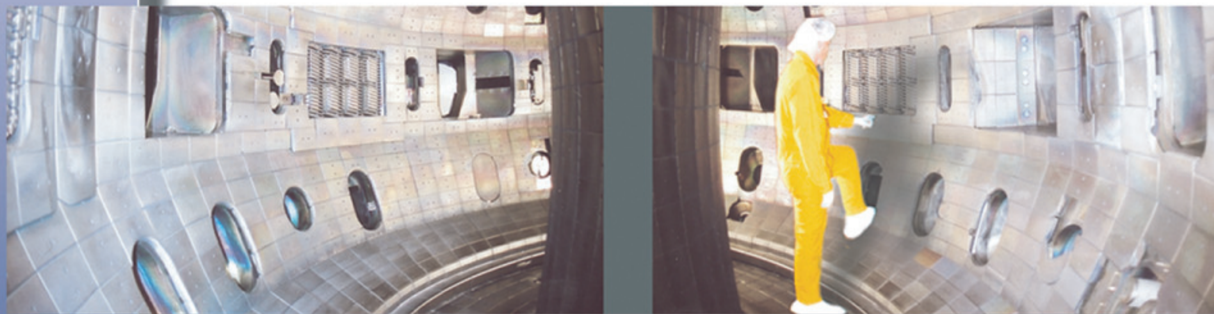

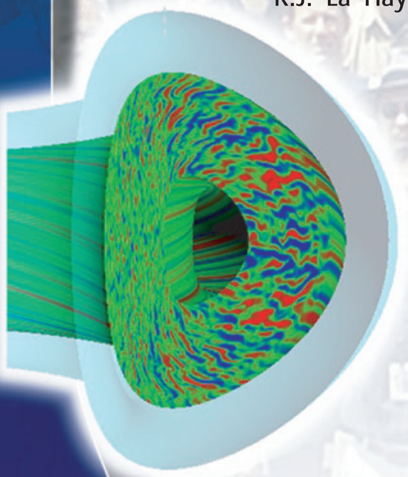

100% Noninductive Operation at High Beta Using Off-Axis ECCD

by

M. Murakami

in collaboration with

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Vilamoura, Portugal

November 2, 2004

DIII–D
NATIONAL FUSION FACILITY
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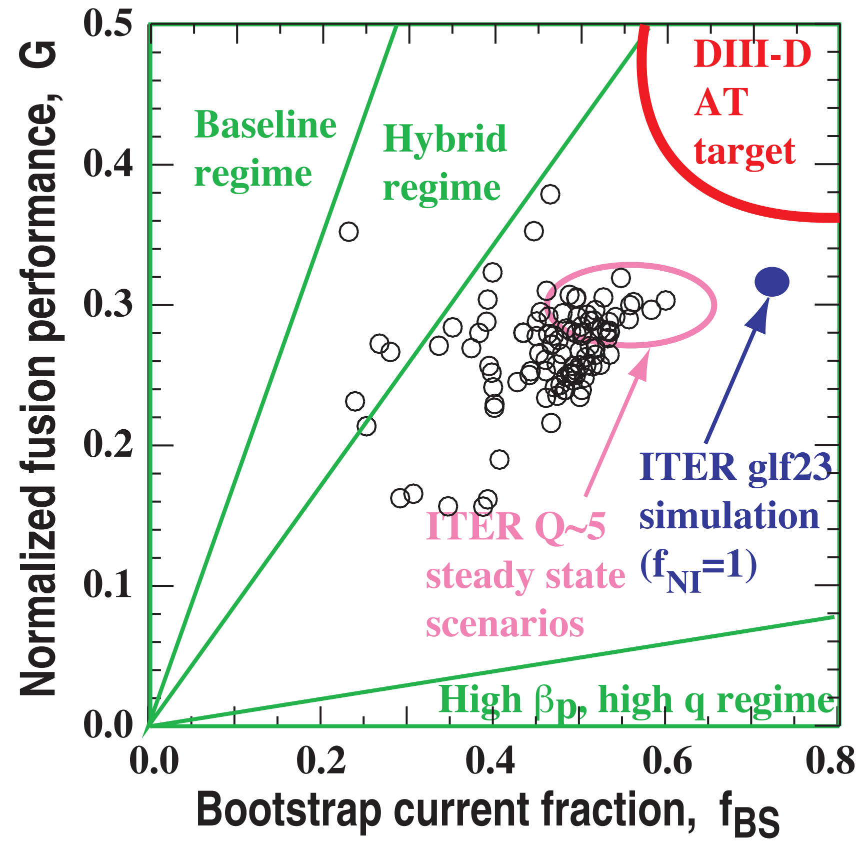
DIII-D *AT* PROGRAM GOAL: SCIENTIFIC BASIS FOR STEADY STATE, HIGH PERFORMANCE OPERATION IN FUTURE TOKAMAKS

- Steady-state operation
  - 100% noninductive fraction: $f_{NI} = I_{NI}/I_p$
  - High Bootstrap current fraction: $f_{BS} = I_{BS}/I_p \propto \beta_p$
- Maintaining sufficient fusion gain with reduced engineering parameters
  - Hgh β_T
  - High τ_E
  - $\Rightarrow$ High Normalized fusion performance: $G = \beta_N H/q^2$
- DIII-D *AT* experiments have demonstrated performance required for *ITER* steady state scenario



T. Luce: OV1-3

G. Sips: IT/P3-36

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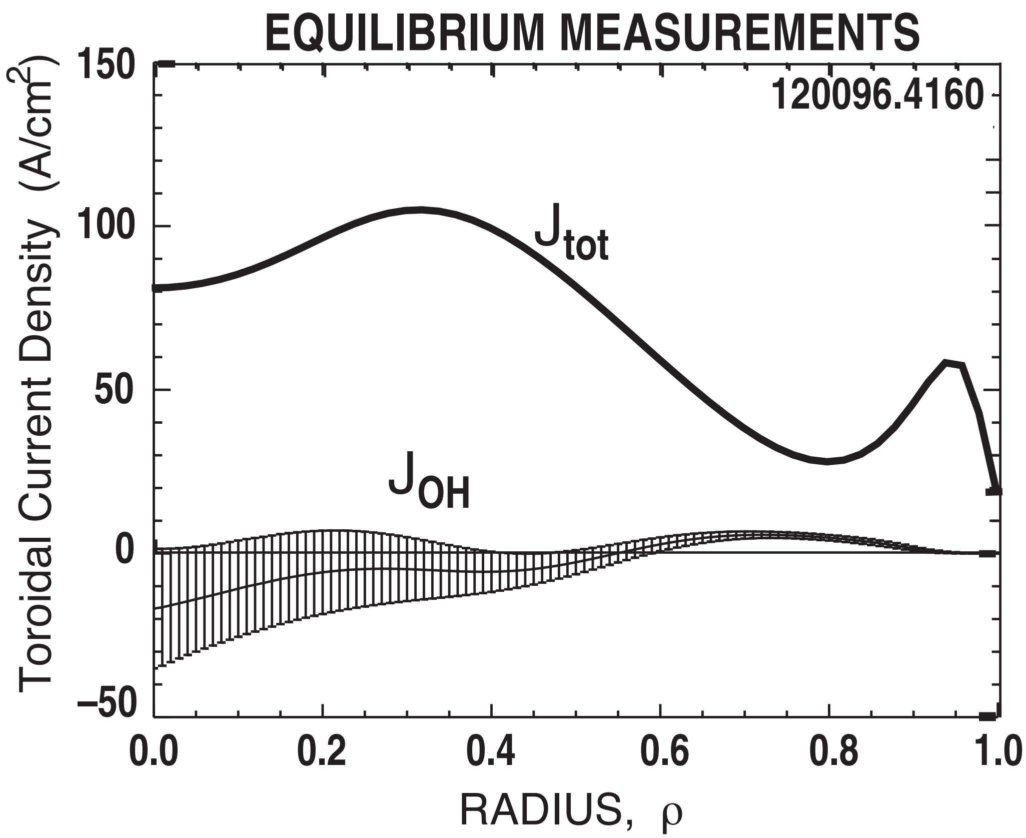
100% NONINDUCTIVELY DRIVEN PLASMAS OBTAINED WITH GOOD CURRENT DRIVE ALIGNMENT



- $f_{NI} = 1 - f_{OH}$; $J_{OH} = \sigma_{neo} E_{||} \propto \sigma_{neo} \partial \Psi_{pol} / \partial t$
- f_{OH} = 0.5%, f_{NI} = 99.5%
- β_T = 3.5%, β_N = 3.6, q_{95} = 5.4

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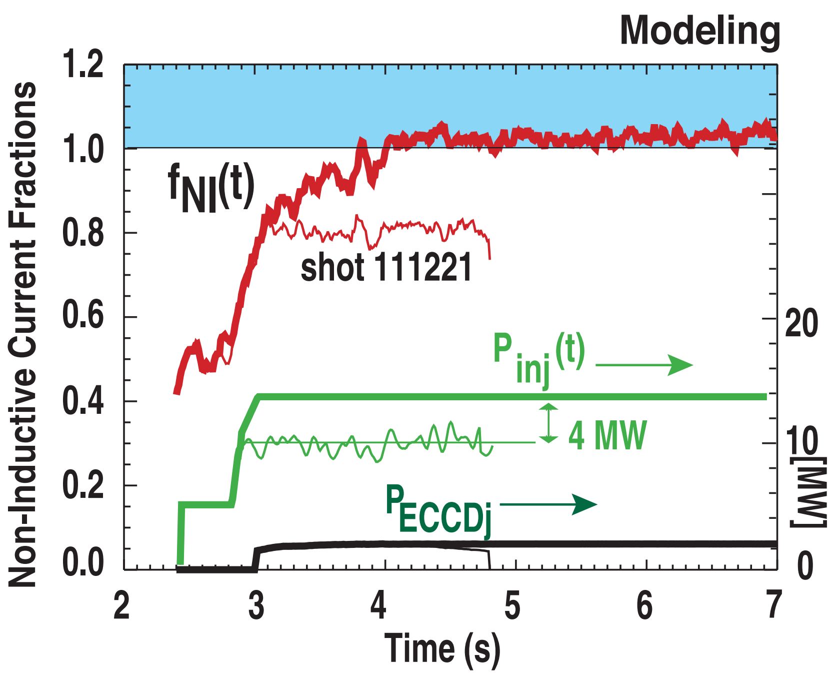
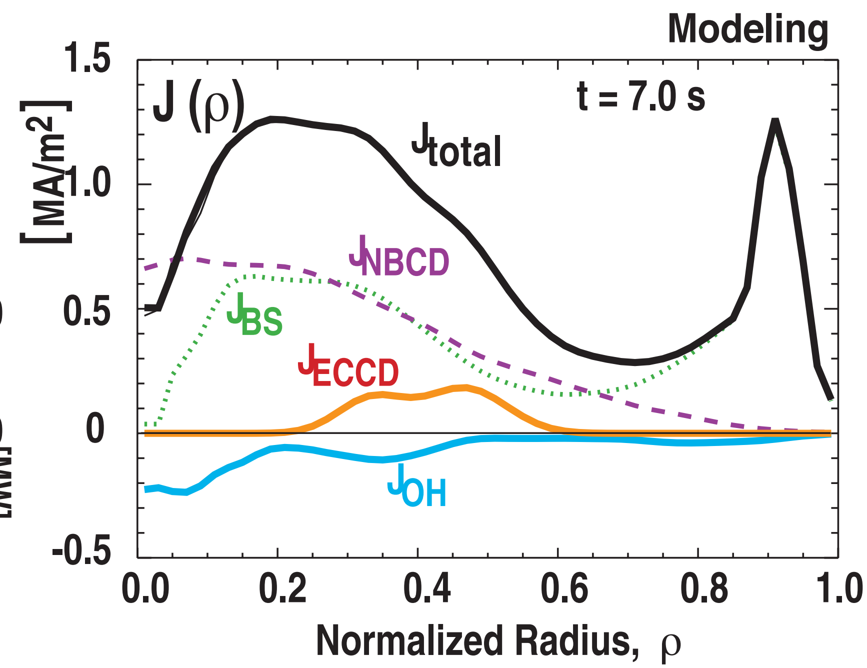
CRITICAL ISSUES COVERED IN THIS TALK

- Self-consistent solutions for full noninductive, high performance operation requires:
  1. f_{NI} = 100%
  2. Good current drive alignment
  3. Pressure profile evolution stable for ideal MHD and NTMs
  4. Current profile stops evolving ($E_{||} \approx 0$ everywhere)

- Predictive modeling:
  - Validated by the experiment
  - Projects longer sustainment of 100% noninductive in DIII-D
  - Applied to the ITER steady-state scenario development

PREDICTIVE SIMULATIONS INDICATE PREVIOUS ECCD DISCHARGE COULD BE EXTENDED TO 100% NONINDUCTIVE WITH INCREASED NBI POWER





- Two transport models produce consistent results:
  - Scaled experimental transport coefficients
  - Recalibrated GLF23

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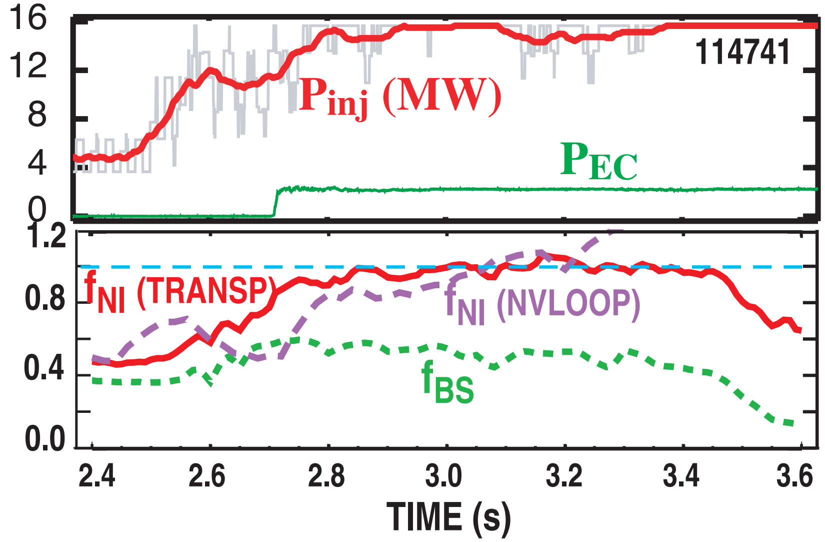
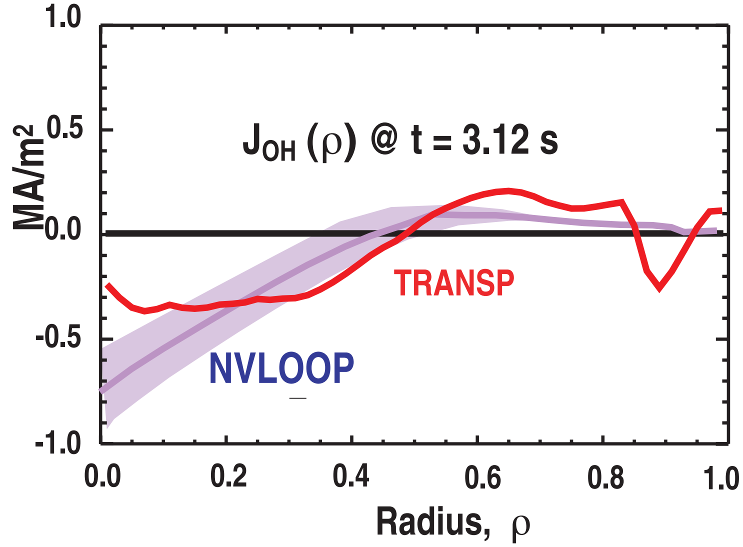
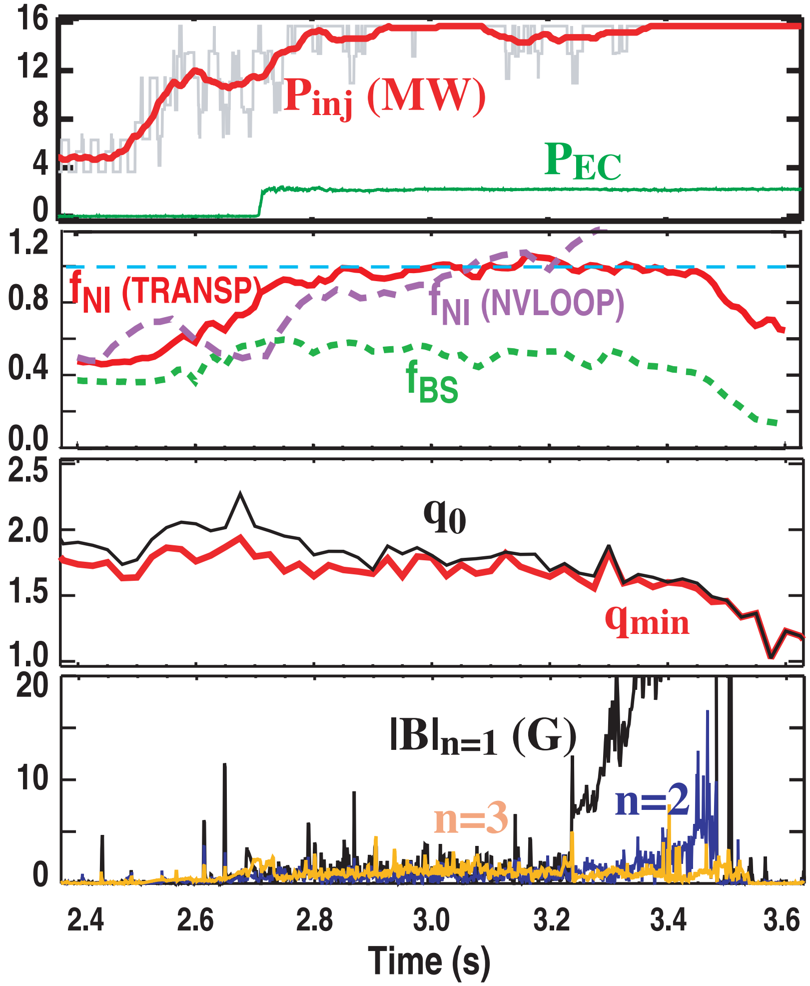
WITH HIGHER NBI POWER, 100% NONINDUCTIVE CURRENT ACHIEVED, BUT NOT FULLY RELAXED

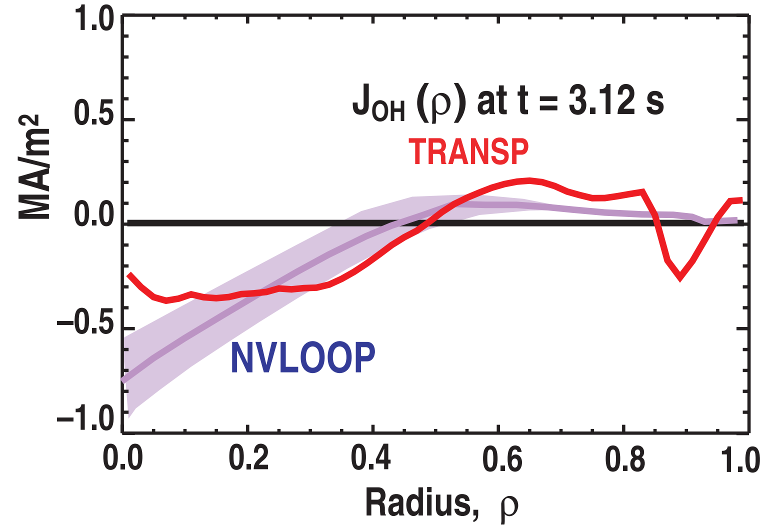




- Achieved net $f_{NI} \approx 100$ % with $\beta_N \approx 3.5$, $\beta \approx 3.6\%$
- However, local Ohmic current is NOT zero

WITH HIGHER NBI POWER, 100% NONINDUCTIVE CURRENT ACHIEVED, BUT NOT FULLY RELAXED





- Achieved net f_{NI} ≈100 % with $\beta_N \approx 3.5$, $\beta \approx 3.6\%$
- However, local Ohmic current is NOT zero
- Neutral beam overdrive near the axis decreases q_0, resulting in *NTM*s
- Confinement somewhat degraded (large P_{NB} demand) in these discharges
  - Rotation velocity often slower
  - Flatter q profiles ... often more monotonic

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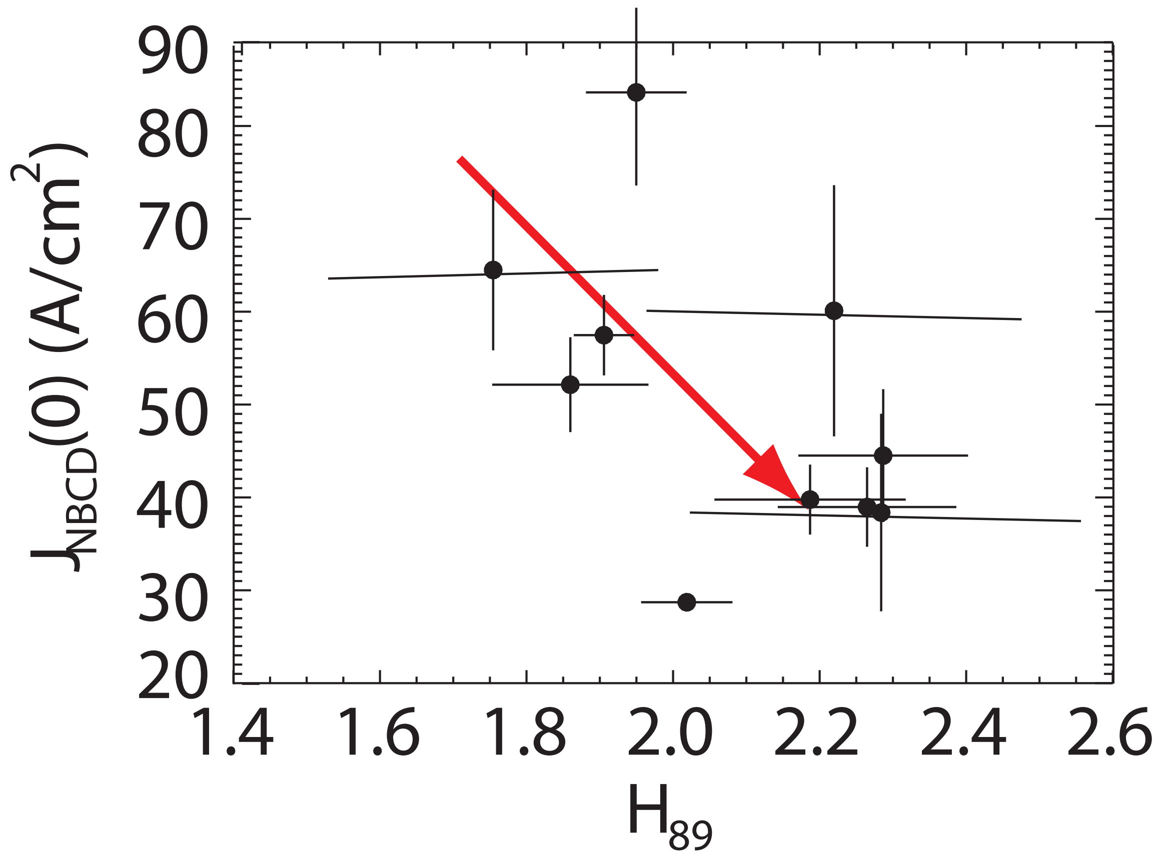
IMPROVED CONFINEMENT RESULTS IN REDUCED NEUTRAL BEAM CURRENT DRIVE NEAR THE AXIS



- **Confinement improvement in recent experiments is attributed to:**
  - **Optimized non-axisymmetric field feedback**
  - **Slightly negative central shear**

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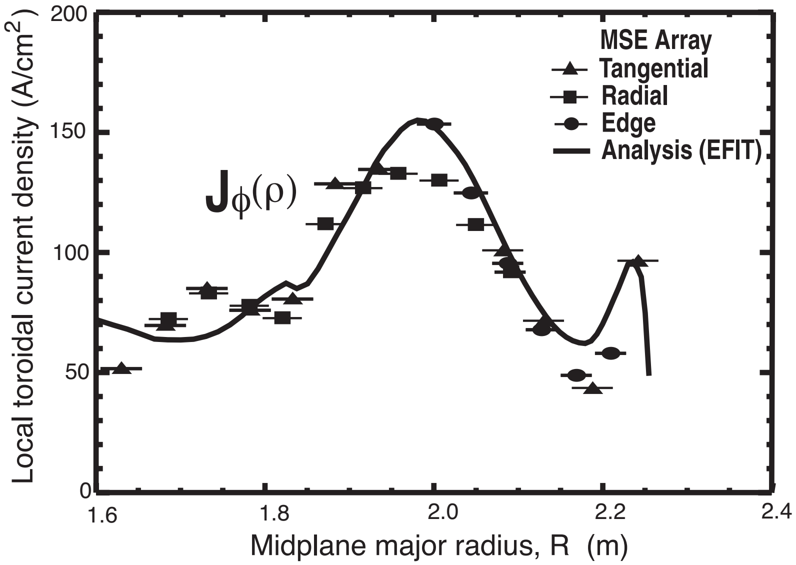
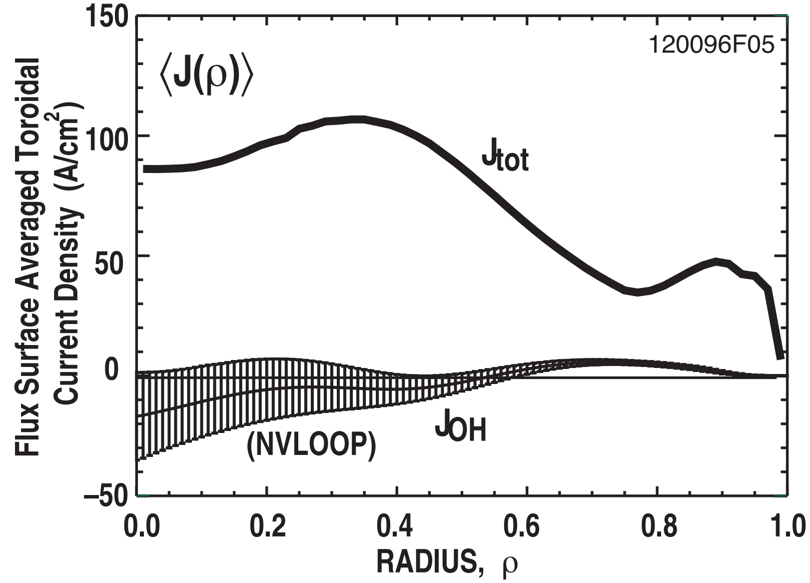
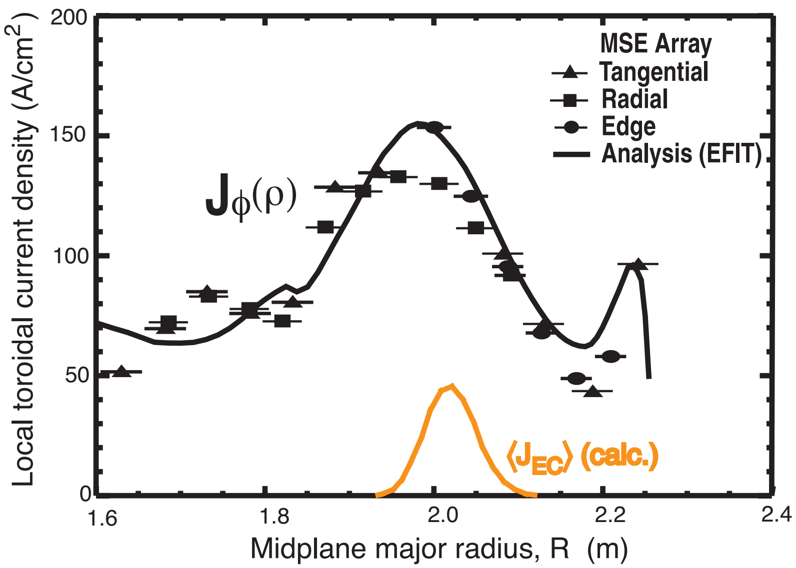
WITH IMPROVED CONFINEMENT, f_{NI}=100% ACHIEVED WITH GOOD CD ALIGNMENT

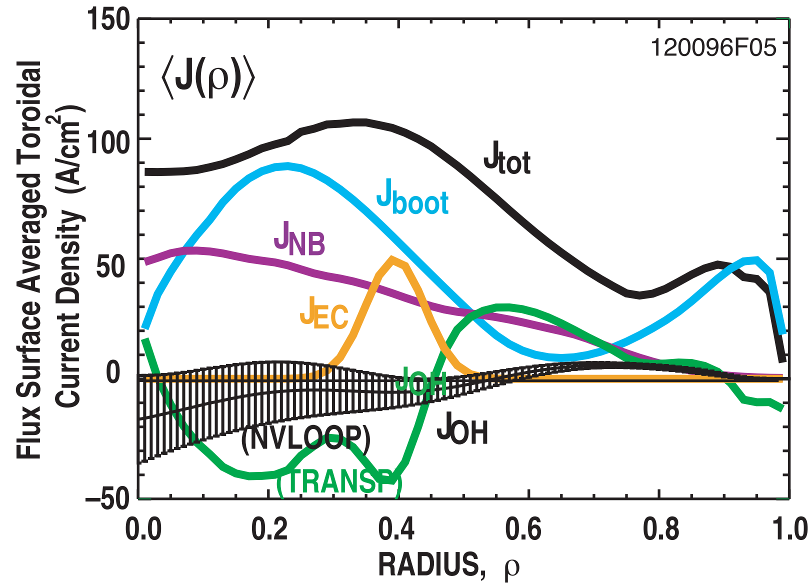




- f_{OH} = 0.5%, f_{NI} = 99.5%

WITH IMPROVED CONFINEMENT, f_{NI}=100% ACHIEVED WITH GOOD CD ALIGNMENT





- f_{OH} = 0.5%, f_{NI} = 99.5%
- Analysis shows: f_{BS}=59% f_{NB}=31% f_{EC}= 8% f_{NI}= 98%
- Challenge:
  - — Measurement: Local representation in EFIT, . . .
  - — Analysis/modeling: Bootstrap model near axis and edge, . . .
- These analyses indicate achievement of $f_{NI} \approx$100%

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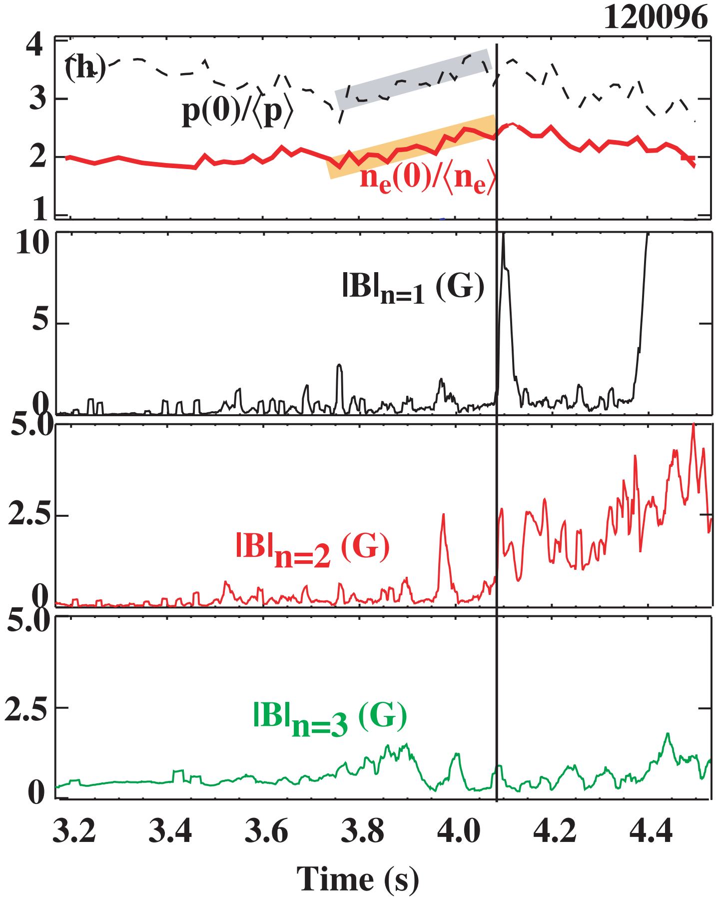
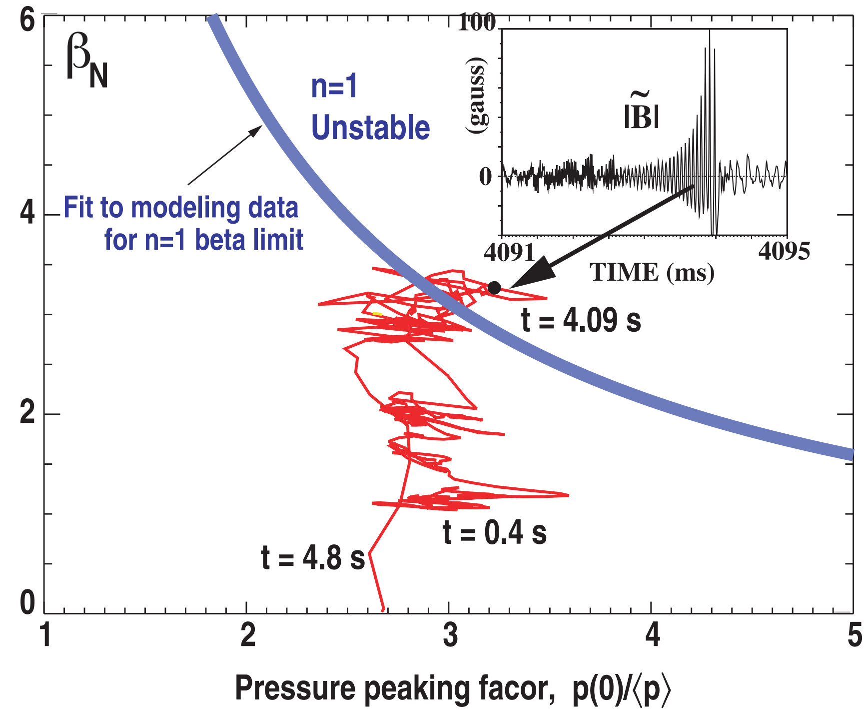
PRESSURE PROFILE EVOLUTION RESULTED IN n=1 FAST GROWING MODE WHICH TRIGGERED n=1 *NTM*

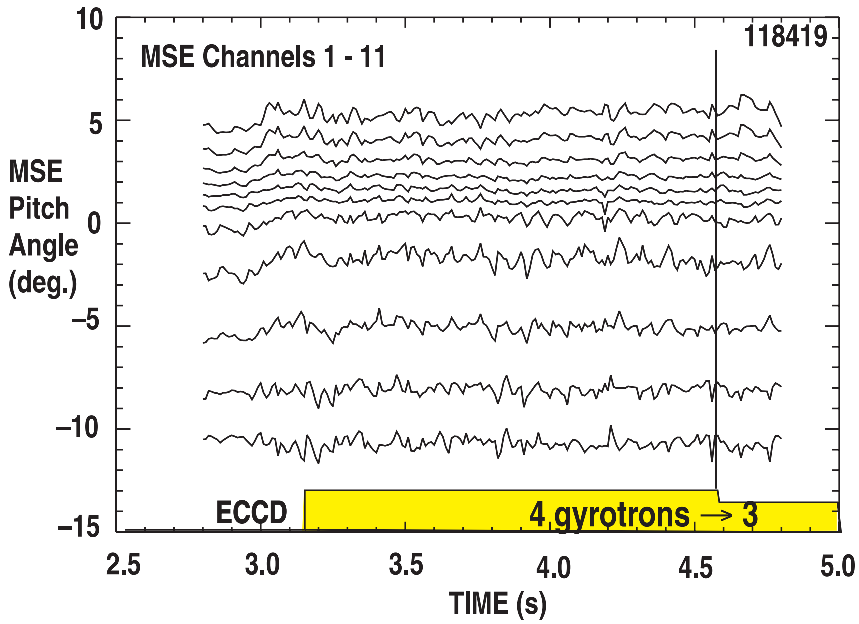


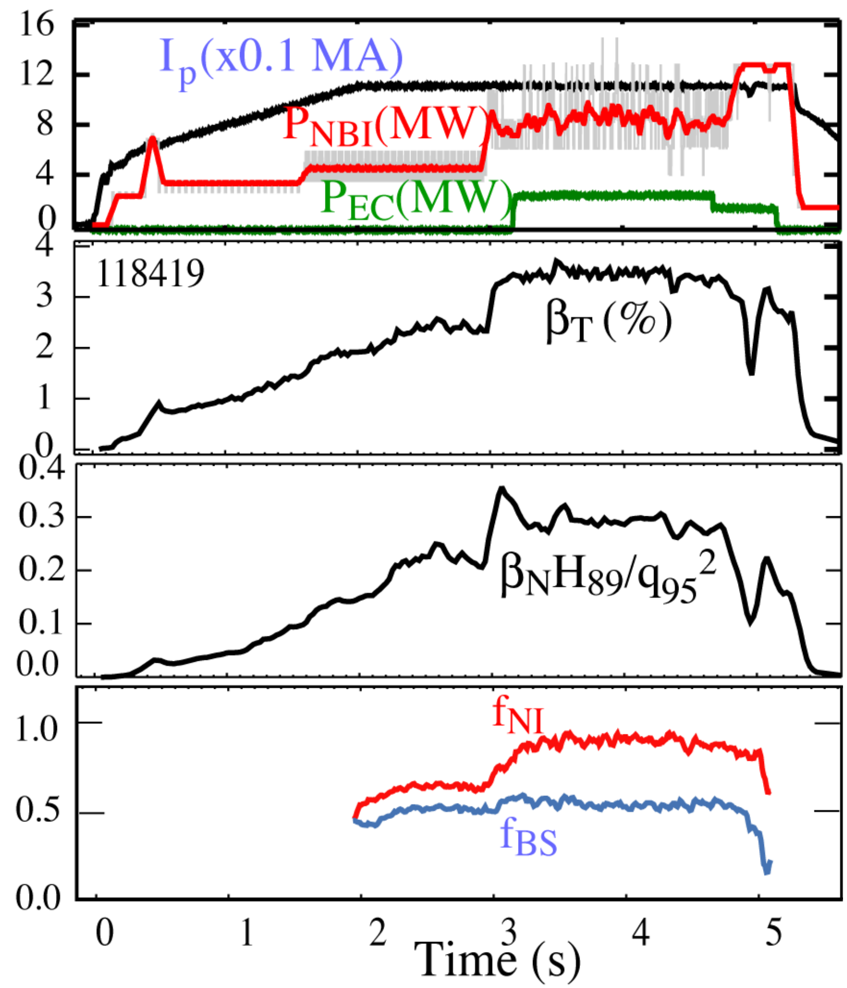


- n=1 ideal instability caused by pressure peaking primarily due to density peaking
- Sustained n=1 NTM terminates high performance phase

J. Ferron: EX/P-2-20

NEARLY FULL NONINDUCTIVE, STATIONARY DISCHARGE OBTAINED, LIMITED ONLY BY GYROTRON PULSE LENGTH





- MSE signals stationary
  ⇒ $J_\phi(\rho)$ stopped evolving
- f_{NI}~ 90% for 1 τ_R (=1.8s)
- β_T = 3.7%, β_N = 3.5, q_{95} = 5.1
- G=$\beta_N H/q^2$ = 0.3 with f_{BS}=63%

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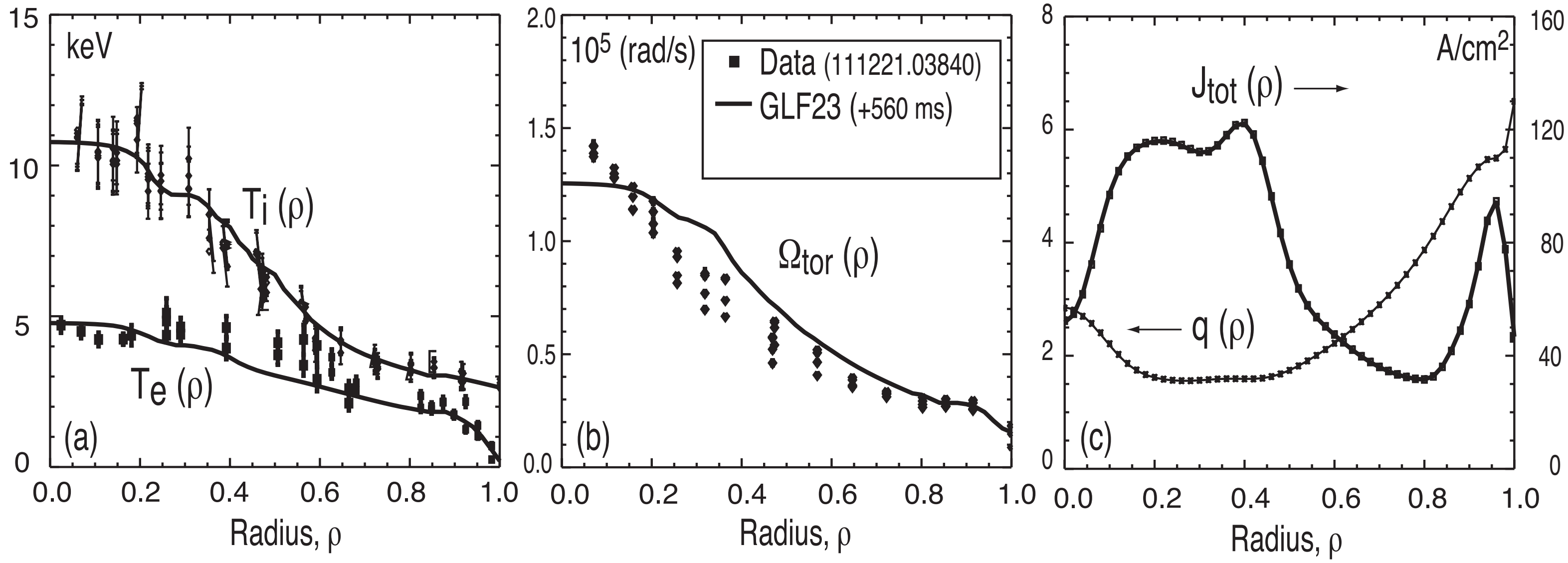
GLF23/ONETWO CAN REPRODUCE EXPERIMENTAL PROFILES REASONABLY WELL, AND ALSO CAN PREDICT STEADY STATE PERFORMANCE IN TOKAMAKS



- **Good coupling between experiment and modeling**

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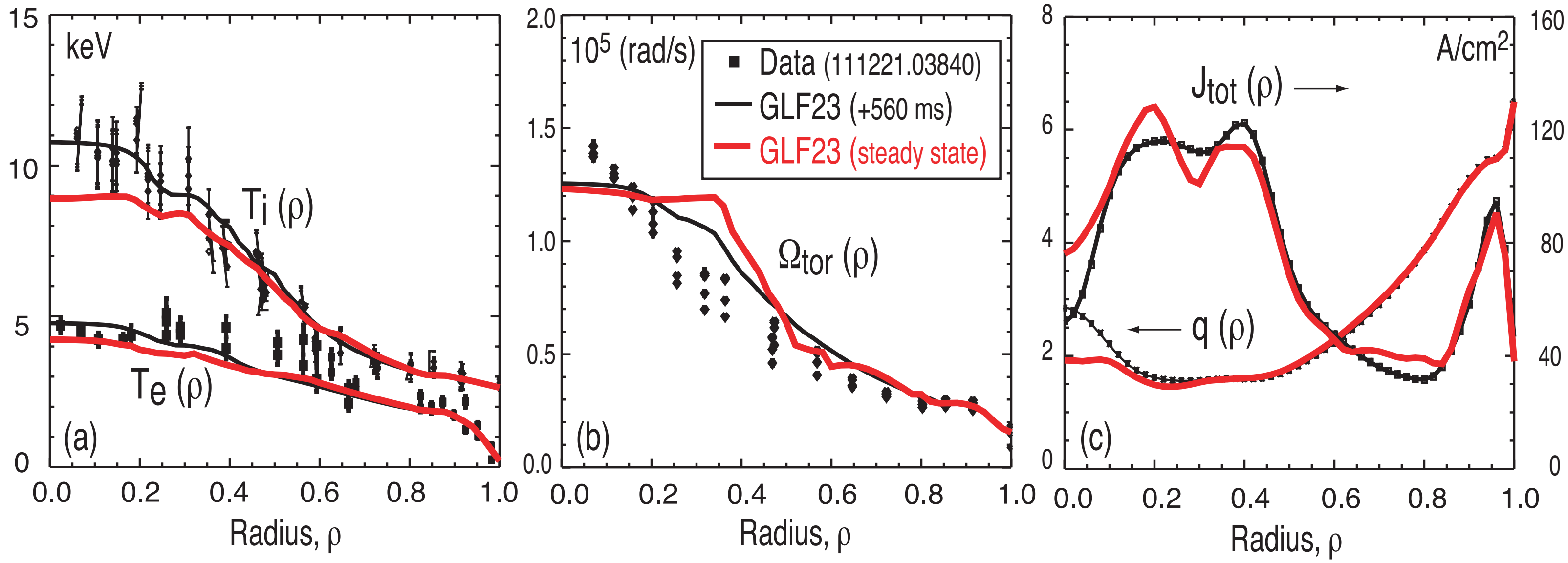
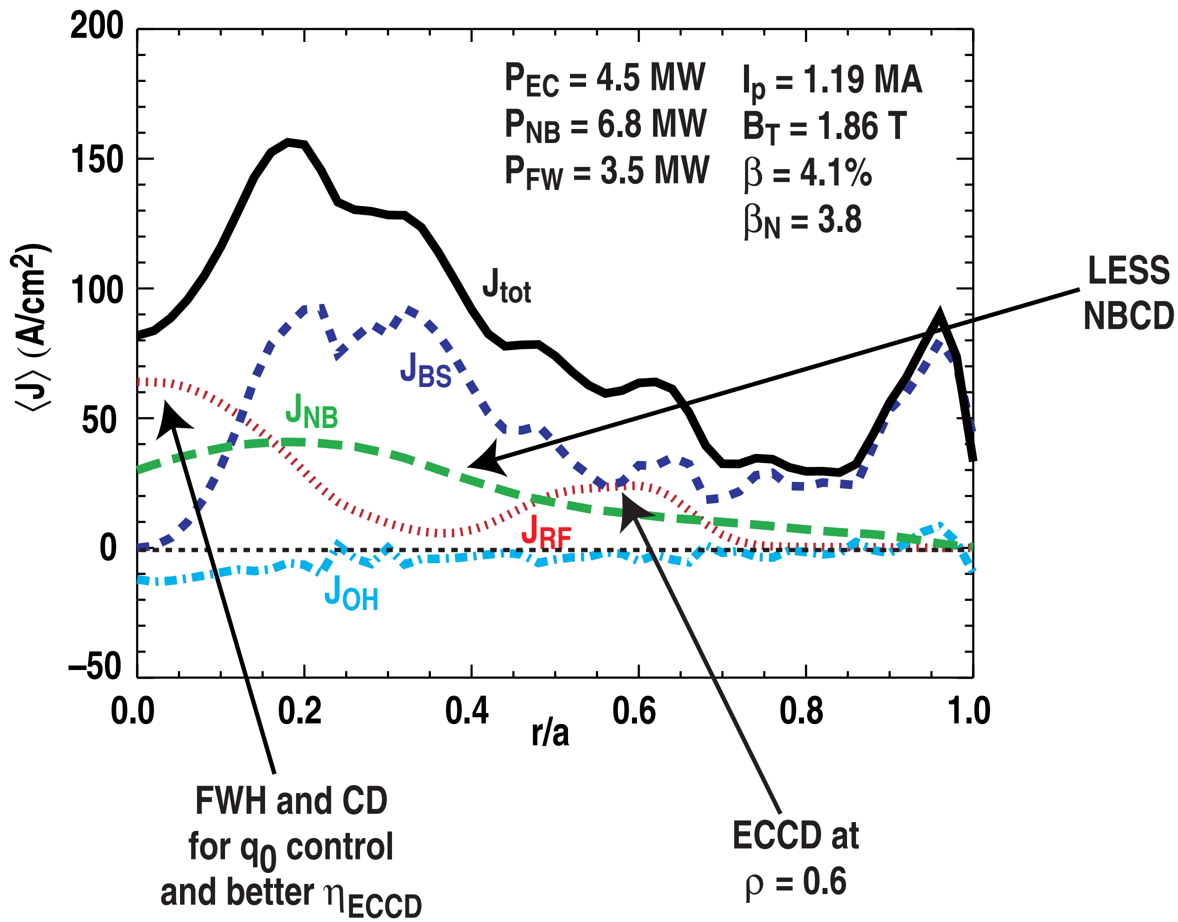
GLF23/ONETWO CAN REPRODUCE EXPERIMENTAL PROFILES REASONABLY WELL, AND ALSO CAN PREDICT STEADY STATE PERFORMANCE IN TOKAMAKS



- Good coupling between experiment and modeling
- Numerical advance (global convergence technique) incorporated into ONETWO allows prediction of steady state in one step (without time stepping calculation)

GLF23 MODELING INDICATES THAT STEADY STATE OPERATION IS POSSIBLE WITH β VALUES CONSISTENT WITH STABILITY LIMITS



- Modeling uses hardware improvements planned for DIII–D:
  - Better control of J(ρ) and p(ρ) at high beta with more EC and FW power with long duration
  - Advanced plasma control system

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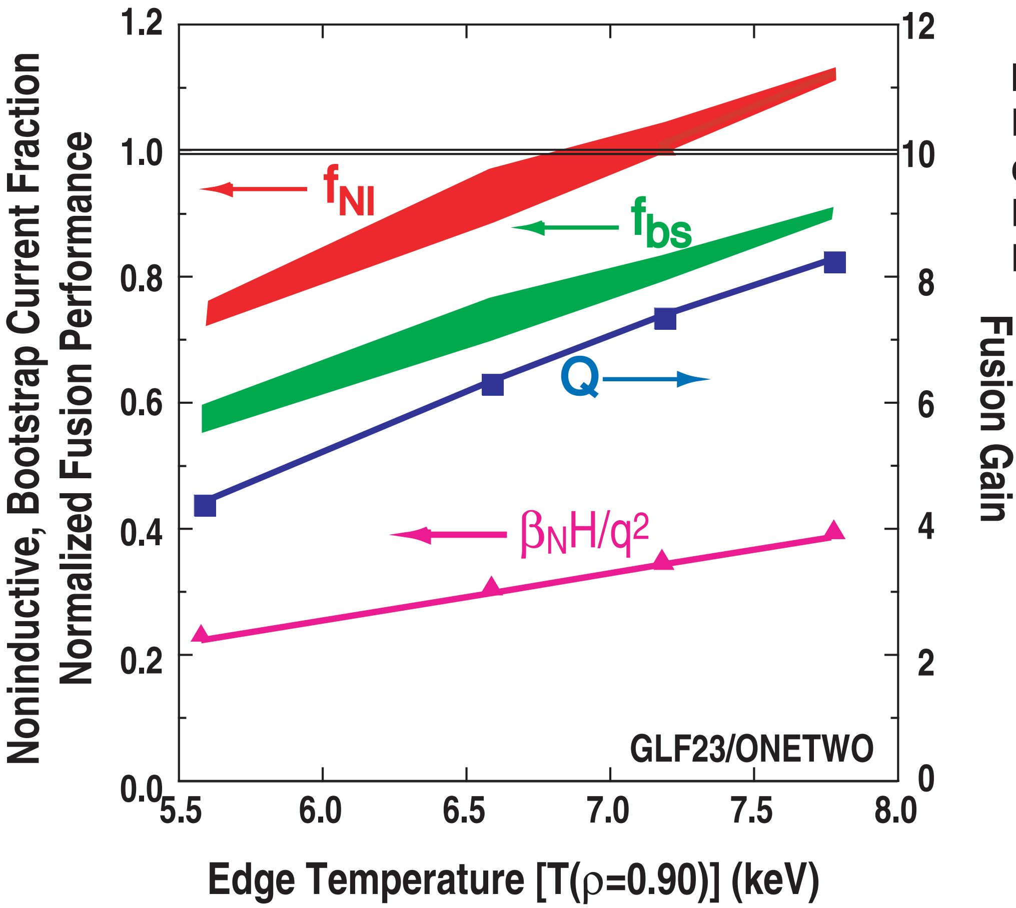
10/31/04: IAEA2004:v3.3 -- MM

MODELING APPLIED TO ITER *AT* SCENARIO PREDICTS f_{NI} = 100% FEASIBLE WITH Q > 7



ITER Day-1:
B_T = 5.3 T, I_p = 9 MA
q_{95} = 4.5, n_e = 1.04 n_{GW}
P_{NB} = 33 MW, P_{IC} = 20 MW
$P_{EC} \leq$ 8 MW

- Stiff transport model ⇒ Core performance related to edge ⇒ Edge temperature scan
- β_{ped}=1.2 % for Tped =7 keV appears to be below max(β_{ped}) for peering-ballooning mode
- It emphasizes importance of understanding the edge pedestal in AT plasmas
- More detail will be discussed by W. Houlberg [IT/P3-33

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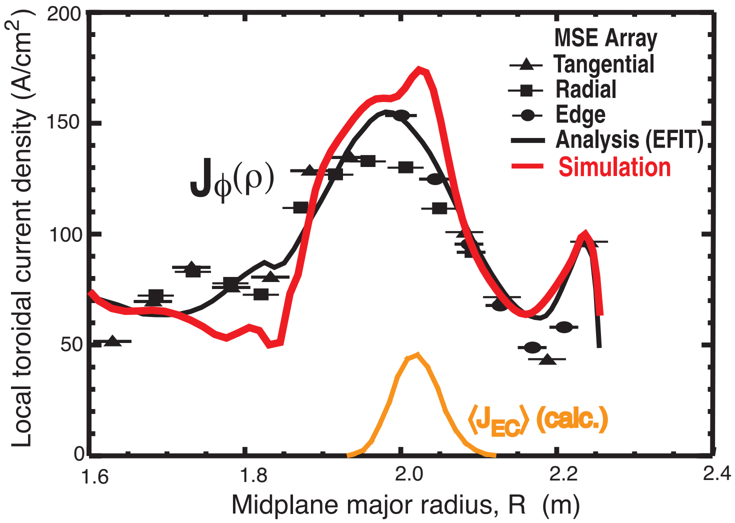
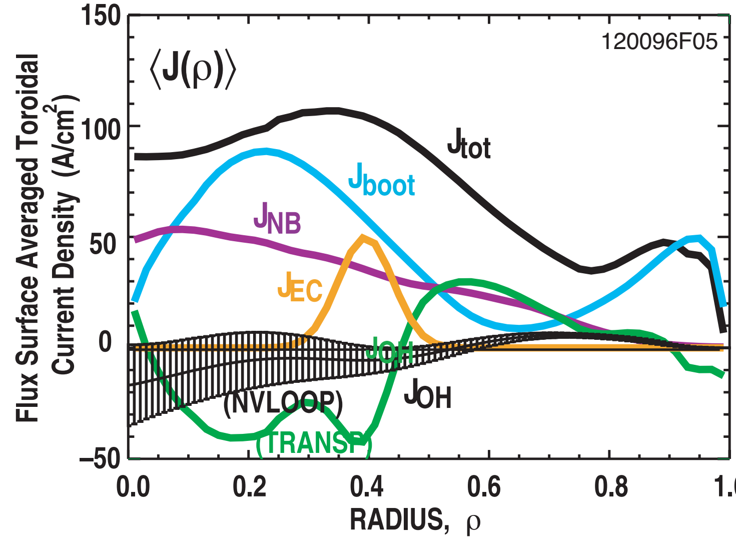
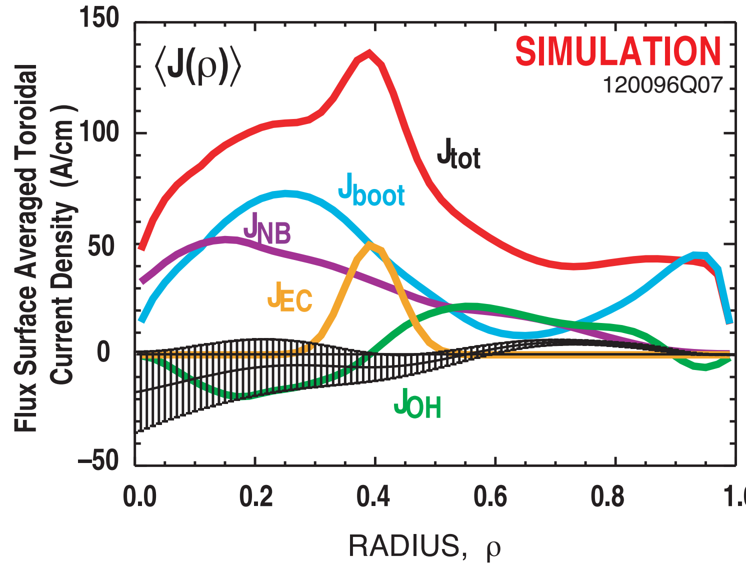
CONCLUSIONS

- 100% noninductively driven plasmas with good *CD* alignment at $\beta_T \leq 3.6\%$ and $\beta_N \leq 3.5$ for up to one current relaxation time
- With good coupling between experiment and modeling, progress has been made in several important areas:
  - Current drive alignment
  - Current profile stationary over one current relaxation time
  - Challenge: Control of current and pressure profile evolution to avoid MHD instabilities to further extend high performance phase
- Future plans include:
  - Better control of J(ρ) and p(ρ) at high beta with more EC and FW power with long duration
  - Advanced plasma control system
- The scientific basis being developed on DIII–D is leading to increased confidence in establishing steady-state scenarios for ITER and beyond

WITH IMPROVED CONFINEMENT, f_{NI}=100% ACHIEVED WITH GOOD CD ALIGNMENT







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- Challenge:
  - Measurement: Local representation in EFIT, . . .
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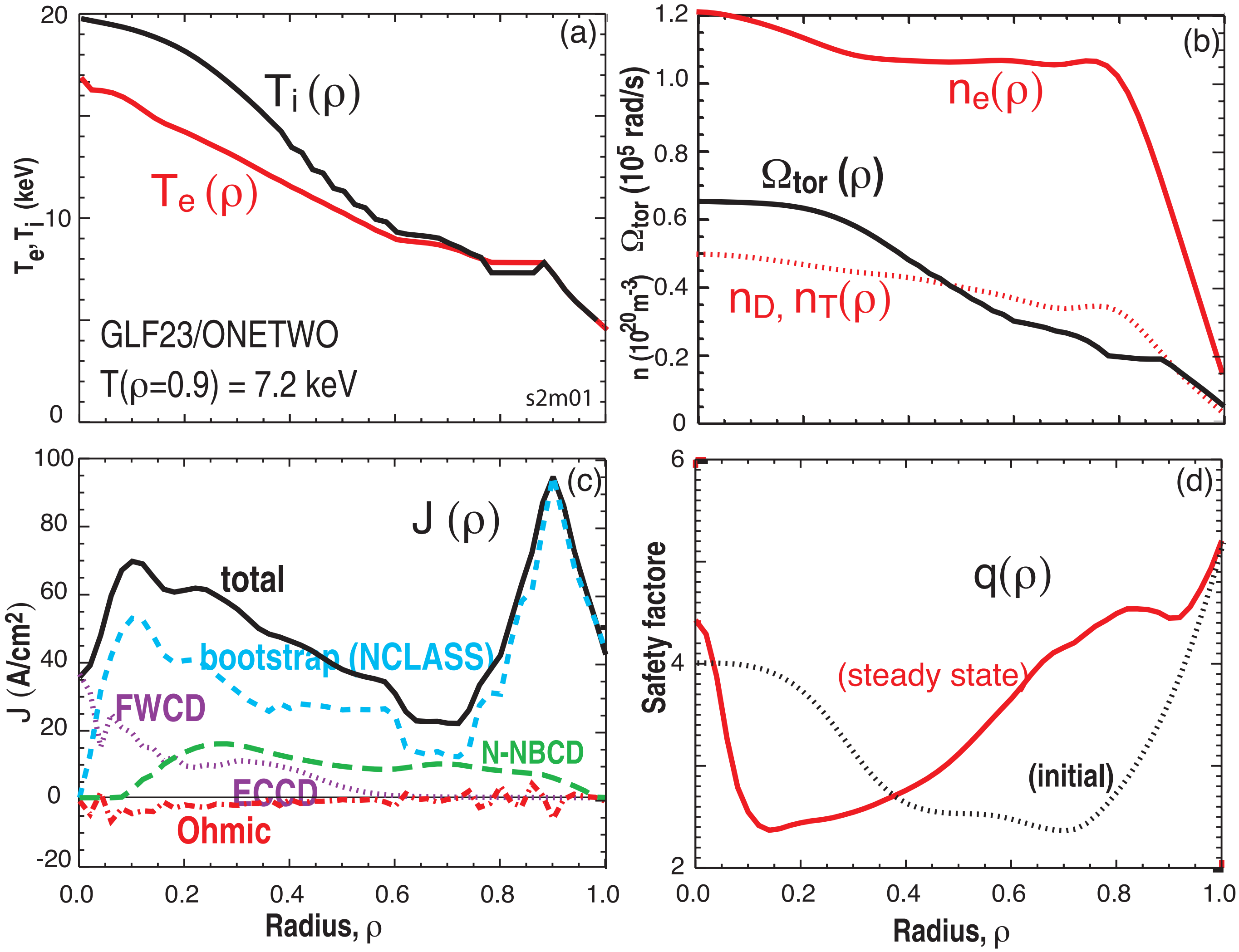
GLF23/ONETWO MODELING FOR ITER STEADY STATE SCENARIO



- The pedestal values of n_e=6e19, T=7keV give β_{ped}=1.3%which is not particularly a high value
- This value corresponds to maximum stable (Pearing-ballooning mode) β_{ped} for Δ_{ped}/a=0.04, and our Δ_{ped}/a is assumed to be larger than that.

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