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Experiments on the National Spherical Torus Experiment - Latest Results

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Experiments on the National Spherical Torus Experiment – Latest Results

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and
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PPPL
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NSTX research is uncovering high beta, low aspect ratio physics central to the ST mission

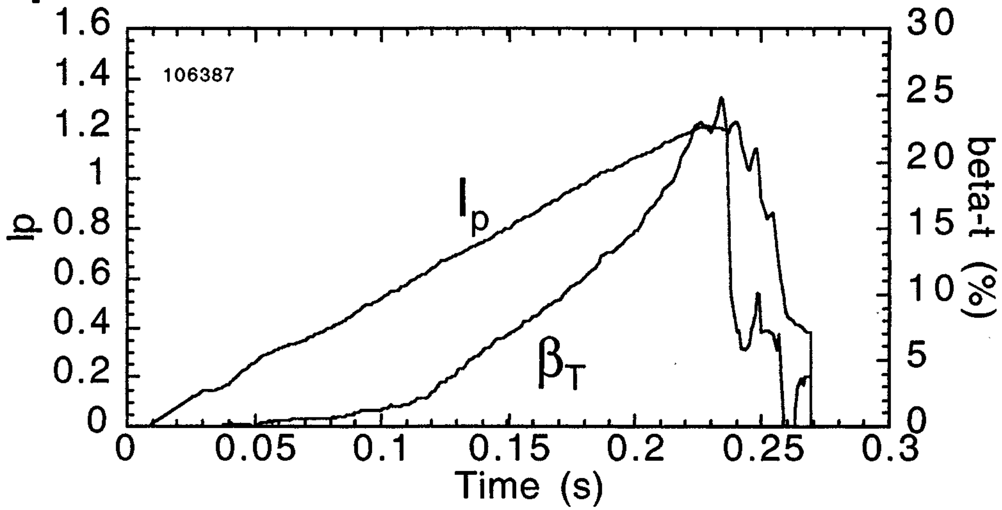
- In this talk: discussion of run plan, execution, and topical science, framed by the milestones we are pursuing

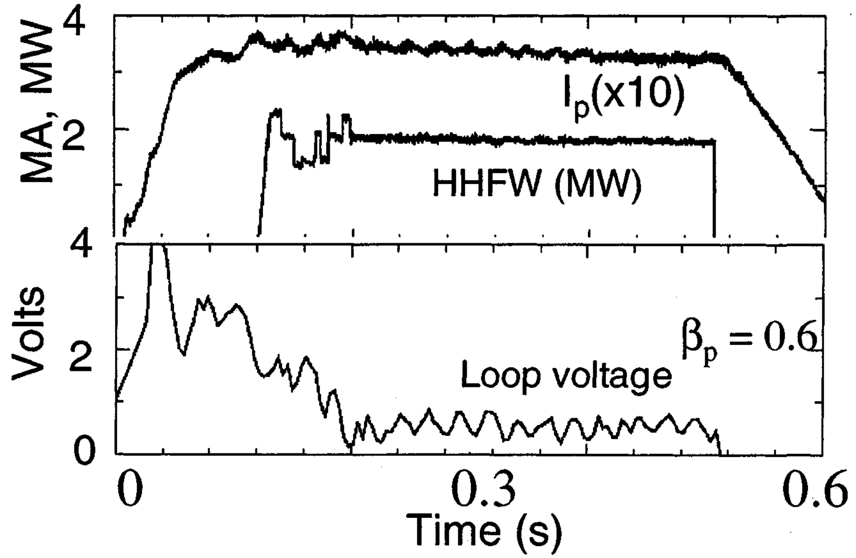
Outline

- Overview of goals, plan, and usage
- Core transport
- HHFW
- MHD
- Boundary physics
- Non-inductive startup
- Summary

Increase in range of operating scenarios enabled topical research

- Reproducible operating scenarios underly all of the research
  - 25% β_T achieved
  - Routine and effective HHFW heating
- Topical studies
  - **MHD**: characterizing β-limiting and pulse-length-limiting modes
  - **Transport** with NBI and HHFW, core and edge
  - **HHFW**: heating, wave-particle and initial CD studies
  - **CHI**: MHD activity generated that is needed for flux closure
  - **Boundary**: Heat fluxes. Wall prep tools
- Cross-discipline studies
  - Beam-induced MHD and heating
  - H mode access requirements, expanded operating space





NSTX milestones and decision points are derived from its proof-of-principle mission

Recall IPPA 2.1: Assess the attractiveness of the ST concept

Milestones are checkpoints towards this assessment

- FY '01 Milestones:
  - Measure confinement properties with auxiliary heating
  - Assess HHFW heating; achieve 6 MW
- Progress reports on FY '02 Milestones:
  - MHD: Global stability without external control
  - Transport: Role of high beta and flow shear on confinement
  - CHI, EBW: Innovative startup techniques
  - HHFW CD physics & effectiveness
- Upcoming decision points:
  - MHD
    - FY '02: Mode stabilization: scientific assessment
    - FY '03: Mode stabilization: technical assessment
  - Advanced particle pumping/fueling, FY '03

We planned an emphasis on topical research, with some time for enabling activity

Division of experimental time, FY '01.

ET Group, Leaders	Plan	Actual
– MHD (Sabbagh, Menard)	15%	21%
– Transport and Turbulence (Kaye, LeBlanc)	15%	17%
– HHFW (Wilson, Swain)	13%	24%
– CHI (Raman, Gates)	13%	8%
– Boundary Physics (Maingi, Skinner): heat flux	6%	2%
Program Enabling/cross-cutting		
– e.g. 1st NBI, control commissioning, boron, calibration	18%	28%
Scientific Contingency	20%	-----

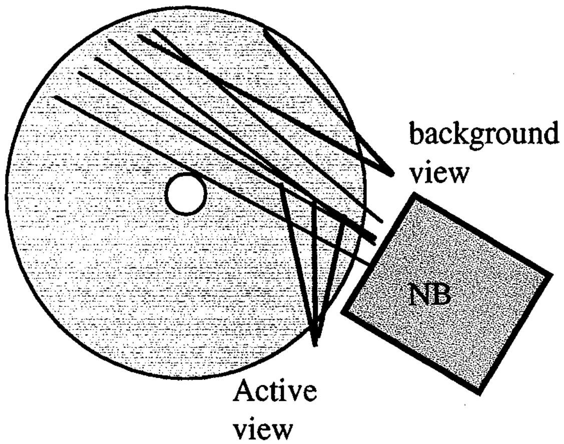
Highlights

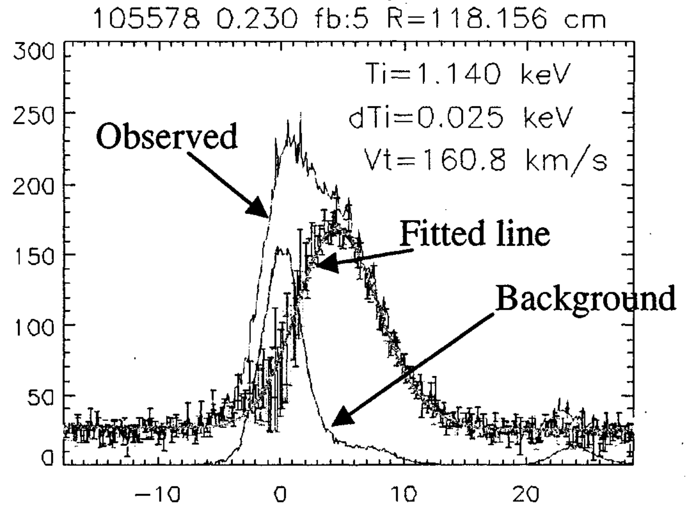
- HHFW: success and broad impact resulted in giving significant contingency time
- Program enabling/cross cutting work also received additional time
- CHI: ~ 2x more days attempted; system setbacks (TF water leak, gas programming)
- Boundary: IR camera repair delayed start

Activities supporting a broad portion of the program are high priority

- NBI long-pulse work
  - Startup optimization
- Diagnostic development & cross-checking
  - $T_i(R,t)$, $V_\phi(R,t)$: Background array installation and calibration for CHERS.
  - T_e from 3 different techniques
- H mode search: dedicated run days to explore operating space
- HHFW & early heating in the pulse
  - Modify the current profile; use as a control tool
- Boronization
  - TMB established; plasma boronization being developed

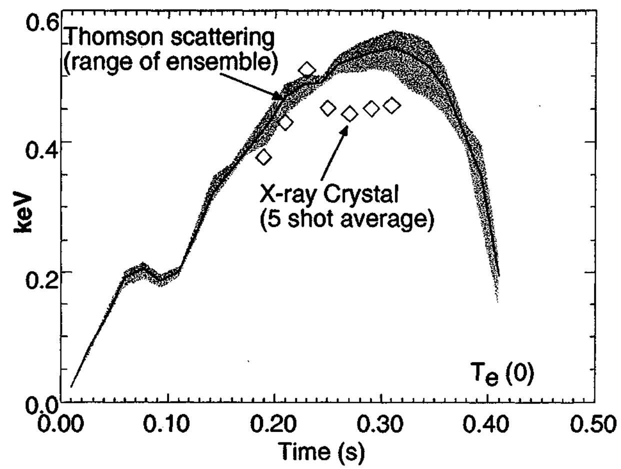
Diagnostics are maturing and being confirmed

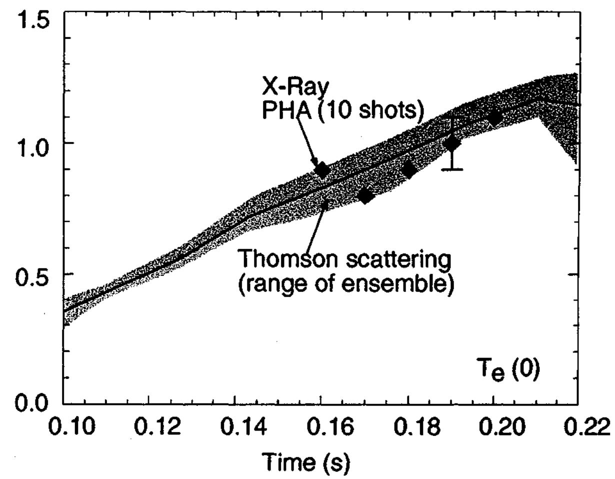




R. Bell

- T_i, V_ϕ: development of direct background measurement
  - Required for time-dependent measurements
  - Required cross-calibrations performed; analysis techniques being developed





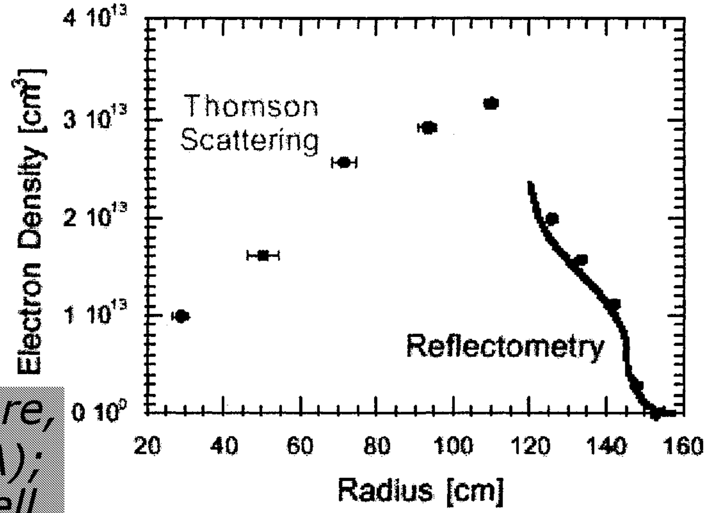
$T_e(0)$ confirmed by 3 independent measurements

LeBlanc,R. Bell; Bitter, Hill

Diagnostics are maturing and are being confirmed (2)

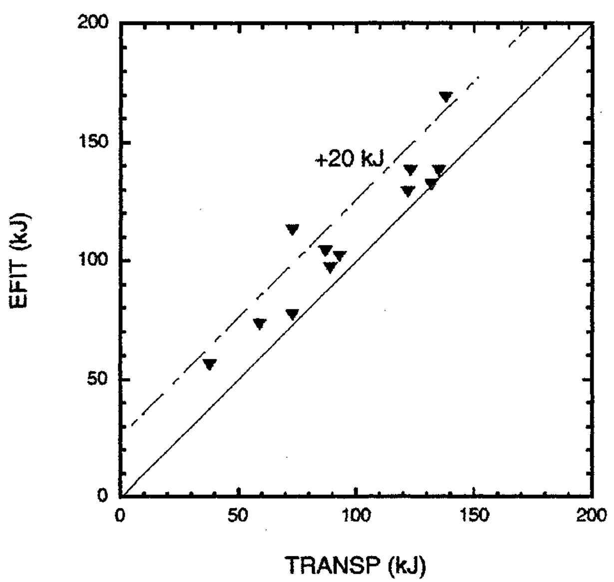
- TS high throughput, small error bars. n_e consistent with reflectometry

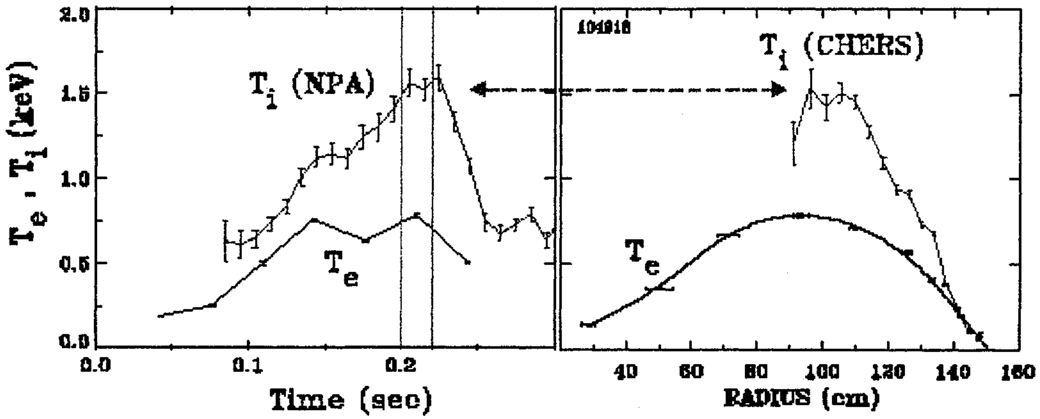
- T_i: CHERS, NPA consistent with each other



Kubota, Gilmore, Peebles (UCLA); LeBlanc, R. Bell

Total Stored Energy Comparison





S. Medley, R. Bell

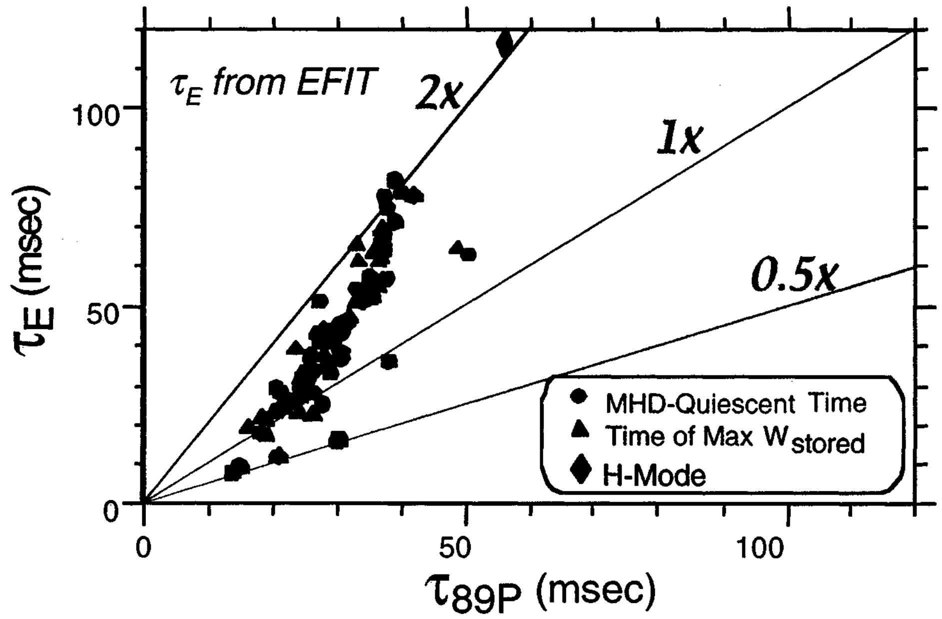
Outline

- Overview of plan, usage, and goals
- **Core transport**
  - NBI heating, τ_E scaling, and power balance; puzzles
  - Possible role of fast-ion MHD
  - Perturbative particle transport
  - Microstability analysis
- HHFW
- MHD
- Boundary physics
- Non-inductive startup
- Summary

FY '01 Milestone: Measure and analyze the confinement of auxiliary-heated NSTX plasmas

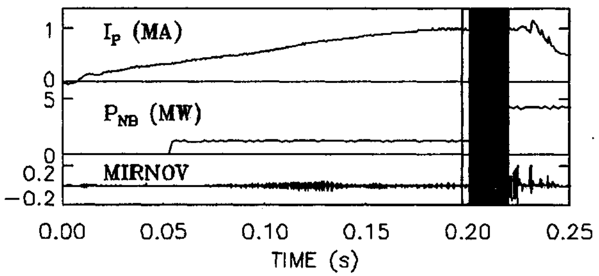
FY '02: Assess the effects of beta and sheared flow on plasma heat loss

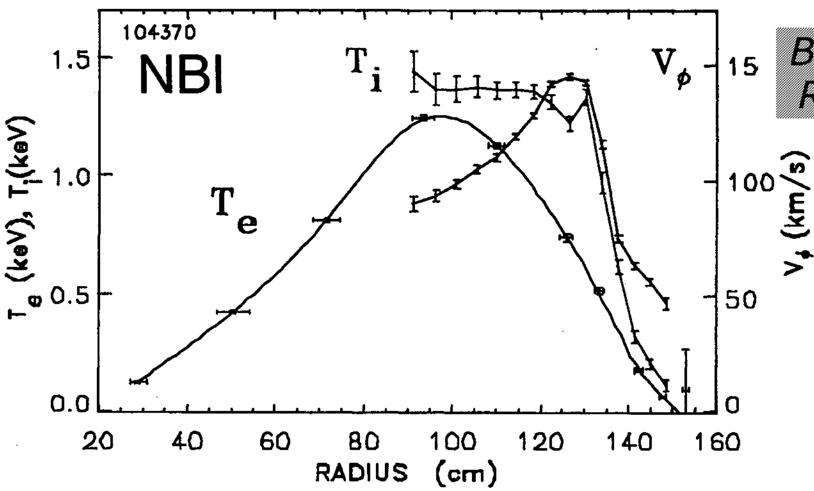
Profile measurements give first indication that favorable confinement with NBI may be due to ion channel



Kaye; Sabbagh (Columbia)

$\beta_{T(EFIT}$ ~ 20%

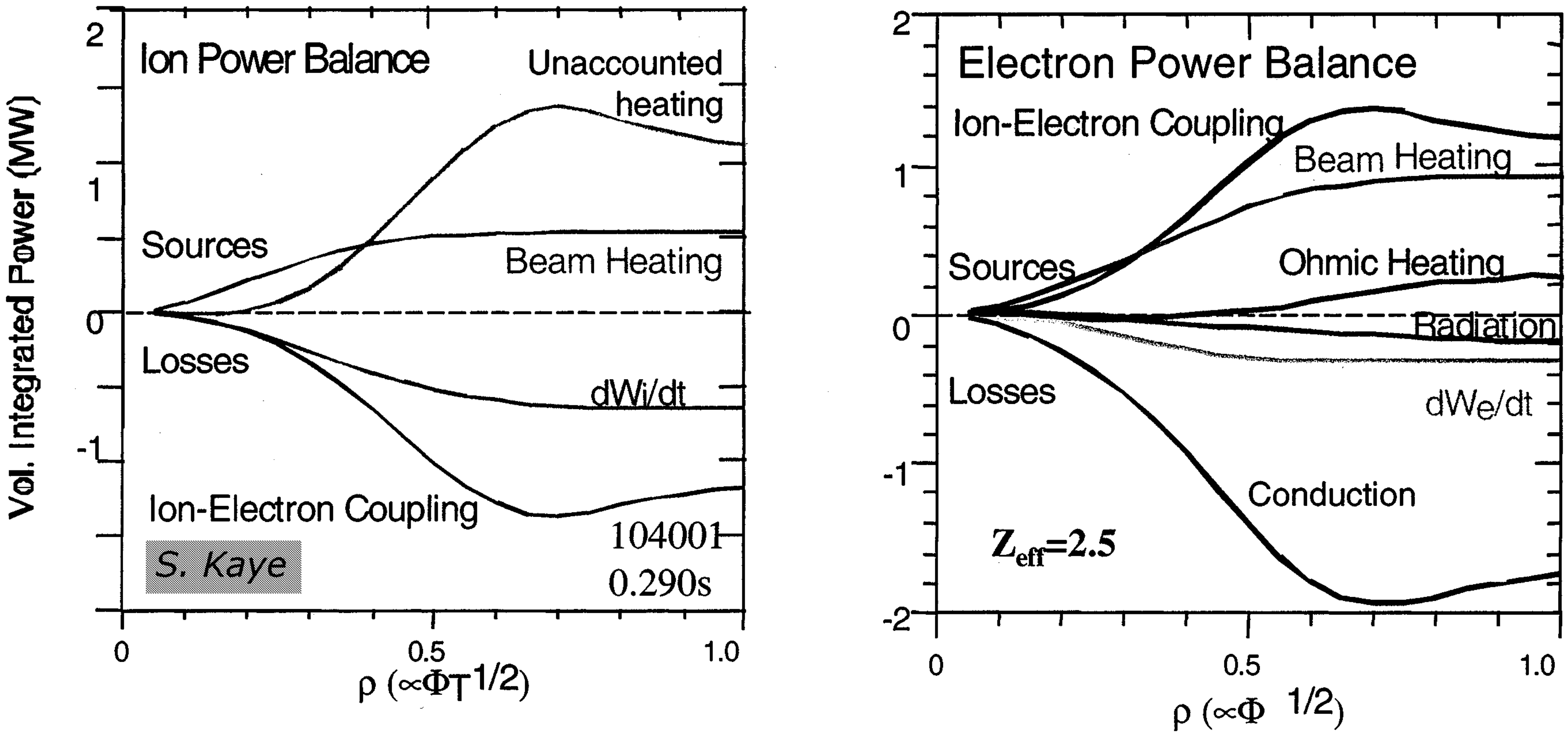




B. LeBlanc, R. Bell

- Broad T_i profile (compared to T_e), even though ~2/3 of beam energy expected to go to electrons
- Large T_i - T_e seen routinely
- High V_ϕ in core & edge

Power balance analysis reveals puzzles

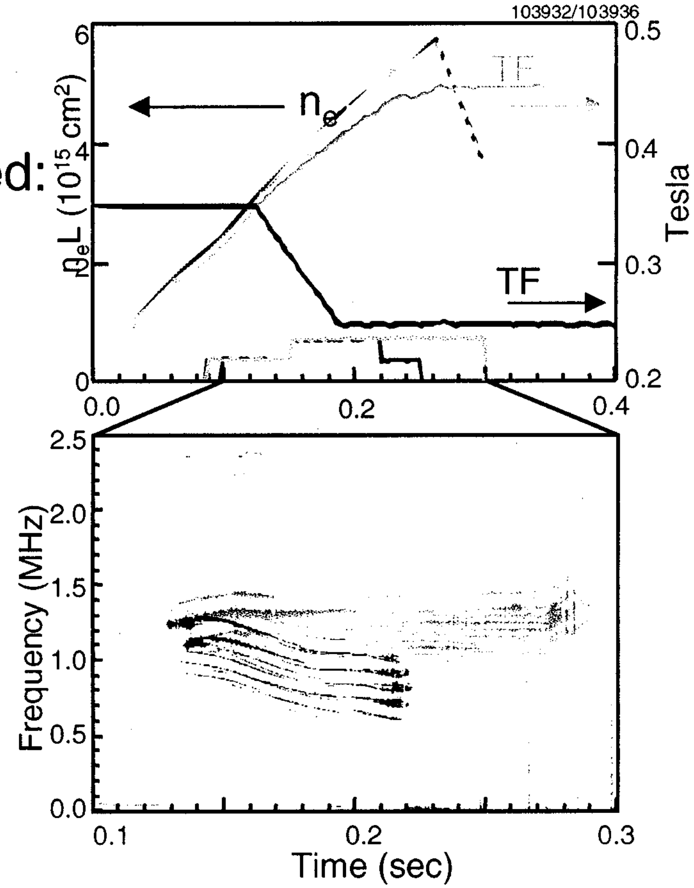


- With NBI: apparent anomalous source of heat to ions, or a heat pinch
  - New heating physics?
  - Small A changes in basics?
  - Requires vigilence in diagnostic calibration

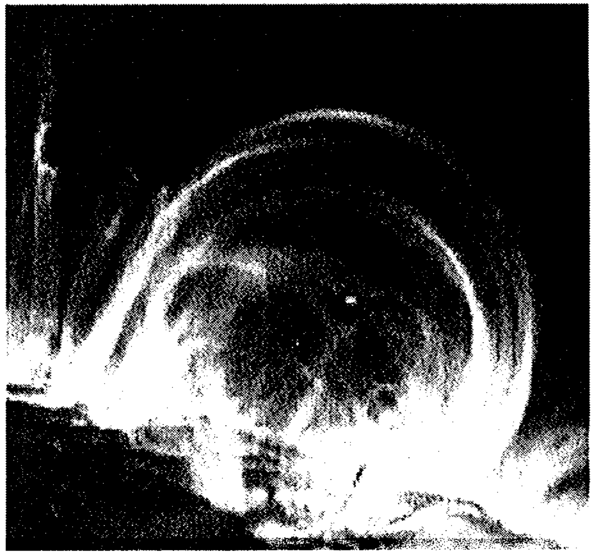
Astrophysics and observed MHD may hold one clue to the power balance puzzle

- Being investigated: Compressional Alfven Eigenmodes

- Modes excited by fast ions; waves transfer energy to thermal ions



Fredrickson (PRL 2001)



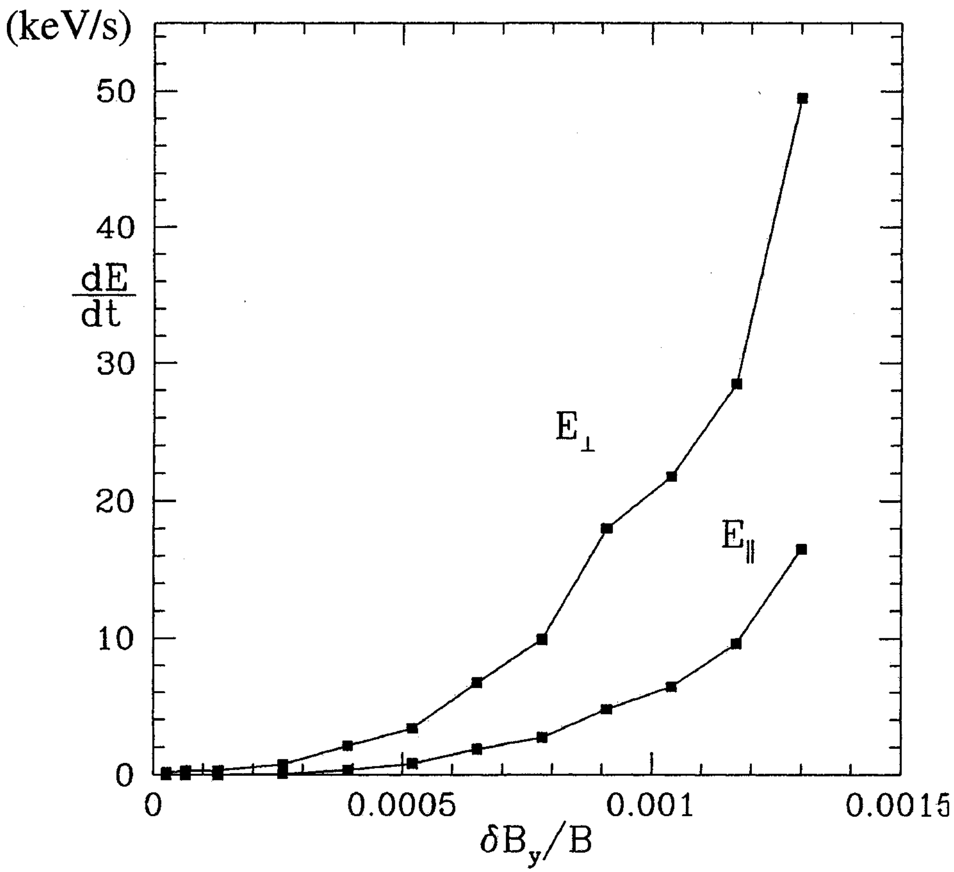
- Theory of stochastic wave heating of corona developed (White)

- Application of theory to ST has begun

- $V_{beam} >> V_{Alfven}$ key

Gates, Gorelenkov, White

Beam-driven Compressional Alfven Waves may heat ions on NSTX



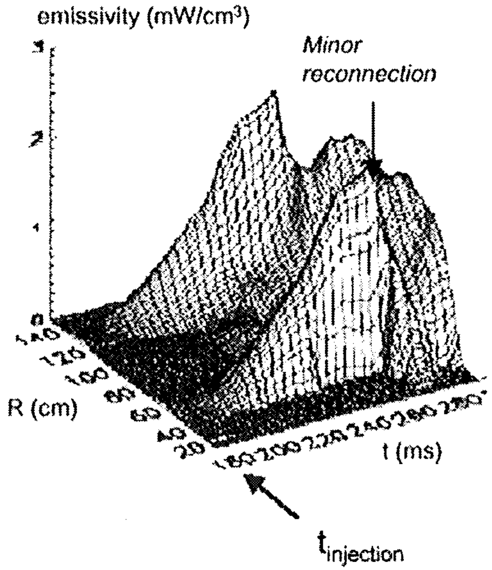
- Simulations of compressional Alfven modes give stochastic ion heating.
- e.g.-- $\delta B/B = 0.001$ with 20 modes centered at half Alfven frequency
- Possible relevance to interpretation of ion-heating on NSTX

D. Gates, N. Gorelenkov, R. White (PRL, 2001)

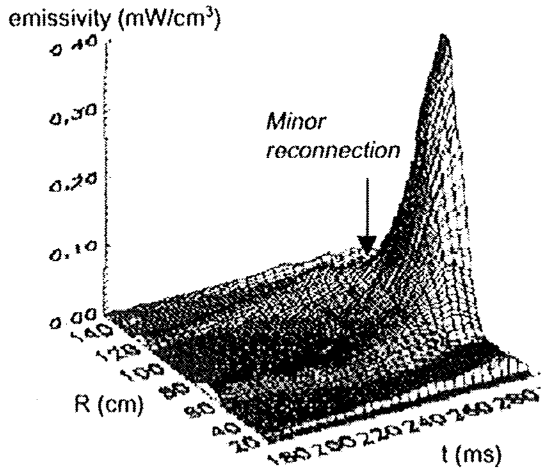
Impurity transport rates are small in the core

- After puff, almost no neon penetrates the core until MHD event near 260 ms
- Modelling suggests core diffusivity < 1 m^2/s, rivaling neoclassical theory
- Low ion particle transport consistent with low ion thermal transport

He-, H-like Ne lines (USXR)

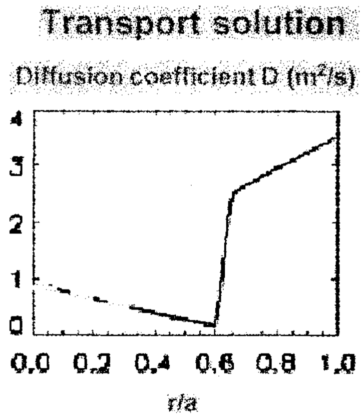


Fully ionized Ne (SXR)



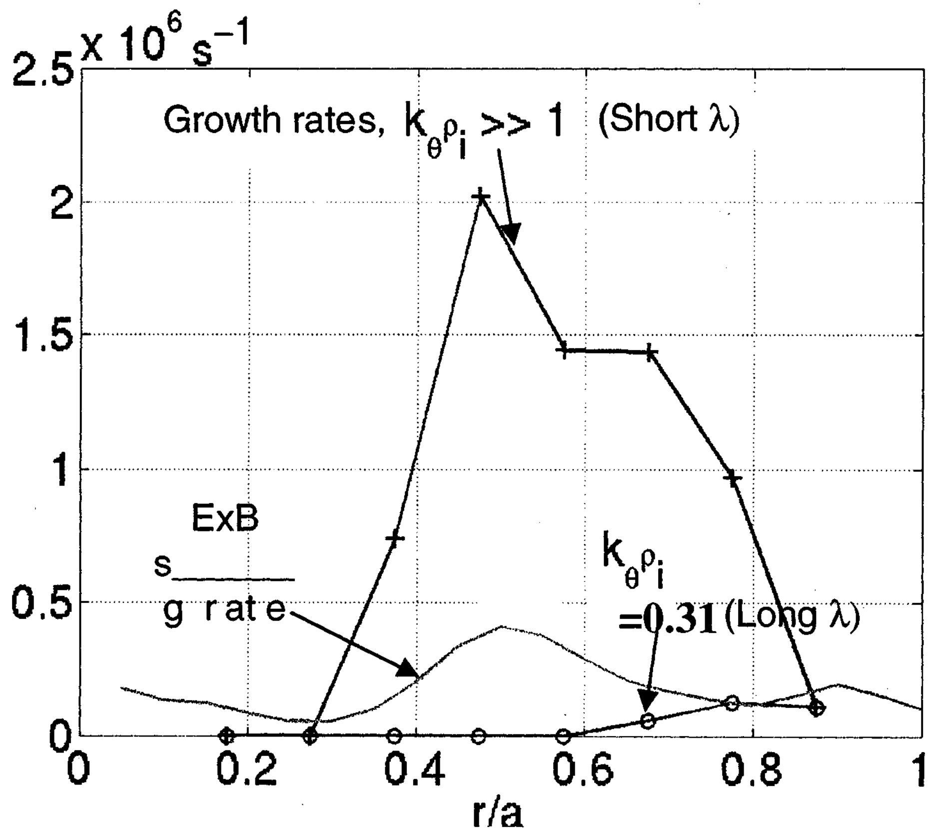
Signals from difference of similar plasmas w/ and w/o neon

Stutman, JHU



Theory: short wavelength modes may dominate transport; long wavelength modes may be suppressed

- Long wavelengths: growth rate lower than **ExB** shear rate
  - Large λ associated with ion thermal transport
- Short wavelengths: growth rates large
  - Responsible for electron thermal transport?
  - Non-linear simulations begun



C. Bourdelle (PPPL), W. Dorland (U. MD)

Outline

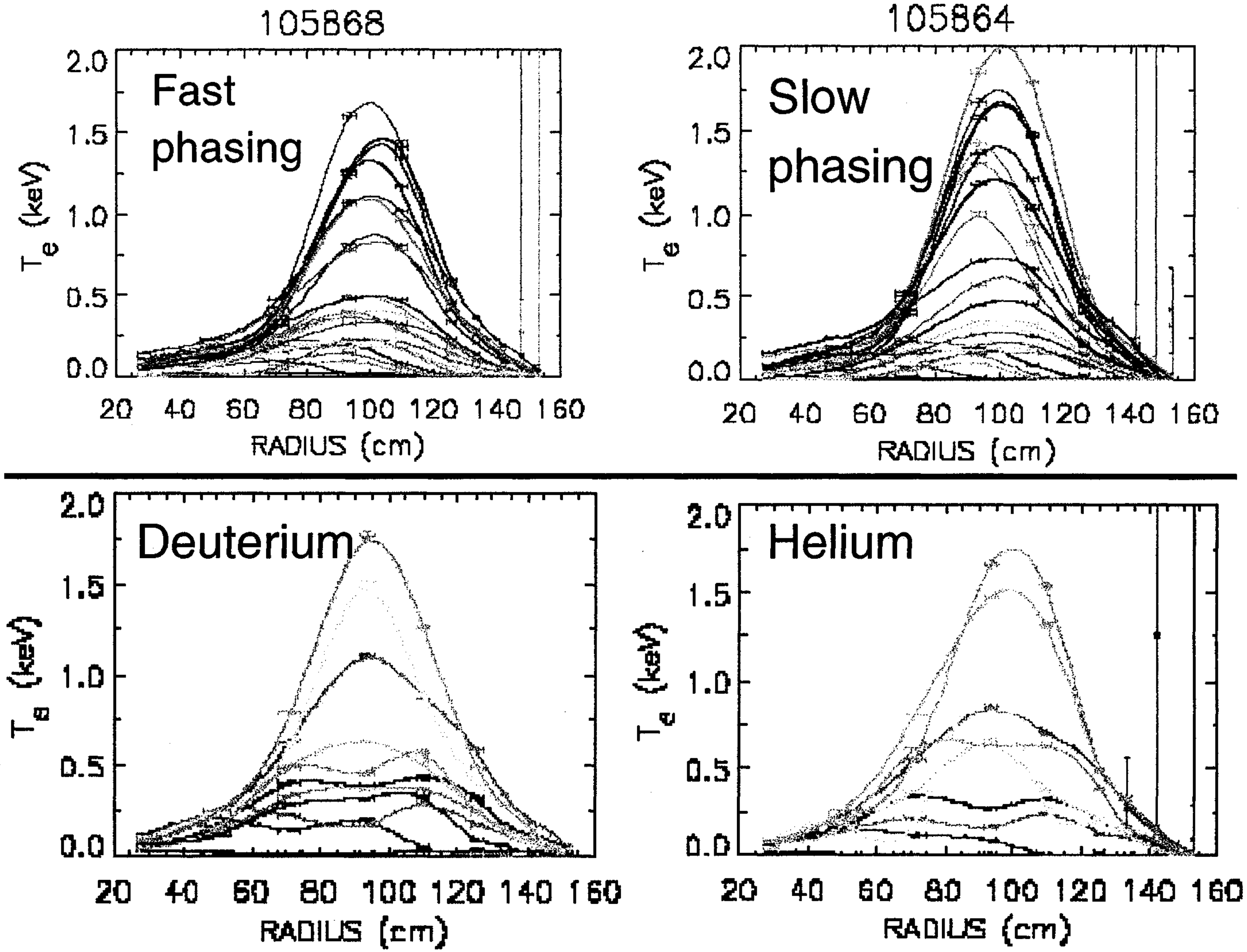
- Overview of plan, usage, and goals
- Transport
- HHFW
  - Heating results
  - Source calculations & electron thermal transport
  - Fast ion interactions and early current drive studies
- MHD
- Boundary physics
- Non-inductive startup
- Summary

FY '01 Milestone: Measure and analyze how HHFW with slow propagation velocity (14 m^{-1})interacts with and heats high-temperature ST plasmas

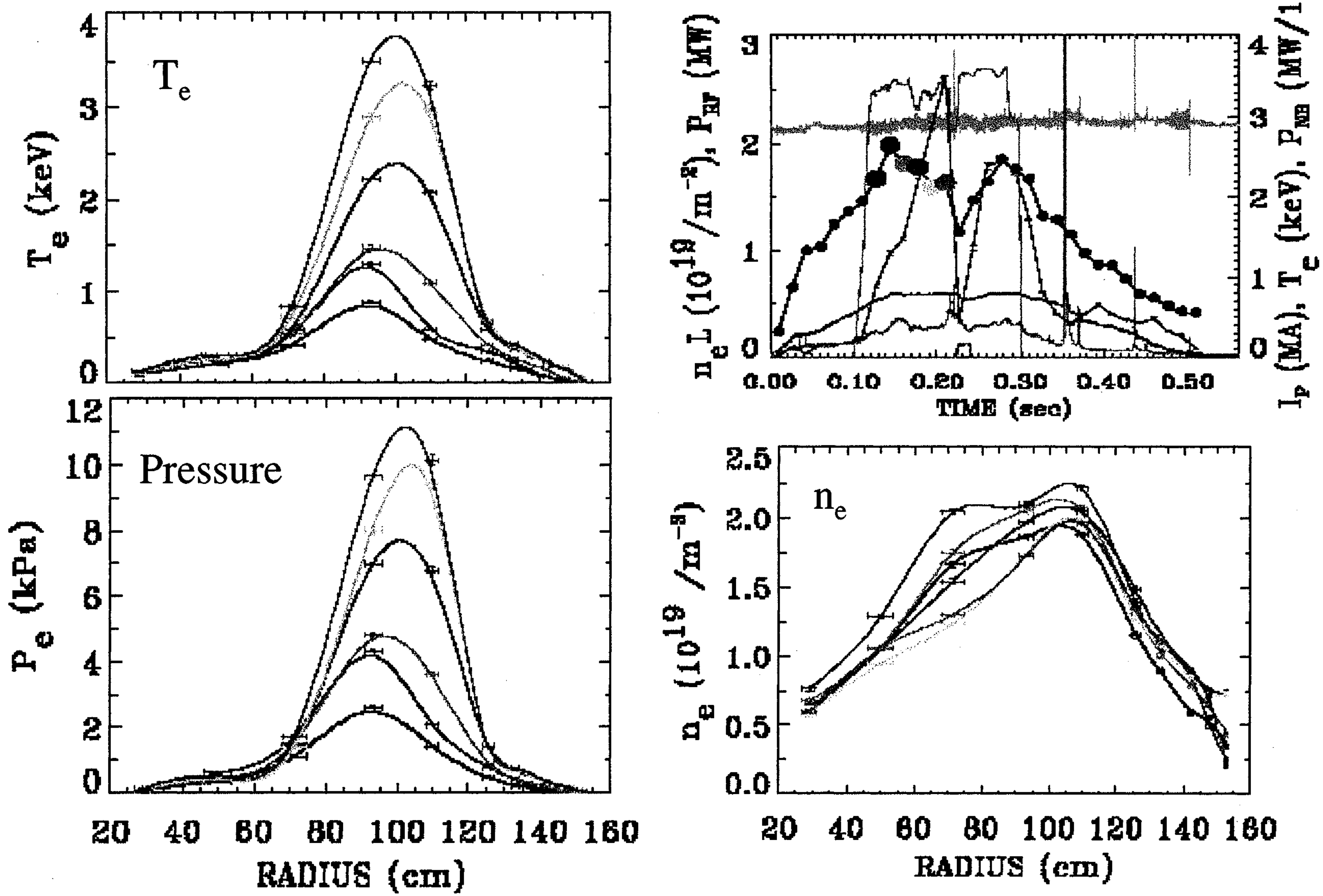
FY '02: Assess the efficiency of HHFW to drive current via direct interactions with the electrons and/or fast ions

HFFW heating observed in a wide variety of conditions

- Fast phasing nearly as good as slow
- Heating similar in D and He^4
  - Previous differences seem related to discharge, not species
- Modulated rf used to measure deposition profile
  - Complicated by electron energy transport physics

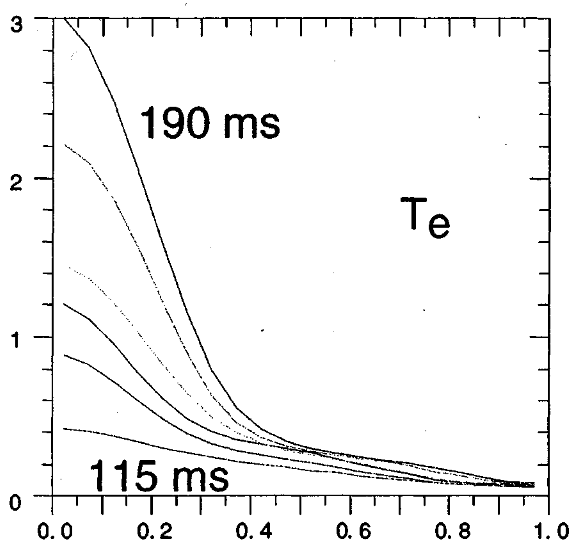


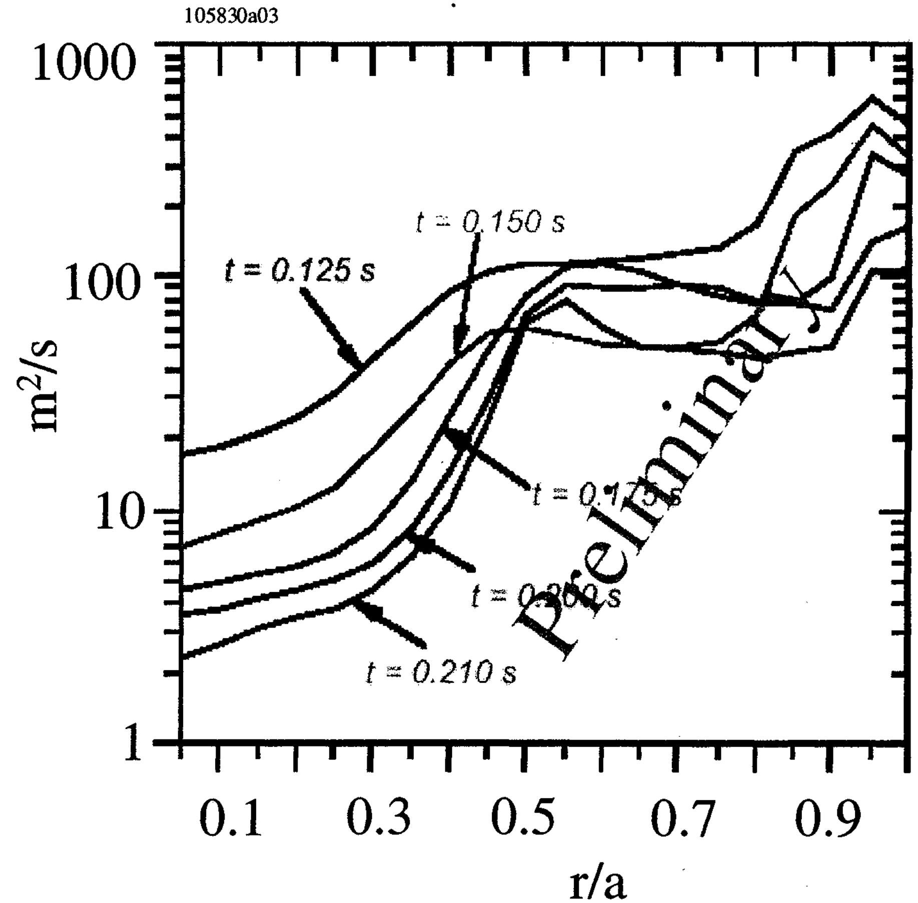
Strong central peaking of T_e observed in some cases



Power balance analysis reveals that reduced electron transport correlated with high ∇T_e

- Core χ_e drops as high T_e develops
  - Steep gradients due to transport changes, not source
  - Conductivity still very high!
- Heating source from HPRT ray tracing (Rosenberg)





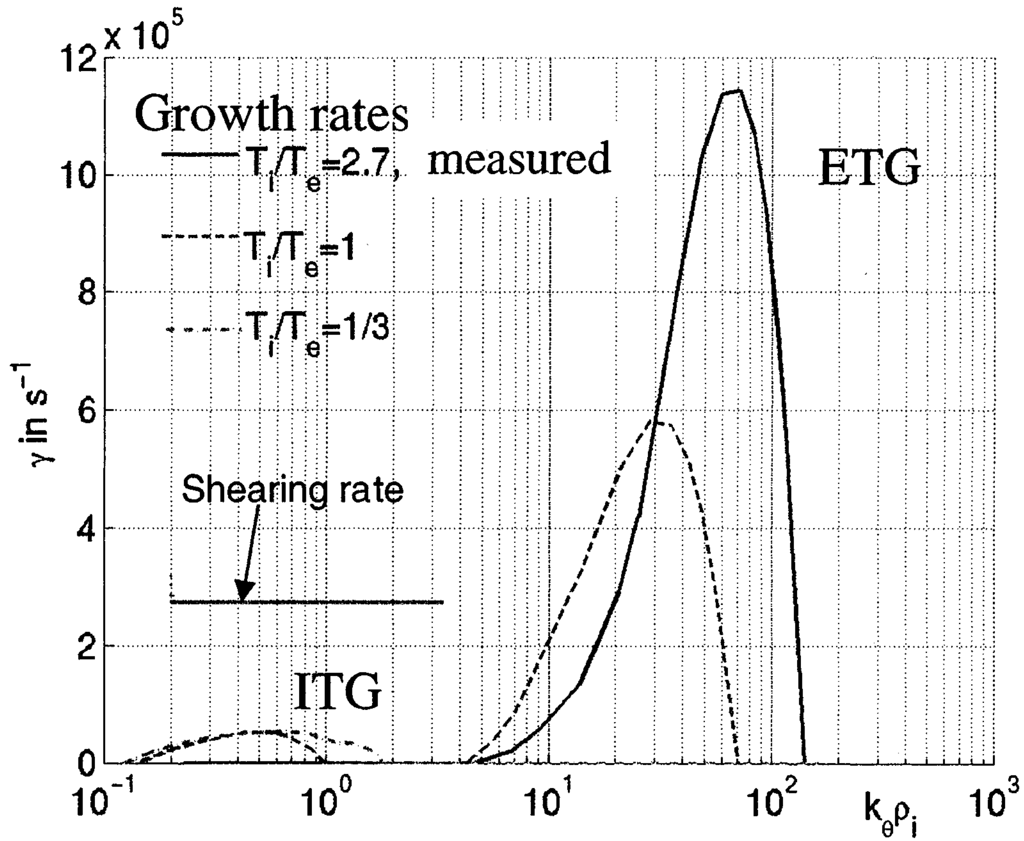
LeBlanc

Turbulence theory suggests testable trend for transport experiments

Conduct a theory experiment: vary T_i/T_e, keeping other profiles constant

- Theory indicates:
  - high T_i/T_e stabilizes ion modes
  - high T_e/T_i *stabilizes electron modes*

\- *Do we see signatures of this in measured confinement trends?*



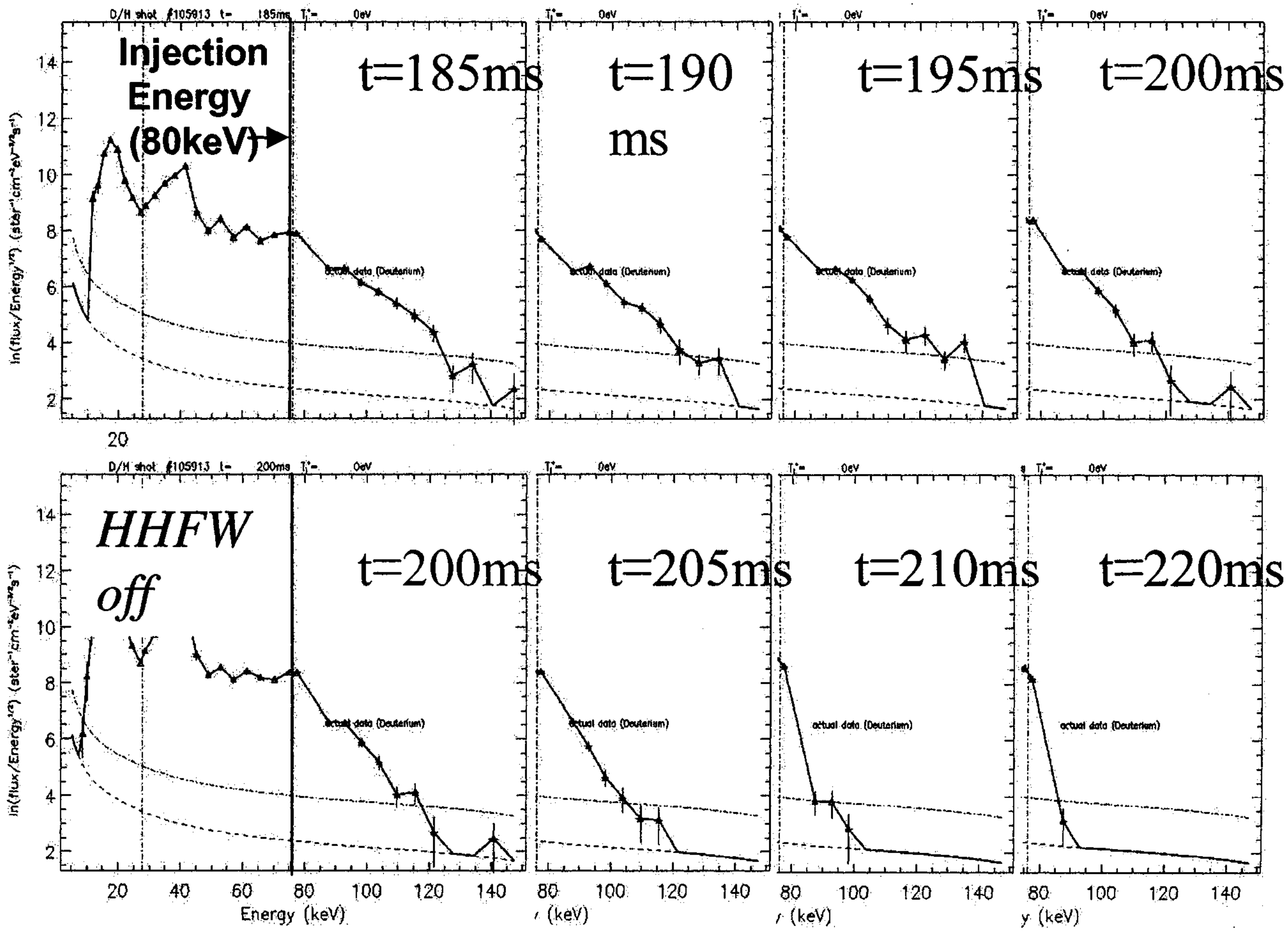
C. Bourdelle

Recent data is the foundation of important tests of wave-particle interactions theory

- ¥HHFW turns off at t=200ms
- ¥NBI Source A on throughout
- ¥D^+ tail extends to 140keV
- ¥Tail saturates in time during HHFW

HPRT code:
50% of rf power absorbed on beam ions

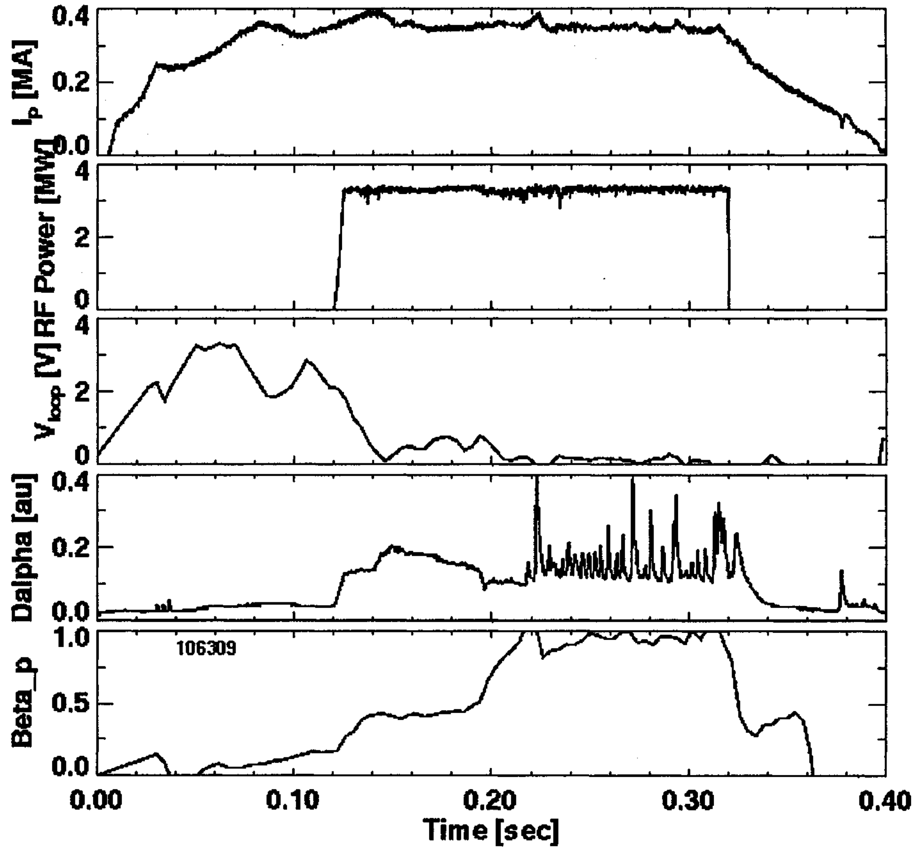
May explain reduction in effective electron heating when NBI is combined with early HHFW



Rosenberg, Medley, Menard

HHFW-driven H modes found

- LSN
- Lower current (350 - 500 kA)
- He and D
- ELMy, ELM-free
- β_p = 1 observed
  - Large bootstrap?
  - Large dip in surface voltage



Starting scenario for future CD work?

High power phasing tests for current drive begun

- Co, counter, balanced fast phasing investigated (7 m^{-1})
- Similar heating, reproducible matching for all phasings
- Not obvious differences in loop voltage evolution
  - Difficult to obtain a long steady shot: H mode target a possibility
  - Need MSE
- Closed loop phase feedback from antenna started
  - Two transmitters in vacuum
- Fast particle interactions studies key part of CD assessment

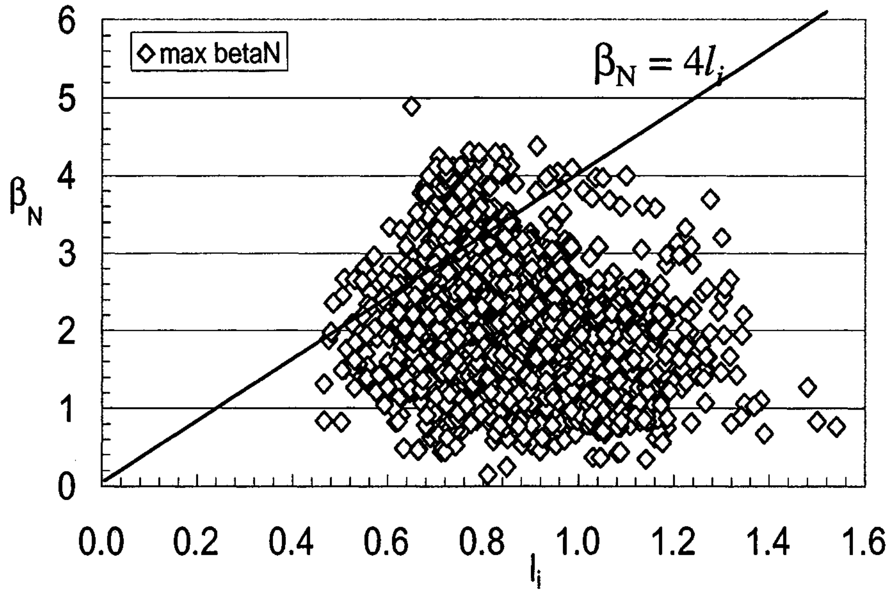
Outline

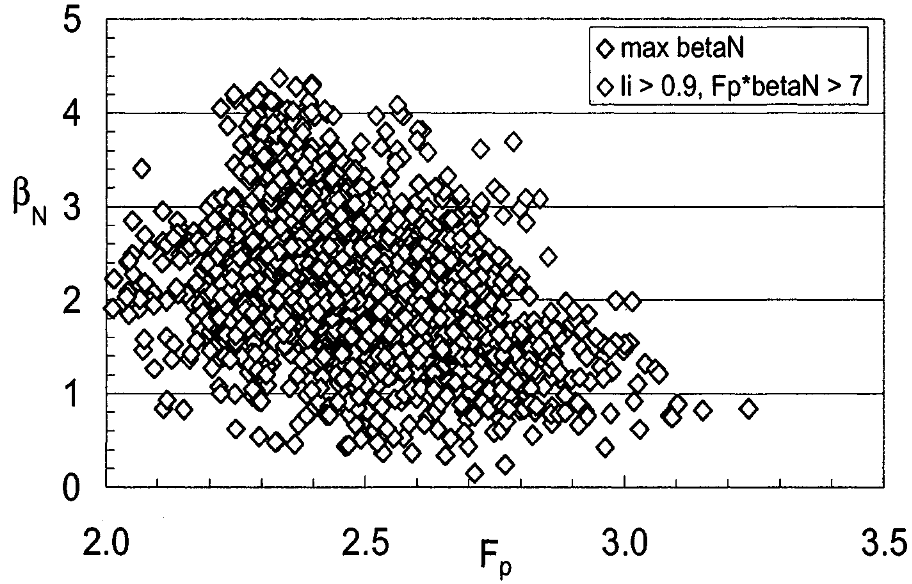
- Overview of plan, usage, and goals
- Transport
- HHFW
- MHD: beta-limiting
  - Range of operations
  - Towards assessing physics of RWM's
  - Locked mode coils/error field detection
  - NTM's
  - Current driven kinks
- Boundary physics
- Non-inductive startup
- Summary

FY '02 Milestone: Measure and analyze the global stability at high beta without active external control

Active feedback decision points:
FY'02: Scientific
FY'03: Technical

Profile variations have been performed to map out operational space for stability studies





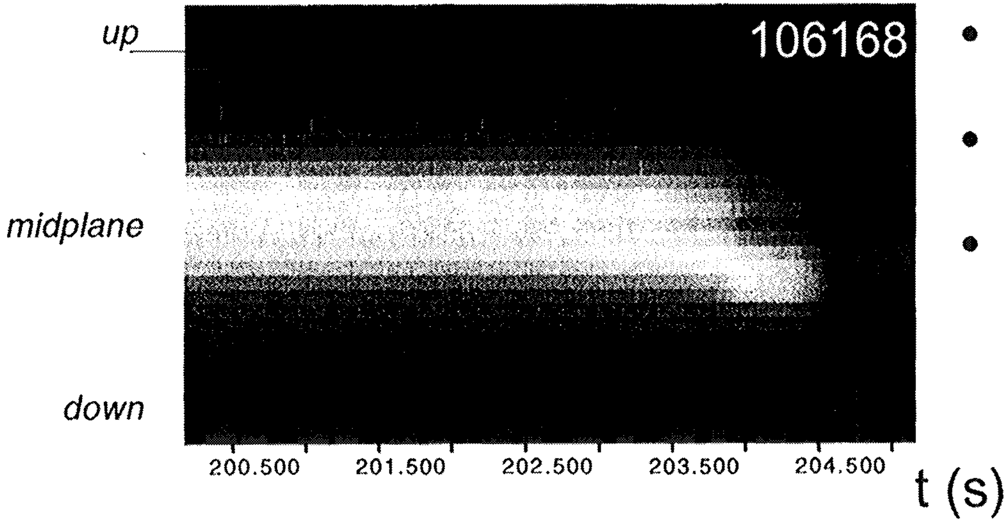
- Maximum β_N increases, then saturates with increased current profile peaking
- Fast beta collapses observed at all values of l_i
- High pressure peaking
- Beta saturation coincident with tearing activity at higher β_N, $\beta_p \sim 0.45$

Taking a step towards an MHD control strategy: identifying the Resistive Wall Mode

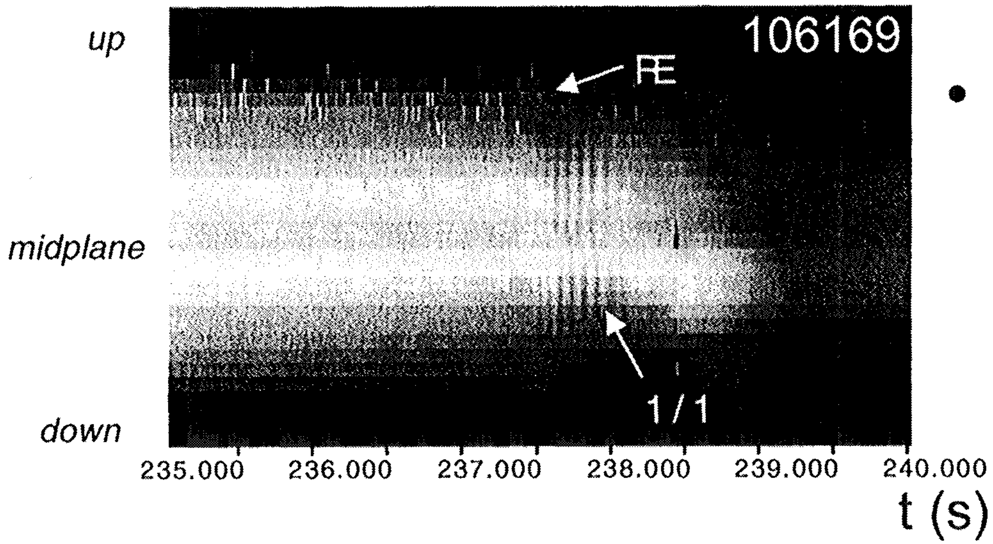
- Dedicated experiments; continued active discussion
- Goals
  - Operate at or above the ideal no-wall beta limit: candidate plasmas have ideal kink-driven collapses
  - Critical rotation frequency test: measure the plasma rotation leading up to the instability
  - Plasma/wall coupling test: Vary the outer gap: determine variation of mode stability
- Techniques
  - Operate with $l_i \sim 0.6$, $\beta_N > 3$
  - Operate clear of sawteeth and low n islands

Sabbagh, Columbia U.

USXR data shows a mode structure resembling a global kink in RWM candidate shots



- RWM Candidate
- Fast collapse
- No core islands and no 1/1 mode before reconnection event (RE)
  - More likely a kink mode onset

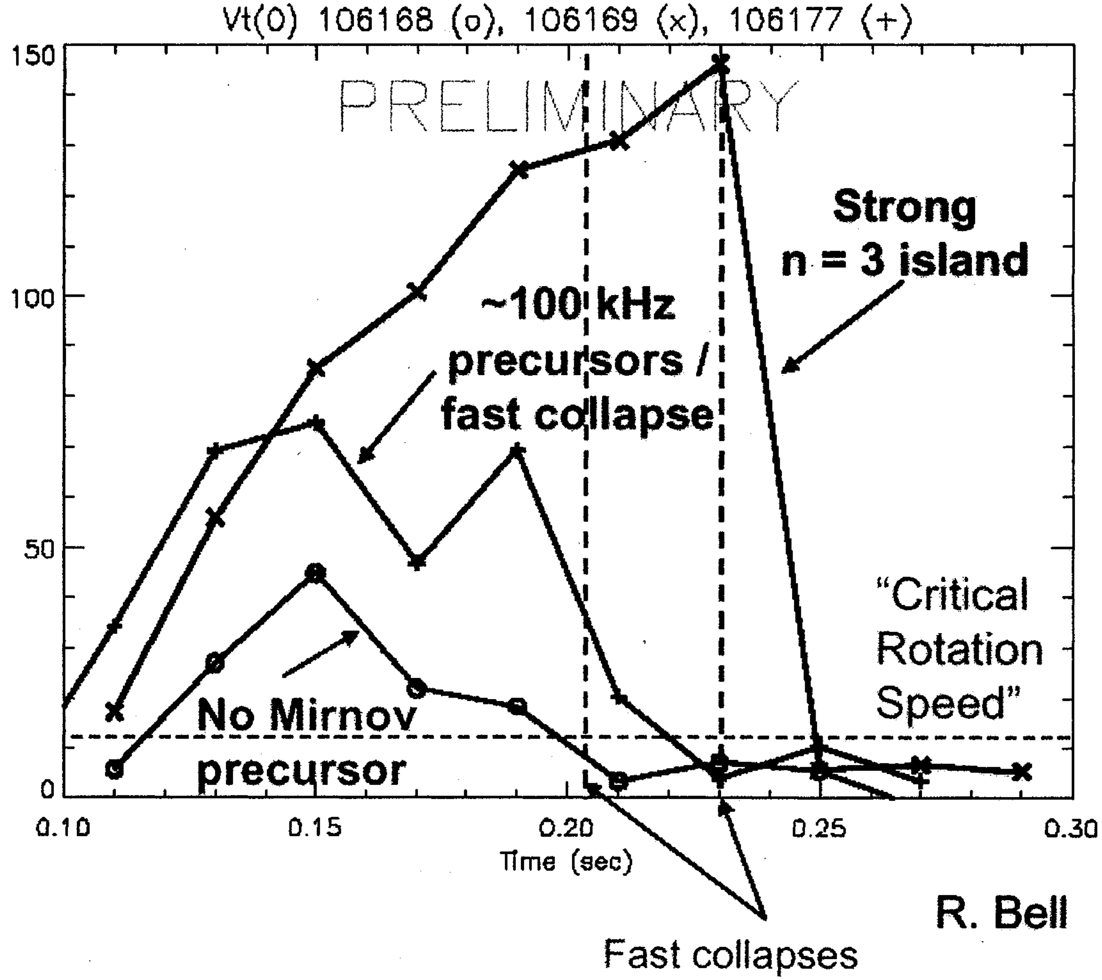


- Plasma with island activity
  - Reconnection event leads to 1/1 mode at 237 ms
  - Less likely a kink mode onset

D. Stutman

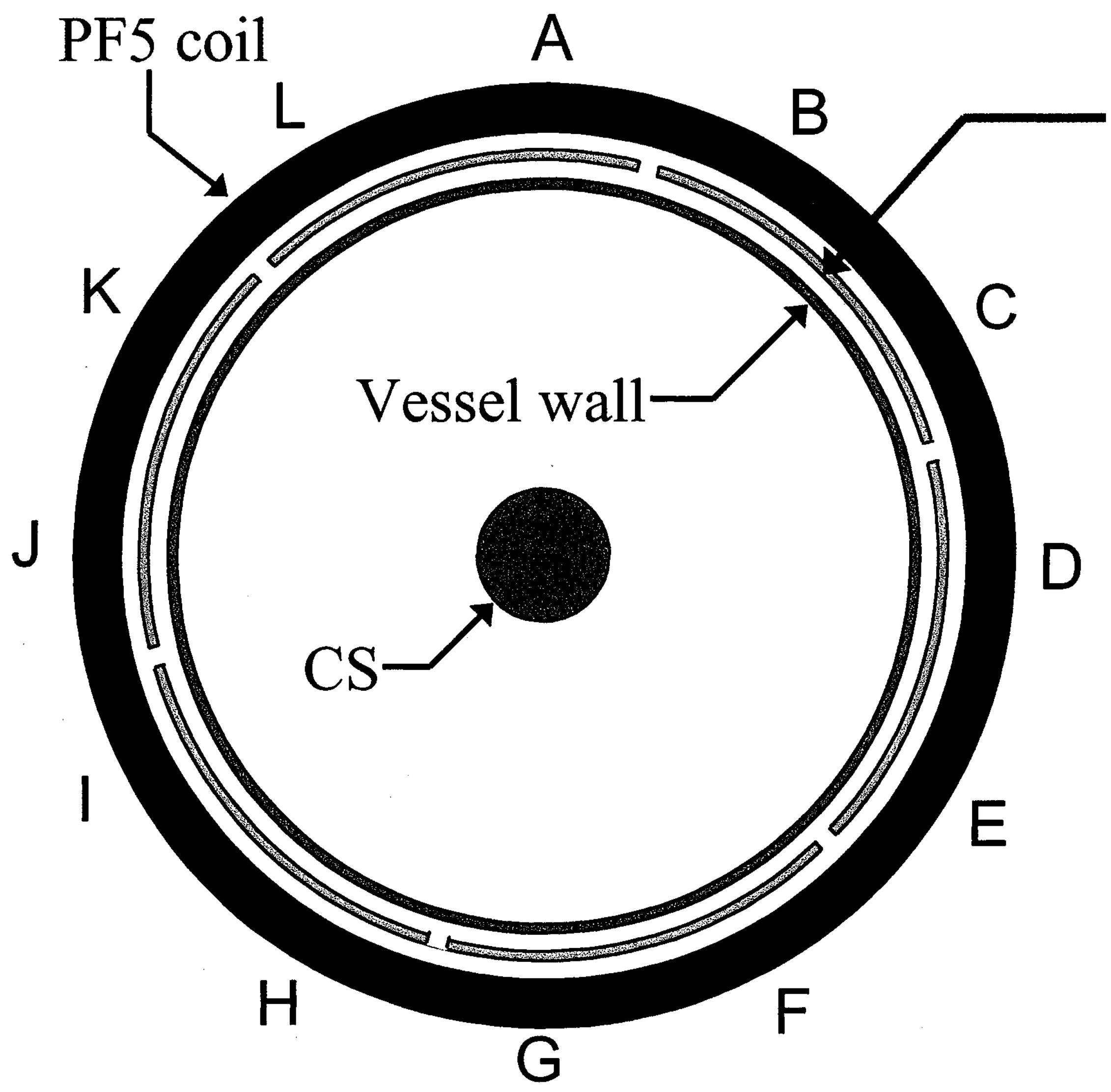
Candidates for RWM have a fast collapse when rotation frequency is below a small value

- "Critical" rotation frequency < 2 kHz at the plasma core at time of collapse, consistent with DIII-D observations of RWM and theory
- Rotation decrease occurs across the entire plasma (preliminary CHERS analysis)



R. Bell

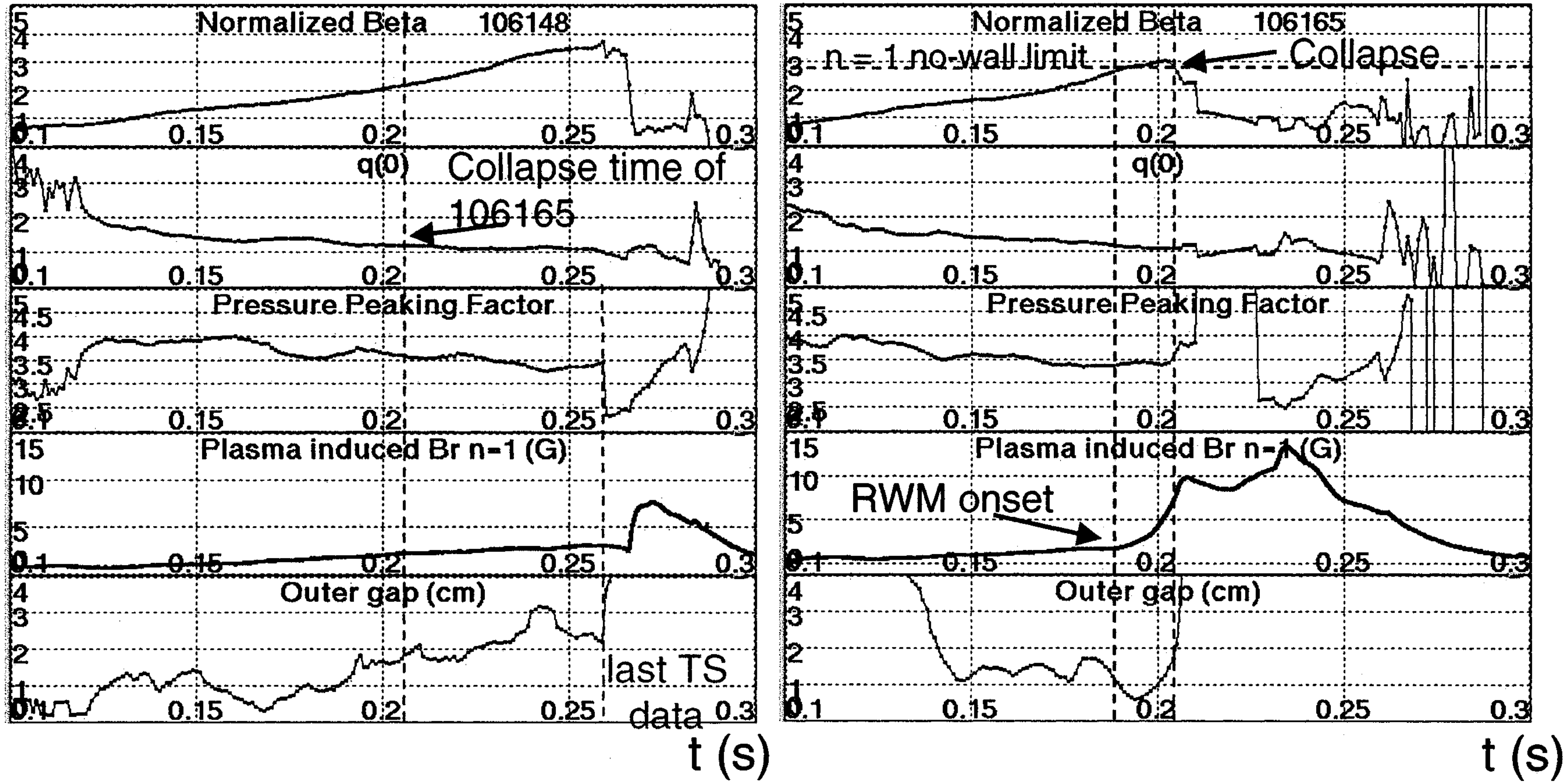
Locked mode coils have been installed, calibrated, and used



- **6 large B_r sensors**
- Opposing sensors are differenced in analog, then integrated
  - MDS+ tree archives uncompensated δB_r
    - J/K-D/E, A/L-F/G, B/C-H/I
  - Remaining calibration done in software (IDL)
- B_r sensors are mounted on PF5 coils
  - PF5 generates large apparent δB_r caused by:
    - Sensor misalignment
    - PF5 non-circularity

J. Menard

RWM candidate driven unstable by greater NBI heating



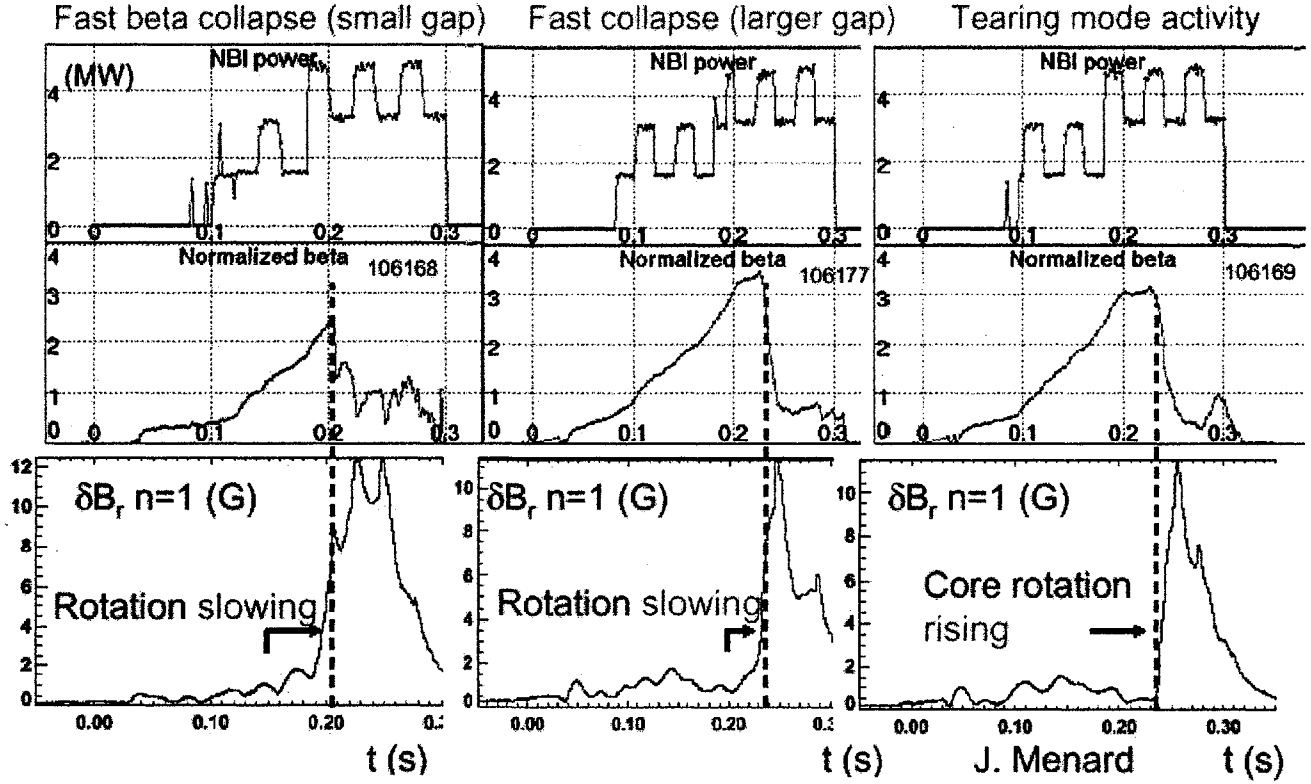
- Control plasma: small outer gap, 1 NB
- Plasma stable until q(0) = 1 (sawtooth)
  - Fast increase of locked mode signal

- Pressure-driven mode: small gap, 3 NB's
- Beta collapse observed 15 ms afer δB_r excursion

Wall-plasma gap scan, δB_r and rotation measurements reveal clues regarding RWM

- Smaller gap
  $\Rightarrow$ longer time between start of rapid growth phase of δB_r and beta collapse
  $\Rightarrow$ stronger wall mode interaction

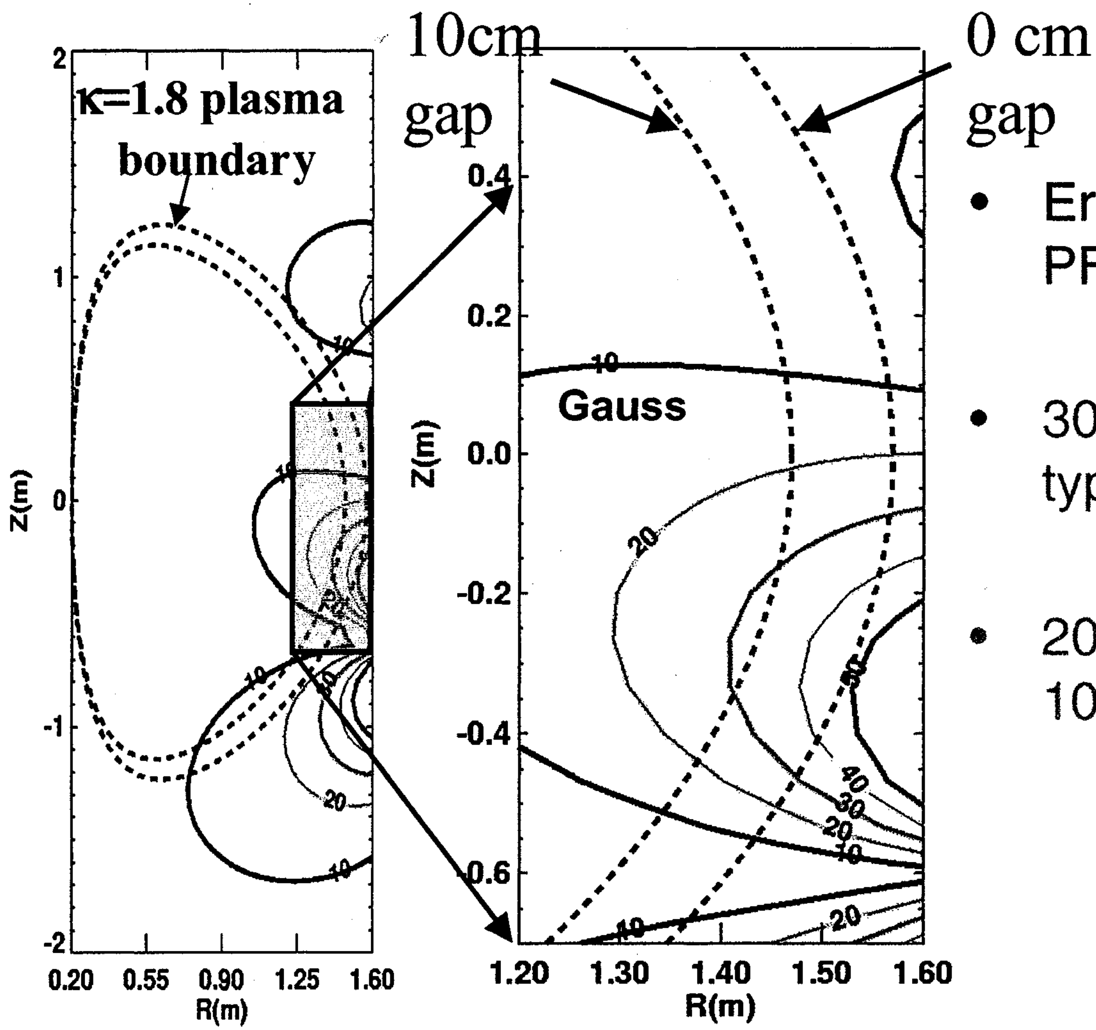
- With clear tearing activity, no observed δB_r precursor to collapse



At least two possible complications

- Theory suggests δB_r largest on inboard side for these β_N's, $\Rightarrow$ weaker wall interactions compared to DIII-D
- Locked mode coils $\Rightarrow$ large field error from PF 5

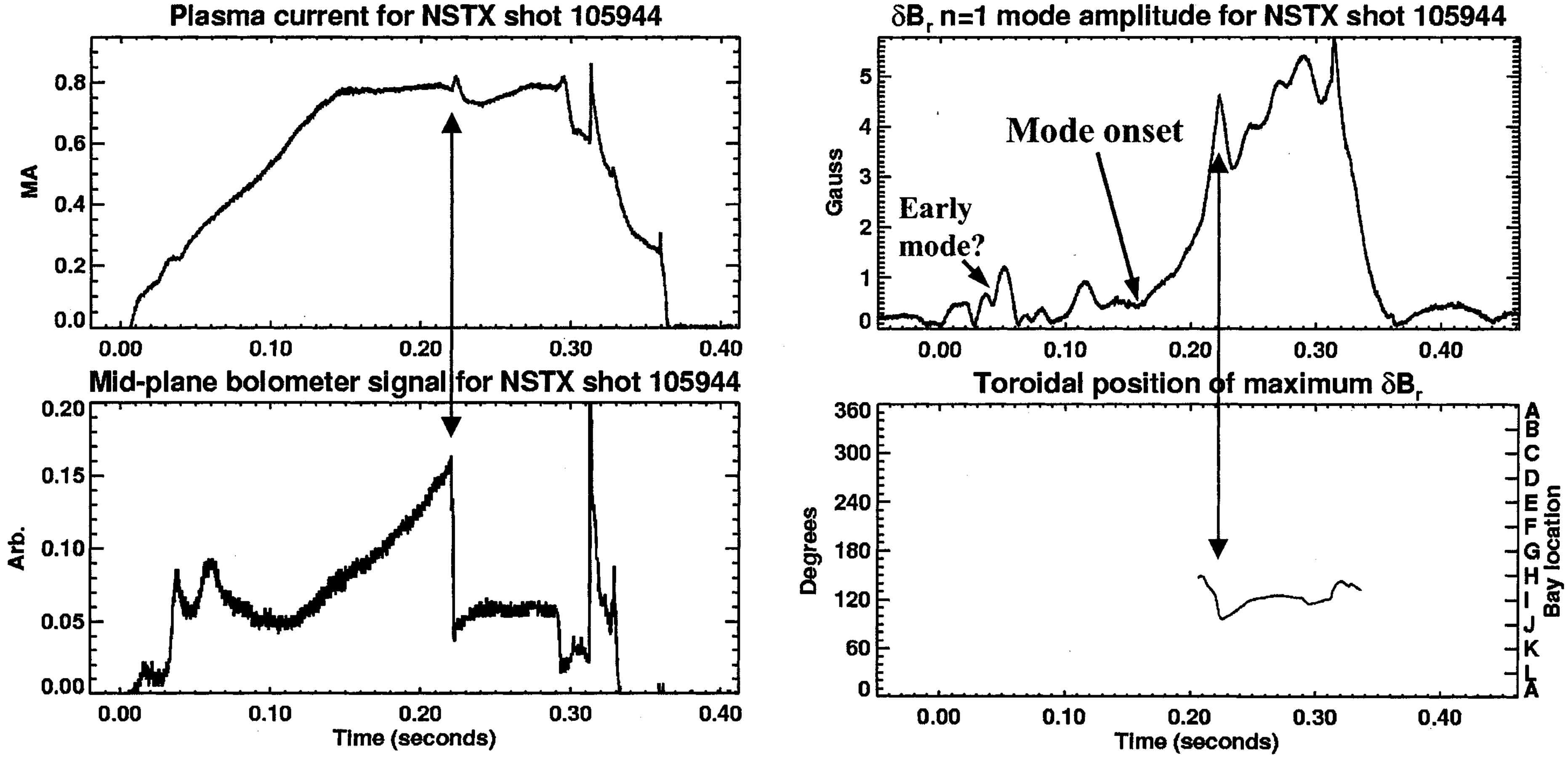
PF5 is apparently responsible for a large *n*=1 field error



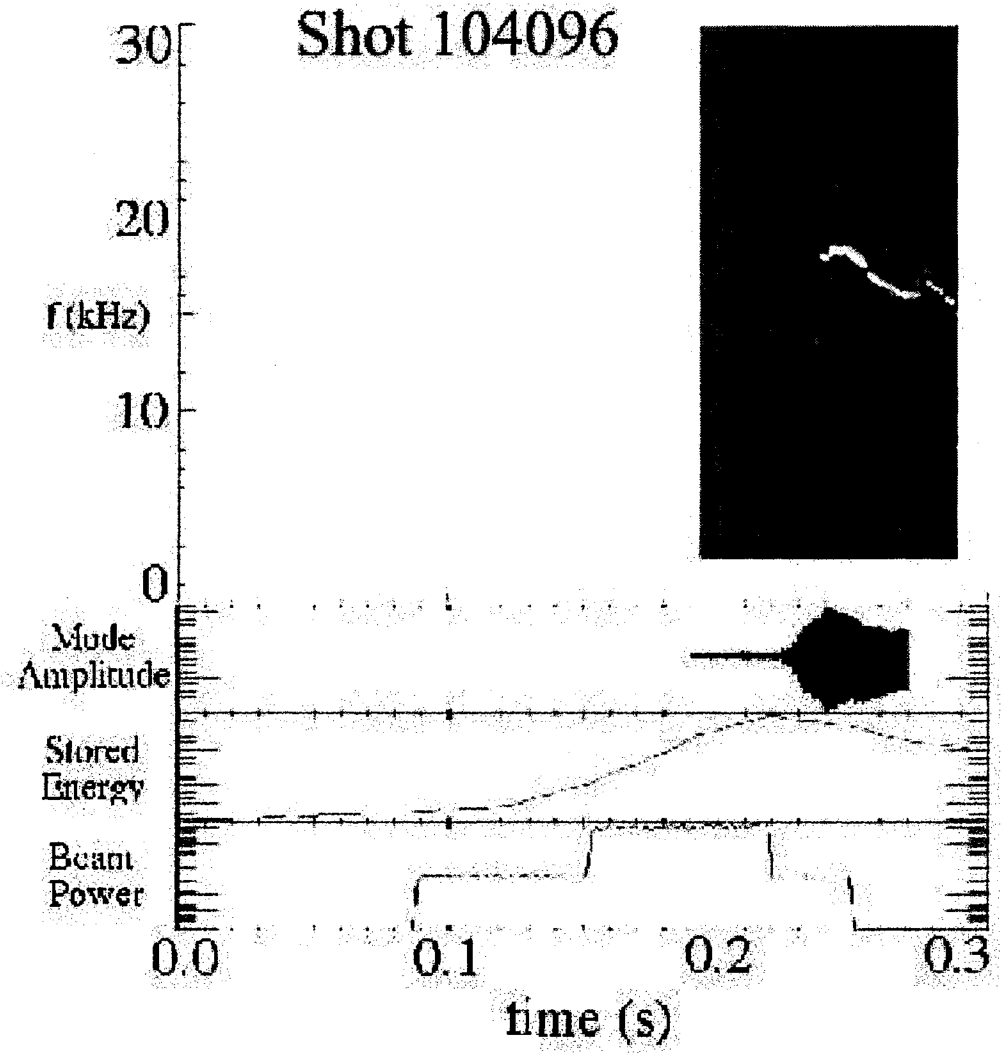
- Error field is localized to lower PF5 coil
- 30-50 Gauss n=1 error field for typical PF5 current and 0 cm gap
- 20-30 Gauss peak error field for 10cm gap

Ohmic shots: often early and prolonged locking

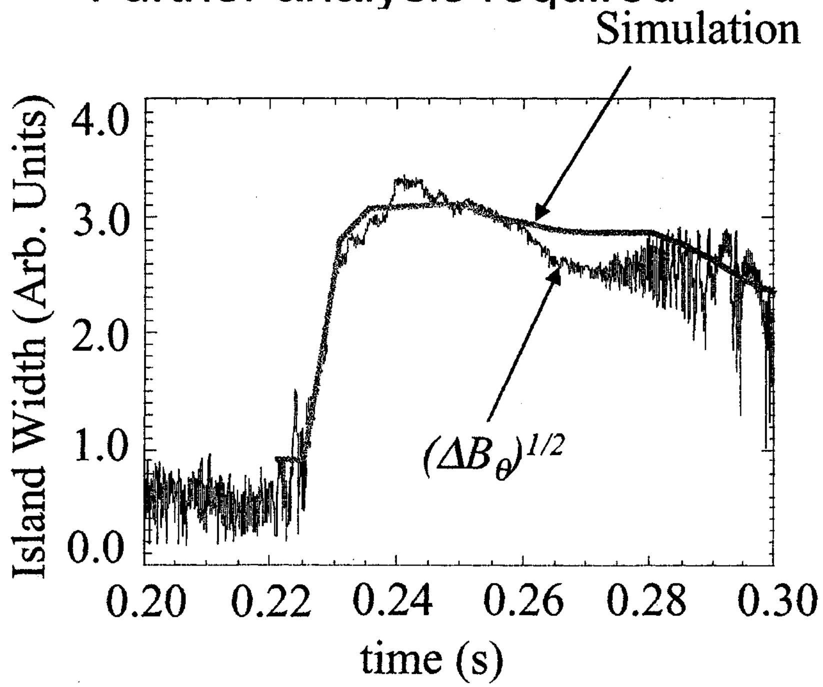
- "Reconnection event" collapse occurs near t=220ms
- Mode growth starts near t=160ms
- Mode persists for 100ms after collapse event



Slow-growing, β-limiting internal modes are likely NTM's

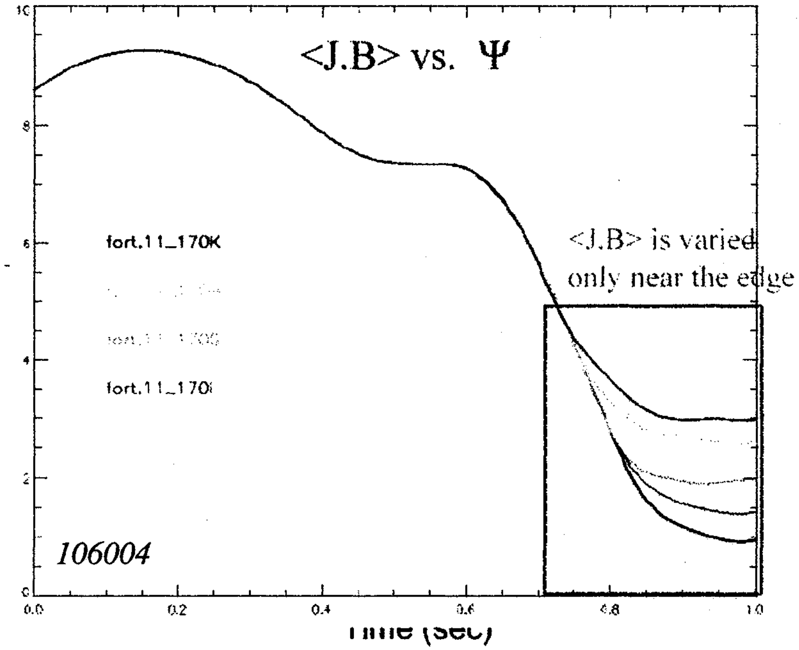


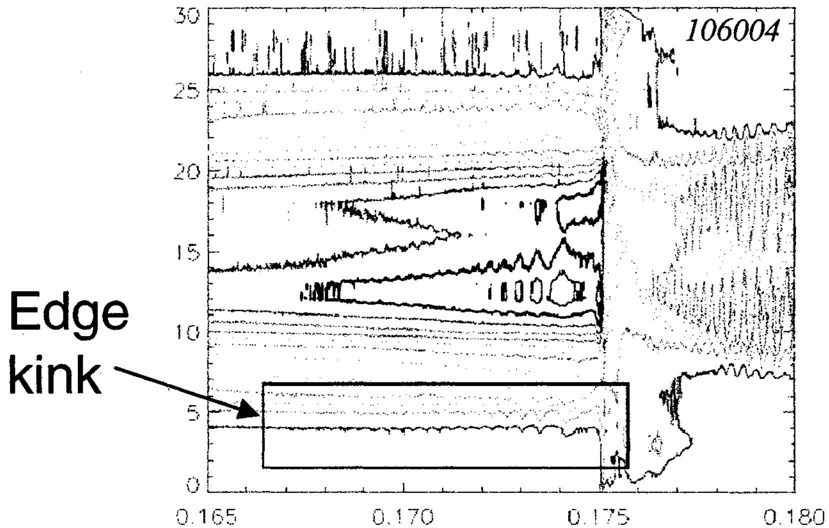
- Coincident with saturation of beta
- Limits $\beta_p \sim 0.4$
- Modes appear near β_{crit}
- Further analysis required

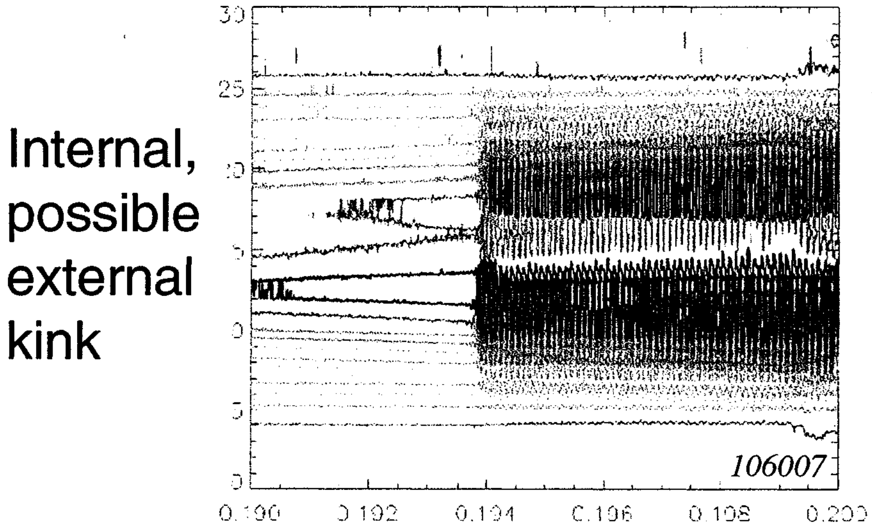


D. Gates, E. Fredrickson

Current-driven kinks observed on NSTX







- B_T ramp-down, I_p ramp-up key elements of XP
- SXR array shows growth of edge kink structure

Manickmam, Fredrickson, Okabayashi

Outline

- Overview of plan, usage, and goals
- Transport
- HHFW
- MHD
- **Boundary physics**
  - H modes and turbulence characteristics
  - Heat and particle flux measurements
  - Wall preparations
- Non-inductive startup
- Summary

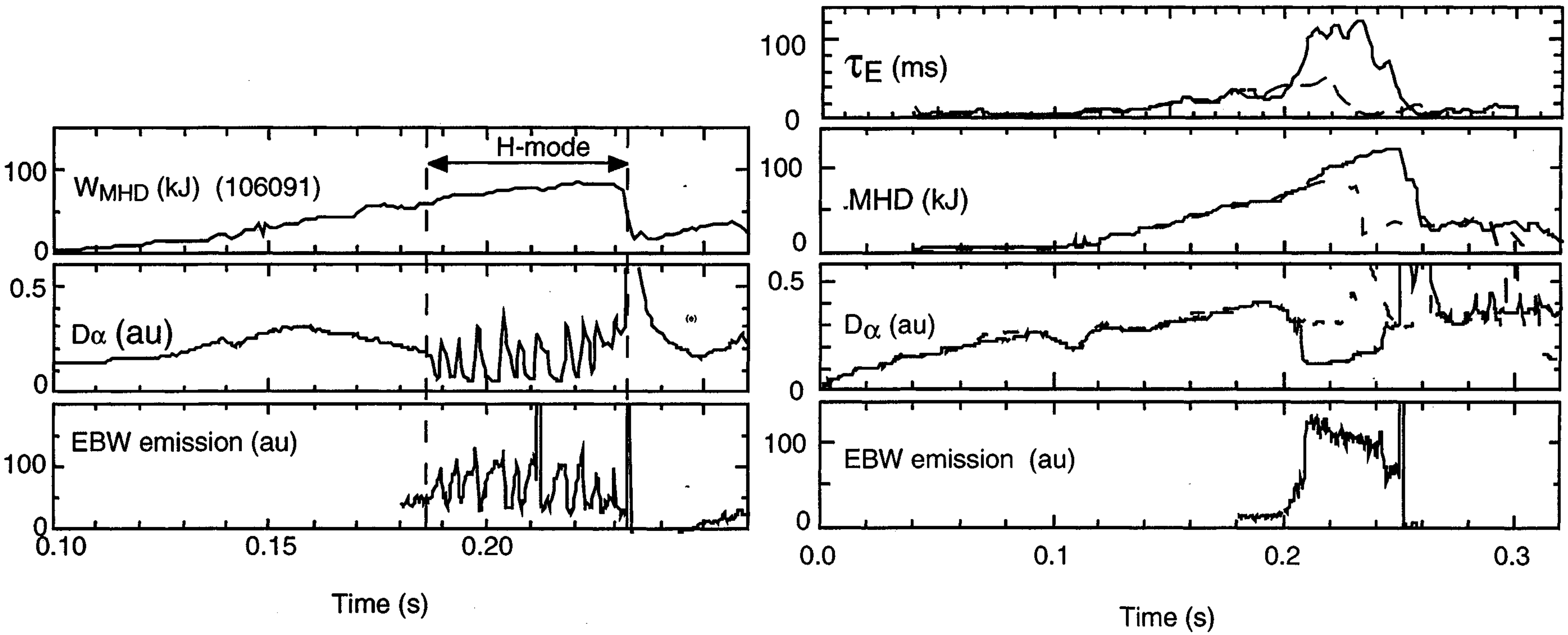
In addition to transport milestones,

FY '03 B.P. Milestone: Measure and analyze the dispersion of edge heat flux and assess the impact on plasma facing component requirements

Both ELM-free and ELMy H-modes have been observed in NSTX

ELMing

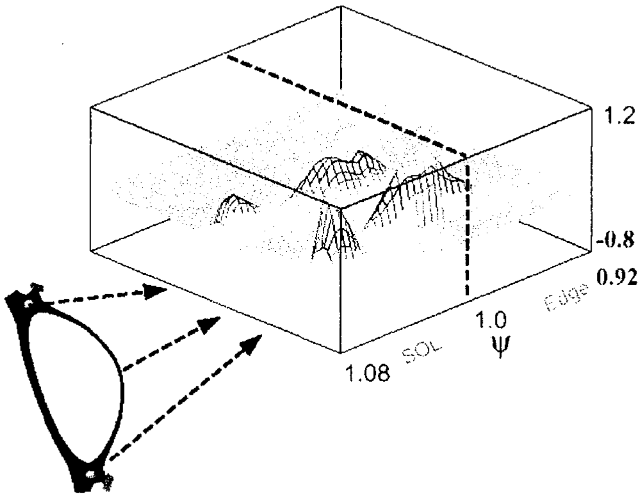
ELM-free

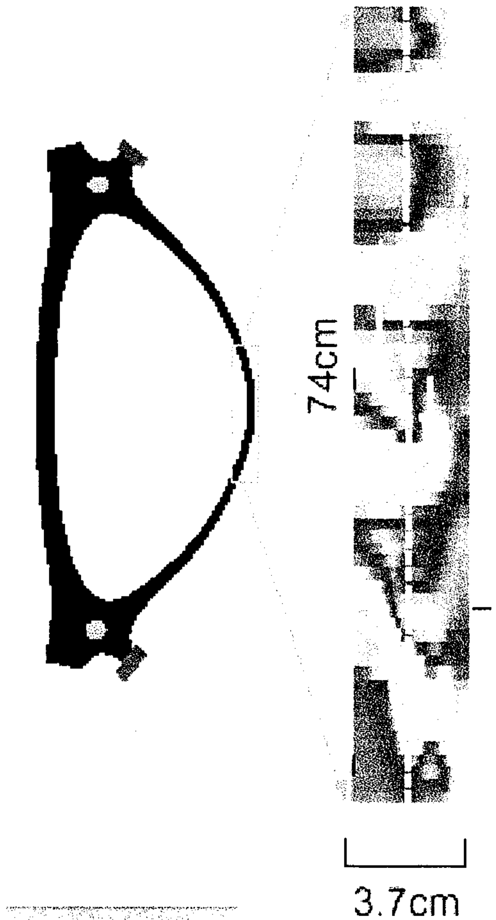


- HHFW and NBI
- Exploration for scenario development, transport, and boundary physics

Theory indicates complex turbulent structures may exist in NSTX edge

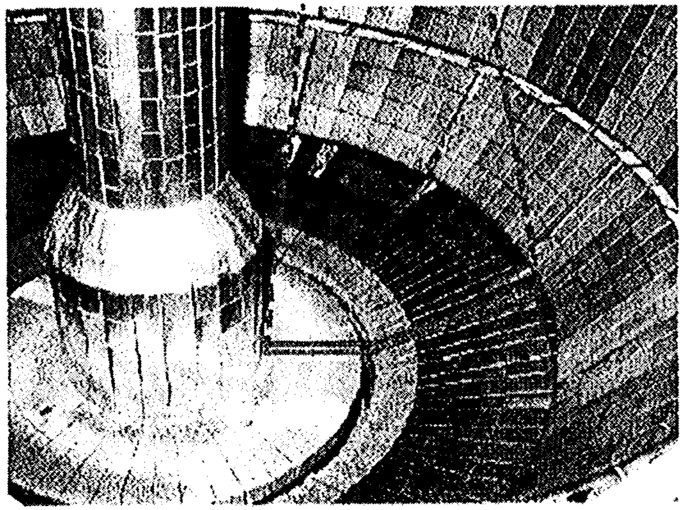
- BOUT code: turbulence modeling
  - 2-fluid,3D Braginskii equation code

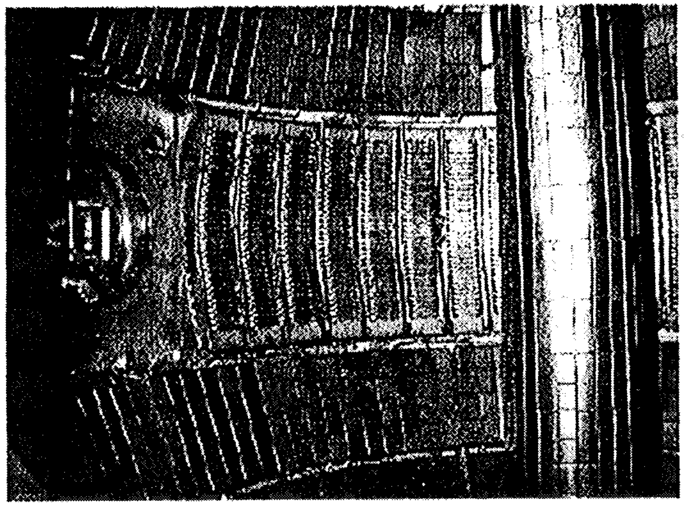


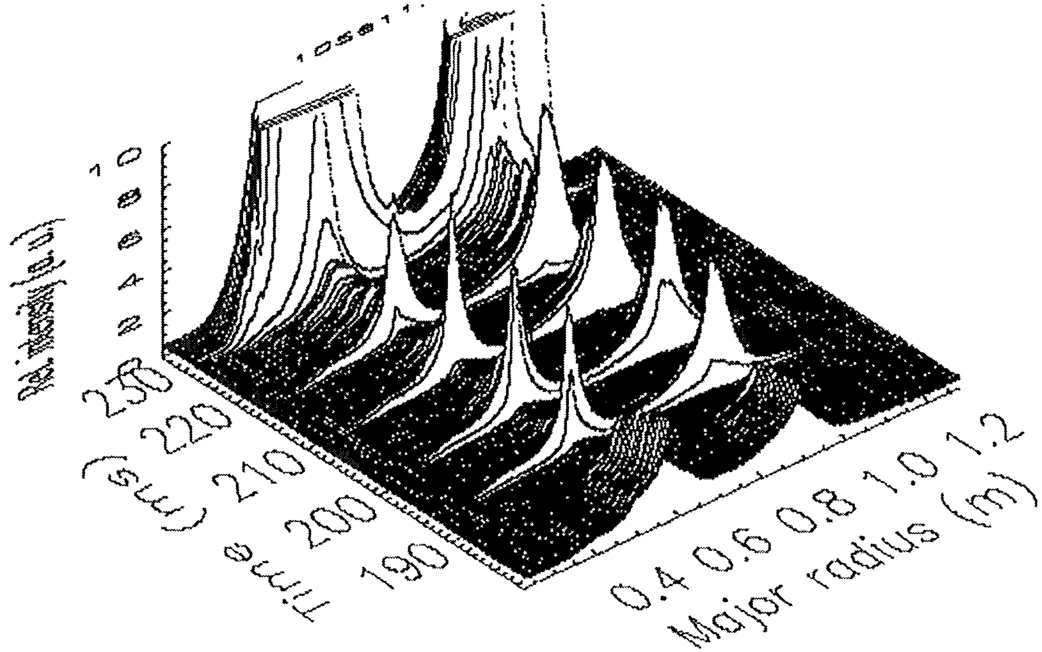


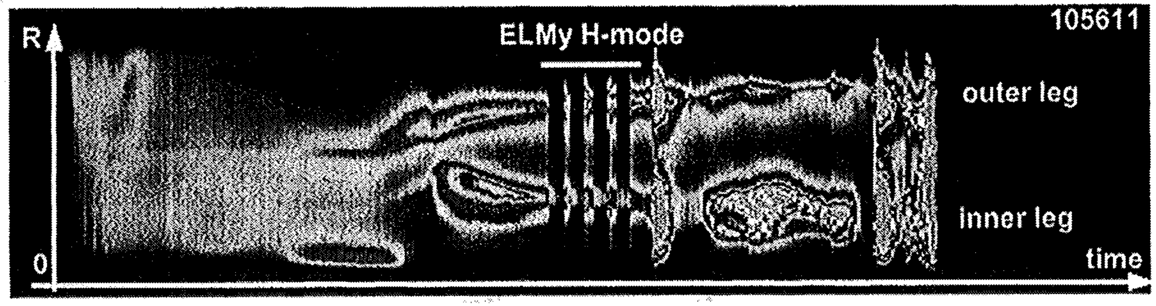
Xu (LLNL)

Influx data being obtained with 1-D CCD arrays





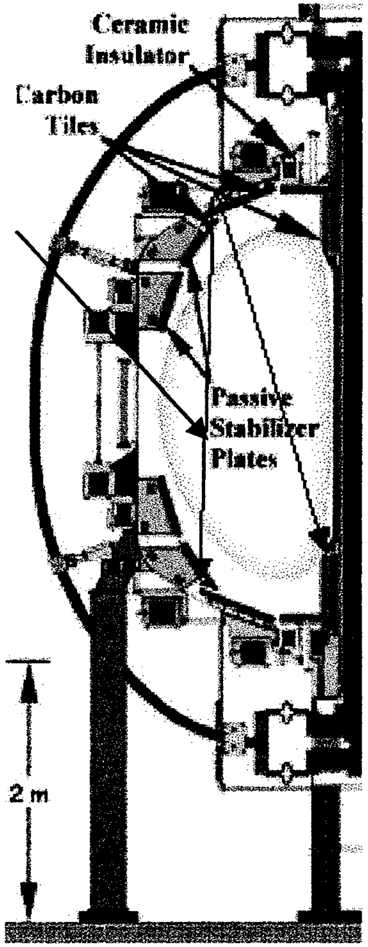


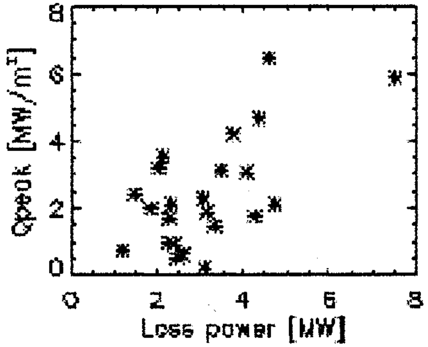


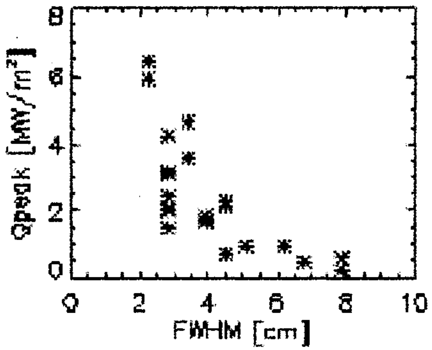
Soukhanovskii; Maingi (ORNL)

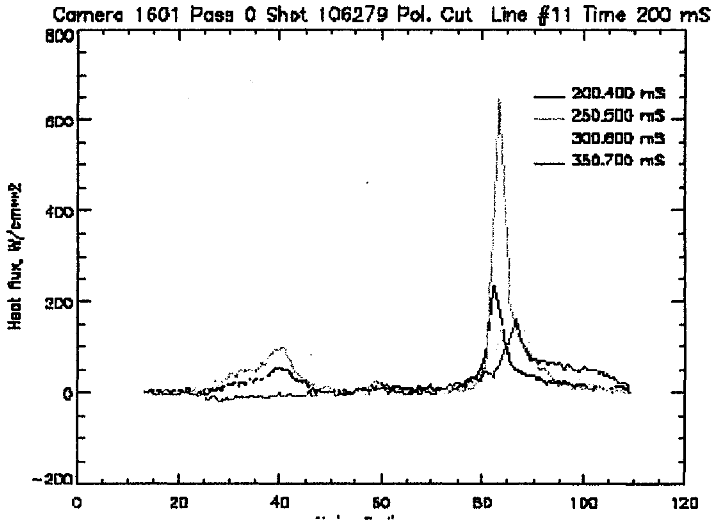
IR camera being used for heat flux studies

IR camera view









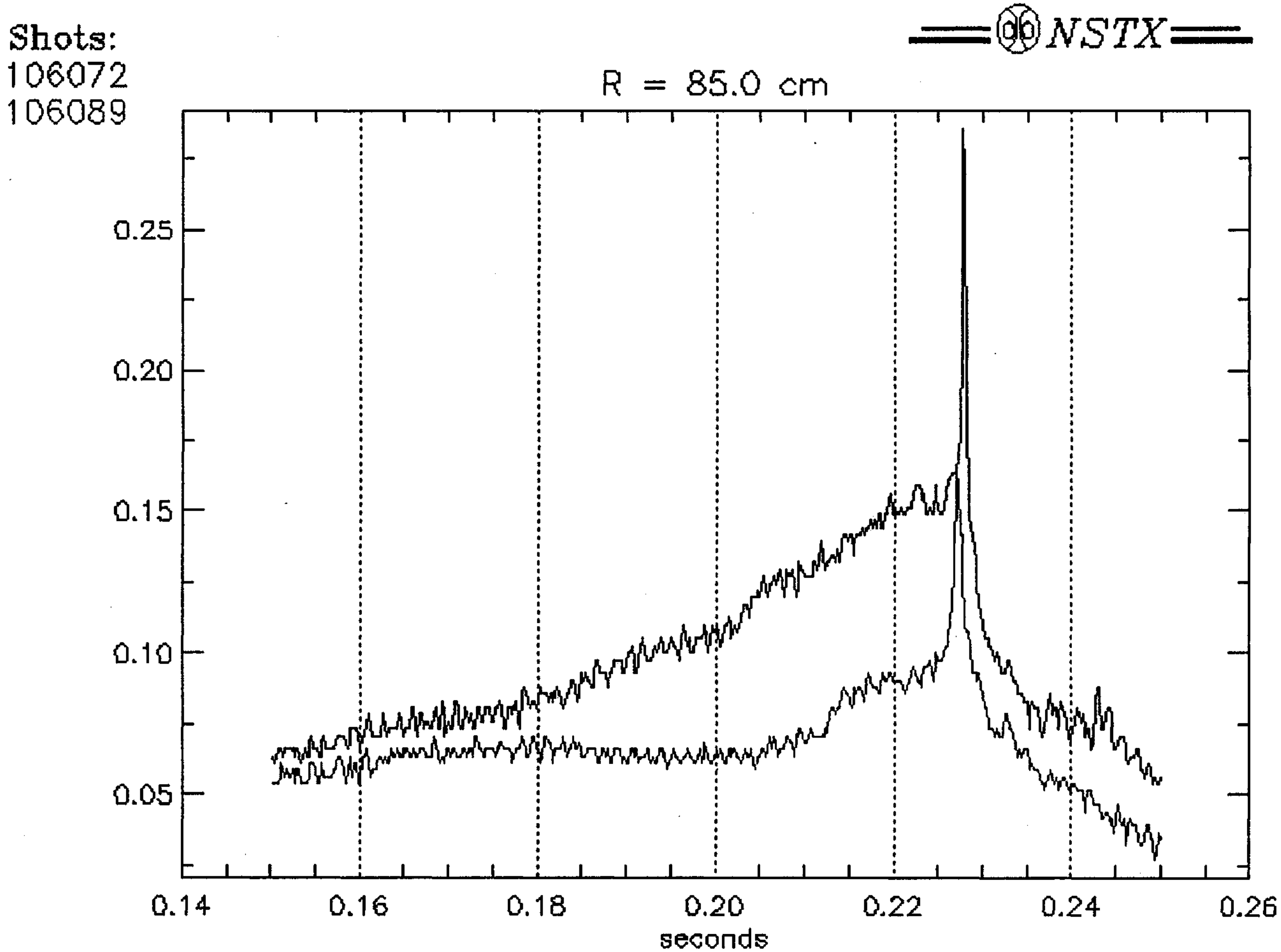
Heat flux peaks during auxiliary heating

Maingi (ORNL)

Boronization consistently reduced impurity influxes, improved performance

- TMB Boronization now a routinely used tool

- Plasma boronization implemented for first time
  - Lower radiated power in ohmic
  - Reduced V-s consumption, longer pulse



Na (KBSI); Maingi (ORNL), Skinner, Kugel

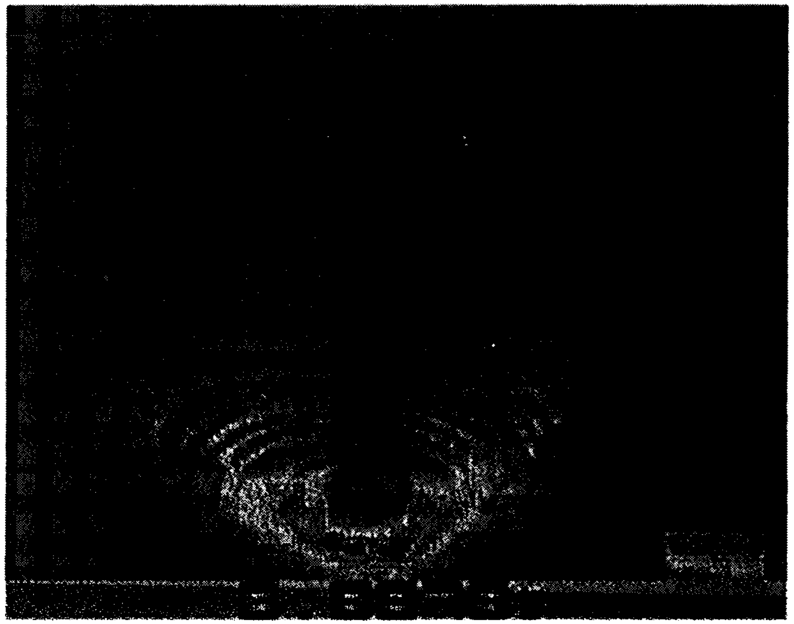
Outline

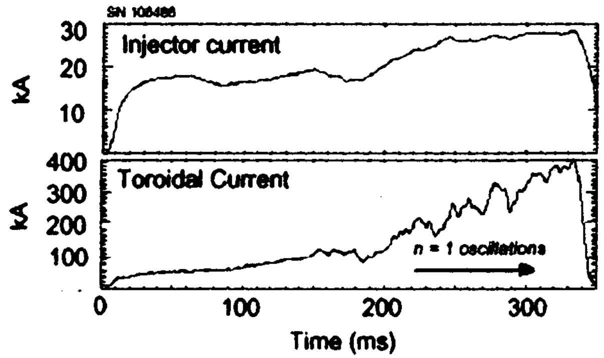
- Overview of plan, usage, and goals
- Transport
- HHFW
- MHD
- Boundary physics
- **Non-inductive startup**
  - Higher currents; $n = 1$ activity
  - Spectroscopy
  - EBW
- Summary

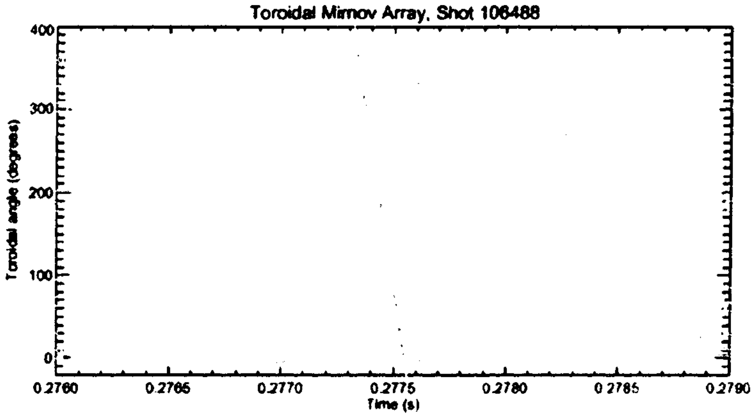
'02 Milestone: Demonstrate innovative techniques for starting up plasma currents in toroidal fusion devices

High currents, strong MHD observed in CHI start-up studies

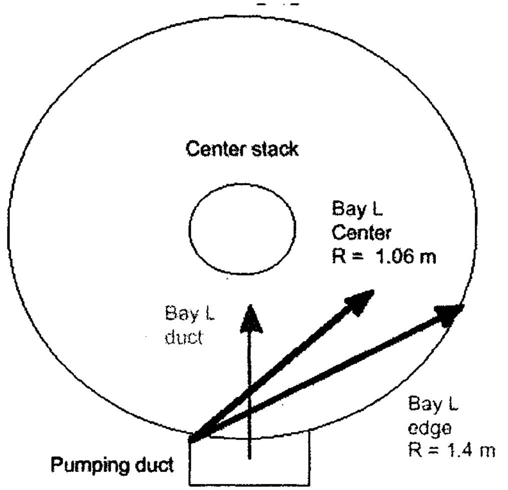
- Up to 390 kA of toroidal current was produced, with 14 times current multiplication
- Discharges sustained for 330 ms
- Strong $n = 1$ oscillations observed

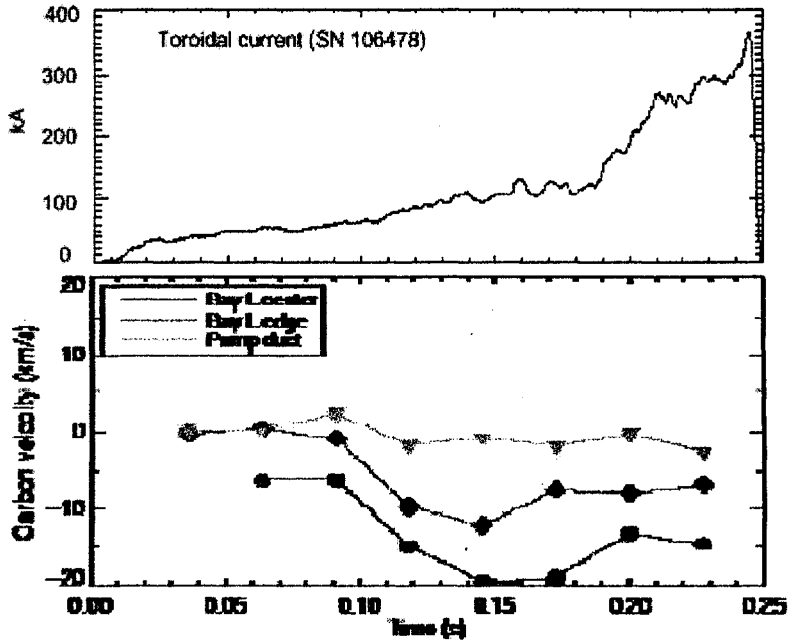




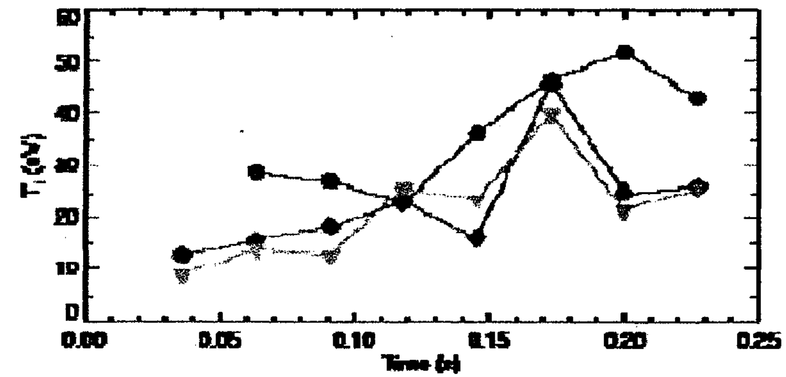


Spectroscopy used to measure T_i and edge plasma rotation in CHI plasmas





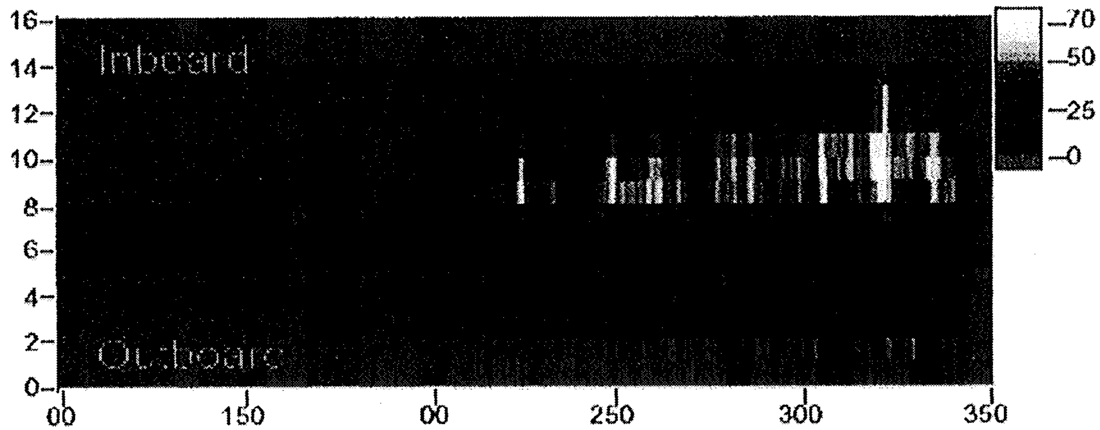
- Direction of rotation is clockwise (same as HIT-II)



- T_i ~ 30 - 50 eV, midplane view
- V_ϕ ~ -10 to -20 km/s

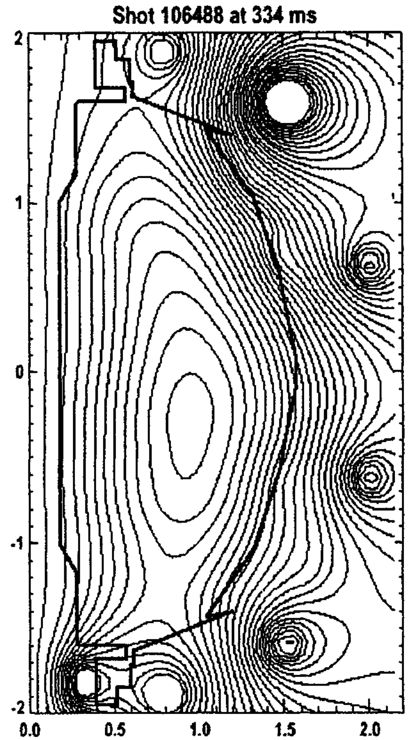
Flux closure is being assessed via further analysis of magnetics and spectroscopy

Array that looks down



Time (ms) from 100 to 350ms

Ip = 390 kA



- USXR emission increases at the higher CHI currents

Stutman, JHU

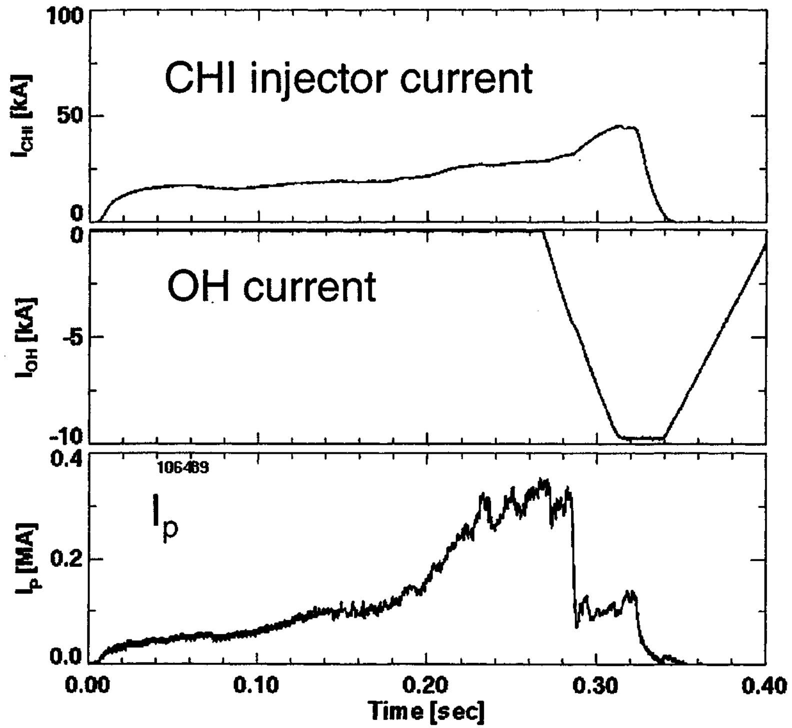
- MFIT consistently shows modest closed flux regions when CHI-driven current is sufficiently high
  - Not seen in absence of n=1 MHD
  - Encouraging, but is not proof of closed mean-field surfaces

Schaffer, GA

A next step for CHI on NSTX is feedback control & handoff with other current drive mechanisms

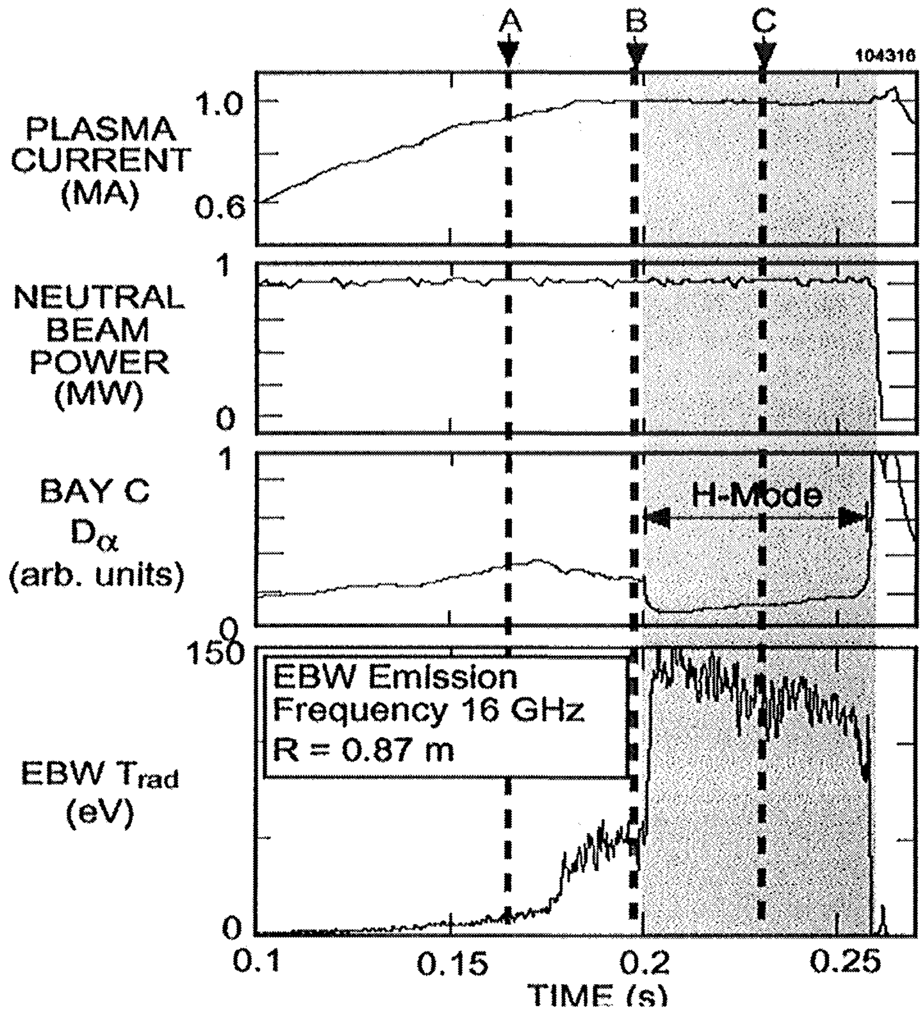
- Control challenge: currents not on flux surfaces play a role in the equilibrium
- Absorber arcs reduced, but still limit experiment efficiency
- EFIT analysis with I_{inj} fitting required

  ⇒ Likely an increase in the fraction of run time required for CHI and control system work



EBW mode conversion efficiency increases at L-H transition when edge density increases

- Mode conversion of EBW from core occurs in scrapeoff in H mode
- Measured EBW conversion efficiency agrees relatively well with calculated values
- On CDX-U, limiter inserted to control L_n demonstrates conversion efficiency can be controlled
- Possible tool for plasma startup, island healing
- Joint research with U. Wisconsin



Physics central to the ST mission is being investigated

- Transport: confinement picture intriguing and potentially important
  - New heating physics specific to the ST?
  - Electron thermal channel may dominate
  - Edge turbulence measurements made; comparison to modelling begun

- HHFW: effective heating in all regimes
  - Fast ion interactions observed
  - CD studies begun; no obvious signatures of HHFW-CD yet

- MHD: Beta-limiting modes being investigated
  - RWM studies underway: well along towards '02 Milestone
  - Importance of locked mode uncovered
  - NTM's, current-driven kinks both being studied

Physics central to the ST mission is being investigated (con't)

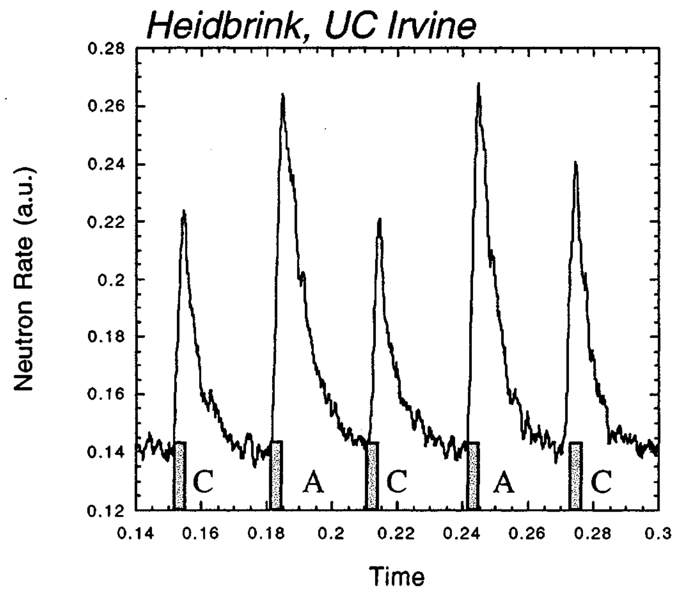
- Boundary physics extended to heat and particle flux studies
  - Comparisons to modelling begun
  - Enabling techniques extended: plasma boronization
  - H mode power threshold established for one condition: ~ 10x usual scaling

- CHI research produced record toroidal current, observed critical MHD activity
  - T_i of 30 - 50 eV measured
  - MFIT analysis consistent with closed flux, not conclusive
  - Absorber arcs reduced, but continue to be an issue
  - First CHI-to-ohmic, ohmic-to-CHI experiments performed; technical exploration stage

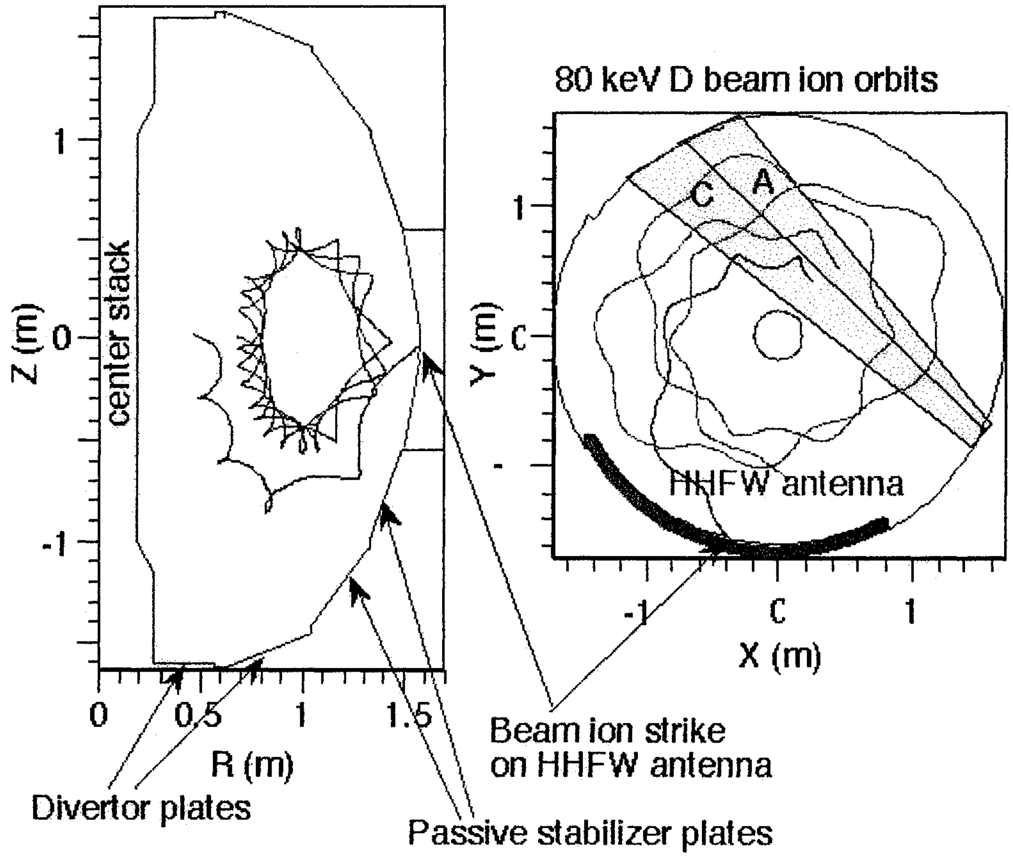
This was an exciting run for the NSTX Team

- The group worked well in a limited amount of time
- For FY '02: day-to-day run coordination duties are handed over to Rajesh Maingi
  - The run scheduling is in good hands!

Detailed orbit calculations being performed to benchmark heat source models



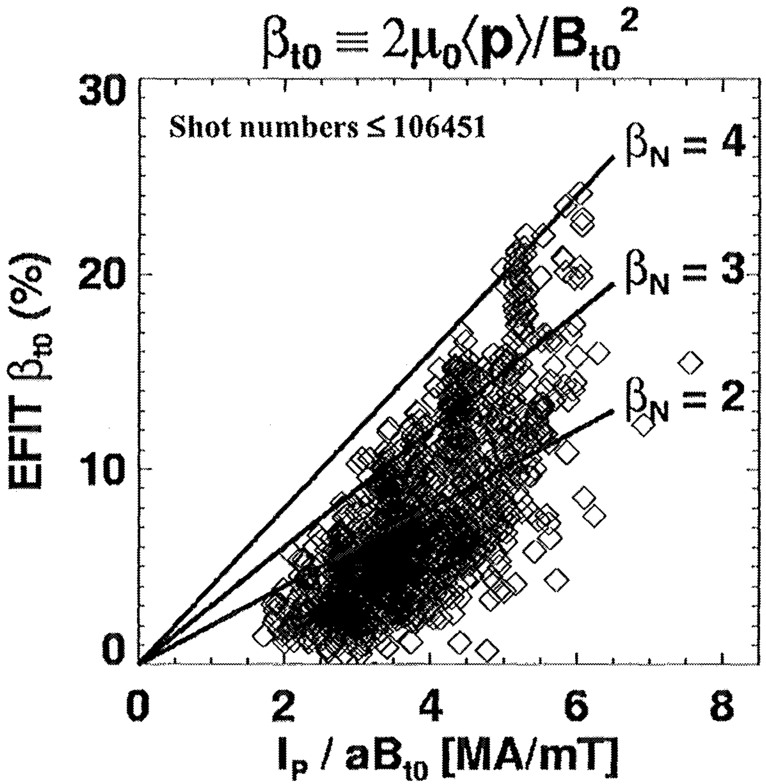
to have different confinement

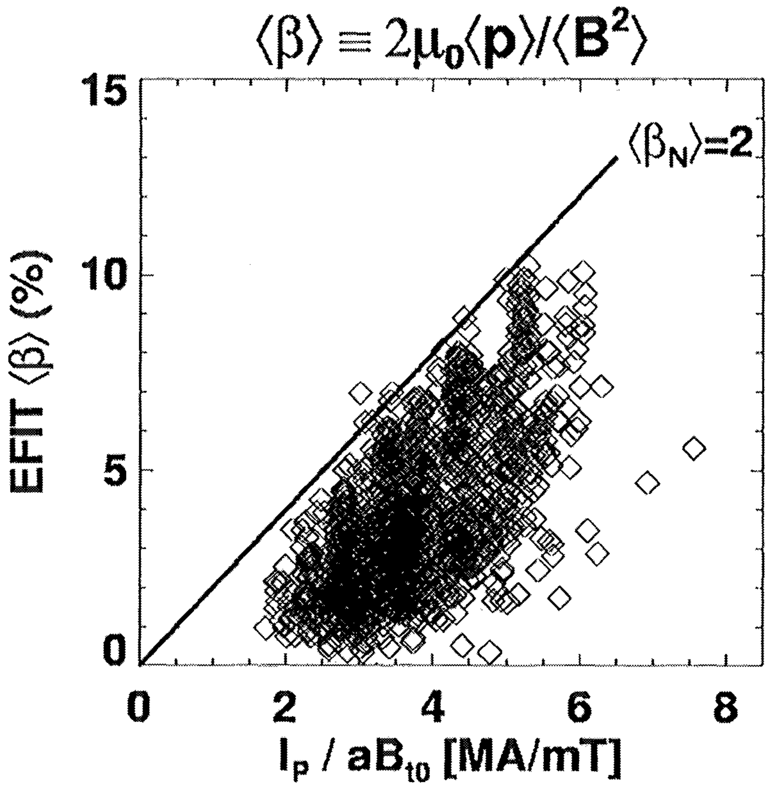


D. Darrow

NSTX has achieved β_{t0}~25% plasmas

- **Data shown below:**
  - **EFIT reconstructions using external magnetics only**
- $\beta_N \leq$ 3-4 ***at peak W_{TOT}***
- I_P/aB_{t0} = 2-6
- $\beta_P \leq 0.55 \Rightarrow$ paramagnetic
- Original Troyon definition of β better fit to present data





EFIT - S. Sabbagh