Research Opportunities and Experimental Plan for FY2003

S. M. Kaye for the NSTX Research Team
PPPL, Princeton Univ.

NSTX PAC-13 Meeting
Princeton, N.J.
Sept 30-Oct. 1 2002

Outline

- Planning process
  - Milestones and relation to IPPA goals
  - New facility and diagnostic capabilities
- Topical area research program organized by ETs
  - Heating and Current Drive (Taylor, Ryan)
  - Co-Axial Helicity Injection (M. Bell, Raman)
  - MHD (Sabbagh, Gates)
  - Transport and Turbulence (LeBlanc, Darrow)
  - Boundary Physics (Kugel, Kaita)
  - Integrated Scenario Development (Maingi, Menard)
- Program emphasis and research plan logic

Program Planning Steps

- PAC-12 (2/02)
- FWP (3/02)
- NSTX Results and Theory Review (9/02)
- NSTX Research Forum (9/02)
- ⇒ PAC Input (9-10/02)
- Refinement of run plan (10-11/02)
- Beginning of FY03 run (12/02)

- Initial Presidential budget guidance – 21 run weeks in FY03

FY03 Milestones Help Drive Research Prioritization

- High-β and τ_E for $\Delta t \gg \tau_E$ (IPPA 3.2.1.6)
- Non-inductive current drive to assist in startup and sustainment of $\geq$ 1 sec pulses (IPPA 3.2.1.2)
- Interactions among resonant error field (REF) response, correction fields and rotation (IPPA 3.2.1.4)
- Edge heat flux dispersion and effect of PFC at high power (IPPA 3.2.1.5)
- Requirements for EBW heating and current drive (IPPA 3.2.1.3)
- Persistent CHI produced currents and coupling to other CD techniques (IPPA 3.2.1.4)

FY04 Milestones

- Avoid/suppress β-limiting modes (IPPA 3.2.1.2)
- Measure j(r) modifications from non-inductive CD (IPPA 3.2.1.4)
- Long-λ turbulence in plasma core (IPPA 3.2.1.1)
- Energetic particle/wave interactions (IPPA 3.2.1.3)
- Edge heat flux at high-β_T, τ_E (IPPA 3.2.1.5)

NSTX Facility Plan (•)

	FY02	FY03	FY04
Experimental Run-Weeks	12	21	20
TF system	• 6 kG		
NBI		• Real-Time β Feedback	
HHFW	• Pre-prog. Phasing	• Antenna Feed-Thru Imp.	• F/B Phase Control
CHI		• New Absorber • Absorber Field Null Control Coils	
EBW		• Optimized Ant. Assembly	
Wall Conditioning Pwr & Part. Cntrl.	• 350 C Bakeout	• Li/Boron Pellet Injector • Density Feedback	
Fueling	• HFS Gas Fueling	• HFS Gas Fueling Improvement	
Resonant Field and RWM Control	• PF5 Realign • Locked Mode Coils	• Prelim. Res. Field Control System • 2x12 Wall Mode Sensors	• 2x24 Wall Mode Sensors
Plasma Equilibrium & Control	•Non-Mag. Pickup Coils • rtEFIT	• 2x6 I-D Mirnovs, Flux Loops for CHI absorber • Density Feedback • rtEFIT Algorithm Dev.	• MIMO (GA)

NSTX Diagnostics Implementation Plan (FY02-04)

* collaborator diagnostics in red

	FY02	FY03	FY04
Experimental Run-Weeks	12	21	20
MPTS	• 20 Ch		• 90 Hz
CHERS	•18 Ch (interim)	• 51 Ch Toroidal	• Pol CHERS
XCS		• 2D	
MSE (Nova)		• CIF 2 • 10 Ch	• LIF
FIReTIP (UCD)	• 2 Ch	• 4 Ch	• 7 Ch
USXR (JHU)	• Pol fan at 2nd Tor pos	• Higher resolution	
Particle Detectors	• 2-D Scanning NPA • Faraday loss probe • Neutron, Diamond Detectors	• Scintillator Loss Probe	
Fluctuations	•Add. Correl. Reflect. (UCLA) • 2D GEM X-ray (Frascati/JHU) • Fast Scan. Edge Probe (UCSD) • MHz Gas Puff Imaging (PSI, LANL)	• Dynamo Probe • High-k Prototype •1 mm Interferometer	• 2D Fast X-Ray Pinhole Camera • MIR
Impurities	•VIPS, VB, Fiberscopes •VUV (JHU)	• Multi-Chord Spectrometer (JHU)	
Divertor and Boundary Physics Cameras	•Langmuir, Tcouples •FRP (UCSD), Coupons (SNL) • Div. 1D CCD (ORNL) • Div. IR Cam. (ORNL) • Fast 2D Div. Visible (Hiroshima U)	• Div. Bol., Edge Flow Spectroscopy • Quartz Dep. Monitors	

Heating and Current Drive Research Directly Related to NSTX Milestones

- Research Topics
  - RF wave physics
    - Absorption and deposition, parasitic effects
    - Plasma confinement
  - Electron heating
  - Non-inductive current drive
  - EBW mode conversion studies

- System modifications and new capabilities
  - HHFW antenna modified to increase voltage/power limit
  - New EBW antenna assembly
    - Radially moving B/N limiters
    - Reflectometer
    - Local gas feed
  - MSE, FIRETIP polarimetry, sFLIP

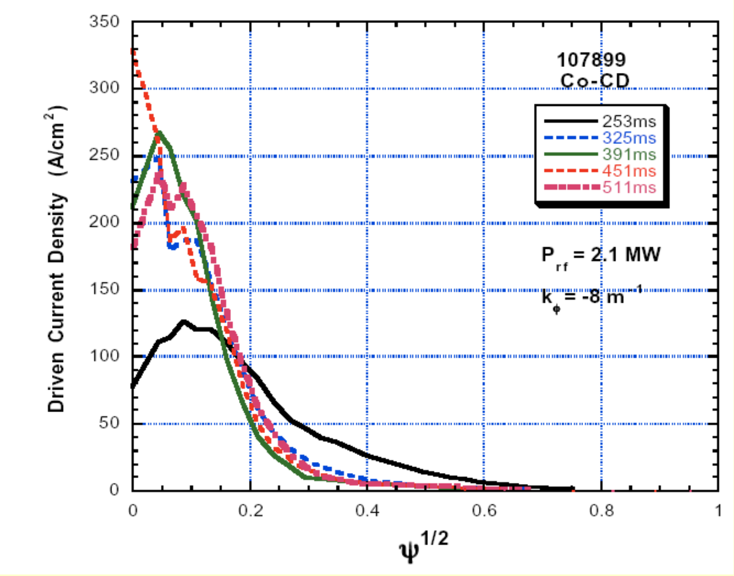
HHFW Heating Experiments and Modeling Will Help Us Understand RF Wave Physics

- System shakedown to achieve maximum power
  - Develop antenna conditioning techniques
  - Develop startup scenarios to optimize coupling to plasma
- Establish deposition control for electron heating
  - Vary gaps, antenna phasing, go to high density
- Obtain H-mode at 800 kA
  - HHFW good tool for probing power threshold
  - HHFW/NBI comparisons to assess effect of rotation
- Continue to develop HHFW modeling tools
  - CURRAY (Mau), HPRT (Menard) – ray tracing
  - TORIC (Bonoli), METS (Phillips) – full wave
  - CURRAY, TORIC incorporated into TRANSP

HHFW Current Drive

- Antenna modifications will allow increase in power
- Use HHFWCD to help increase pulse length to 1 sec
  - Explore HHFW startup with large bore, low density plasmas
  - Improve plasma position control to maintain good coupling
  - Avoid MHD using different I_p ramp rates, RF turn-on times
- Operate at higher density ($5x10^{19}$ m^{-3}) for off-axis CD
- Measure driven current with MSE, FIRETIP polarimetry
- Compare measured $j_{CD}(r)$ to model calculations

Curray CD Calcs



[Mau]

Interactions Between HHFW and NB Fast Ions Can Be Strong

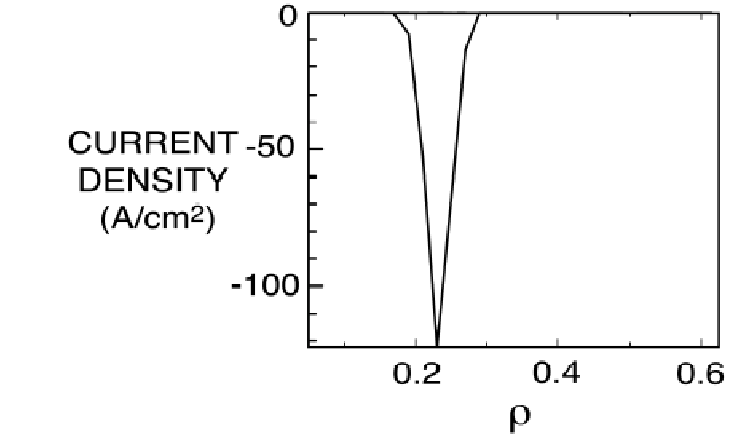
- Extend experiments to understand nature of fast ion acceleration during HHFW (A. Rosenberg, PhD Thesis)
  - Resolve dependence of interaction wrt HHFW phasing
  - Estimate power in tail

  - Higher RF power
  - sFLIP, scanning NPA

EBW Emission Experiments Will Establish Basis for High Power H&CD System

- Demonstrate >80% B-X and/or B-X-O conversion
  - Use B/N limiters to reduce L_n and increase conversion efficiency
  - ORNL reflectometer to measure L_n
  - Local gas feed to ensure adequate density

- Complete GENRAY/CQL3D heating and current drive scoping study



[Taylor, Harvey]

β_T=12%

CD efficiency is 0.1 A/W (comparable to ECCD) with 100% mode conversion

CD accessibility more limited at higher β_T

- EBWCD possible tool for NTM stabilization

Heating & CD Research Addresses Project Milestones

Electron heating →	High β_T, τ_E for long duration
HHFW startup Fast ion/RF interactions Electron heating → HHFW CD	Quasi-steady 1 sec discharges using NICD
Rotation effects (wrt/ NBI) →	REF Response, Correction Fields and Rotation
EBW mode conversion studies →	EBW H&CD requirements

CHI Provides Means for Non-Inductive Startup

- Research Goals
  - Demonstrate persistent toroidal current and closed poloidal flux
  - Extend to higher toroidal current and couple to other current drive schemes
  - Add CHI edge current drive to Ohmic plasmas

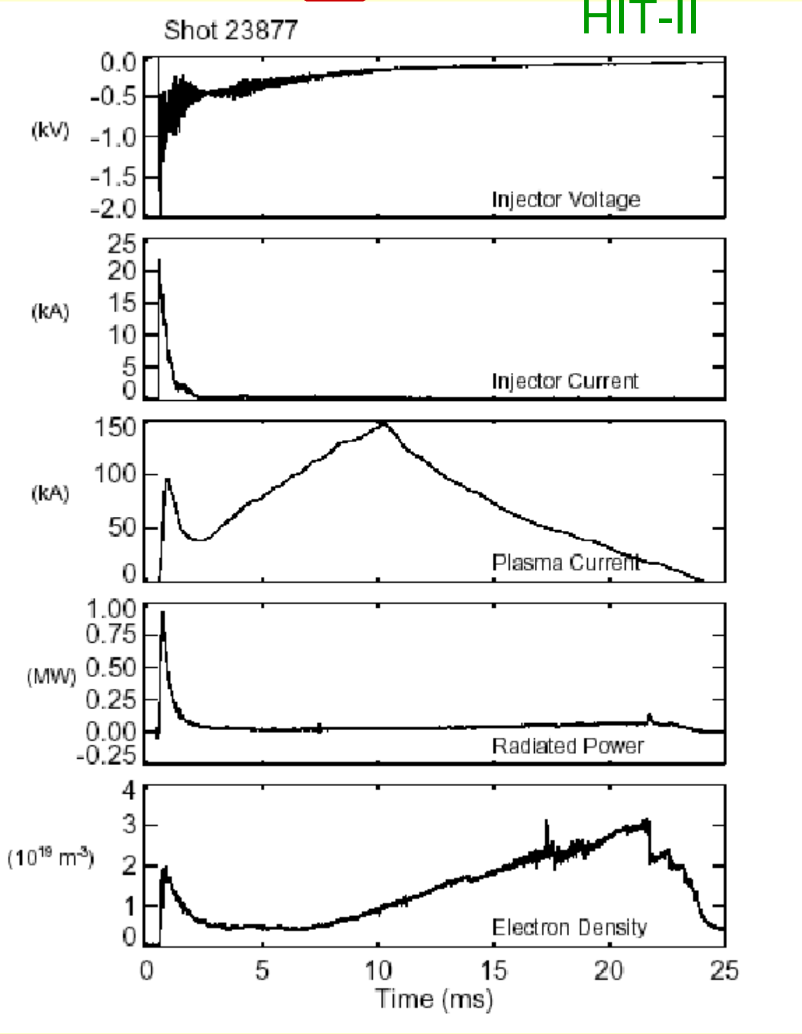
- CHI hardware modifications and new capabilities
  - Components/electronics related to noise and arcing redesigned
  - New, long ceramic insulator
  - PF absorber field control coils
  - Dynamo probe head to measure helicity transport

Employ Short Pulse Startup Scenario Developed on HIT-II

- Successful coupling to OH

- For NSTX
  - I_{inj}~10-30 kA for 10-30 msec
  - Minimally perturbing
  - Determine poloidal flux savings

  - Need to develop short pulse scenario
    - PF1b
    - $I_{inj}(t)$
    - Gas feed rate



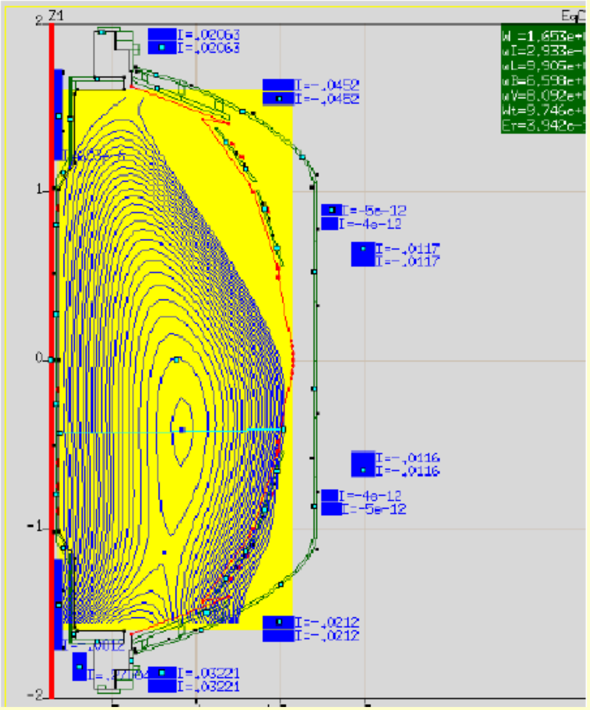
[Raman, Jarboe, Nelson]

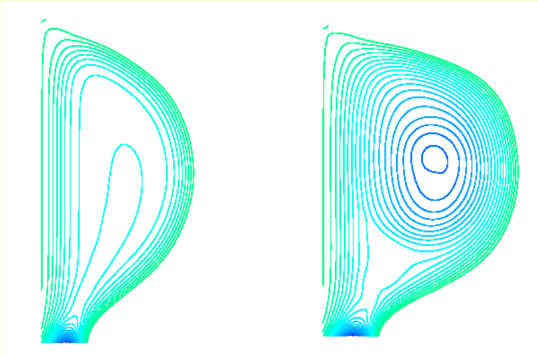
Improvments to CHI System Should Allow Operation at High Toroidal Current (≥400 kA)

- Develop extended CHI pulse
  - New absorber
  - Absorber field control coils
  - Control system development
- Demonstrate flux closure in most favorable conditions
  - Magnetic fluctuations
  - Kinetic profiles (USXR, MPTS)
  - Equilibrium reconstruction and modeling
- Couple high current CHI-initiated plasma to other current drive schemes (OH, HHFWCD)

CHI Modeling Effort Spans Wide Range of Approaches

- ESC: Equilibrium reconstruction (Zakharov)
- EFIT: Equilibrium reconstruction (Lao, Schaffer)
- TSC: Dynamic simulation code (Jardin)
- 3DMHD: 3D equil. and non-linear stability code (Tang)





CHI Research Addresses Project Milestones

NSTX

Non-inductive startup->OH
Transient
High current

→ Persistent CHI current

→ Quasi-steady 1 sec discharges using NICD

→ Couple to other CD techniques

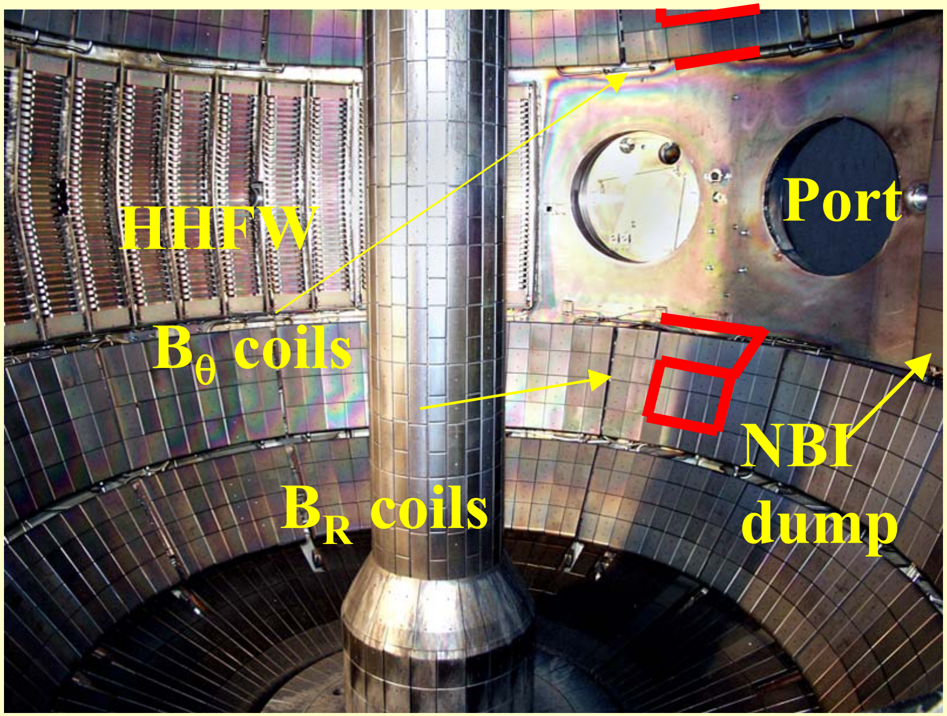
High current startup → Demonstrate flux closure

MHD Research Topics

- Research Topics
  - Error field resonance studies
  - Effect of rotation on modes
  - RWM, core and edge (ELM) disruption physics
  - Fast-ion driven MHD modes

- New capabilities
  - Divertor Mirnov array
  - RWM sensors (12 B_p, 12 B_r)
  - EF/RWM control coils
  - MSE (2->10 channels)
  - 1 mm interferometer/polarimeter

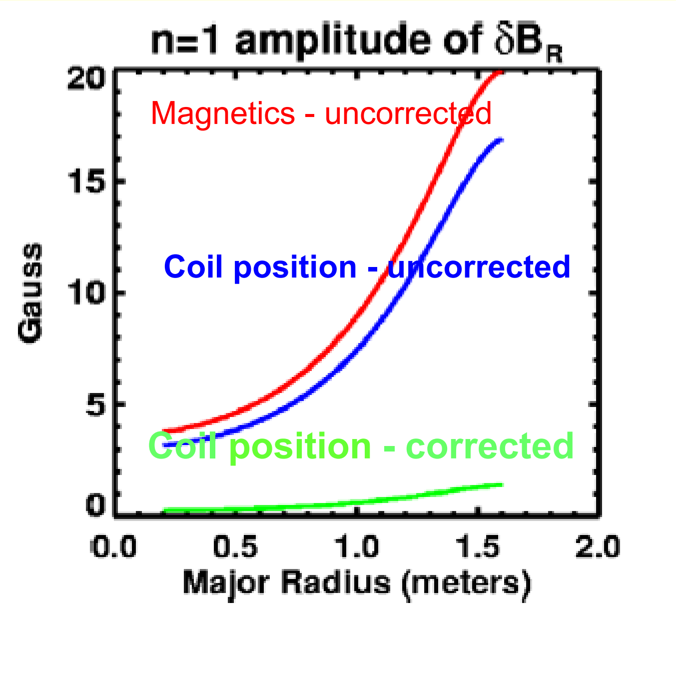
[Menard, Sabbagh, …]



Error Field Resonance, Correction Coils and Rotation Physics

- PF5 realignment led to a significant reduction in error field, clear locked mode threshold

- Calibrate new internal RWM/EF sensors with external LM sensors
- Identify regimes w/o modes at low density
- Study effects of rotation on mode
  - NBI pulses to change plasma rotation
- Study EF amplification
  - Approach no-wall limit at low density
  - Look for appearance of LM
- Study NTM physics at reduced EF
- Assess preliminary EF/RWM control system

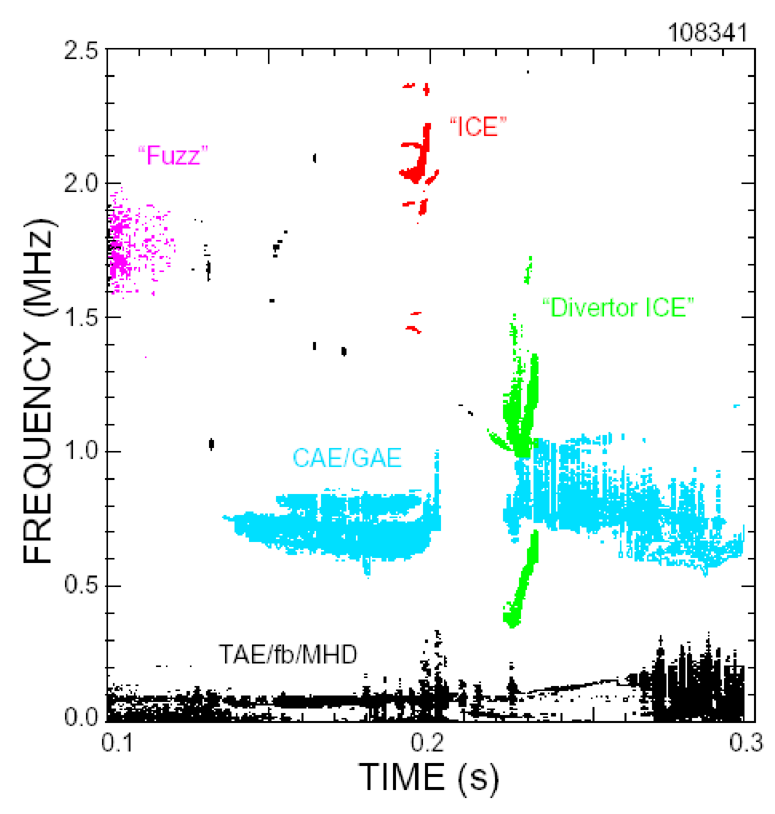


[Menard]

Assess Impact of Fast Ion Instability Drive

- Extend study of "*AE" modes, fishbones, and their impact on ST plasmas
  - Measure high-f MHD
  - Complete comparison to ATs through similarity experiments (NSTX/DIII-D)

Modes up to 15 MHz inferred



- Determine amplitude and extent of CAE modes using core reflectometry/polarimetry
  - Implications for stochastic heating

[Fredrickson]

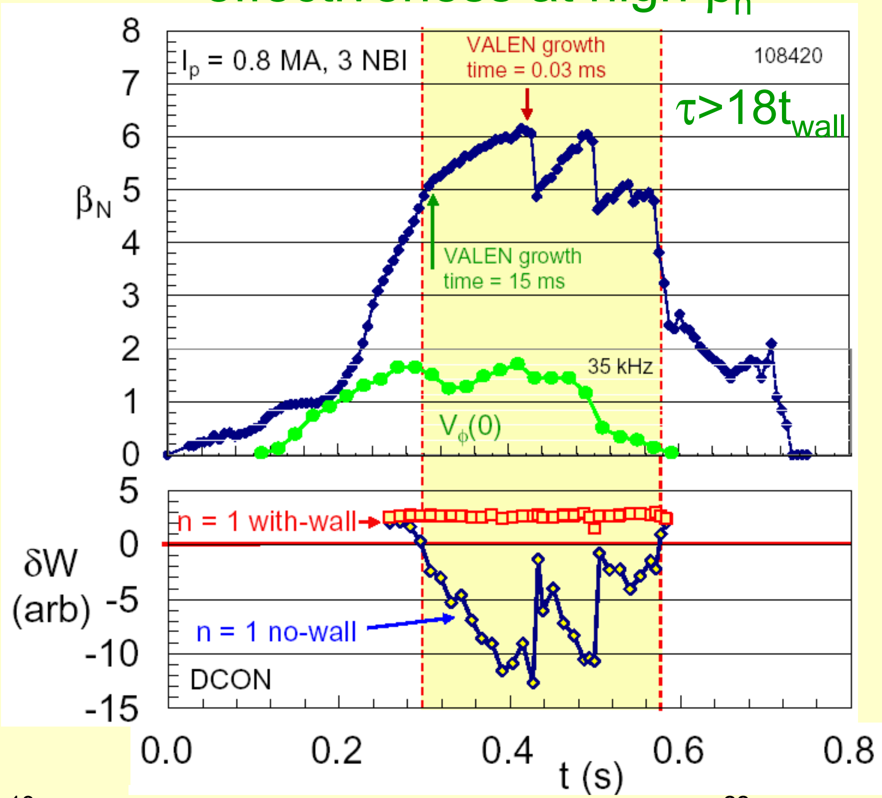
Study stabilization physics of RWM at high- β_n

NSTX

- NSTX plasmas operate significantly above no-wall limit
  - RWM/rotation damping physics important in this regime

Passive stabilization may lose effectiveness at high β_n

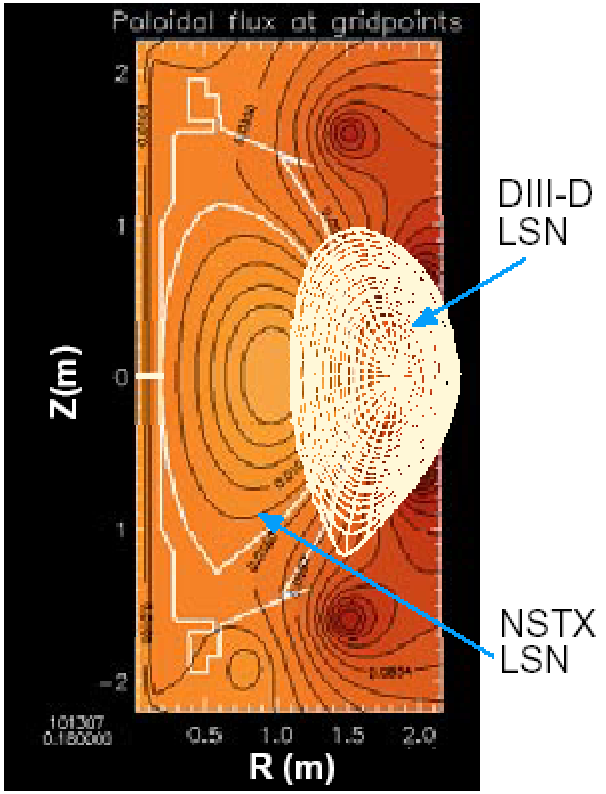
- Maintain RWM-stabilized discharges for longer durations
  - Effectiveness of passive stabilization at high β_n
  - Real-time β-feedback
- Critical rotation frequency, dependence of v_ϕ on q_{min}



[Sabbagh]

RWM Physics (cont'd)

- Determine R/a effects on RWM
  - NSTX/MAST, NSTX/DIII-D similarity experiments
- Rotation damping physics of RWM (Zhao, proposed PhD dissertation topic)
  - Conduct experiments to vary key physics parameters in RWM rotation damping theories

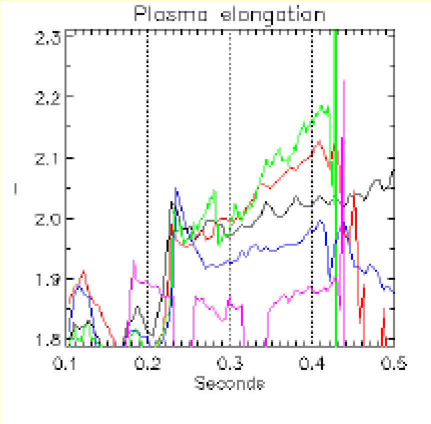


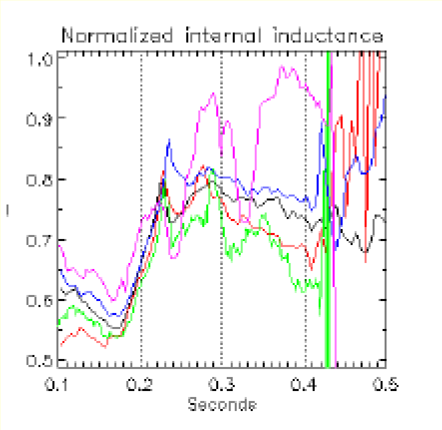
Paoletti, Sabbagh (Columbia)

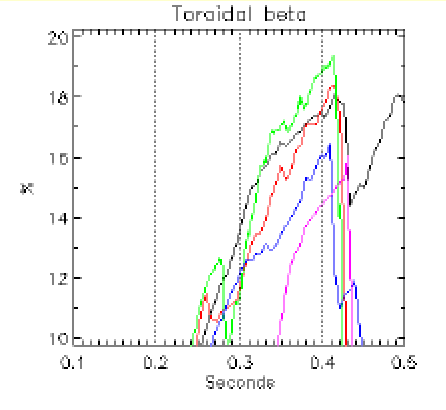
[Sabbagh, Synakowski]

Enhanced Shaping Offers Possibility to Further Increase β_T

- High-β_T ($\leq$ 34%) obtained in high-δ discharges
- Strong shaping generally leads to lower l_i, higher q_{min}







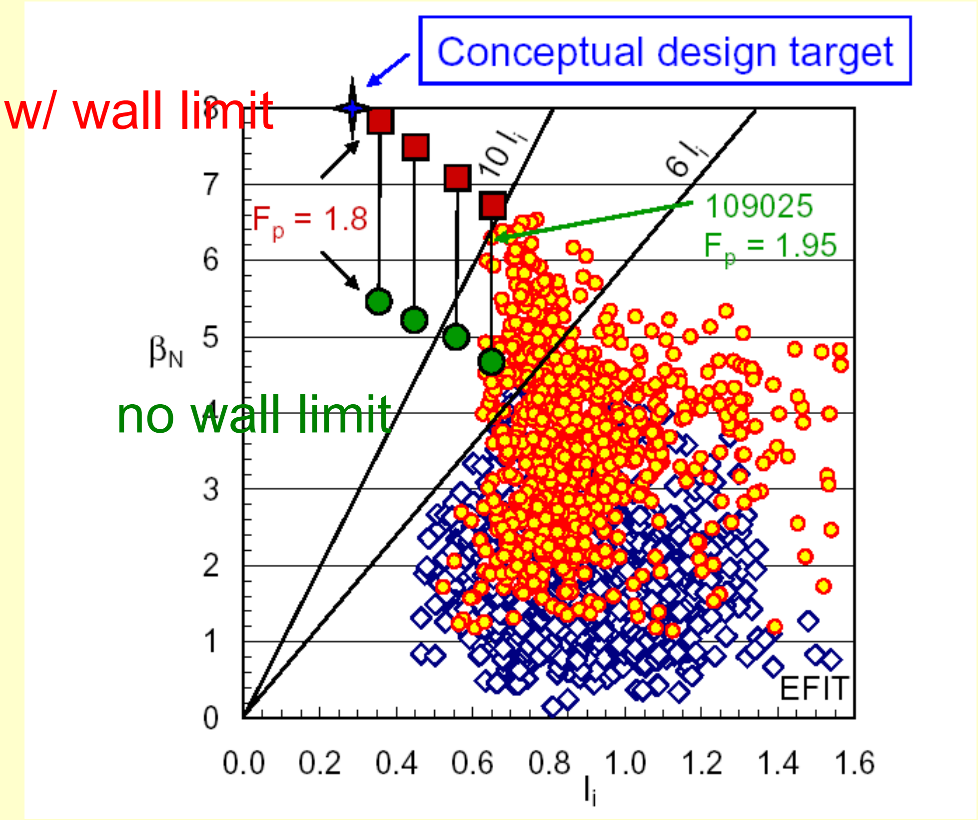
[Menard]

- Increase κ to 2.2-2.3 in 800 kA LSN
  - Probe stability limits wrt no-wall and wall limits
- Scan δ at high κ in DND and LSN
  - Look also for ELM trigger physics

A Stable Path to the Research Goal of β_T=40% Exists

- Strong shaping to lower l_i and raise q_{min}, as well as maintaining broad pressure profiles, are key to attaining target

- Maintain/lower F_p to demonstrate trend towards optimized target
  - H-modes
  - Fueling
  - HHFW



[Paoletti]

MHD Research Addresses Project Milestones

Error field resonance, control Effect of rotation RWM studies Strong shaping Fast ion driven instabilities ELM physics	→	High β_T, τ_E for long duration
Real-time β-feedback (cross-cutting w/ ISD) Strong shaping ELM physics	→	Quasi-steady 1 sec discharges using NICD
Locked mode/RWM studies	→	REF Response, Correction Fields and Rotation

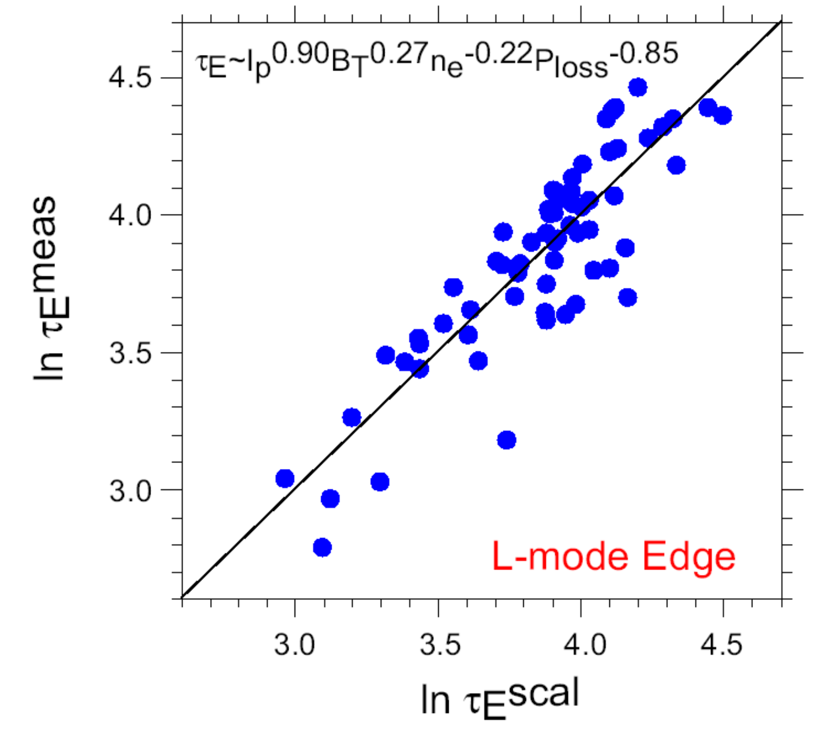
NSTX Offers the Potential for Uncovering New Transport Physics

- Research Topics
  - Parametric dependence of confinement
    - Role of aspect ratio
  - ***Dependence of τ_E on β***
    - Electromagnetic effects, e^- physics as β_T approaches unity
  - Local transport properties
    - Role of electron vs ion confinement
    - Role of rotation and rotational shear
  - Characterize fluctuations
  - Fast ion heating and confinement

- New capabilities
  - 51 point toroidal CHERS
  - Correlation reflectometry
  - MSE
  - 4 channel FIRETIP
  - sFLIP

Determine Parametric Dependences of τ_E

Differences between results from single parameter scans (Stutman) and statistical analysis exist

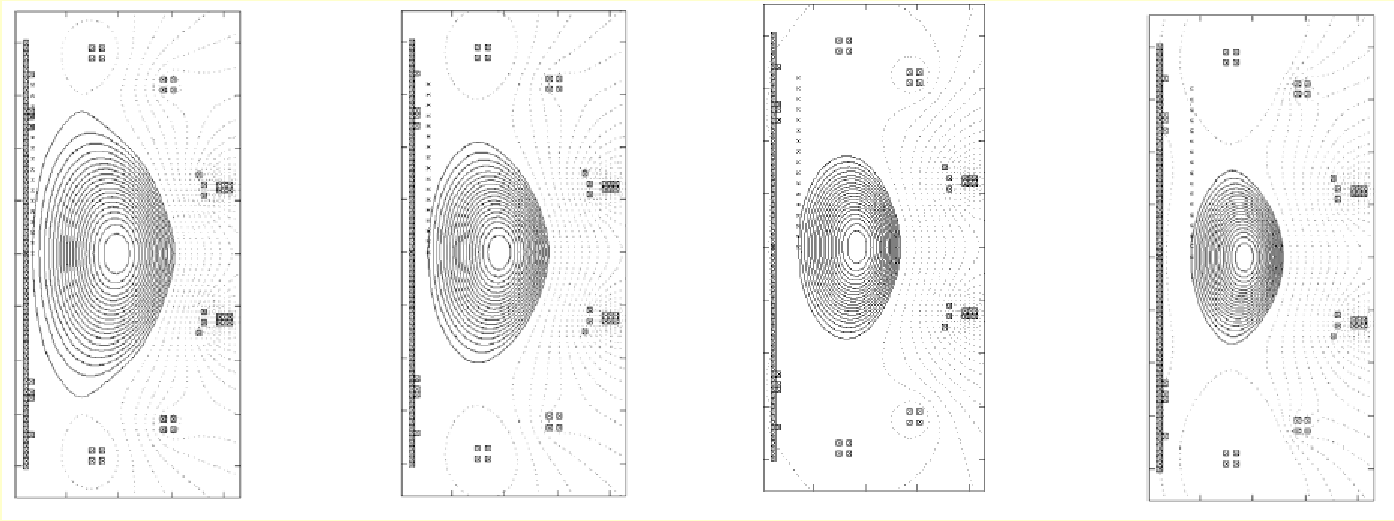


- Extend scaling studies
  - Resolve parametric dependences
  - Dynamic vs steady-state behavior
  - Configuration and shape, H(s-s) vs non-H
  - Dimensionless scalings in β, ρ^*
  - P_{thresh} scalings, H-mode fueling

[Kaye]

Effect of Aspect Ratio Can Be Determined From Intra- or Inter-Machine Experiments

- Within NSTX, A=1.25-2 (at fixed q_{cyl})

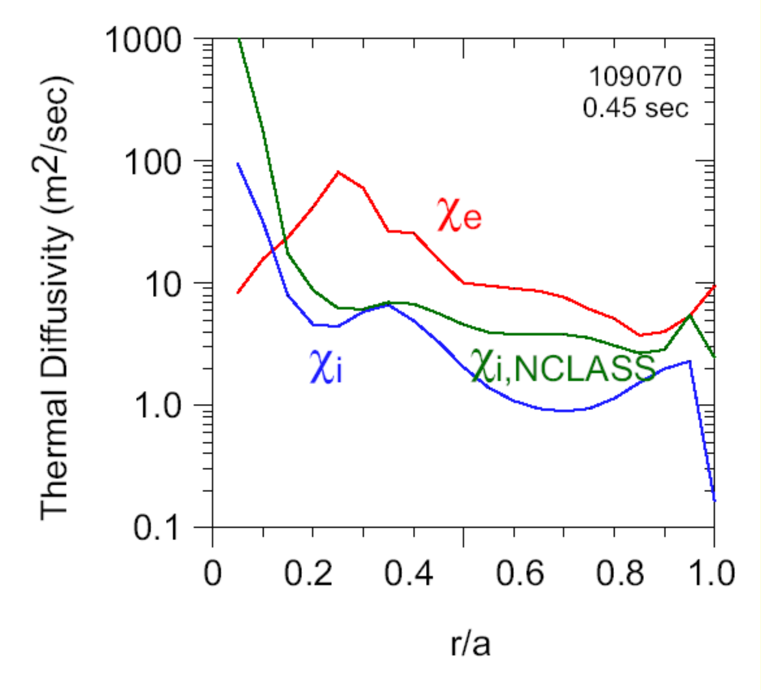


[Kaye, Paoletti]

- Connect to other ST (NSTX/MAST)
- NSTX/DIII-D similarity experiment
- Similarity experiments cross-over research topics
  - T&T, RWM physics, TAE-mode physics, edge transport

Assessment of Local Transport Properties are Crucial Part of All Scaling Studies

- Recalibration of MPTS & CHERS (and new CHERS) allows for routine transport analysis of discharges
  - Local transport reanalysis just starting
  - Determine if T_i/T_e anomaly still exists

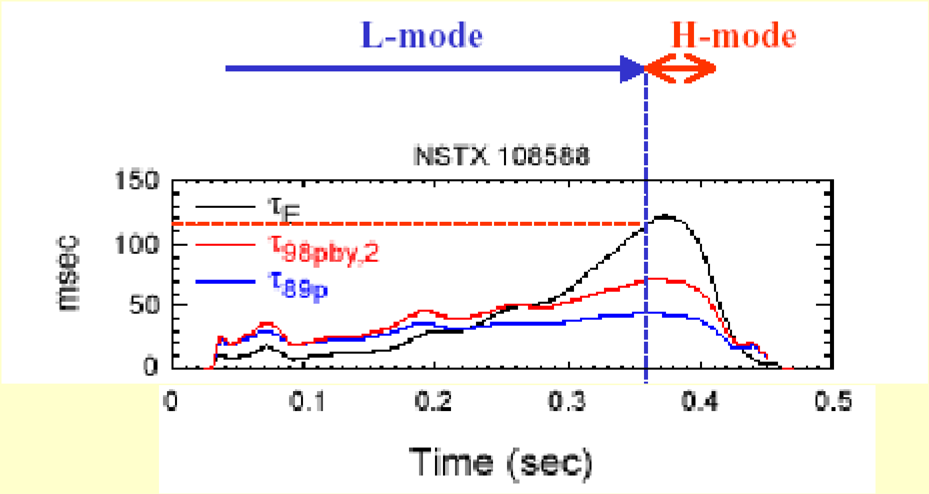


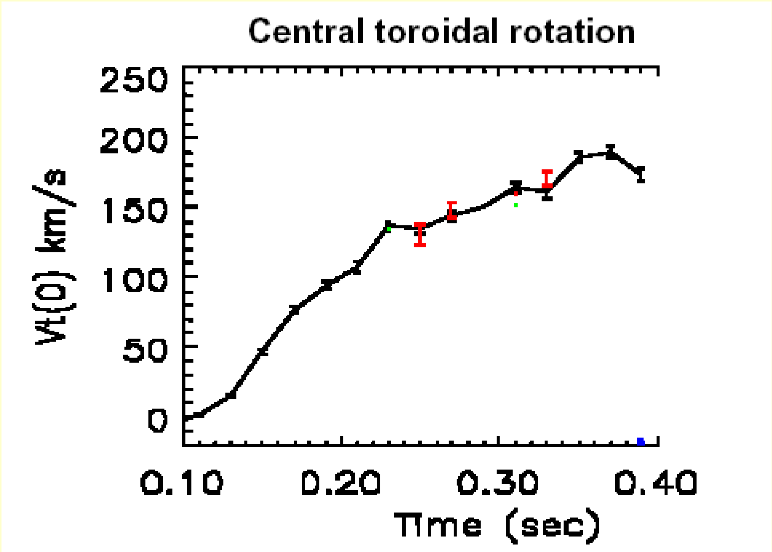
[Kaye, R. Bell, LeBlanc,..]

- Determine importance of electron vs ion loss channel
  - Impurity injection/pellets for “ion” transport
  - GS2, GYRO; linear and non-linear
- Global and local scaling results will form NSTX basis for ST confinement database (NSTX/MAST)
  - Plan to populate database this year

Determine the Relation Between Rotation and Confinement

- Monotonic increase of τ_E associated with monotonic increase in rotation – causality?





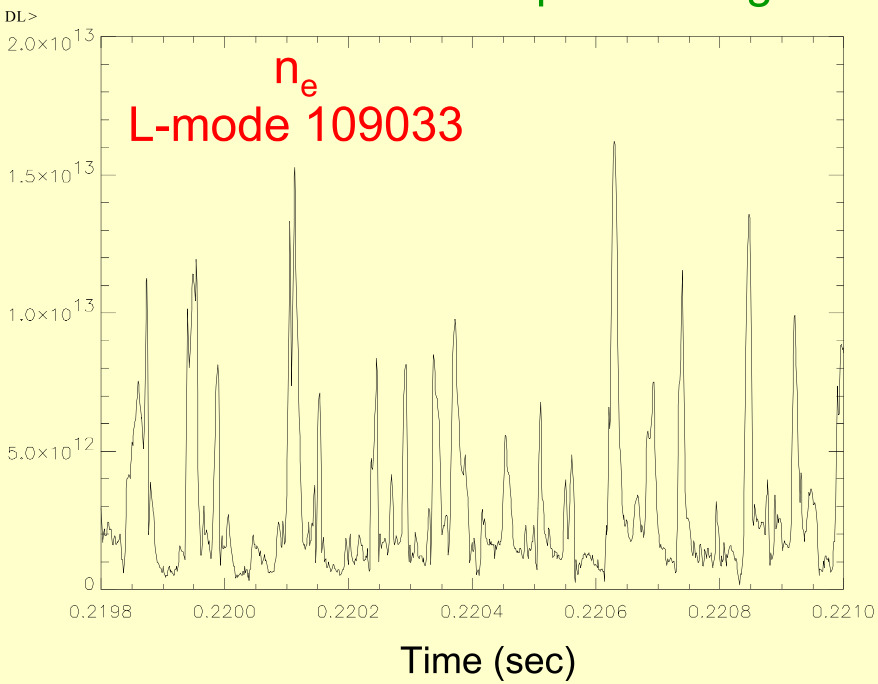
- HHFW vs NBI transport
  - Vary NBI source
- Momentum transport studies

[Stutman, R. Bell, Kaye]

Characterizing Fluctuations Will Help Identify Underlying Transport Physics

- Extend edge turbulence studies
  - Use full complement of diagnostics
  - L-H, ELMs, intermittent transport
- Begin to assess core turbulence
  - FIRETIP for ITGs in L-mode core
  - Prototype µwave scattering for ETGs
- Relate correlation reflectometry results to local transport properties

Intermittant Transport Strong



[Boedo]

Transport and Turbulence Research Addresses Project Milestones

NSTX

Confinement scaling
Effect of R/a, rotation → High β_T, τ_E for long duration
Fast ion confinement
H-mode studies

P_{thresh} → Quasi-steady 1 sec discharges using NICD
Steady-state H-mode studies
ELM Physics

Effect of rotation → REF Response, Correction Fields and Rotation
- HHFW/NBI comparison
- Momentum transport
- Vary NBI sources

Boundary Physics

- Research Topics
  - Edge heat flux dispersion
  - Understand ST edge
  - Density control

- New capabilities
  - Li/B pellet injector
  - Hot surface boronization
  - Fast reciprocating probe
  - Divertor bolometer, fast divertor camera, fast divertor IR camera

Heat Flux Scaling Addresses NSTX Milestone Directly

- High heat loads expected and measured
  - Potentially limiting for multi-sec pulse length
  - Big issue for next step ST
- Understand heat flux scaling and power accountability
  - Quasi-steady heat flux vs I_p, n_e, P_{heat}
  - Compare H- and non-H-modes
  - Measure in/out ratios in SN and DN configurations
  - Detailed characterization of edge for SOL transport studies
  - NSTX/MAST ST comparative study
  - Measurements will be compared with UEDGE calculations
- Test methods for reducing heat flux
  - X-point sweeping
  - Divertor detachment using D_2 puff

Density Control A Key Issue For Long Pulse Discharges

- Density typically continued to rise throughout high confinement/performance discharges
  - Is this a fueling or a transport issue?

- Wall conditioning techniques for controlling density
  - Helium discharge conditioning
  - Boron and Lithium pellet injection
  - Improved boronization/TMB fueling

- Other techniques
  - HFS gas fueling improvements
  - ELMs
  - Central electron heating

Boundary Research Addresses Project Milestones

Heat flux scaling
Edge characterization
Heat flux reduction

→ Edge heat flux dispersion and effect on PFC at high power

Wall conditioning

Density control
Heat flux reduction

→ Quasi-steady 1 sec discharges using NICD

→ High β_T, τ_E for long duration

ISD Research Will Focus on Producing High Performance Plasmas Using Various Control Techniques

- Research Topics
  - Simultaneous high-β_T and high τ_E for long duration
  - Produce quasi-steady 1 sec pulses using non-ind. CD
  - NBI/HHFW compatibility

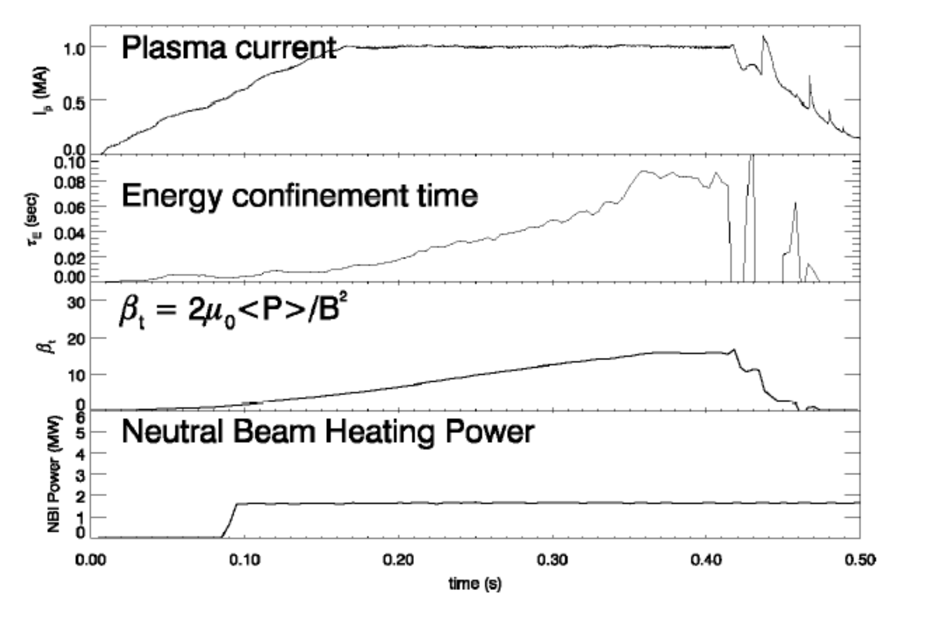
- New capabilities
  - rtEFIT shape control: dedicated time for algorithm development
  - MIMO validation (GA): FY04+ implementation
  - Density feedback
  - Wall conditioning
  - Impurity fueling control
  - NBI control for β-feedback

High-$\beta_T\tau_E$ Discharges Produced in High-δ DND H-mode Discharges

High-δ DND

1 MA, β_T=17%, τ_E=80 msec

- MHD limits confinement



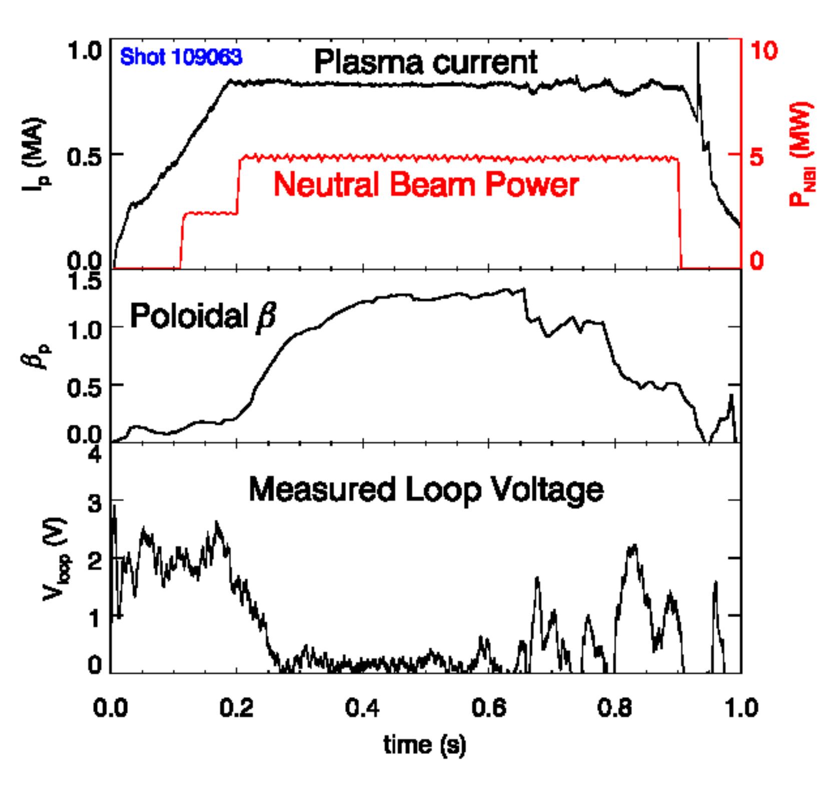
[Gates, Maingi]

- Will attempt improved ramp-up to delay MHD
  - Higher q_{min}
- Attempt to combine ITB with H-mode
  - Improve τ_E through Li pellet injection
  - Plug electron loss channel

Current Profile Control is Key to Developing Long-Pulse Discharges

- H_{97L}>2, >50% non-ind. CD
- Core disruptions as p-profile evolves and q_{min} drops
- Attempt to raise q_{min}, lower flux consumption
  - Raise κ in LSN (increase q, f_{BS})
  - Faster I_p ramp in high-δ DND
  - Early HHFW heating to raise T_e
  - PF only startup
- Long-pulse issues
  - Density control (improved HFS gas feed, wall conditioning)
  - Divertor heat flux (potential)

1-Sec Discharge



[Menard]

ISD Research Addresses Project Milestones

Plasma control system development → Couple CHI to other CD schemes

Optimize/maintain j(r), p(r)
- f_{bs}, q_{min}

HHFW/NBI compatibility
Plasma control system development

→ Quasi-steady 1 sec discharges using NICD

→ High β_T, τ_E for long duration

Draft run time allocations for FY '03

	FY 2002(actual)		FY 2003 (draft)	
HHFW heating & CD	12 days	(19%)	15 days	(14%)
CHI	3 days	(5%)	15 days	(14%)
Transport	13 days	(21%)	13 days	(12%)
MHD	12 days	(19%)	13 days	(12%)
ISD	10 days	(16%)	13 days	(12%)
Boundary (heat flux)	5 days	(8%)	8 days	(8%)
Enabling/cross-cutting	7 days	(11%)	10 days	(10%)
Scientific Contingency	{13 days	(20%)}	18 days	(17%)

Research Plan Logic – Temporal Progression of Research Activities

NSTX

	Early Run	Mid-Run	Late Run
H&CD	HHFW system shakedown Electron heating HHFW/fast ion interaction EBW mode conversion	HHFWCD HHFW/NBI comparisons (rotation) HHFW H-modes	HHFWCD w/j(r) measurements
CHI	CHI transient startup	High CHI currents CHI plasma control development	Demonstrate flux closure CHI edge CD CHI->non-ind. CD
MHD	EF/RWM sensor calibration Locked mode studies Fast ion and CAE studies	RWM rotation effects, passive stab. ELM physics Similarity experiments High-β_T	Possible active REF/RWM ctl. Stability studies with j(r) meas.
T&T	Global conf. dependences & local transport studies Fast ion htg. & confinement	P_{thresh} scaling Similarity experiments	Dimensionless scalings Characterize fluctuations
Bdy	He conditioning Density control	Li/B pellets Improved boronization/TMB fueling Heat flux scaling and edge char.	Fast edge transport Detached divertor
ISD	rtEFIT development	HHFW/NBI compatibility Long-pulse H-modes	High-$\beta_T\tau_E$ Quasi-steady 1 sec discharges

Research elements scheduled according to start, not finish

Reduced Run Time Will Hamper Scientific and Technical Progress

- Retained milestones
  - High-β and τ_E for $\Delta t >> \tau_E$
  - Non-inductive current drive to assist in startup and sustainment of $\geq$ 1 sec pulses
  - Edge heat flux dispersion and effect of PFC at high power
- Reduced scope milestones
  - Persistent CHI produced currents and coupling to other CD techniques
- Delayed milestones (by one year)
  - Interactions among resonant error field response, correction fields and rotation
  - Requirements for EBW heating and current drive

NSTX Is Developing a Comprehensive Run Plan to Address a Broad Spectrum of Scientific Issues

- Addressing these critical elements will allow us to achieve our Research Milestones
- Most experimental proposals will take advantage of significant new facility and diagnostic capability to dig deeper into underlying physics
- 21 run weeks is critical to achieving all our goals