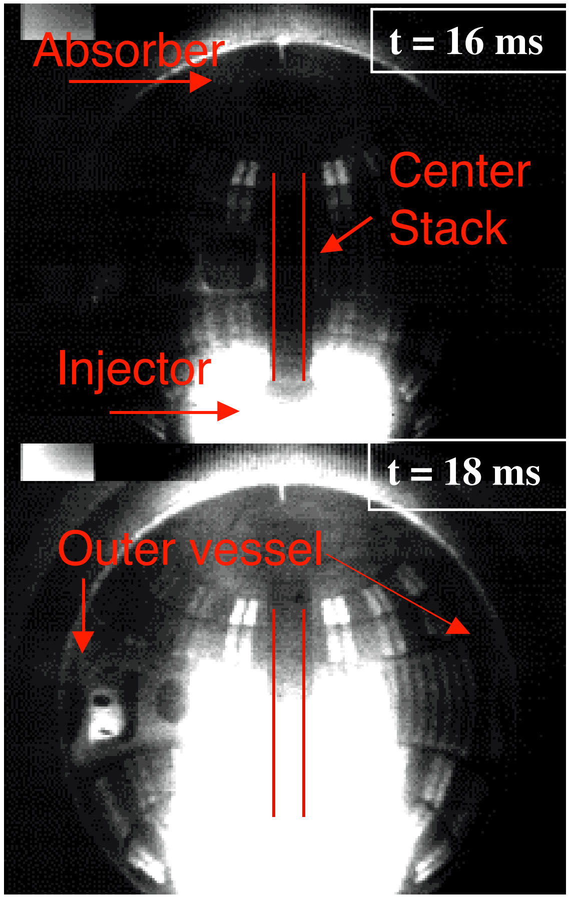
- 3D MHD studies and measurement simulations to form a physics-based understanding of CHI and how it might extrapolate

Strong collaboration with HIT-II (Univ. of Washington)

Status of CHI Research

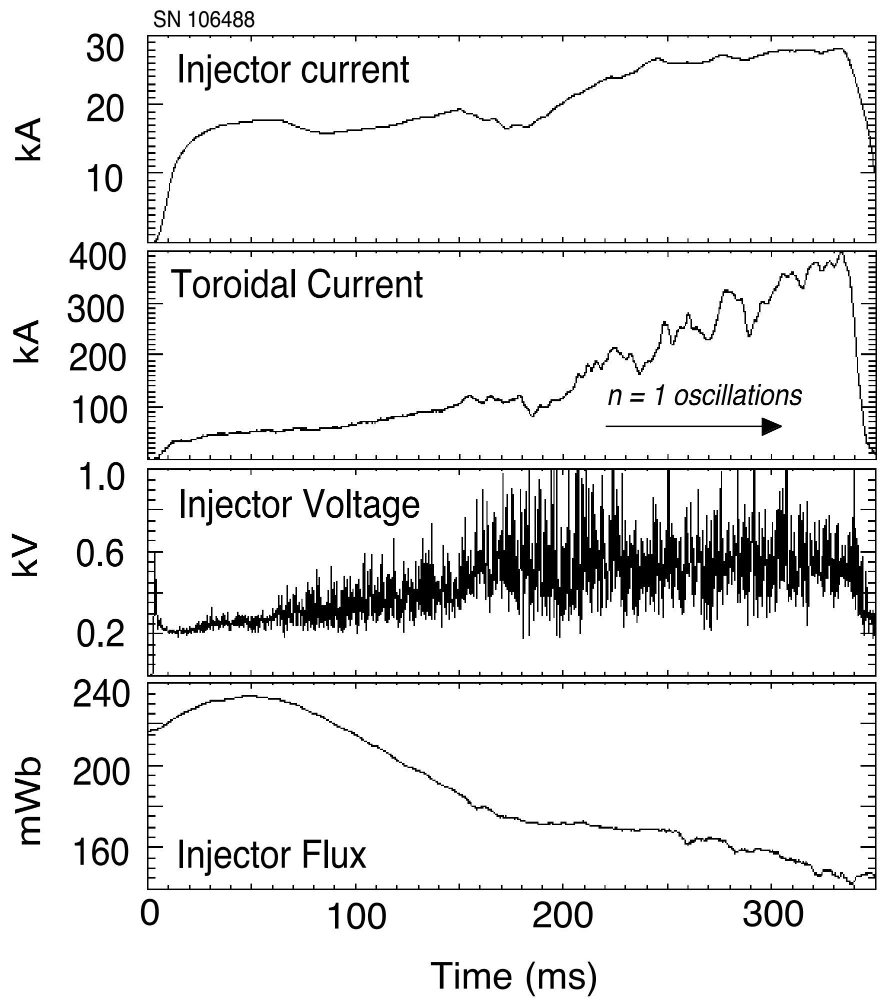
Simple Description of CHI Start-up





- Expect reconnection to redistribute edge current to interior, forming closed surfaces

Produced 400kA Plasma with 14x Current Multiplication

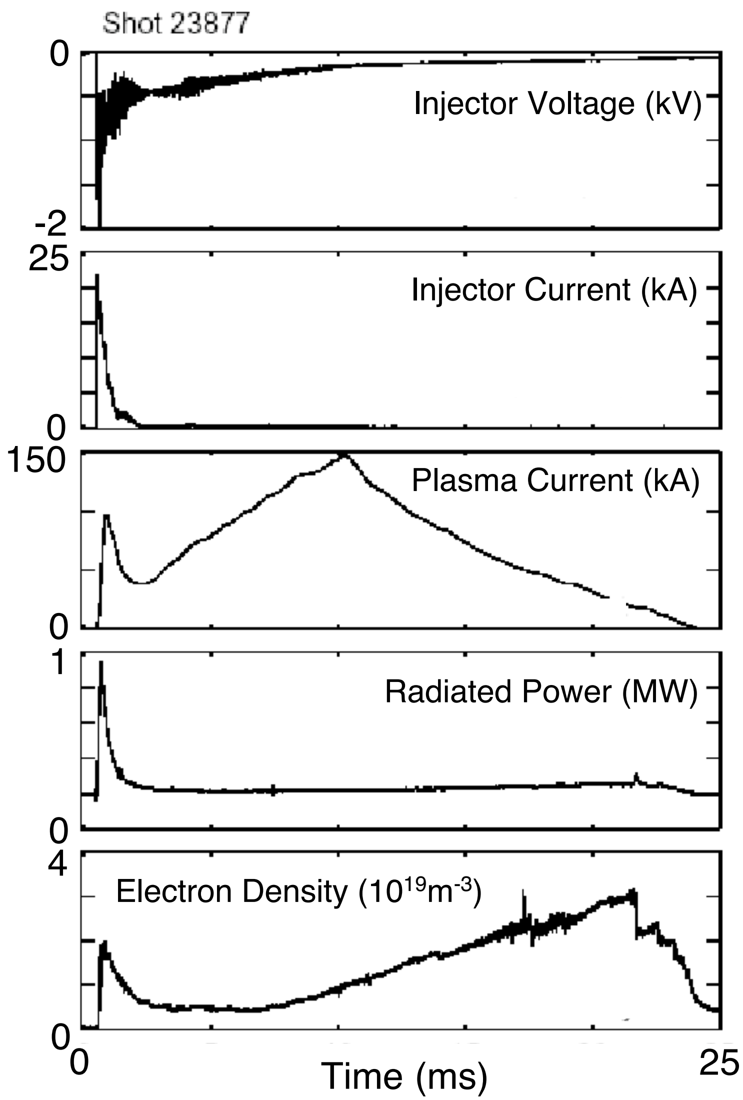


- Evidence for *n=1* MHD, consistent with flux closure
- B-field pickup coils and soft X-rays indicate large scale reconnection activity
- Need feedback control to stabilize CHI-produced discharge

Technical Problems Have Limited CHI Operational Space

- Arcs across absorber gap on nearly all CHI shots
- Arcs external to vacuum vessel also occur
- Hardware upgrade to address absorber arc problem
- Old absorber uses short insulator length and no PF coils
- New absorber has longer insulator and stray field reducing coils

Recent Work on HIT-II Demonstrates Short-Pulse CHI and Induction can be Coupled



Raman, Jarboe, Nelson

- New CHI startup tested on HIT-II uses transient (< 50 ms) pulse:
  - *Successful handoff to inductive operation*
  - *Reduced V-s consumption*
  - *Reproducible discharges with record currents on HIT-II*
- Will be tested on NSTX this year

HIT - II

CHI 5-Year Research Plan

2003: Test CHI Physics

- Study handoff of CHI startup to inductive plasma
- Explore new short pulse startup scenario
- Develop tools for steady state operation
- Reestablish CHI startup to ~ 300 kA and investigate new absorber performance

2004-5: Optimize CHI, Test Edge CHI CD and Absorber Field Nulling

- Couple CHI startup to heating and non-inductive current drive methods, including assist from outer PF coils
- Establish edge CHI CD in an already established discharge and investigate effect of CHI on edge flows and rotation
- Establish preferred method for CHI startup (transient versus steady state)
- Implement absorber field nulling

2006-8: Integrate CHI with Other Non-Inductive CD Tools & Optimize Edge CHI CD for Long Pulse

- Demonstrate hand-off of CHI plasma to solenoid-free CD system, ramping to high poloidal β
- Detailed MSE J(R) measurements of CHI discharges
- Understand processes that lead to flux closure and mechanisms that sustain closure
- Investigate edge CHI current drive in high β, high bootstrap, steady-state discharges

HHFW, EBW and CHI May Provide Tools to Enable Solenoid-Free NSTX Operation at High β

HHFW:

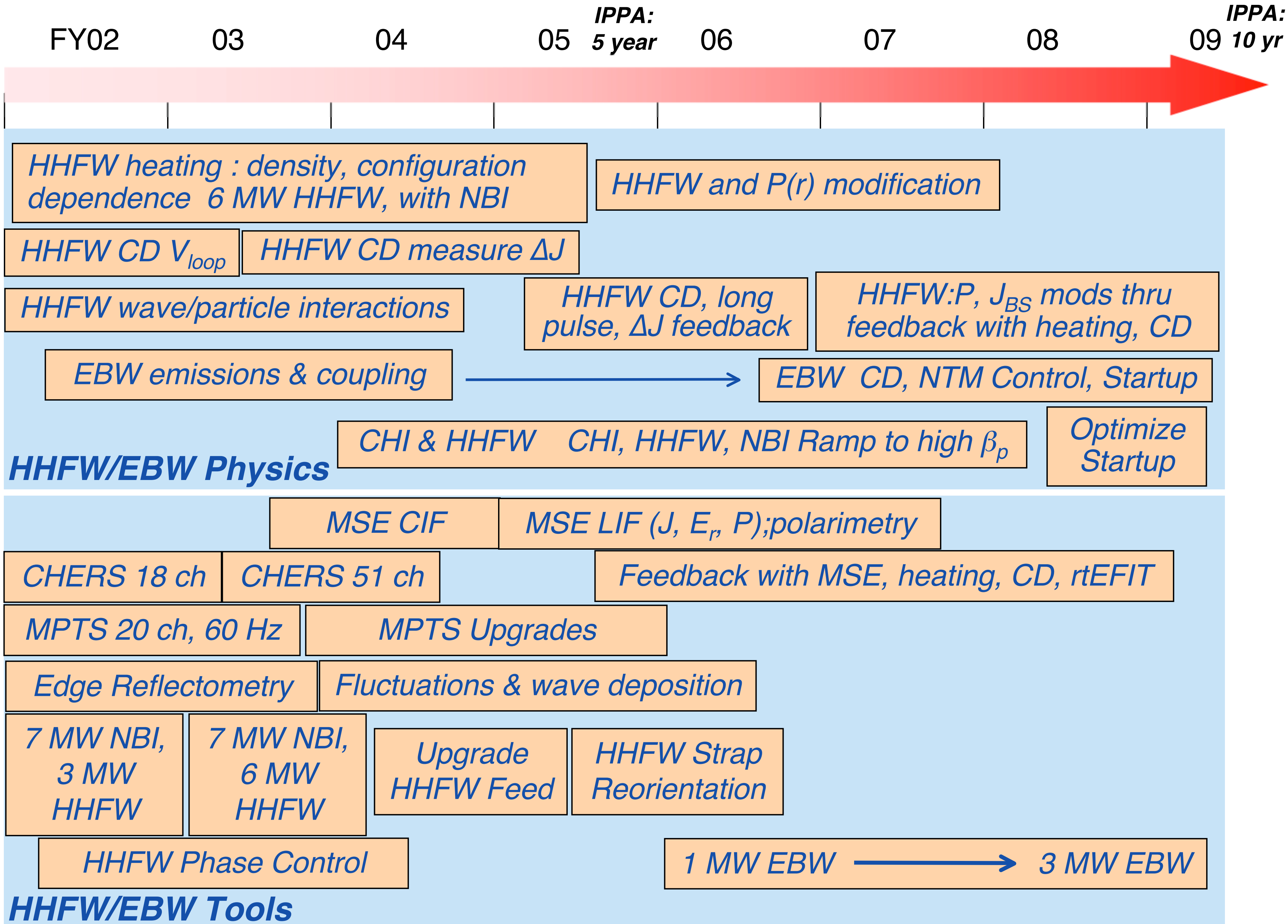
- Strong electron heating; evidence for CD & NBI ion interaction
- 5-yr goal: HHFW-assisted startup, current sustainment and pressure profile modification

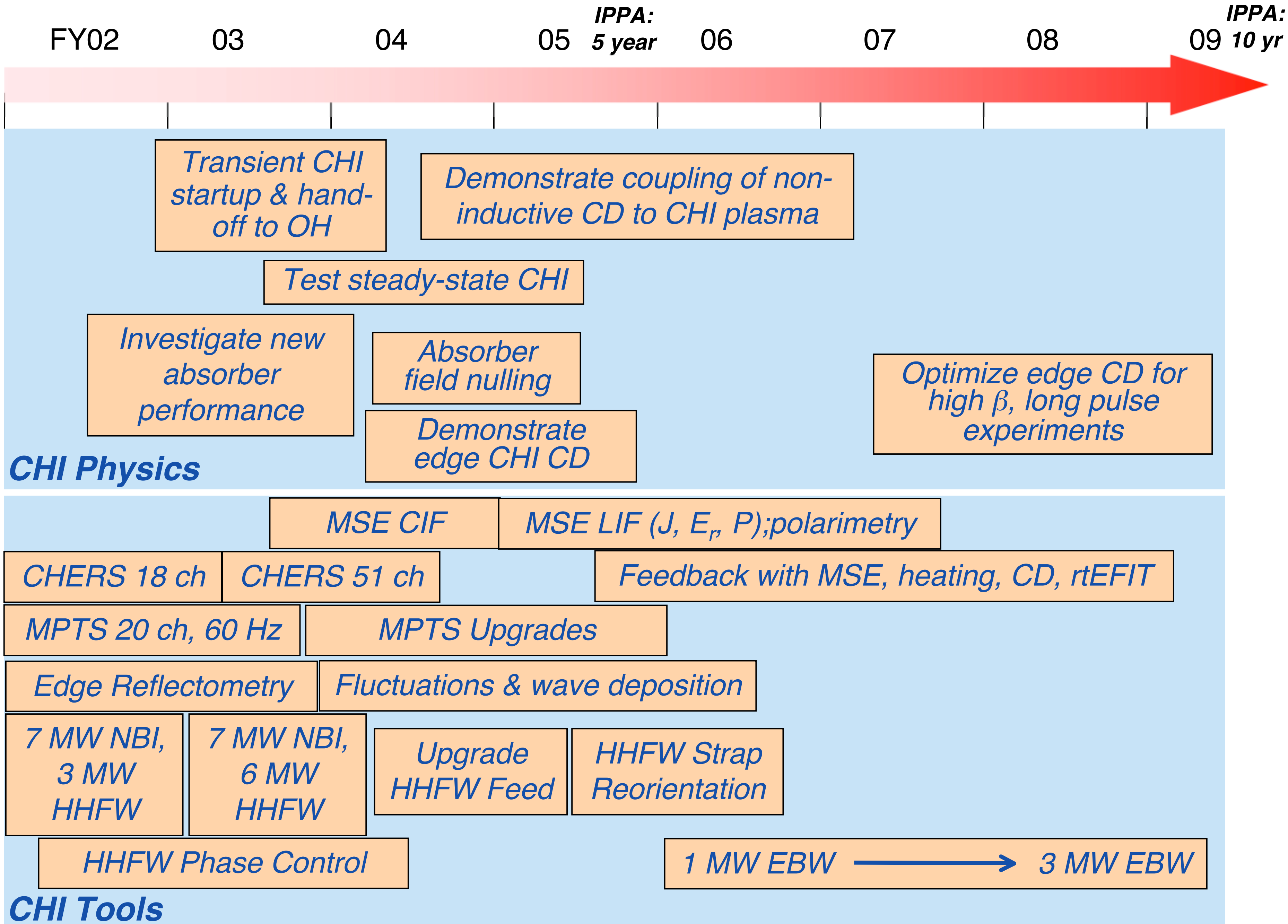
EBW:

- With limiter, C_{bx}> 95 % on CDX-U, ~ 50% on NSTX
- Install 1-3 MW EBW system in 2006-7
- 5-yr goal: EBW startup & MHD suppression

CHI:

- Produced 400kA CHI plasma on NSTX , improved short pulse CHI tested on HIT II
- 5-yr goal: optimize CHI startup, edge current drive & rotation


FY02
03
04
05
IPPA:
5 year
06
07
08
09
IPPA:
10 yr
HHFW heating : density, configuration dependence 6 MW HHFW, with NBI
HHFW and P(r) modification
HHFW CD V_{loop}
HHFW CD measure ΔJ
HHFW wave/particle interactions
HHFW CD, long pulse, ΔJ feedback
HHFW:P, J_{BS} mods thru feedback with heating, CD
EBW emissions & coupling
EBW CD, NTM Control, Startup
CHI & HHFW
CHI, HHFW, NBI Ramp to high β_p
Optimize Startup
HHFW/EBW Physics
MSE CIF
MSE LIF (J, E_r, P);polarimetry
CHERS 18 ch
CHERS 51 ch
Feedback with MSE, heating, CD, rtEFIT
MPTS 20 ch, 60 Hz
MPTS Upgrades
Edge Reflectometry
Fluctuations & wave deposition
7 MW NBI, 3 MW HHFW
7 MW NBI, 6 MW HHFW
Upgrade HHFW Feed
HHFW Strap Reorientation
HHFW Phase Control
1 MW EBW
3 MW EBW
HHFW/EBW Tools


FY02
03
04
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IPPA: 5 year
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IPPA: 10 yr
Transient CHI startup & hand-off to OH
Demonstrate coupling of non-inductive CD to CHI plasma
Test steady-state CHI
Investigate new absorber performance
Absorber field nulling
Demonstrate edge CHI CD
Optimize edge CD for high β, long pulse experiments
CHI Physics
MSE CIF
MSE LIF (J, Er, P);polarimetry
CHERS 18 ch
CHERS 51 ch
Feedback with MSE, heating, CD, rtEFIT
MPTS 20 ch, 60 Hz
MPTS Upgrades
Edge Reflectometry
Fluctuations & wave deposition
7 MW NBI, 3 MW HHFW
7 MW NBI, 6 MW HHFW
Upgrade HHFW Feed
HHFW Strap Reorientation
HHFW Phase Control
1 MW EBW
3 MW EBW
CHI Tools