DIII–D PROGRAM
RECENT RESULTS AND FUTURE PLANS

by
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Institute of the Americas, University of California at San Diego

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INTRODUCTION

- Advanced Tokamak results and plans
- ECH and ECCD
- Divertor research
- Stability physics
- Confinement and ITB
- Overall future plans

THE DIII–D PROGRAM WORK WITH OTHER PROGRAMS INTERNATIONALLY TO OPTIMIZE THE TOKAMAK APPROACH TO FUSION ENERGY PRODUCTION

- Main focus – Advanced Tokamak research
- Resolve key enabling issues for next step toward fusion energy
- Advance the science of magnetic confinement on a broad front

OUTSTANDING RECENT RESEARCH RESULTS

- **Advanced Tokamak**
  - Good progress on AT scenarios (β_N H_{89P} ~ 9 for 2 s)
  - First results using smart conducting shells for wall stabilization
  - Increased physics understanding of edge and internal plasma instabilities
  - Exploration of internal transport barriers with counter injection and pellets
  - Exciting new work affecting turbulence using impurity atoms
- **Next Steps**
  - New discovery — ELM-free H–mode without impurity accumulation or density buildup
  - New discovery — H–mode confinement quality above the Greenwald limit with gas fueling and pumping
  - A scientific basis for the choice of the optimum shape of the plasma
- **Broad Science**
  - Measurement of the complex 2–D flow patterns in the edge plasma
  - Studies of self-organized criticality
  - Movies of edge-plasma turbulence from plasma fluctuation measurements

DIII–D ADVANCED TOKAMAK 5–YEAR RESEARCH PLAN

Physics Development

- $\beta_N H_{89}$ ~9 for 2s ($16\tau_E$)
- ITB Physics
- Edge Stability
- Neoclassical Tearing
- Resistive Wall Mode
- AT Divertor
- ECCD Physics Validation

Physics Integration

- Integrated long duration scenarios (10 seconds) with high normalized beta, confinement enhancement, bootstrap fraction, and radiative divertor

— Increased stability limits

— Use and optimization of transport barriers at high beta

— Non-inductive current sustainment with high bootstrap current fraction

— Divertor power and particle control

CY	1999	2000	2001	2002	2003	2004
Checkpoints				◆ Progress Checkpoint		FESAC Checkpoint ◆
Operation Periods	▬	▬	▬	▬	▬	▬
Current Drive (EC)		△ 4 Gyrotrons	△ 6 Gyrotrons	△ 8 Gyrotrons	○ 9.5 MW Long Pulse	
Fueling and Edge Control	▲ Inside launch pellet	▲ Upper Divertor				
Resistive Wall Mode Control	▲ 6 Coil Feedback			△ 18 Coil Feedback		
Diagnostics	▲ Central Thomson	▲ Upper Divertor Diagnostics	△ Edge J(r)	△ Electron Transport	△ 3-D Equilibrium	

Other Options

- ○ Divertor Improvement
- ○ Counter NBI
- ○ Liquid Jet
- ○ In-vessel wall stabilization systems
- ○ Diagnostics

▲ = Completed △ = Planned ○ = Option

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PRIMARY INTEGRATED SCENARIO NCS USING OFF–AXIS ECCD

	2001	2002	2003
P_{EC} (MW)	2.3	4.5	7.0
P_{FW} (MW)	3.5	3.5	6.5
P_{NBI} (MW)	4.1	3.8	6.5
B_T (T)	1.6	1.75	1.95
I_P (MA)	1.0	1.3	1.6
I_{BOOT} (MA)	0.65	0.9	1.07
I_{ECCD} (MA)	0.15	0.2	0.35
β_N	4.0	5.3	5.7
H_{89P}	2.8	3.5	3.5
$\bar{n}/n_G$	0.3	0.4	0.4
Wall stabilization	6-coil	18-coil	18-coil

($\rho_{ITB} \sim \rho_{qmin}$)

χ_e – various models

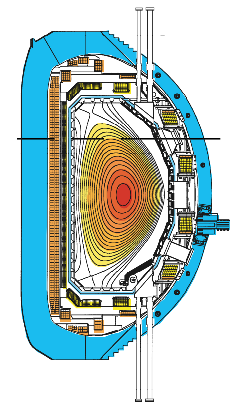
χ_i ~ neoclassical inside $\rho(q_{min})$

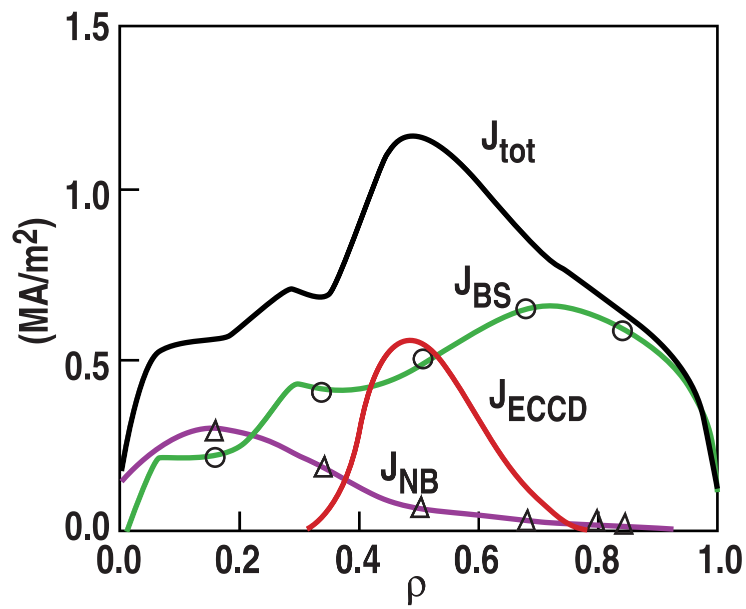
~ $5 \times$ neoclassical at edge

Solved for T_e, T_i, J(r)

Off-axis ECCD

n_e(r) fixed





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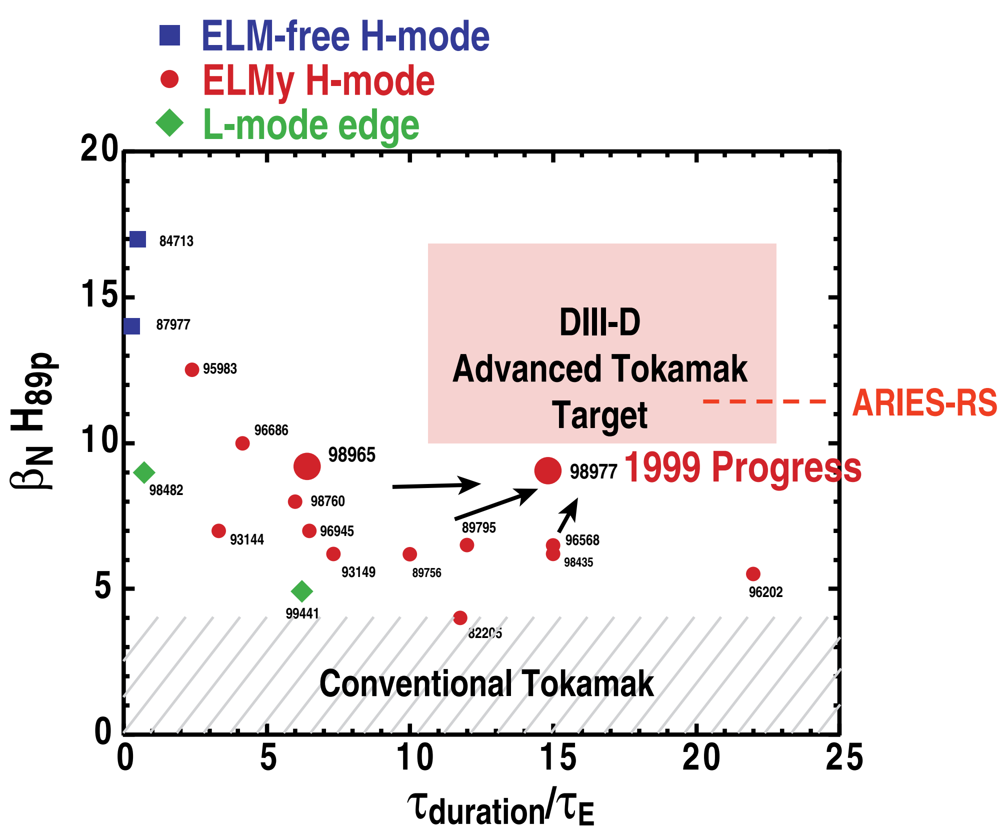
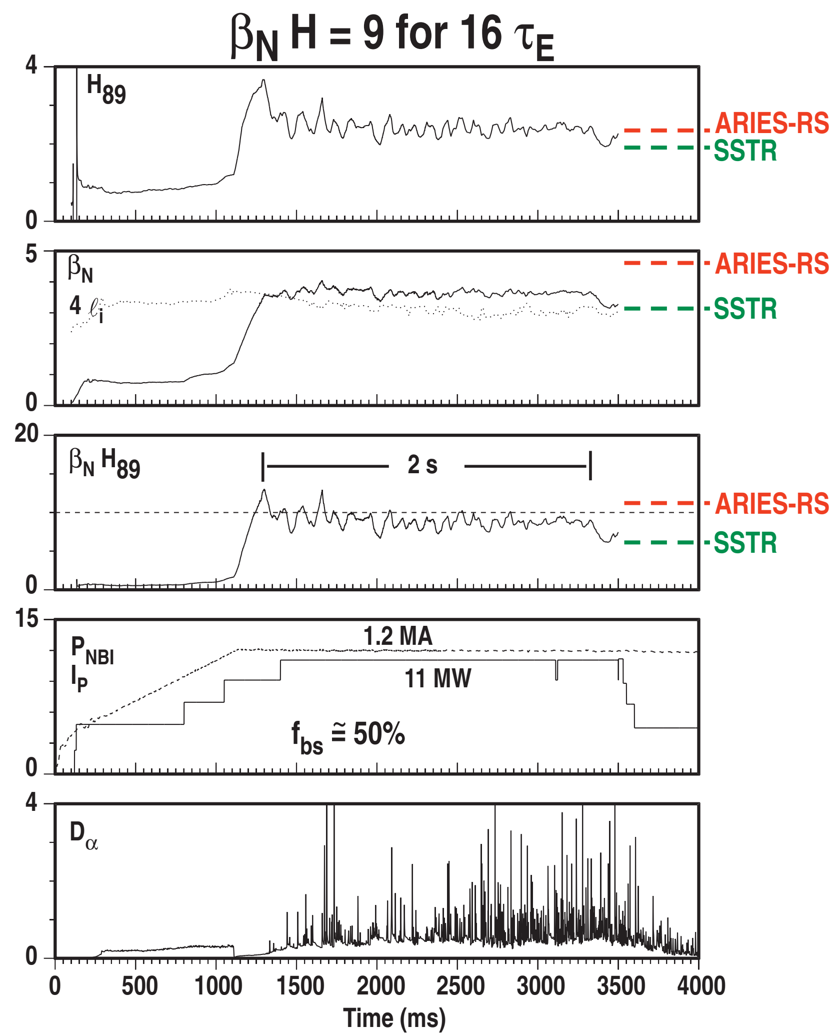
SIGNIFICANT IMPROVEMENT IN LONG-PULSE ADVANCED TOKAMAK PERFORMANCE HAS BEEN ACHIEVED (T#2)

- Recent emphasis is on increasing the duration of high performance and increasing the fraction of bootstrap current
- 2001 goal, β_N H > 10, τ_{dur} > 2 s, f_{BS} > 50%





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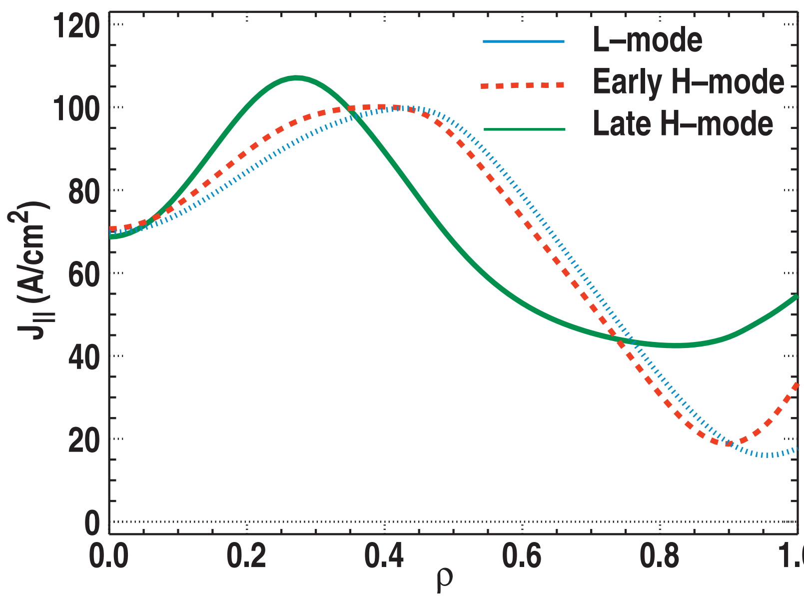
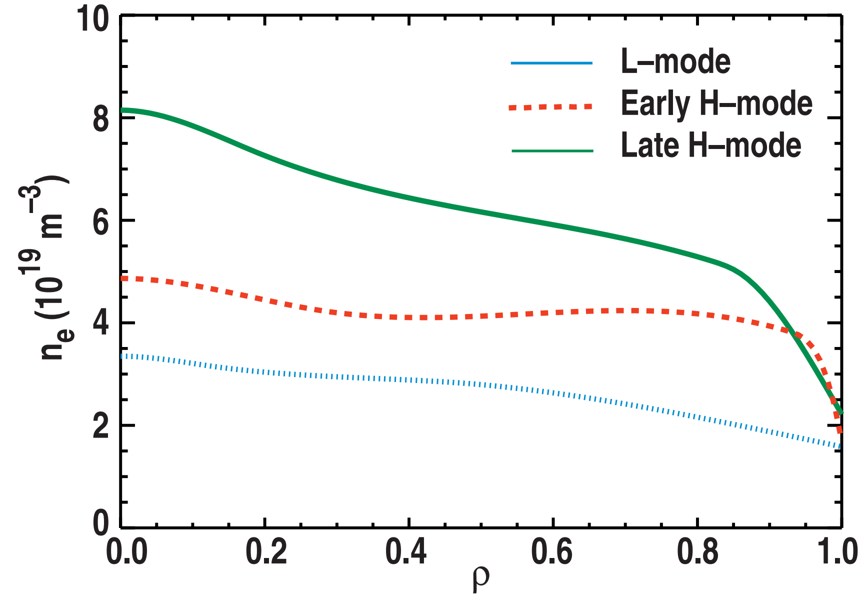
DENSITY CONTROL AND NON-INDUCTIVE CURRENT SUSTAINMENT ARE REQUIRED TO ACHIEVE STATIONARY HIGH PERFORMANCE

- Current profile diffuses to unstable profile



- Density continuously grows at constant β



- Future work
  - Density control with high triangularity closed divertor
  - Current profile control with ECCD

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GENERAL ATOMICS

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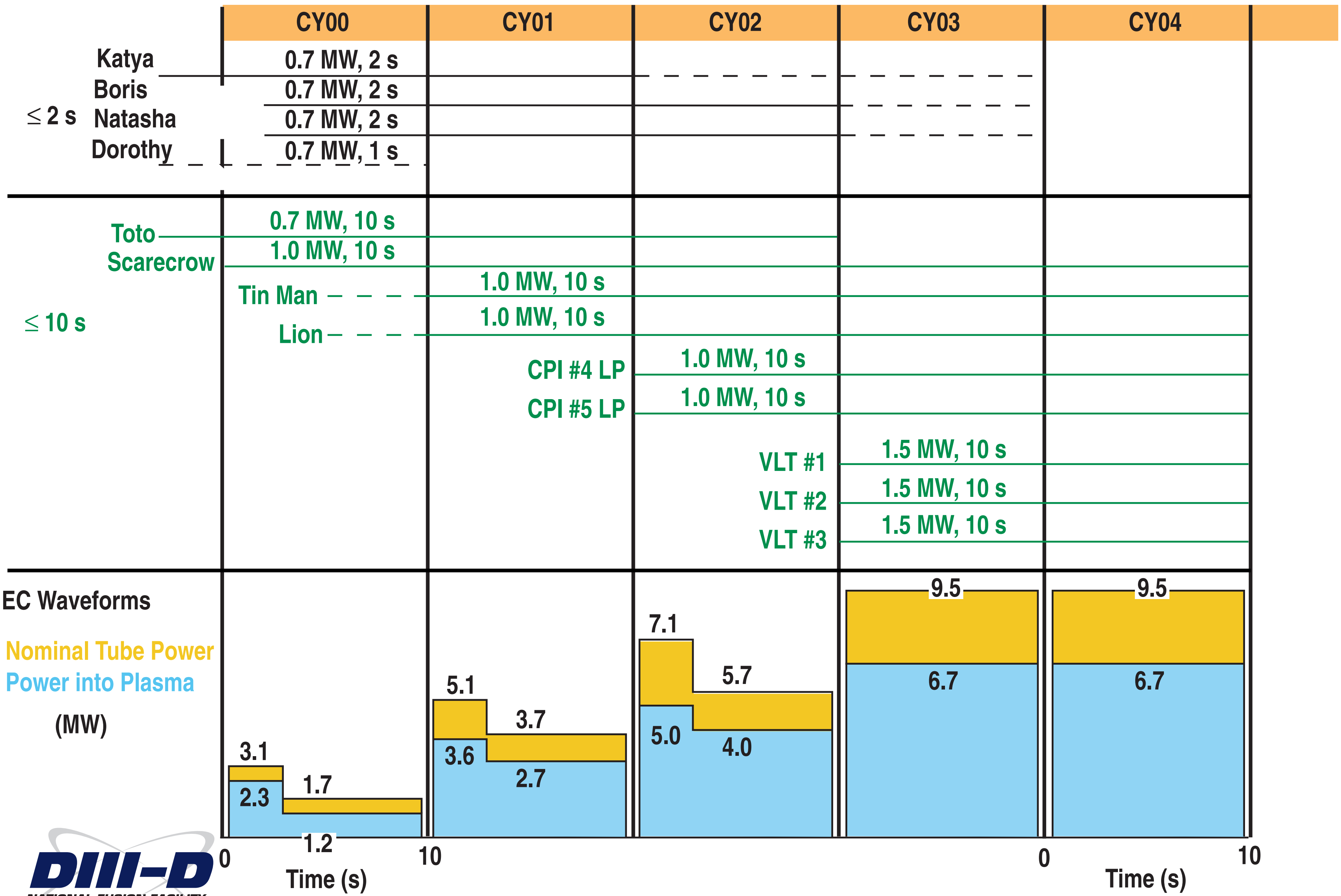
EC SYSTEM PLAN



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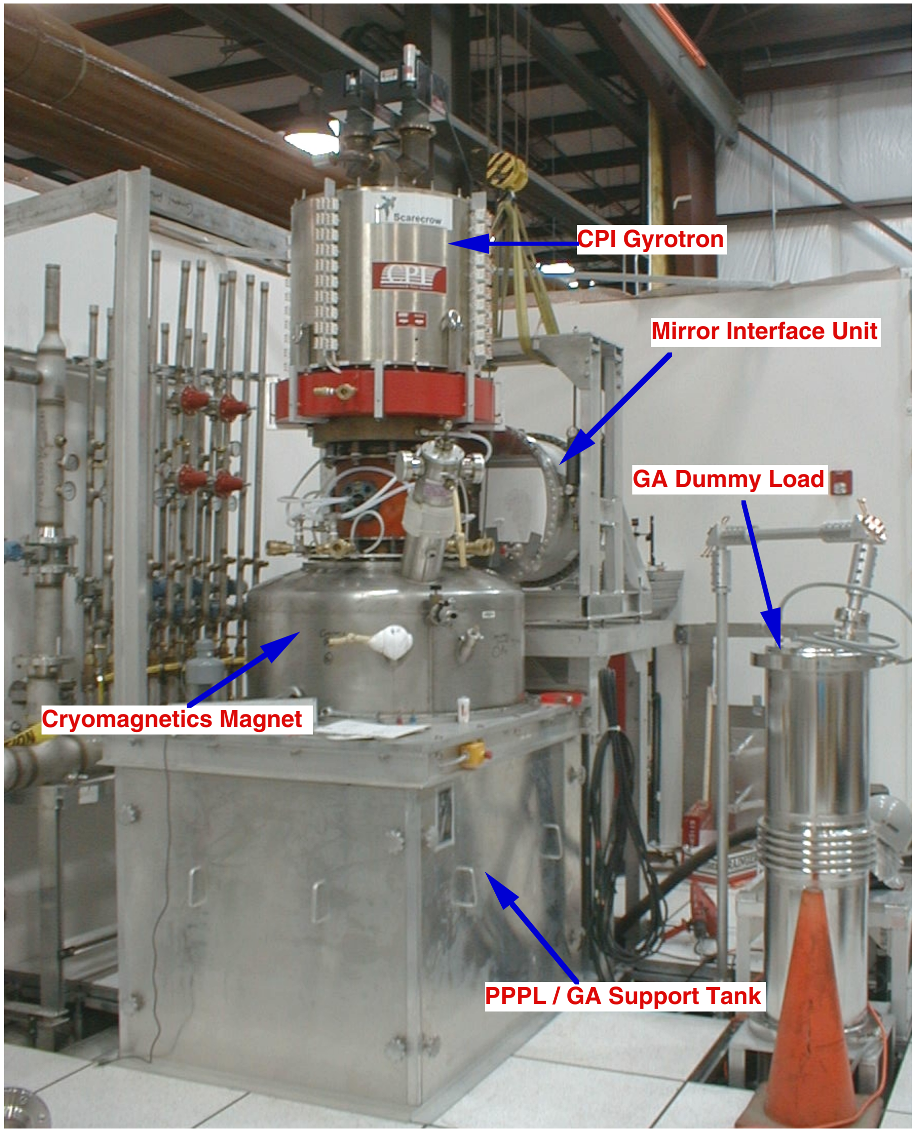
HIGH POWER EC SYSTEMS (110 GHz) BEING IMPLEMENTED FOR ADVANCED TOKAMAK PROFILE CONTROL

All 1 MW Class Gyrotrons

- Short pulse (2 seconds) gyrotrons
  - 2 from TdeV
  - 1 from Russia
- Long-pulse Diamond window gyrotrons (10 seconds)
  - 1 development unit
  - 3 new units
    - ★ 550 kW, 10 s test

New Diamond Window Gyrotron



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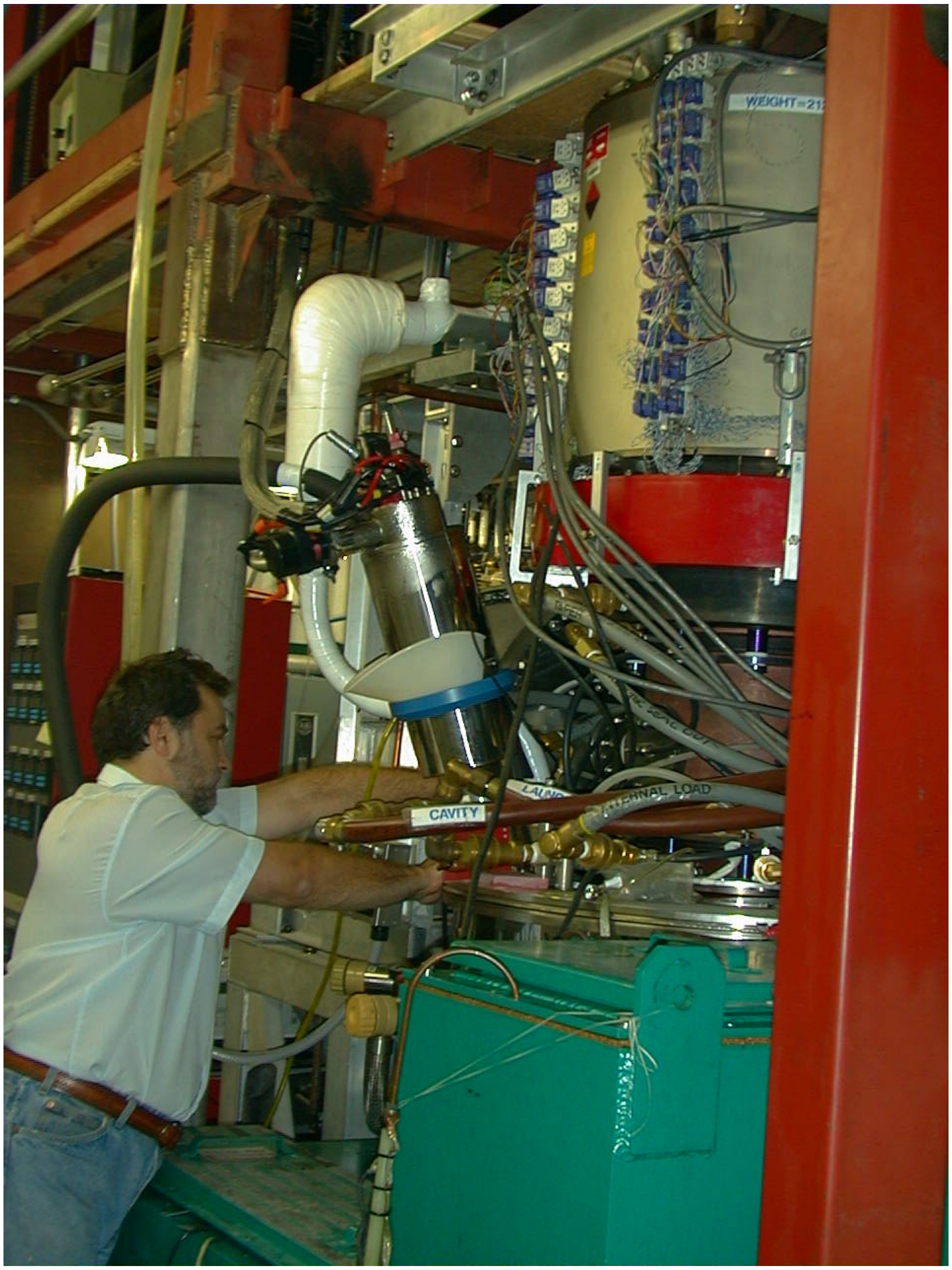
CPI GYROTRON TOTO READY FOR OPS — 650 kW FOR 2.5 s INTO DIII–D USING PPPL LAUNCHER



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CPI Communications & Power Industries

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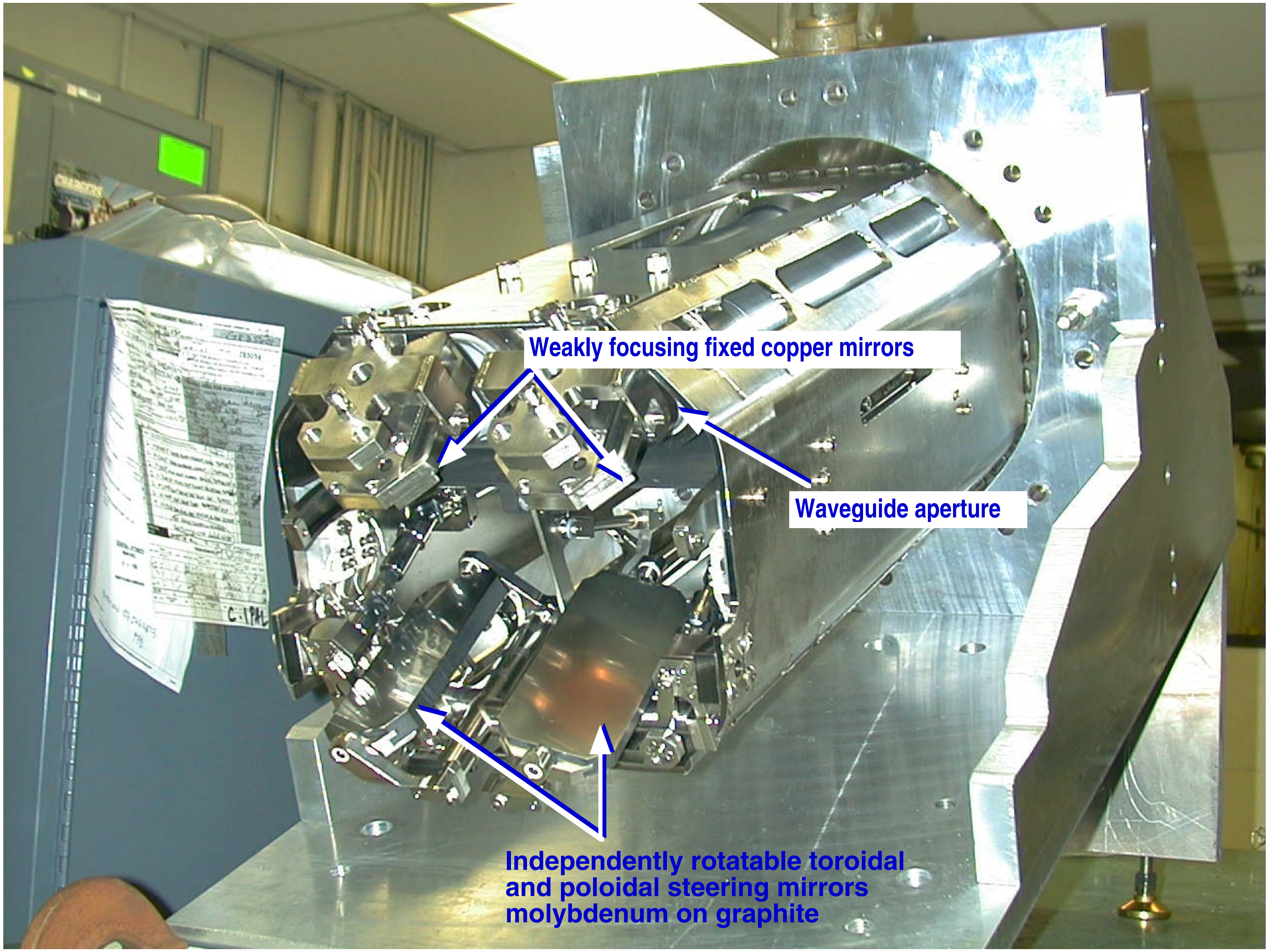
PPPL FULLY ARTICULATING ECH LAUNCHER

Co-counter experiment already performed in a single day using this launcher and TOTO



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PPPL PRINCETON PLASMA PHYSICS LABORATORY

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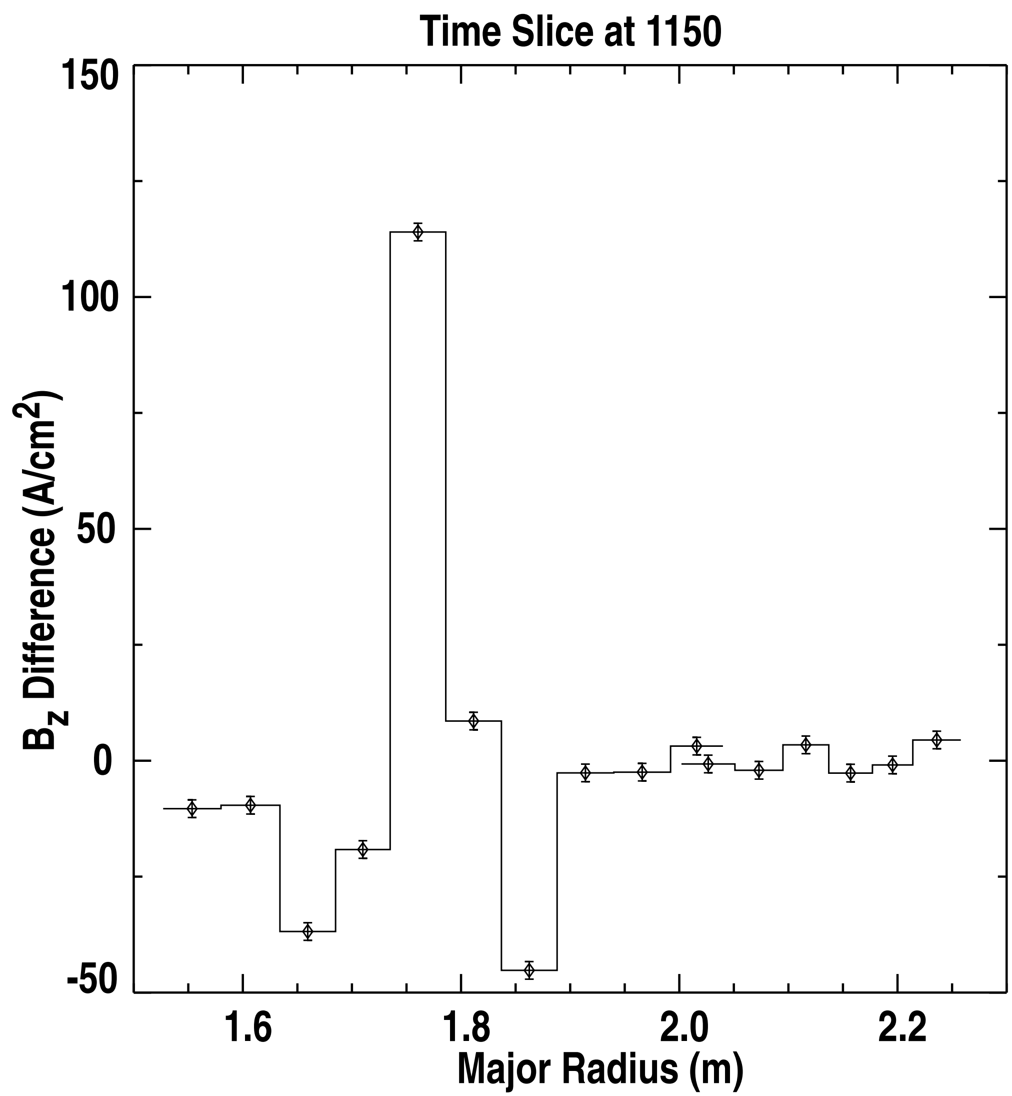
NEW CAPABILITY PROVIDED BY PPPL STEERABLE LAUNCHER ALLOWS CO/COUNTER ECCD COMPARISON

- ECCD reversed on successive shots using PPPL launcher
- Narrow profile of driven current: main current drive effects occur between one pair of MSE chords
- Future work
  - Validation of current drive models
    - ✶ X-ray camera (PPPL)
  - Validation of NTM stabilization by reversing current drive
  - Transport barrier control
  - Long-pulse steerable launcher (PPPL)



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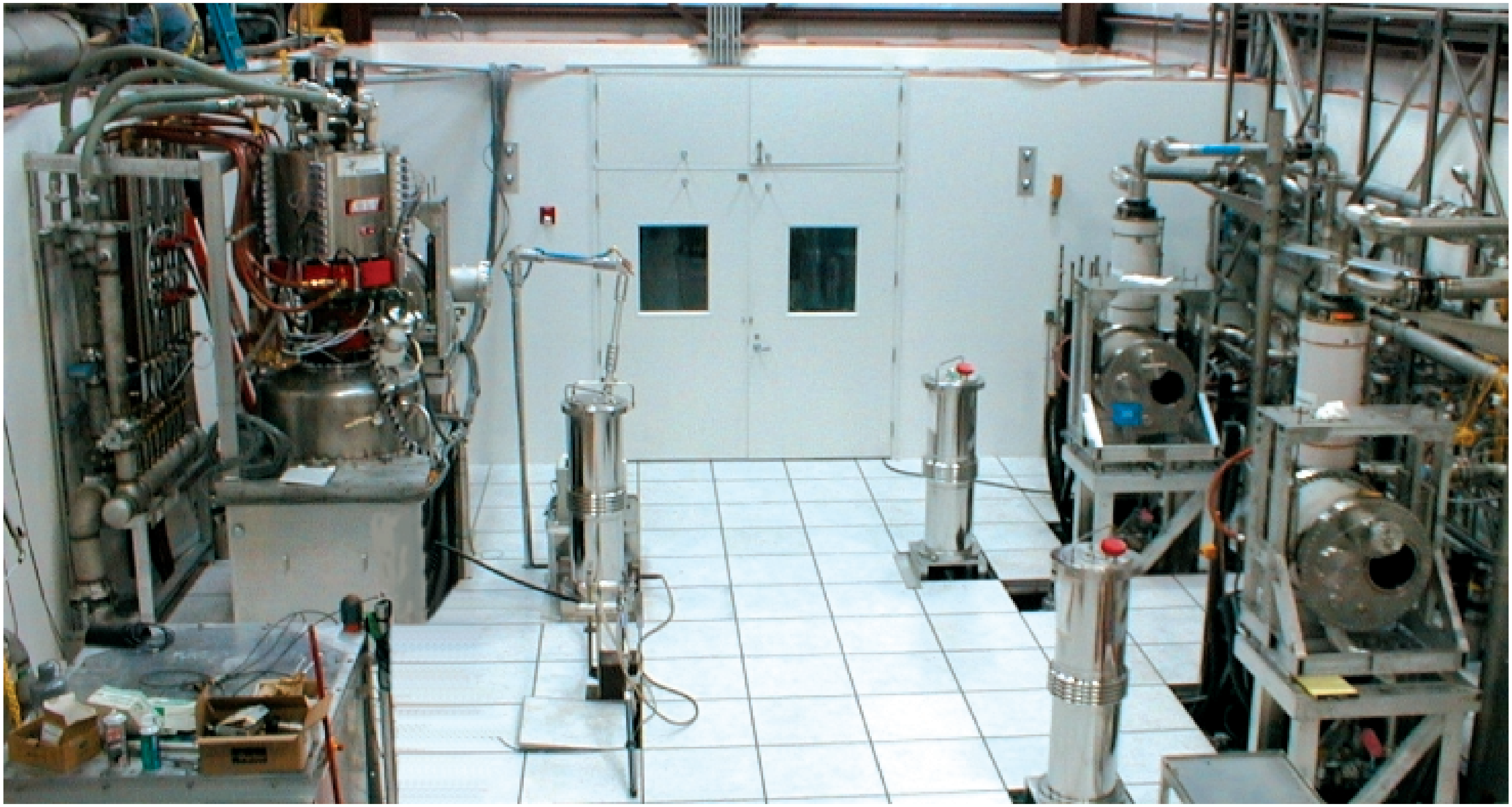
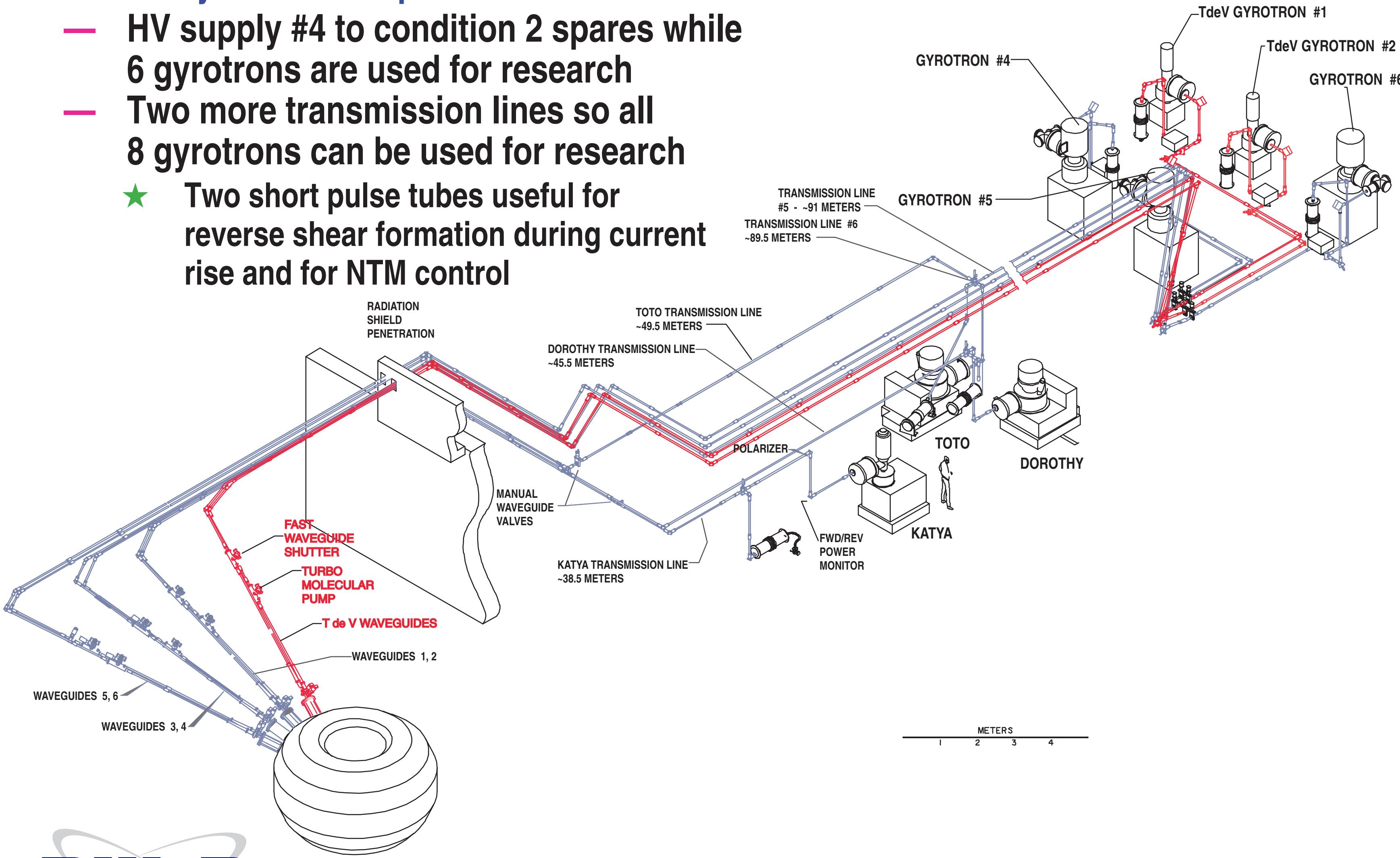
NEW GYROTRON ROOM IS FILLING UP

CPI (Scarecrow — left) and TdeV (Boris and Natasha — right)



EC SYSTEMS FOR LONG-PULSE DEMONSTRATION OF INTERMEDIATE AT SCENARIOS

- FY01 system — 8 gyrotrons in 8 sockets
- Further system development
  - HV supply #4 to condition 2 spares while 6 gyrotrons are used for research
  - Two more transmission lines so all 8 gyrotrons can be used for research
    - ★ Two short pulse tubes useful for reverse shear formation during current rise and for NTM control



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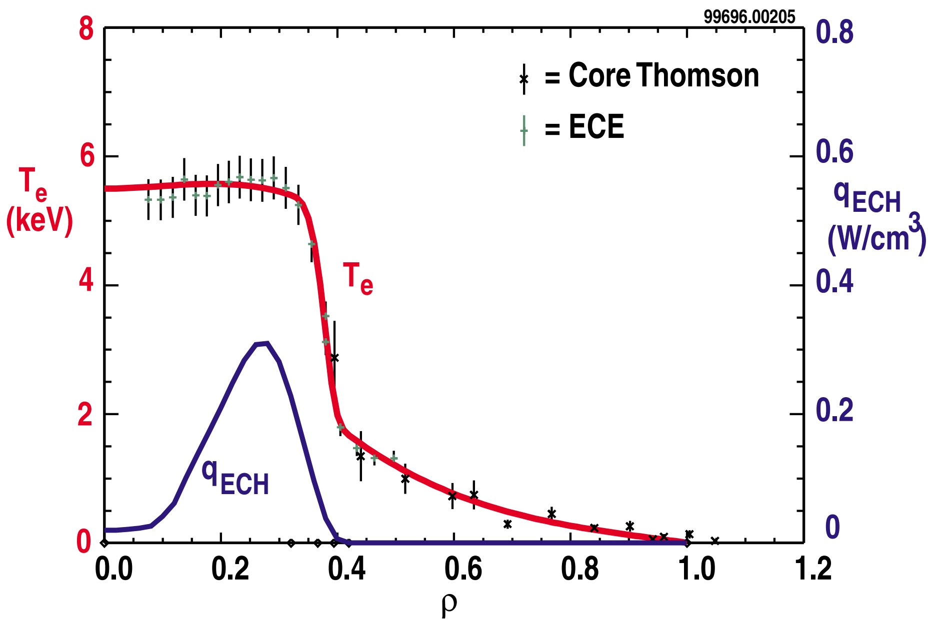
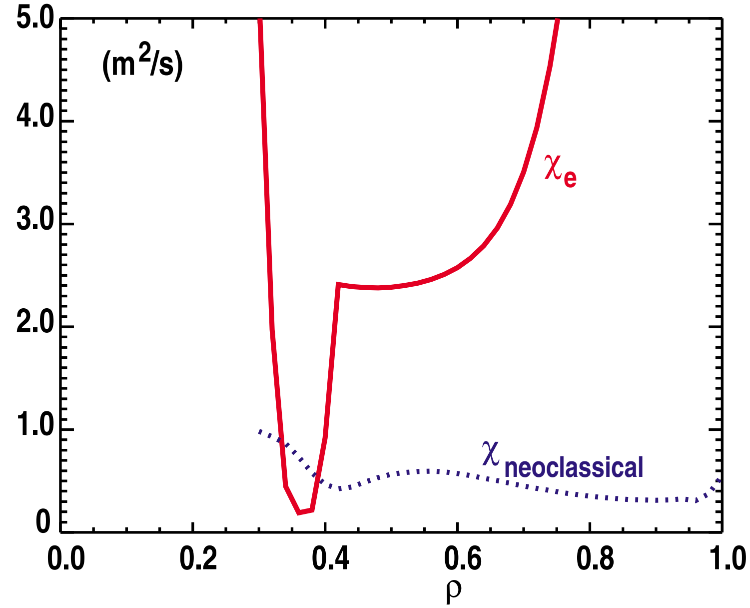
ECH/ECCD IS USEFUL CONTROL TOOL FOR EVALUATING ELECTRON TRANSPORT AND TRANSPORT BARRIERS

T_e profile shows very strong gradient



Electron diffusivity is near ion neoclassical diffusivity in the steep gradient region



- Future work: evaluate ITB control
  - Location of deposition $\rightarrow \rho_{ITB}$
  - Width of deposition $\rightarrow$ width of ITB
  - Steerable antennas, long pulse ECH

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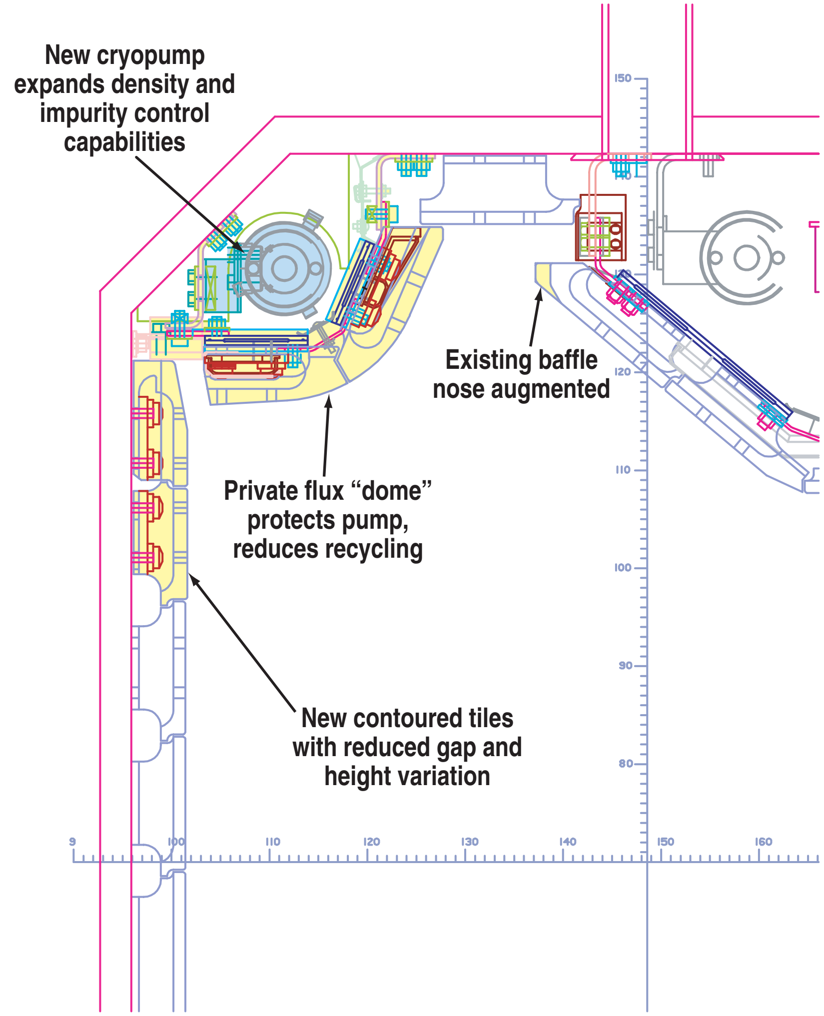
THE DIII–D DIVERTOR 2000 HAS SEVERAL UNIQUE FEATURES TO SUPPORT ADVANCED TOKAMAK PROGRAM AND DIVERTOR RESEARCH

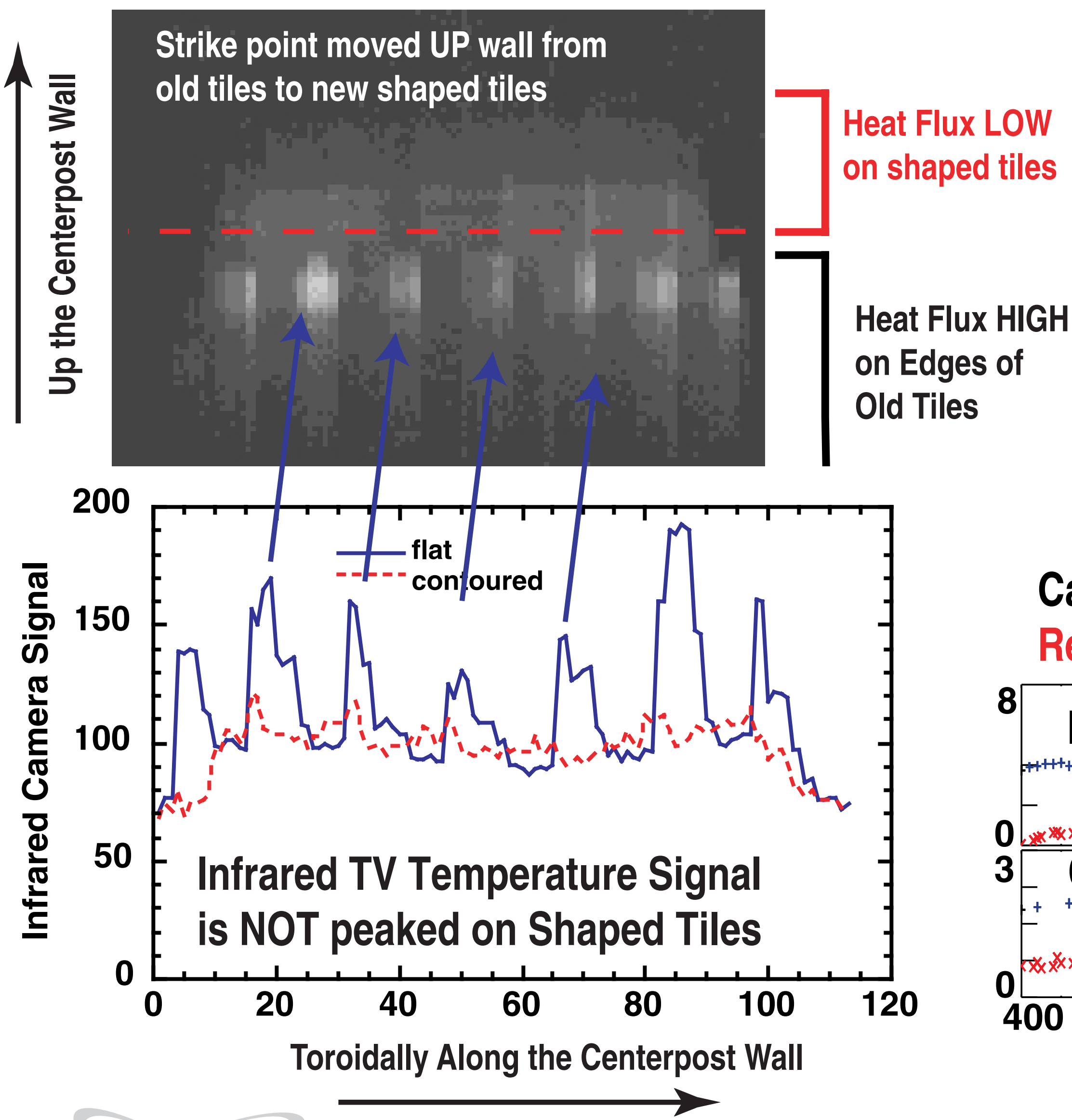
- Independently operated divertor pumps at both upper strike points and at the lower outer strike point provide flexibilty
  - Allow particle control in a wide range of triangularity, elongation, double null and single null
  - Comparison of open and baffles configurations in same device
  - Detachment control by adjusting the ratio of inboard to outboard exhausts
  - Impurity enrichment by puff and pump at low density
- Low leakage to pumping speed ratios nearly eliminates recycling through baffle structure

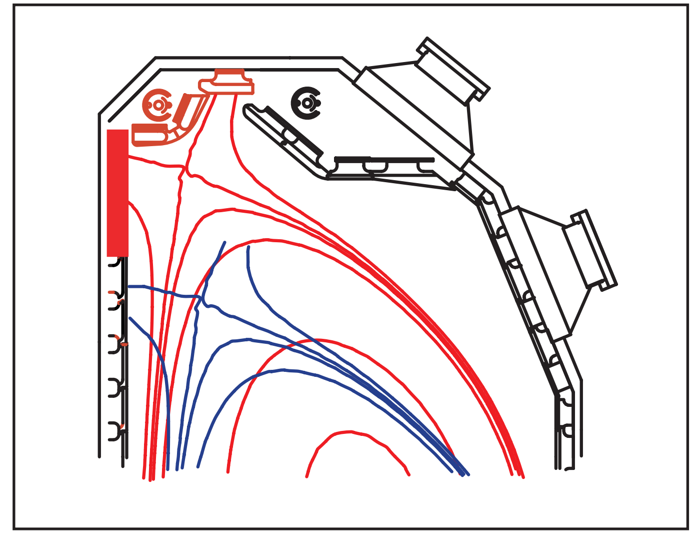
Outer upper pump;	$2\ m^3\ s^{-1} : 37\ m^3\ s^{-1}$
Inner upper pump;	$1\ m^3\ s^{-1} : 20\ m^3\ s^{-1}$
Lower pump;	$2\ m^3\ s^{-1} : 20\ m^3\ s^{-1}$

NEW DIVERTOR SUPPORTS HIGH TRIANGULARITY PLASMAS

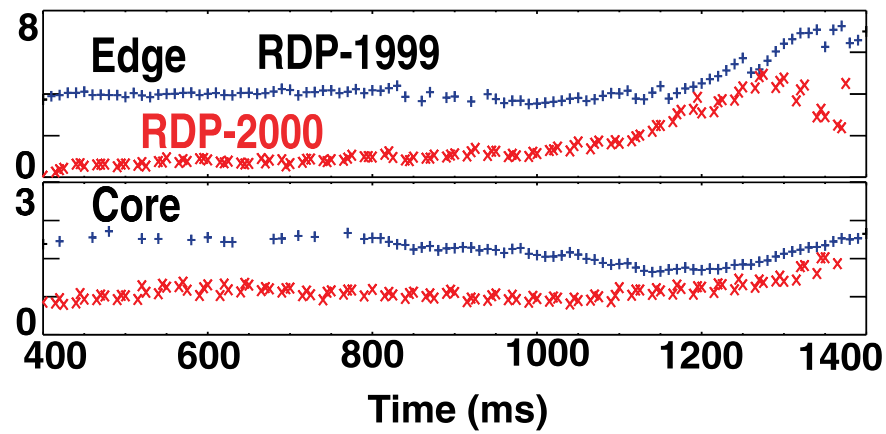


Impurity Control In AT Plasmas With Careful Tile Shaping





Carbon Concentration (%) is Reduced Compared to Previous Operation



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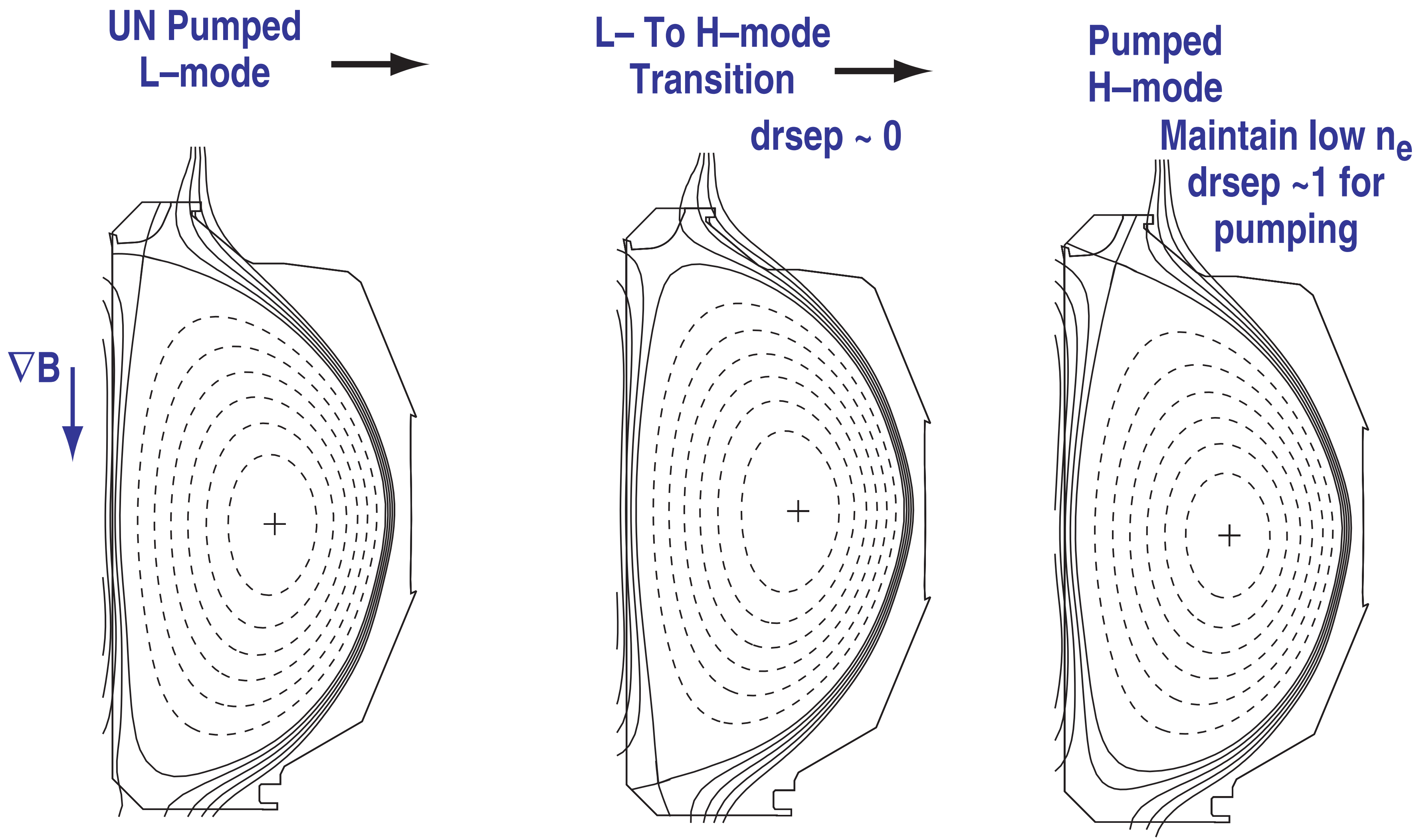
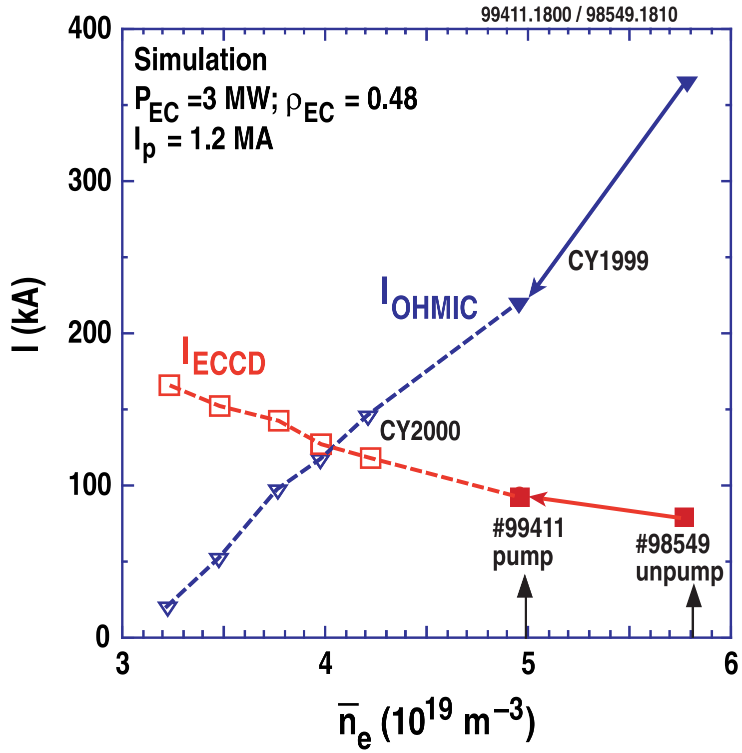
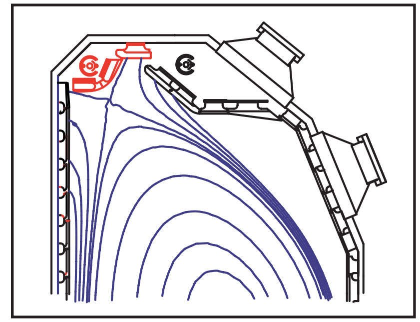
AT Scenario Uses Divertor Shapes For Real-time Control

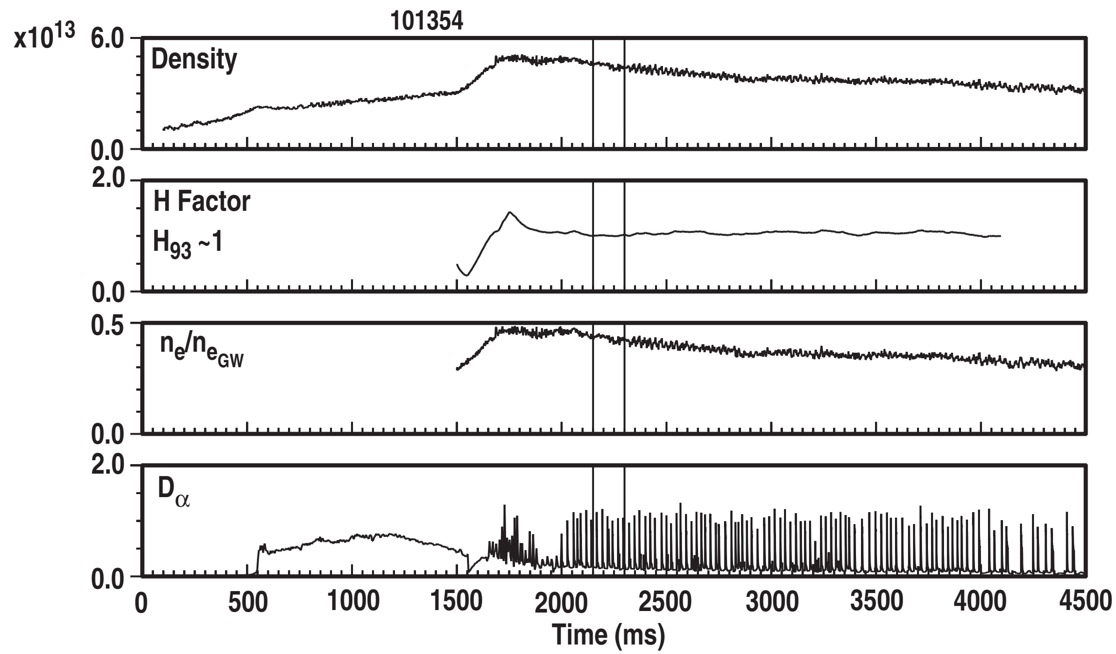


With available ECH power on DIII–D, density and impurity control are critical - these are provided by the divertor



- $I_{CD} \propto \frac{T_e}{n_e} \frac{1}{(Z_{eff} + 5)}$





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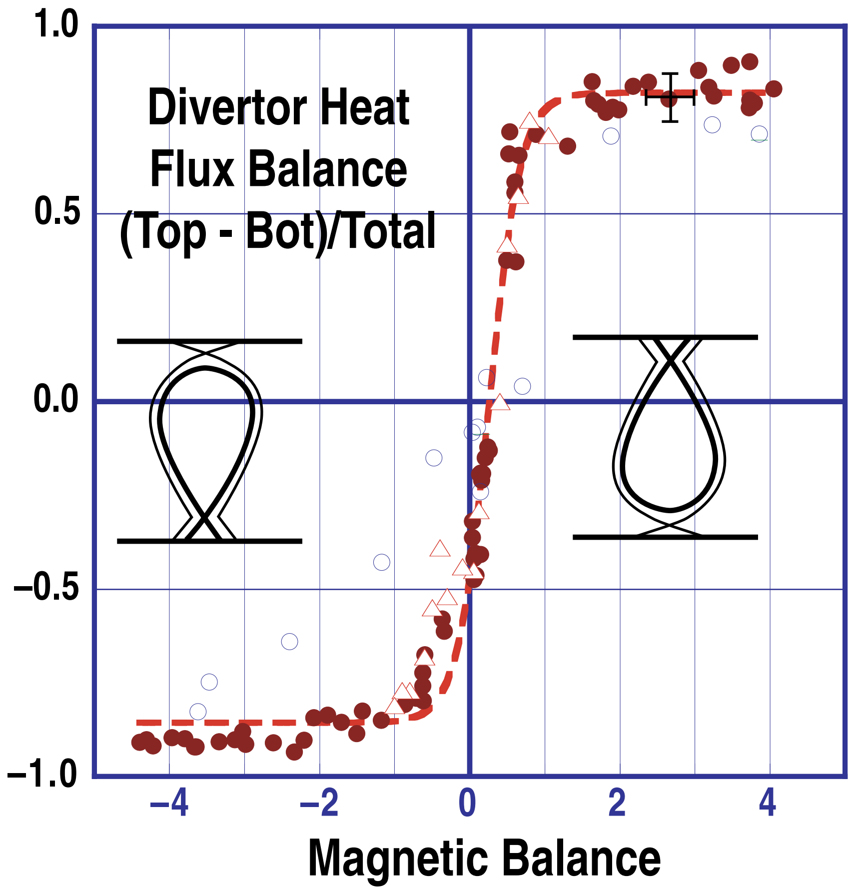
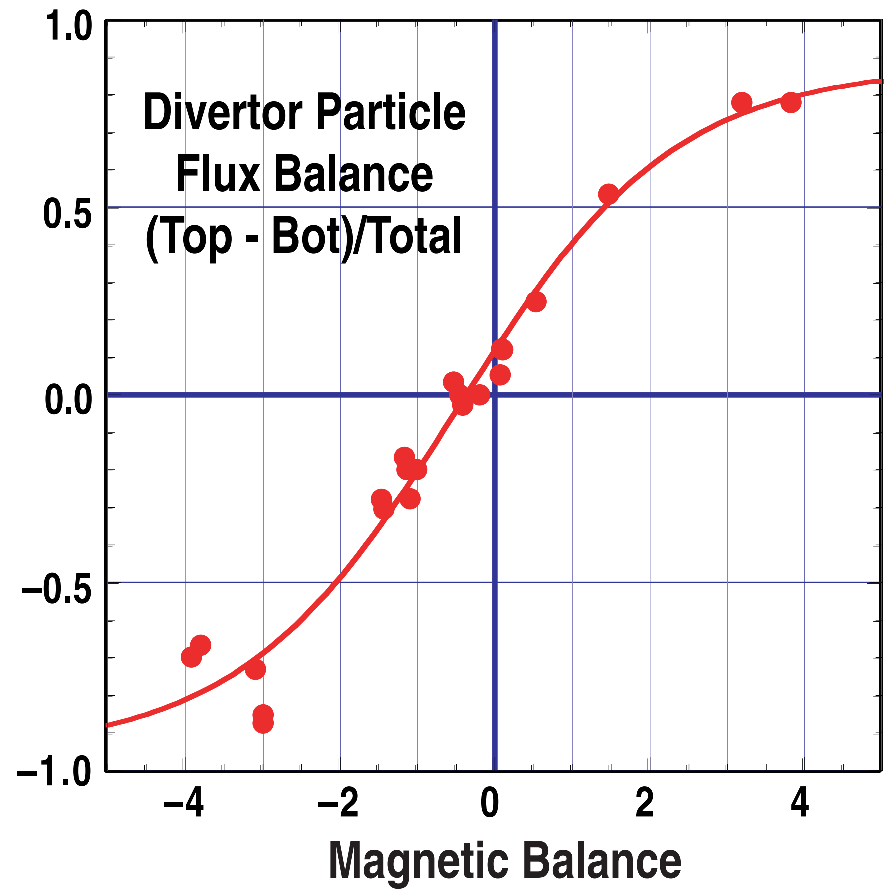
Magnetic balance can be used for power and particle control





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We have a high density divertor solution

We have a reasonable scientific basis for a conventional long-pulse tokamak divertor solution at high density (collisional edge, detached)

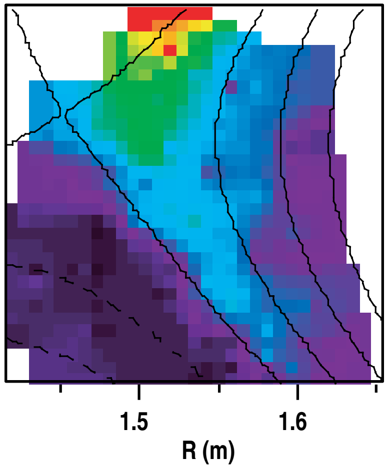
- Low Te recombining plasma leads to low heat and particle fluxes at wall
- Adequate ash control, compatible with ELMing H–mode confinement
- Appropriate for future tokamaks (e.g. to high density ITER-RC)
- Concerns about ***simultaneously*** handling disruptions/ELMs and tritium inventory which shorten divertor lifetime

The challenge is to find self consistent operating modes for other configurations ...

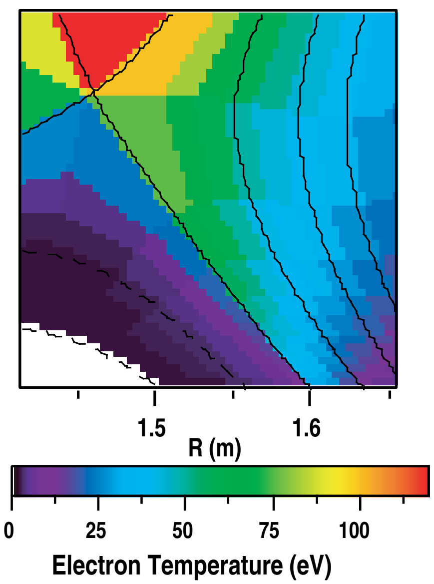
(U.S. Snowmass working group, July 2000)

Detached divertors for particle and power handling

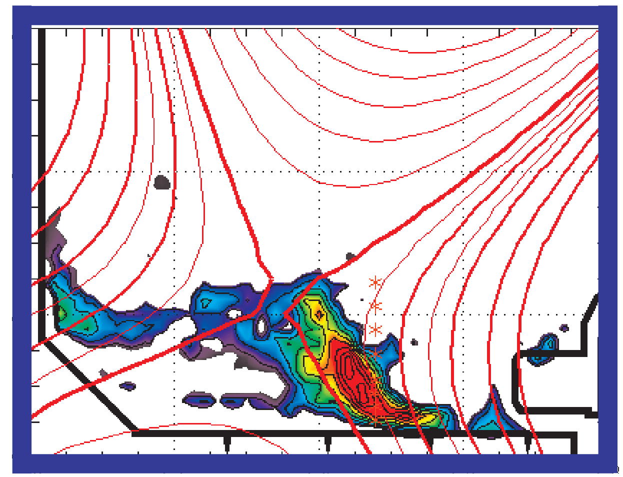
Data Shows Low T_e



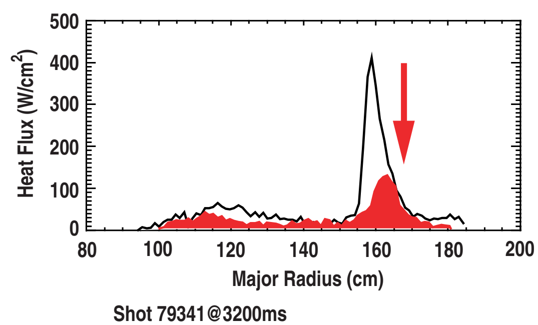
Model Shows Low T_e



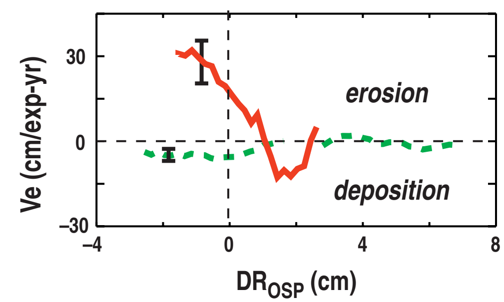
Recombining Plasma Near Plate (D_γ/D_α)



Divertor Heat Flux is Reduced



Erosion is Reduced



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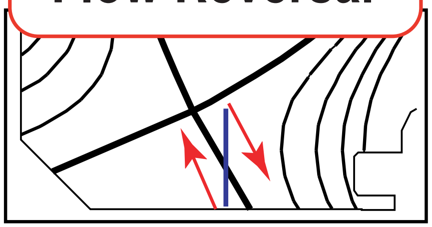
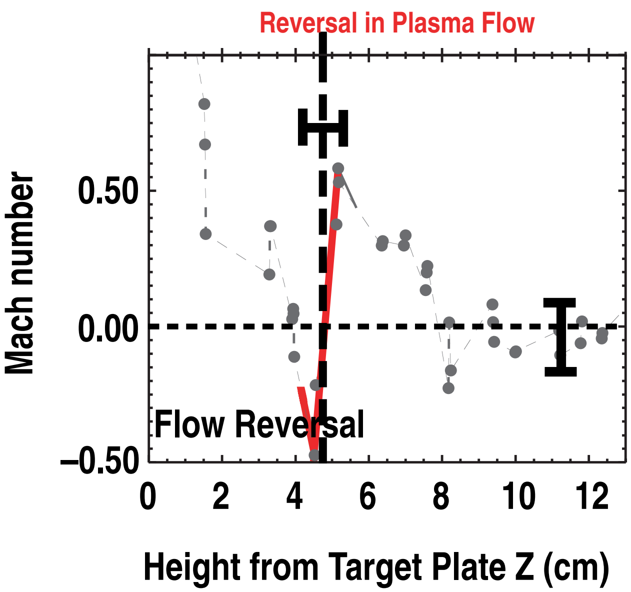
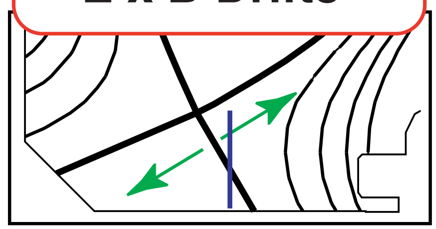
New physics in the x-point and private flux region

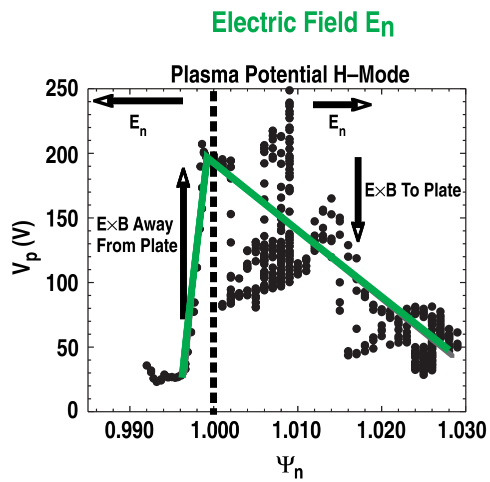
Flow Reversal



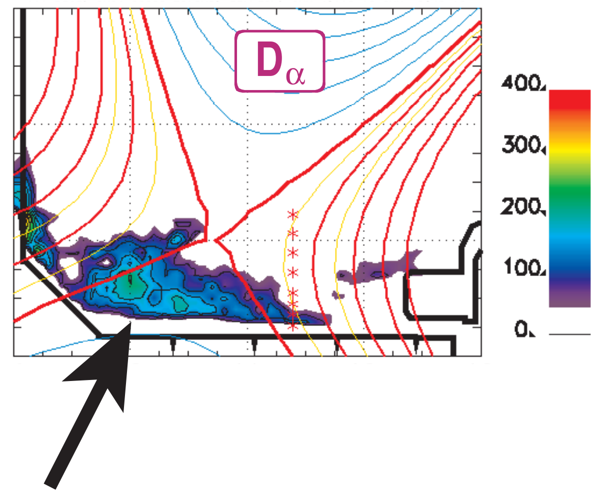


E x B Drifts





Recombination in "Private Flux"



Appreciable T_e, n_e In this Region

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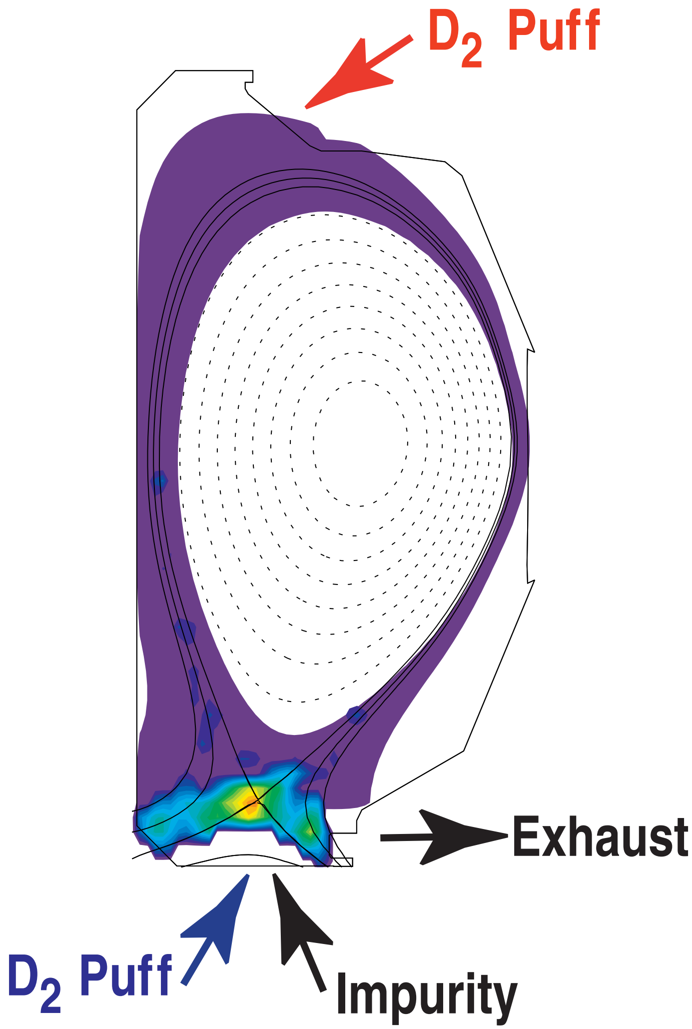
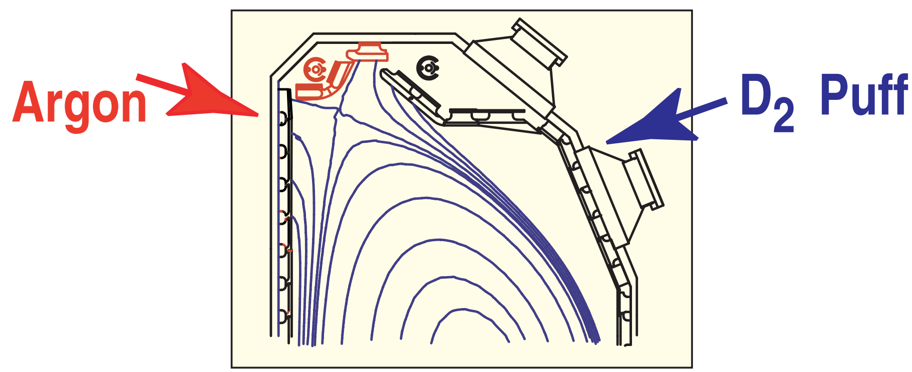
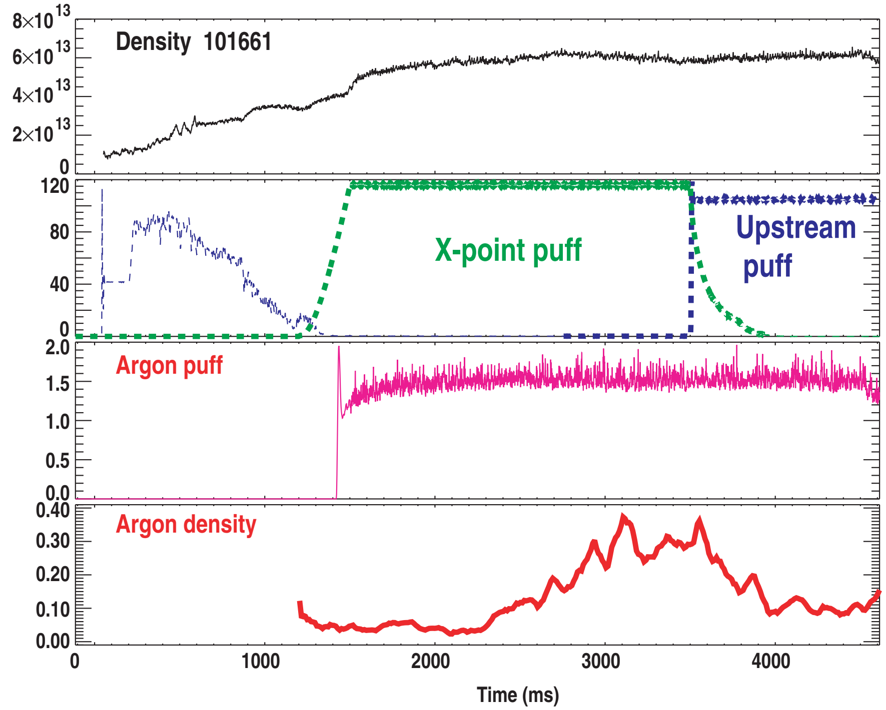
Puff And Pump In Both The Open And Closed Divertors







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"AT Divertors are not just for heat flux reduction"

Advances in detached plasmas by this community have made possible a high density divertor solution (with some caveats, of course!) ...

- Now divertor particle control is vital for AT modes
- Shaped plasmas are "standard", needed for high performance
- Real Time Shape control enables H-mode power threshold control, particle control
- Current profile control (ECCD) is at the heart of the AT, *Impurities* are important!

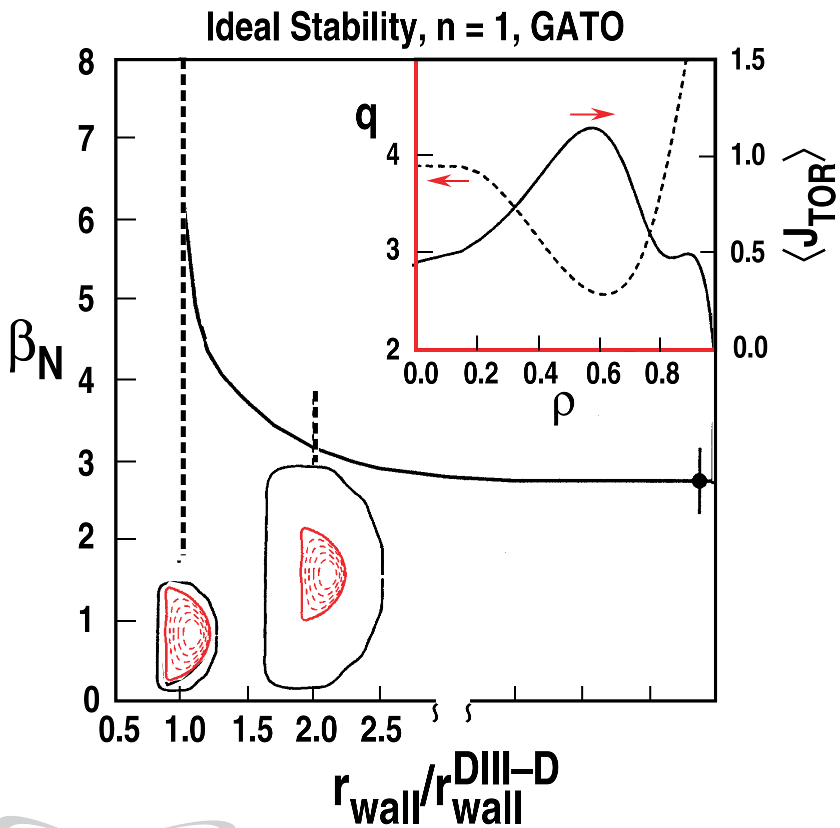
Heat flux control in AT plasmas is expected to require impurity flow control

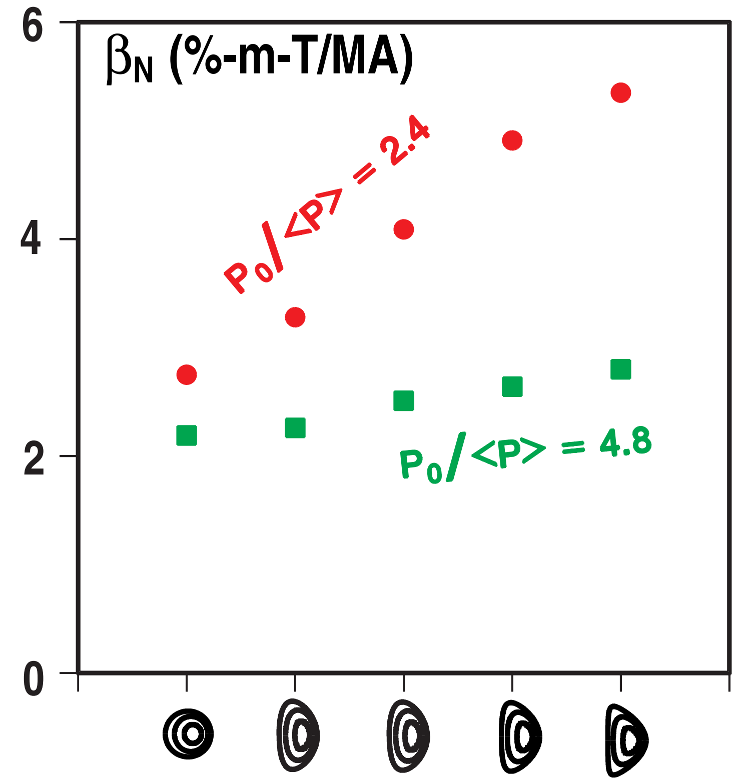
- "Puff and Pump" or active flow control, need progress in understanding flows
- Lots of new, exciting physics in the pedestal and x-point region

WALL STABILIZATION AND PLASMA SHAPING ESSENTIAL FOR HIGH PERFORMANCE ADVANCED TOKAMAK OPERATION

- $\beta_N \equiv B_T/(I/aB$
- β_N ~ 6 with wall stabilization
- β_N ~ 3 without wall stabilization

- $B_T \; B_p = 25 \left(\frac{1+k^2}{2}\right) \left(\frac{\beta_N}{100}\right)^2$
  - $B_p \rightarrow f_{BS} = C_{BS}\, \varepsilon^{1/2} B_p$
  - $B_T \rightarrow P_{FUS} \propto B_T^2\, B_T^4$





. . . motivates RWM Thrust #4

. . . motivates optimal divertor shape Thrust #5

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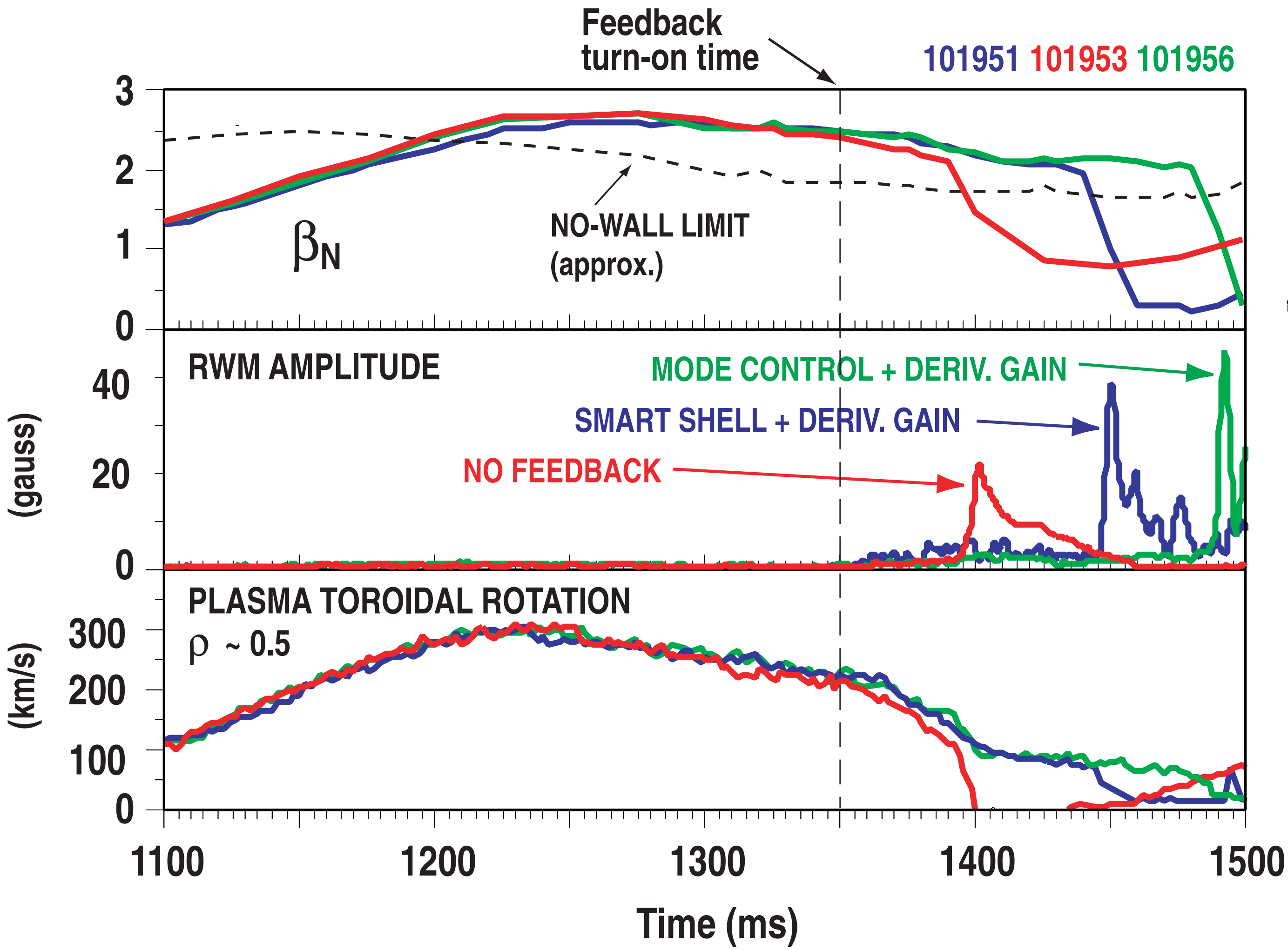
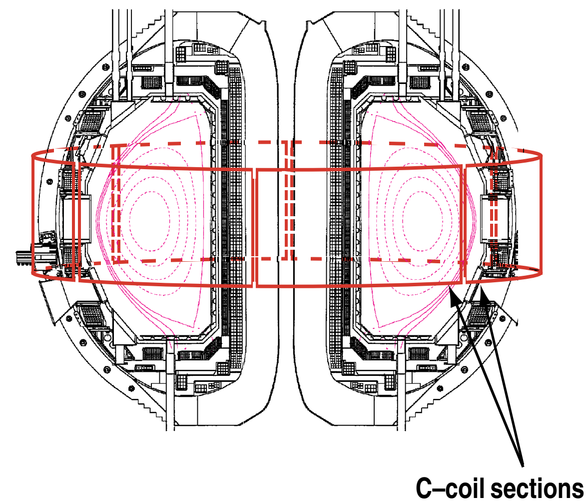
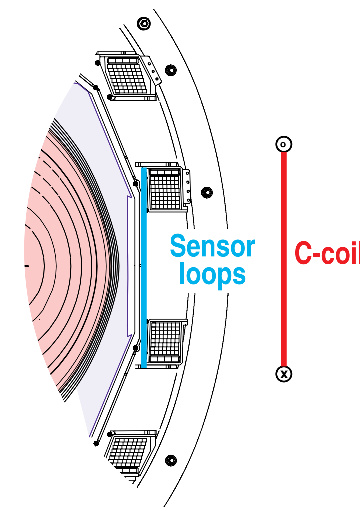
ACTIVE FEEDBACK STABILIZATION EXTENDS HIGH β DURATION

(March 2000)







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PPPL PRINCETON PLASMA PHYSICS LABORATORY

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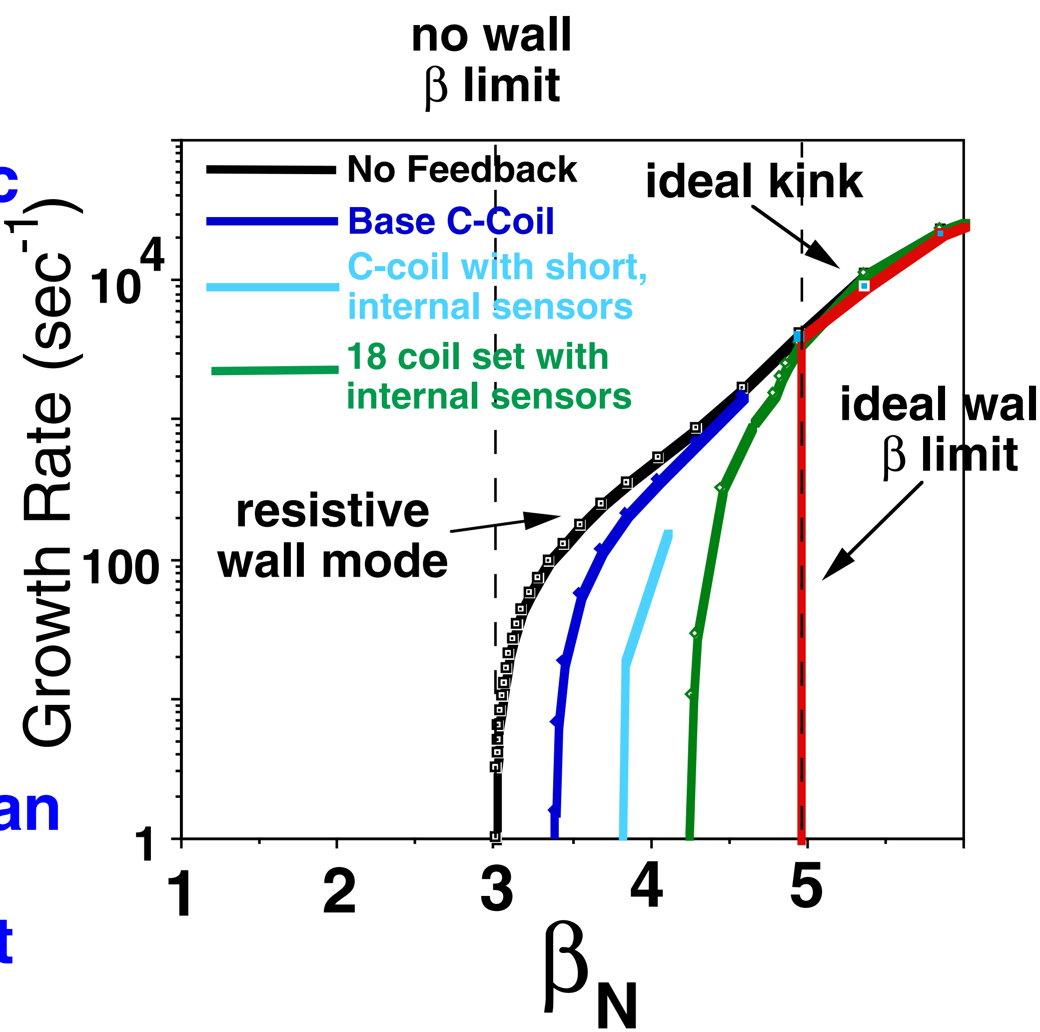
VALEN 3D Feedback Control Model Predicts β Can be Improved Towards Ideal Limit in DIII-D

- Existing 6 coil set can increase RWM stability limit to β_N ~ 3.4 for basic "smart shell" control algorithm.
- Three control system improvements:
  - shorter sensor coils
  - internal sensor coils
  - extended 18 coil set
- System improvements can extend performance towards ideal wall β_N limit



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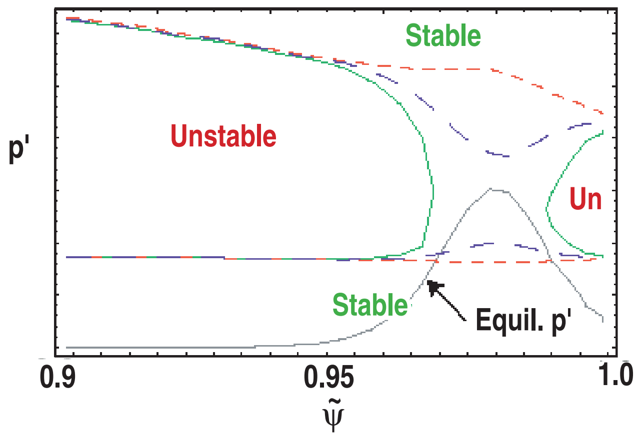
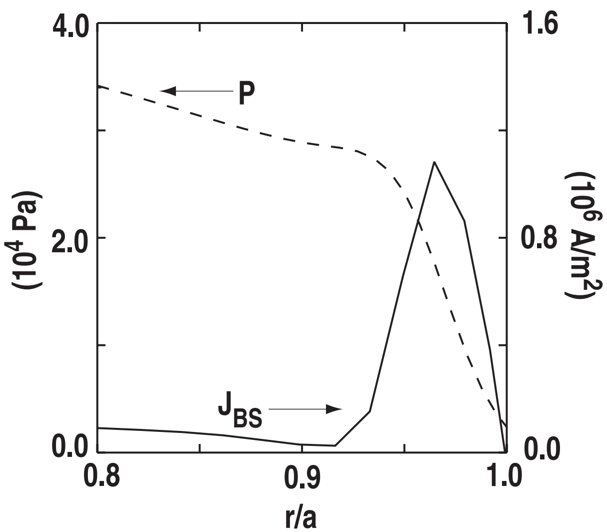
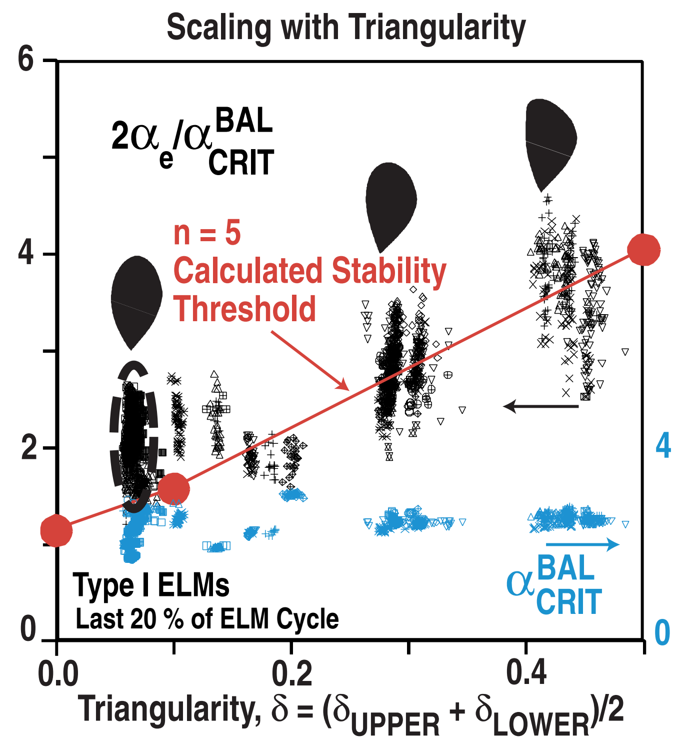
DETAILED EDGE MEASUREMENTS AND THEORY ARE LEADING TO AN UNDERSTANDING OF EDGE PEDESTAL PHYSICS

- P´ exceeds prediction from first regime ballooning
- n ~ 5 driven by local P´ and local J_{BS}







- Future plan to measure J_{edge} to validate models with
  - Lithium beam polarimetry

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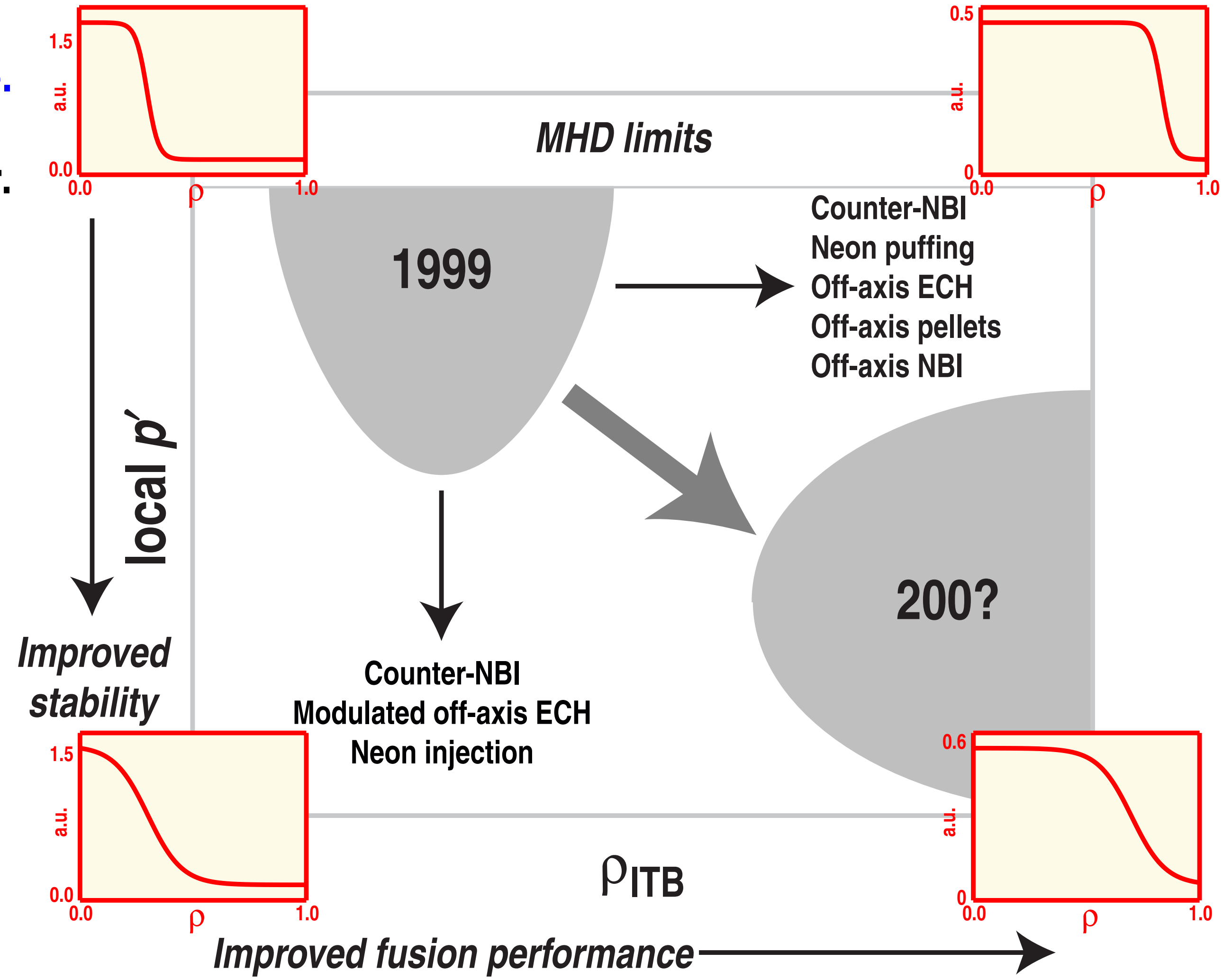
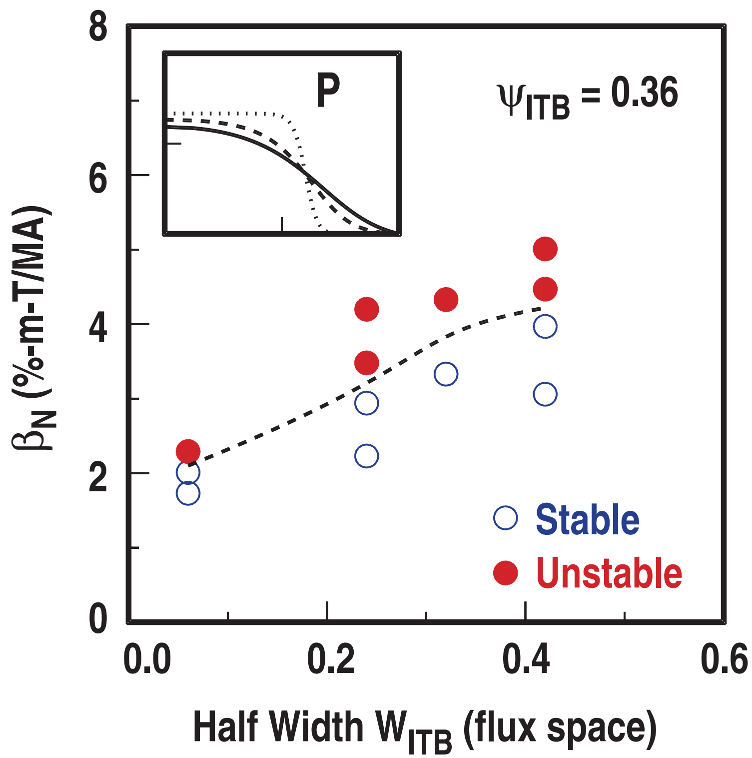
THE GOAL OF THRUST 7 IS TO ESTABLISH CONTROL OVER THE INTERNAL TRANSPORT BARRIER

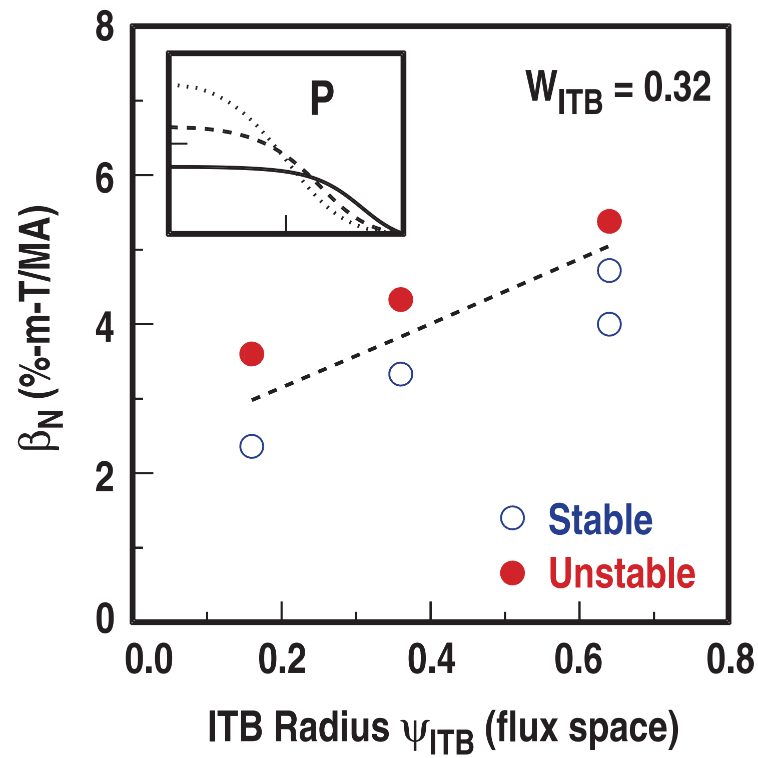
- Increase spatial extent of barrier.
  - Increased fusion performance.
- Control pressure gradient in barrier.
  - Avoid MHD instabilities which can terminate ITB or disrupt discharge.
- Maintain elevated/reversed *q* profile.
  - Avoid MHD instabilities when $q_{min} \Rightarrow 1$.
  - Impacts ITB characteristics, especially in n_e and T_e profiles.
  - Take advantage of favorable impact of counter-NBCD and bootstrap currents in broadened barriers.



STABILITY LIMIT IMPROVES WITH INTERNAL TRANSPORT BARRIER WIDTH AND RADIUS

- Fixed shape DND, $q_{95} = 5.1$, $q_0 = 3.2$, $q_{min} = 2.2$
- Hyperbolic tangent pressure representation
- Ideal n = 1, wall at 1.5a





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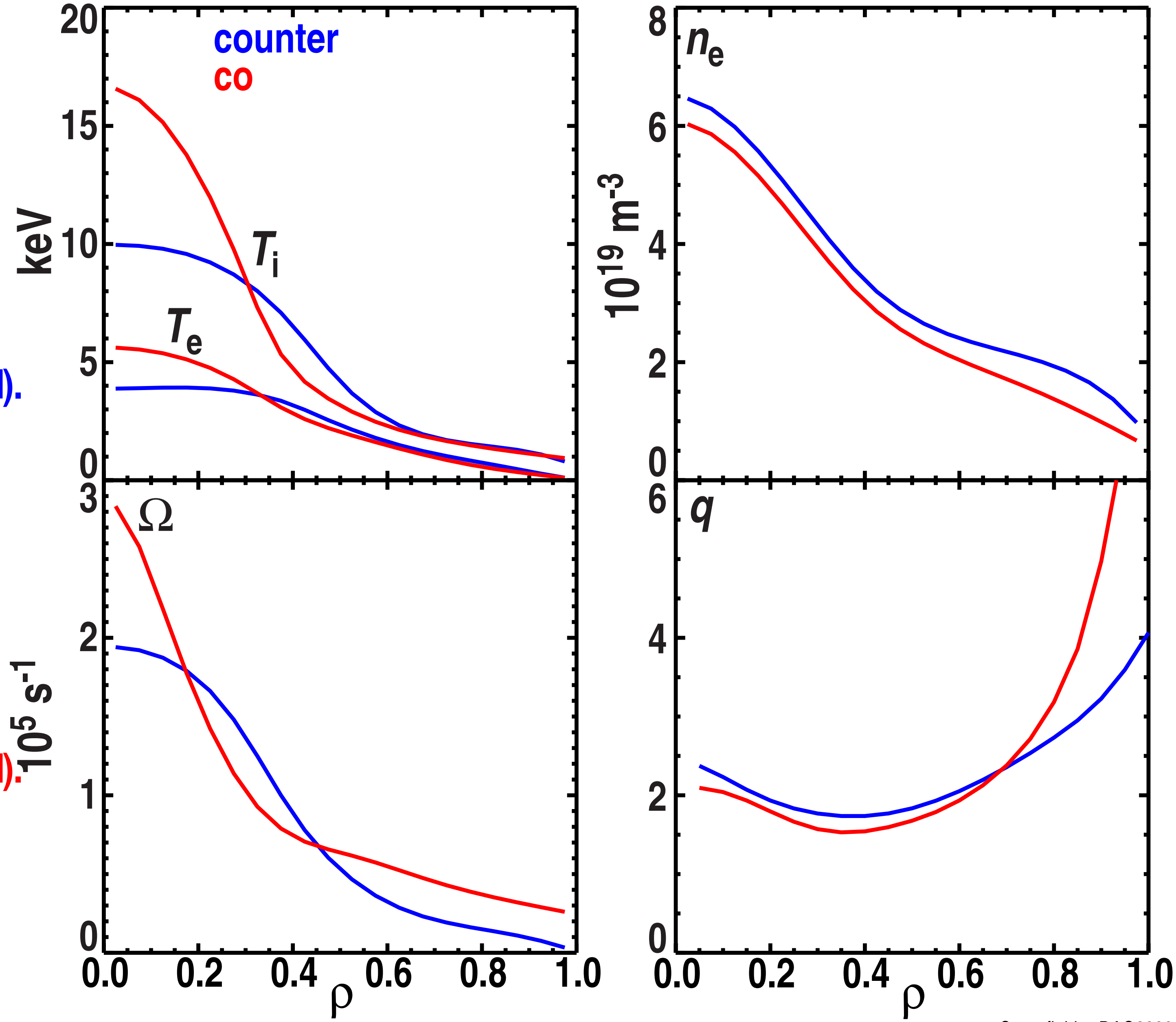
COUNTER-NBI RESULTS IN BROADER PROFILES

- 99849 (1.17s):
  - Counter-NBI
  - W = 0.9 MJ
  - P_{NBI} = 11.2 MW (6.5 MW absorbed).
- 87031 (1.82s):
  - Co-NBI
  - W = 1.2 MJ
  - P_{NBI} = 9.6 MW (7.6 MW absorbed).



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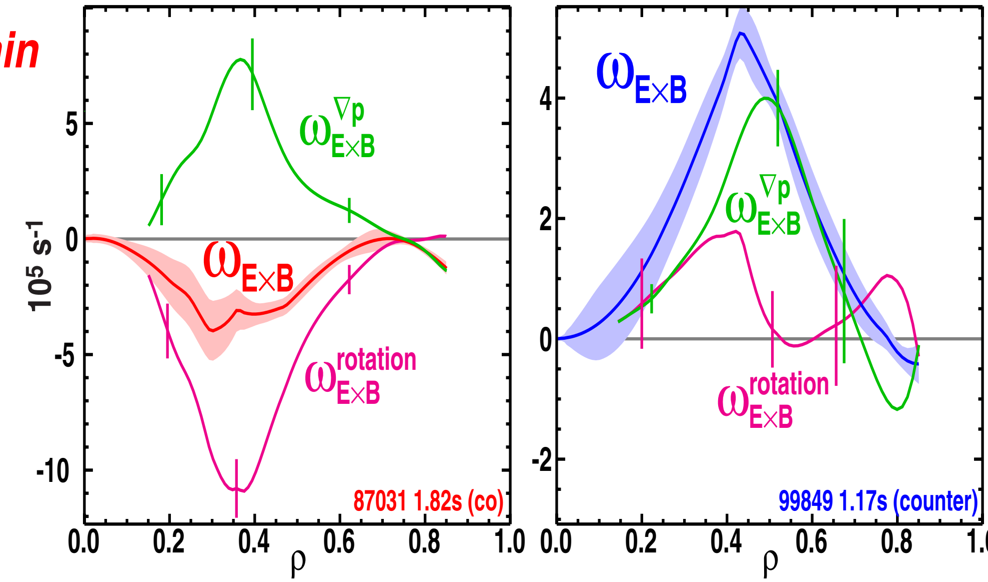
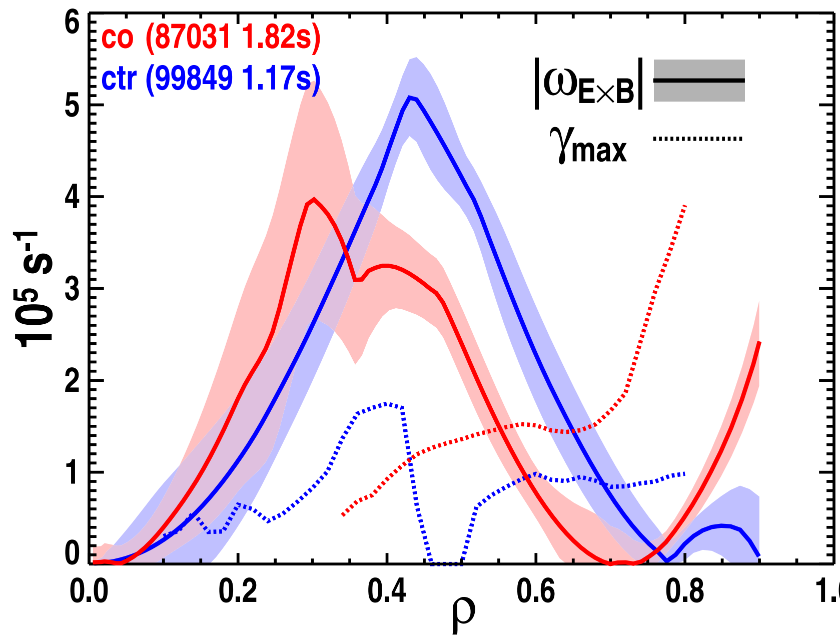
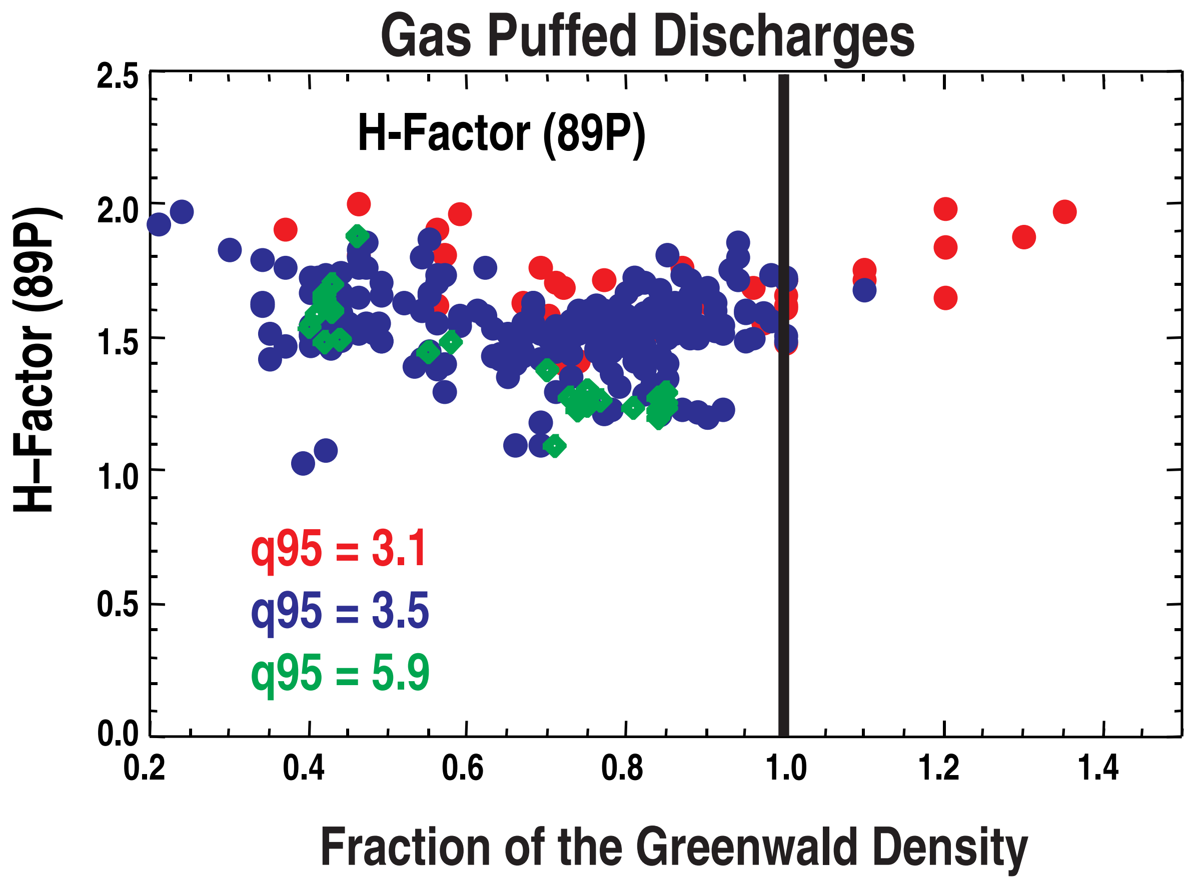
COMBINATION OF ∇p AND ROTATION EFFECTS IN $\omega_{E\times B}$ NATURALLY BROADENS COUNTER BARRIERS

- Shearing rate $\omega_{E\times B}$ separated into ***thermal main ion*** rotation and pressure gradient terms.
  - Total calculated from CER impurity measurements.
  - Main ion pressure term from profile measurements.
  - Rotation term by subtraction.
- Stability to drift ballooning modes calculated using a linear gyrokinetic stability (GKS) code.
  - Non-circular, finite aspect ratio equilibria with fully electromagnetic dynamics.
- With counter-NBI:
  - Linear growth rates smaller at at large ρ, possibly due to higher Z_{eff} near edge (core Z_{eff} ª 2.5 in both cases).
  - Shearing rate profile extends to larger ρ.





GAS FUELED H–MODE DISCHARGES WELL ABOVE THE GREENWALD DENITY IN DIII–D



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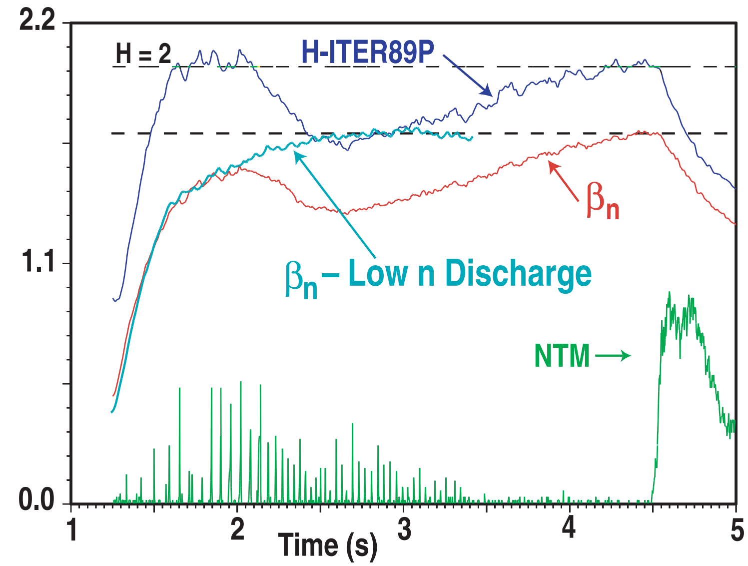
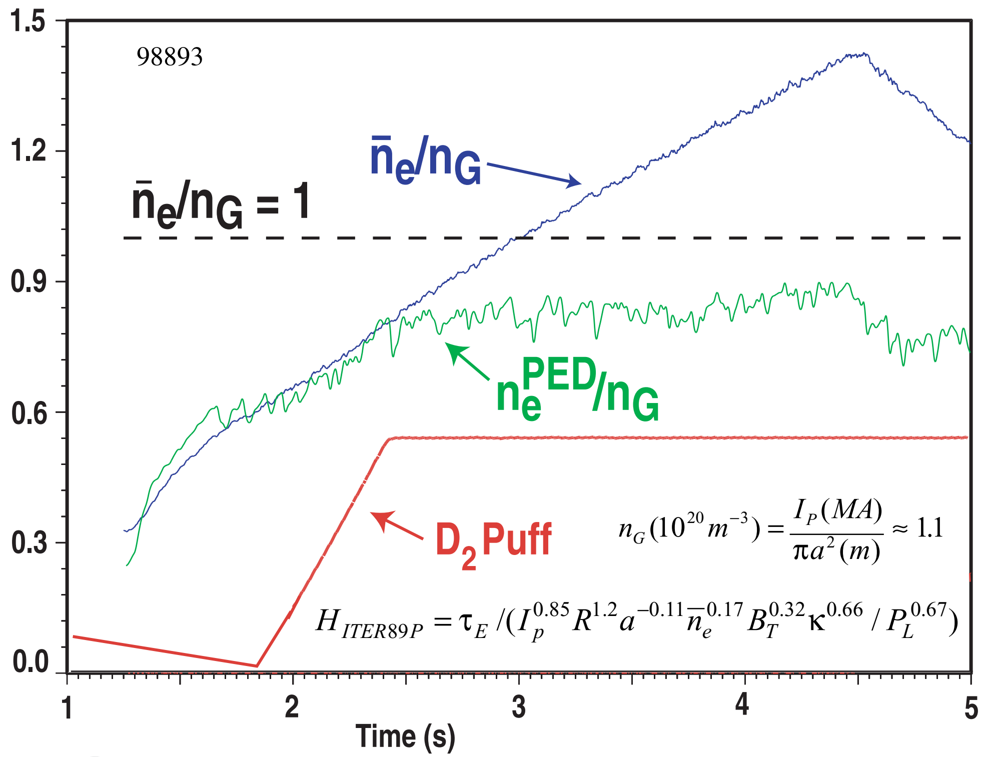
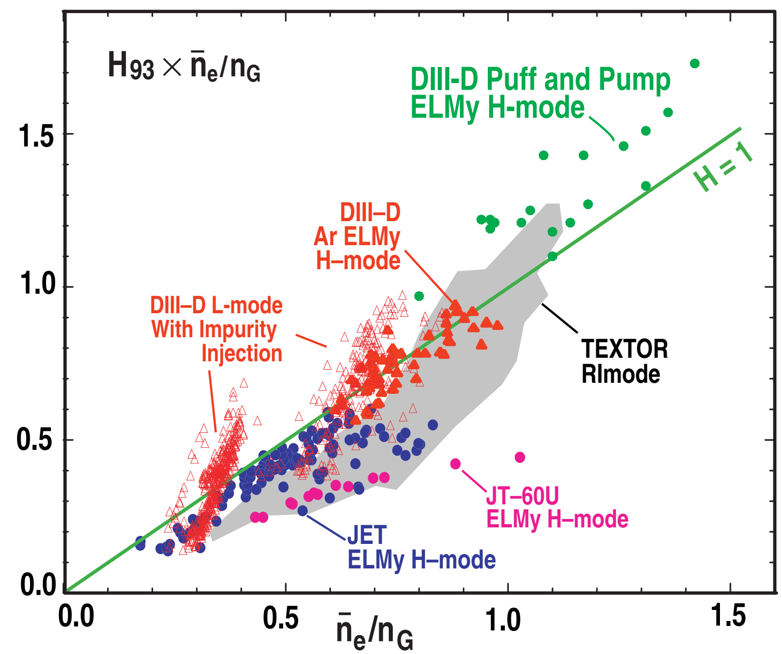
GAS PUFF FUELED H–MODE DISCHARGES WITH HIGH ENERGY CONFINEMENT ABOVE THE GREENWALD LIMIT ON DIII–D

- Plasma stored energy, W, increases with density after an initial decrease following the start of gas injection
- n and W increase limited by MHD
- Stored energy is comparable to low density discharge at the same heating power







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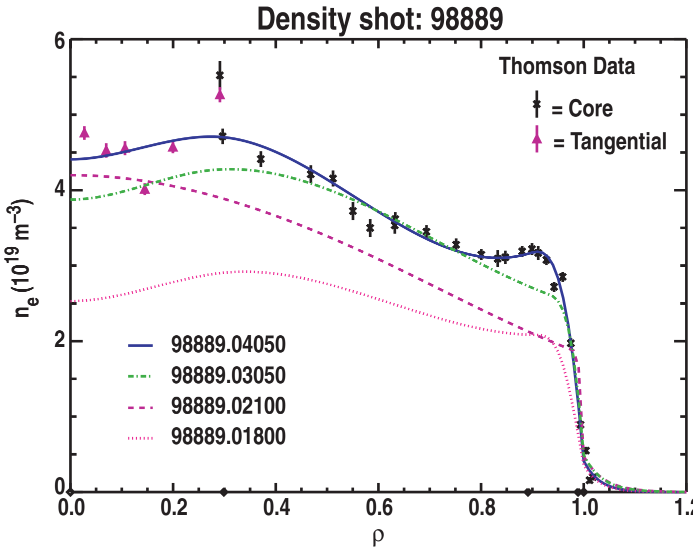
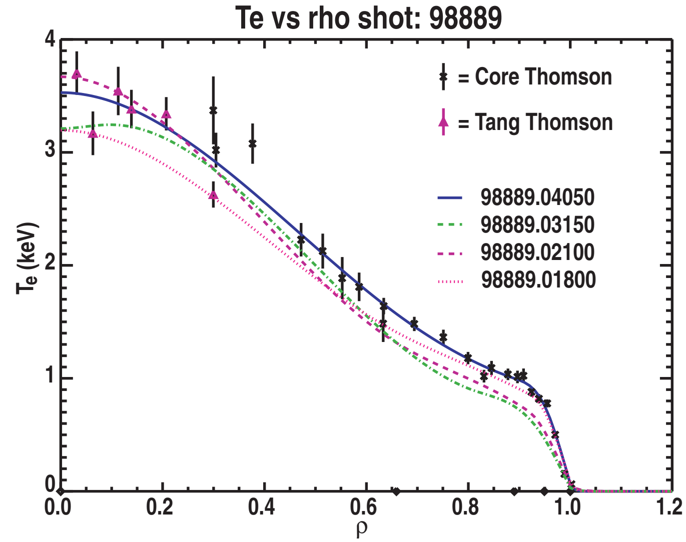
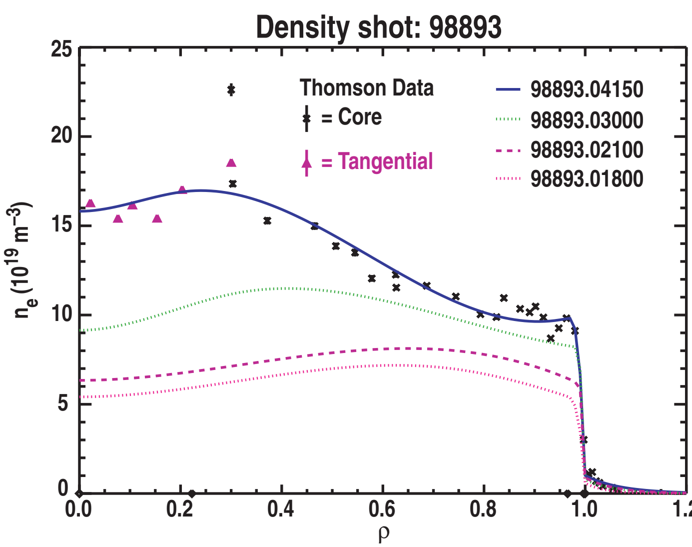
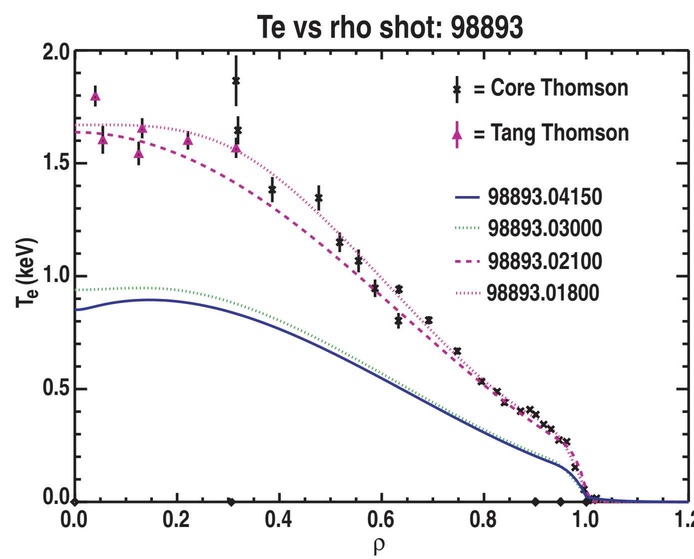
LOW AND HIGH DENSITY PUMPED DISCHARGES HAVE SIMILAR DENSITY PROFILES









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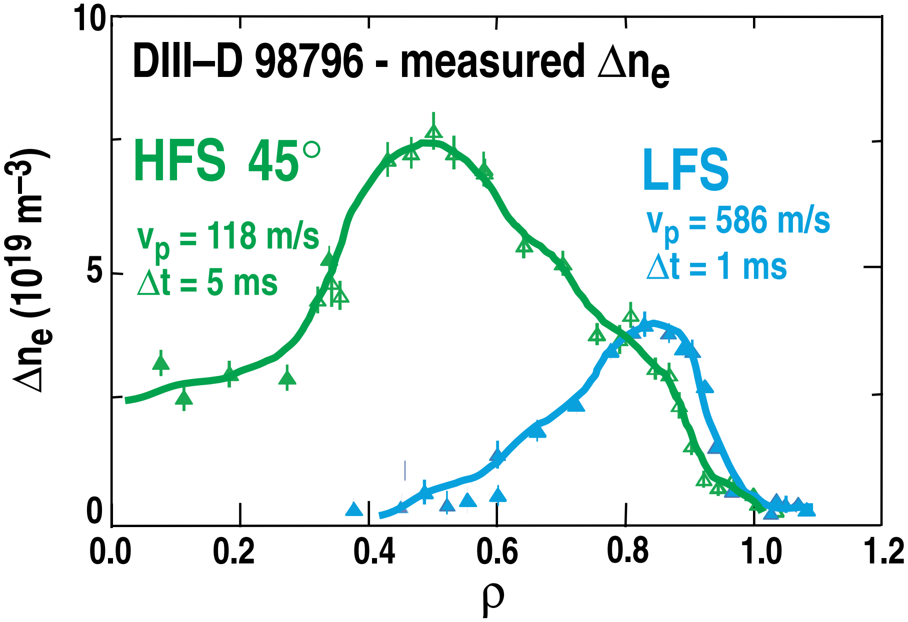
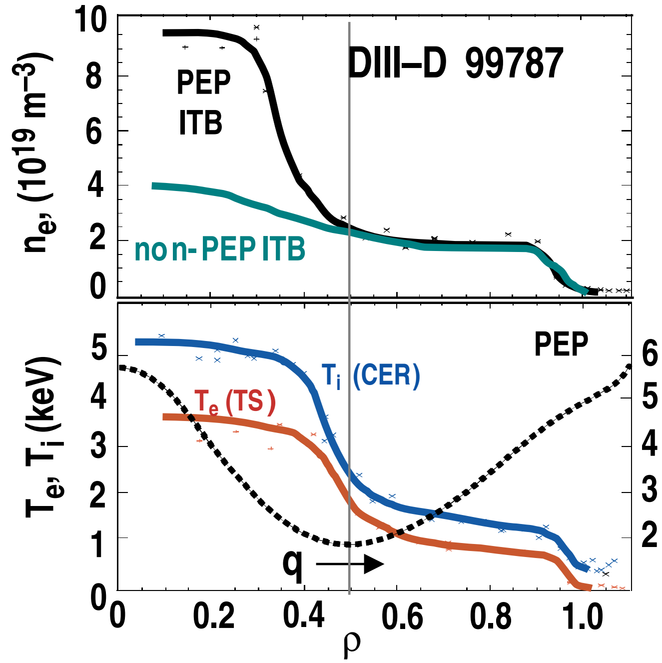
HIGH FIELD SIDE PELLET INJECTION ALLOWS EVALUATION OF INTERNAL TRANSPORT BARRIERS WITH $T_e \sim T_i$

2.7 mm Pellets - HFS 45° vs LFS



New capability in ITB control



- HFS pellet injection yields deeper particle deposition than LFS injection, consistant with theory
- Future work on ITB control and H–mode control with pellet

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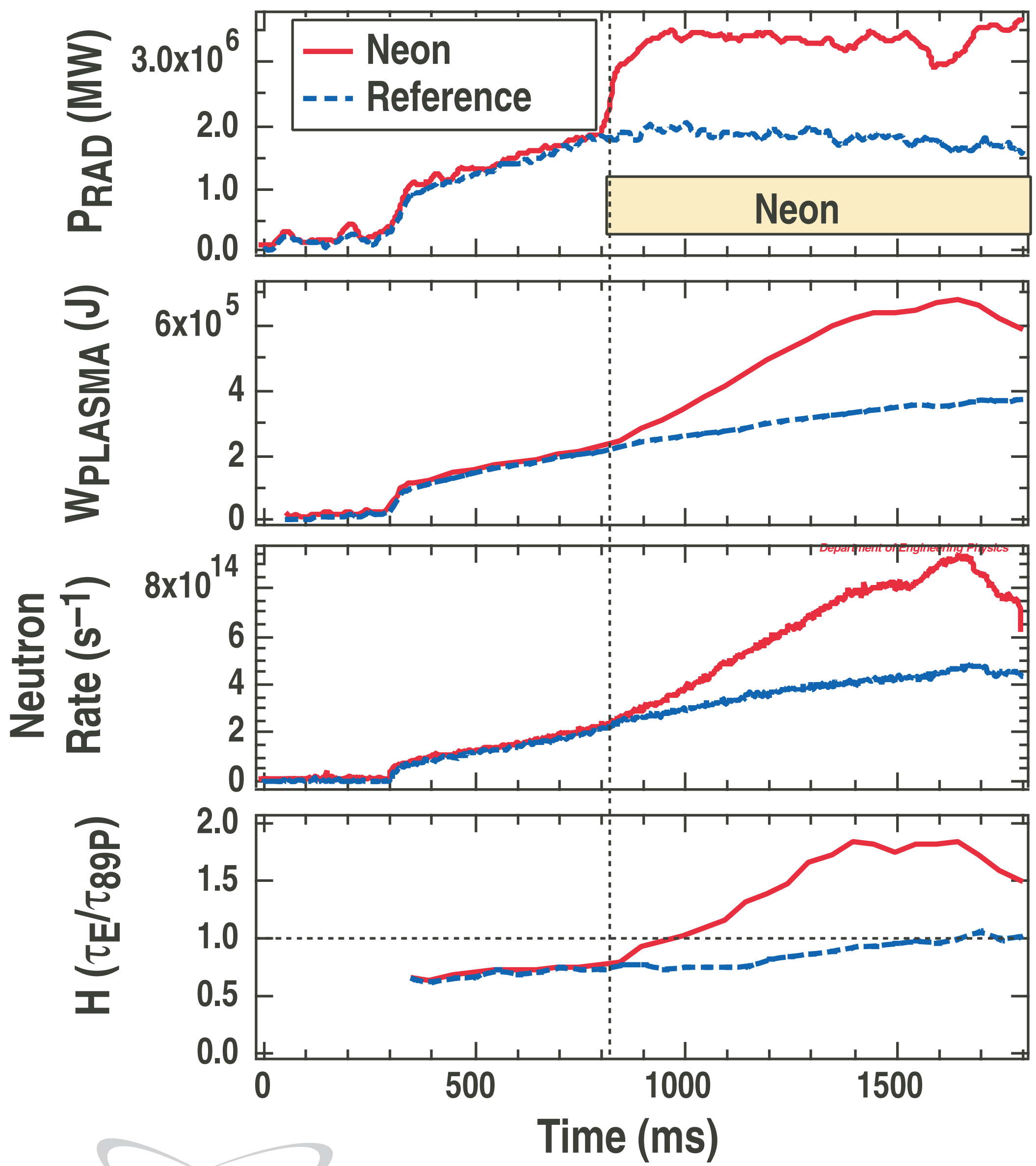
CONFINEMENT INCREASES DRAMATICALLY WITH NEON



- Radiated power: 3.5 MW, 75% of input power
- Stored energy increases by 80%
- Neutron rate doubles; confinement increase overwhelms dilution
- τ_E increases to $H_{89P} = 1.8$ despite radiation
- $\tau_E = W_{PLASMA} / (P_{INPUT} - dW/dt)$

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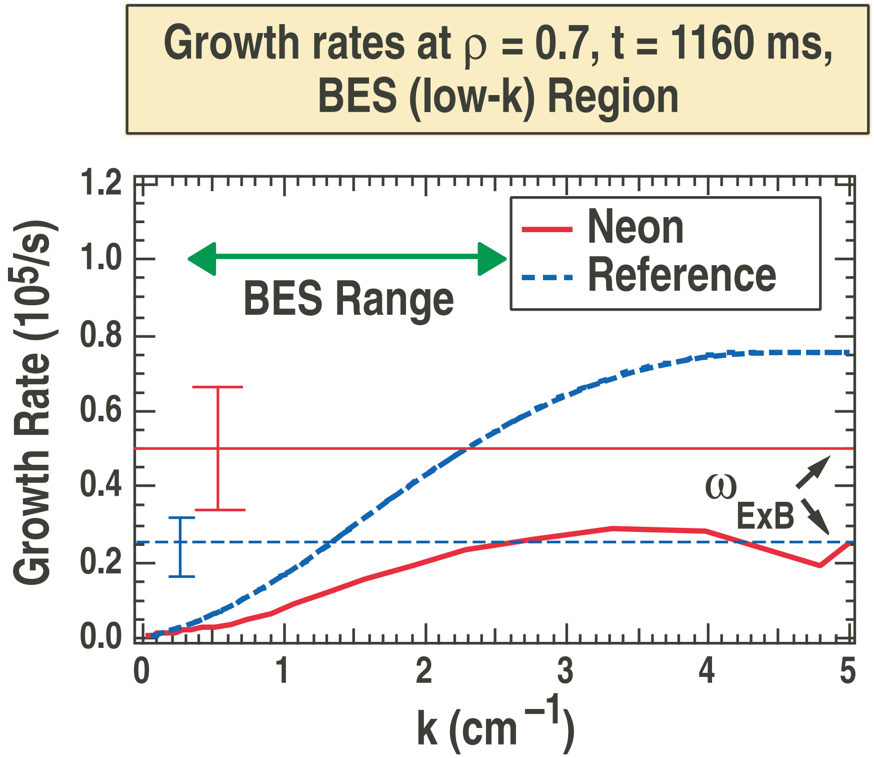
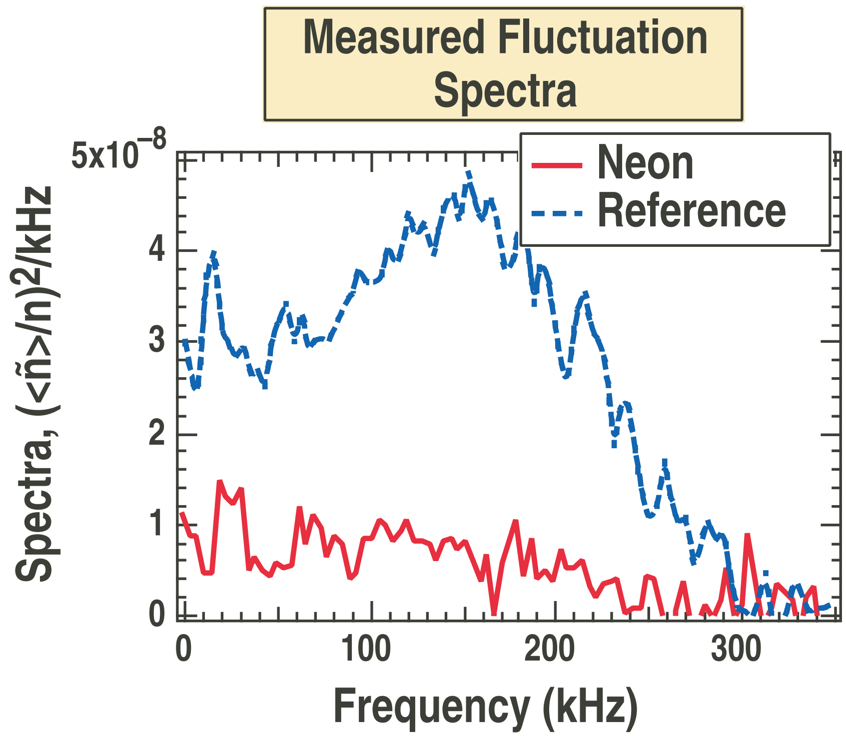
GKS CALCULATIONS OF LINEAR STABILITY GROWTH RATES SHOW SIGNIFICANT REDUCTION AT LOW-k





- ExB shearing rates exhibit opposite behavior, increasing in neon shot, further suppressing turbulence:

Neon: $\gamma_{lin} < \omega_{EXB}$, Reference: $\gamma_{lin} > \omega_{EXB}$

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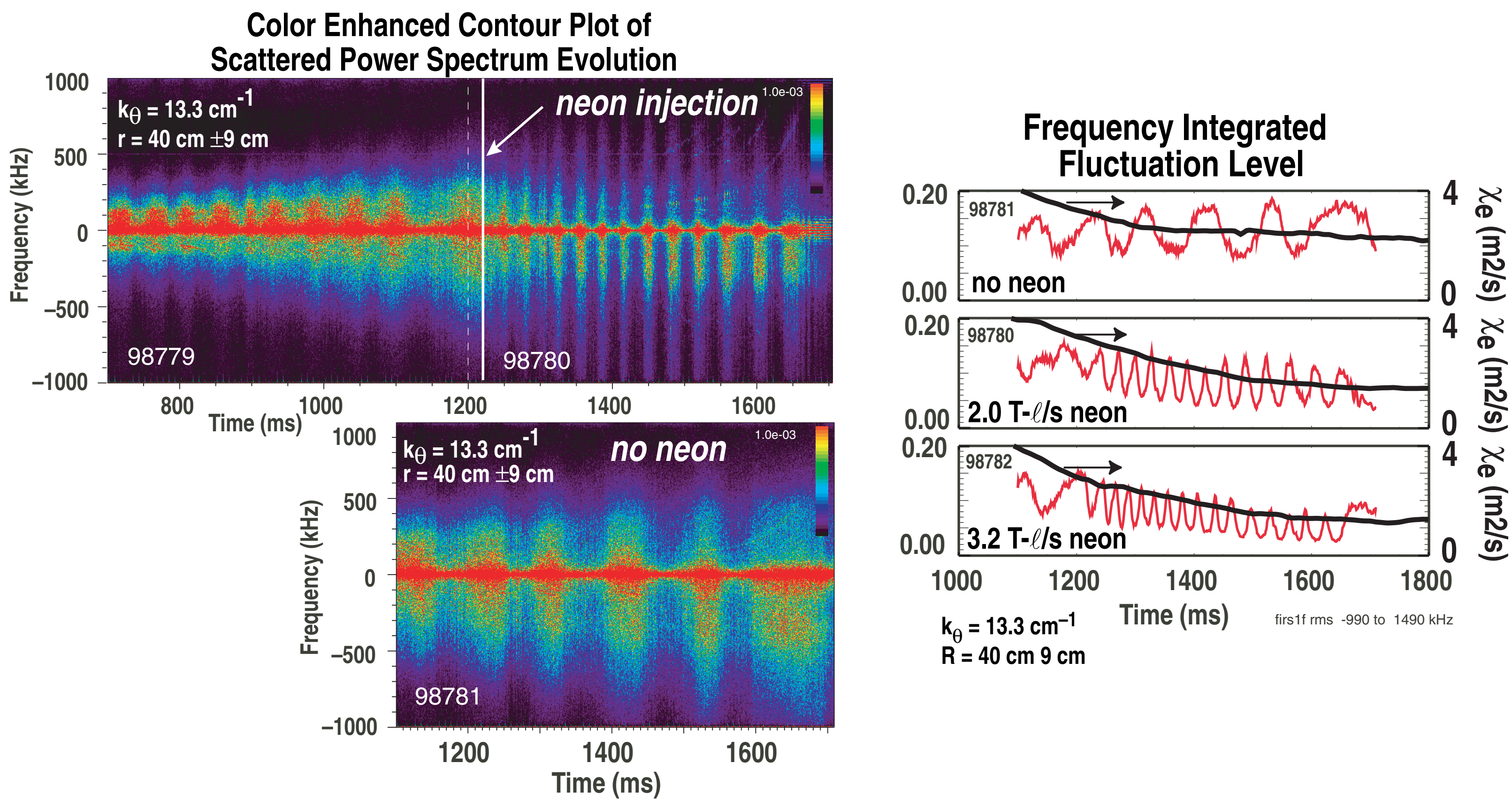
Department of Engineering Physics

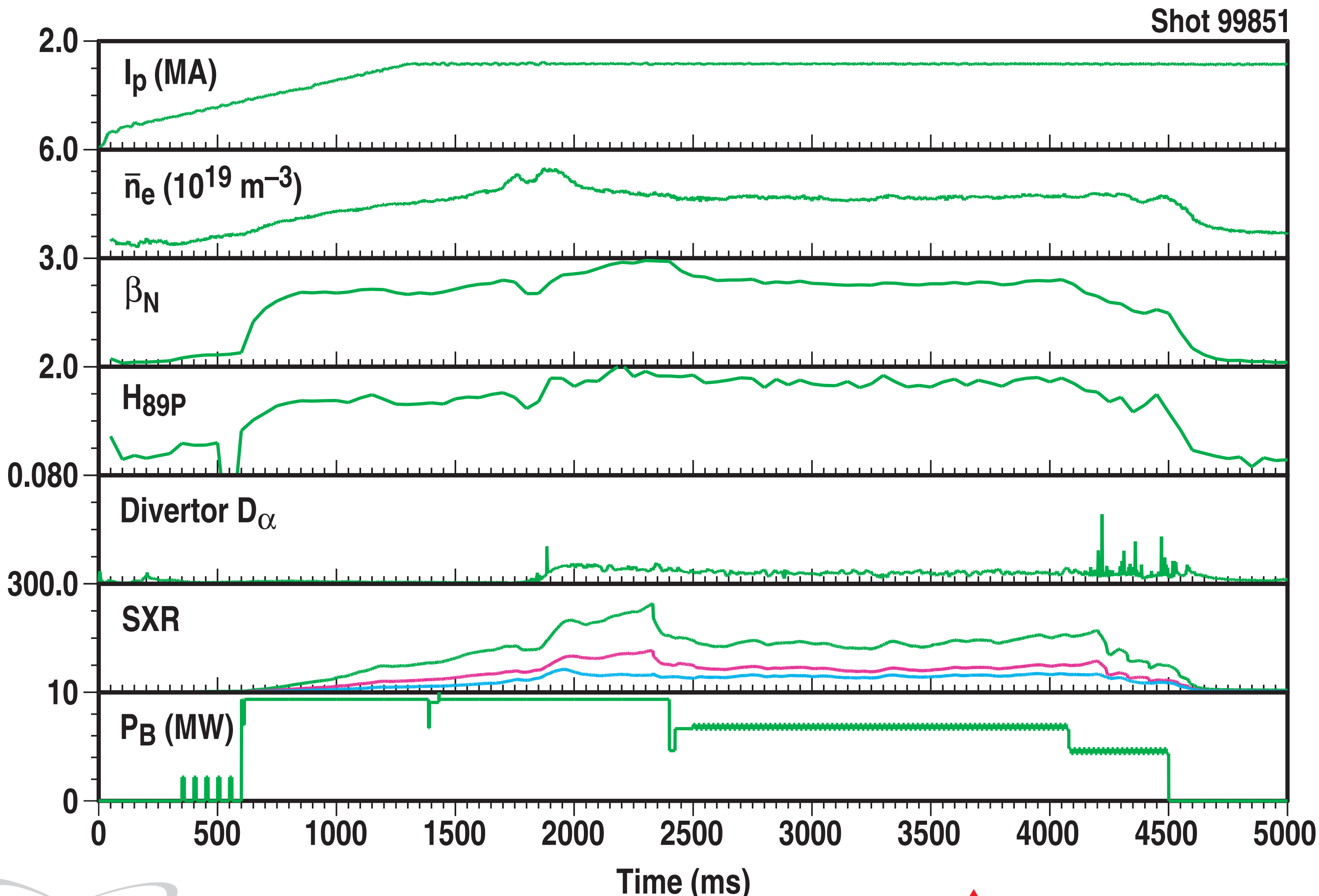
FUTURE RESEARCH DIRECTION -
HIGH k TURBULENCE AND ELECTRON TRANSPORT

- Measurements in range $0.5 < \rho < 0.8$, $k_\theta = 13.3\ cm^{-1}$



– Improved short wavelength measurements needed (improved FIR scatting)

STEADY-STATE, ELM-FREE, SAWTOOTH-FREE SHOT WITH DENSITY CONTROL



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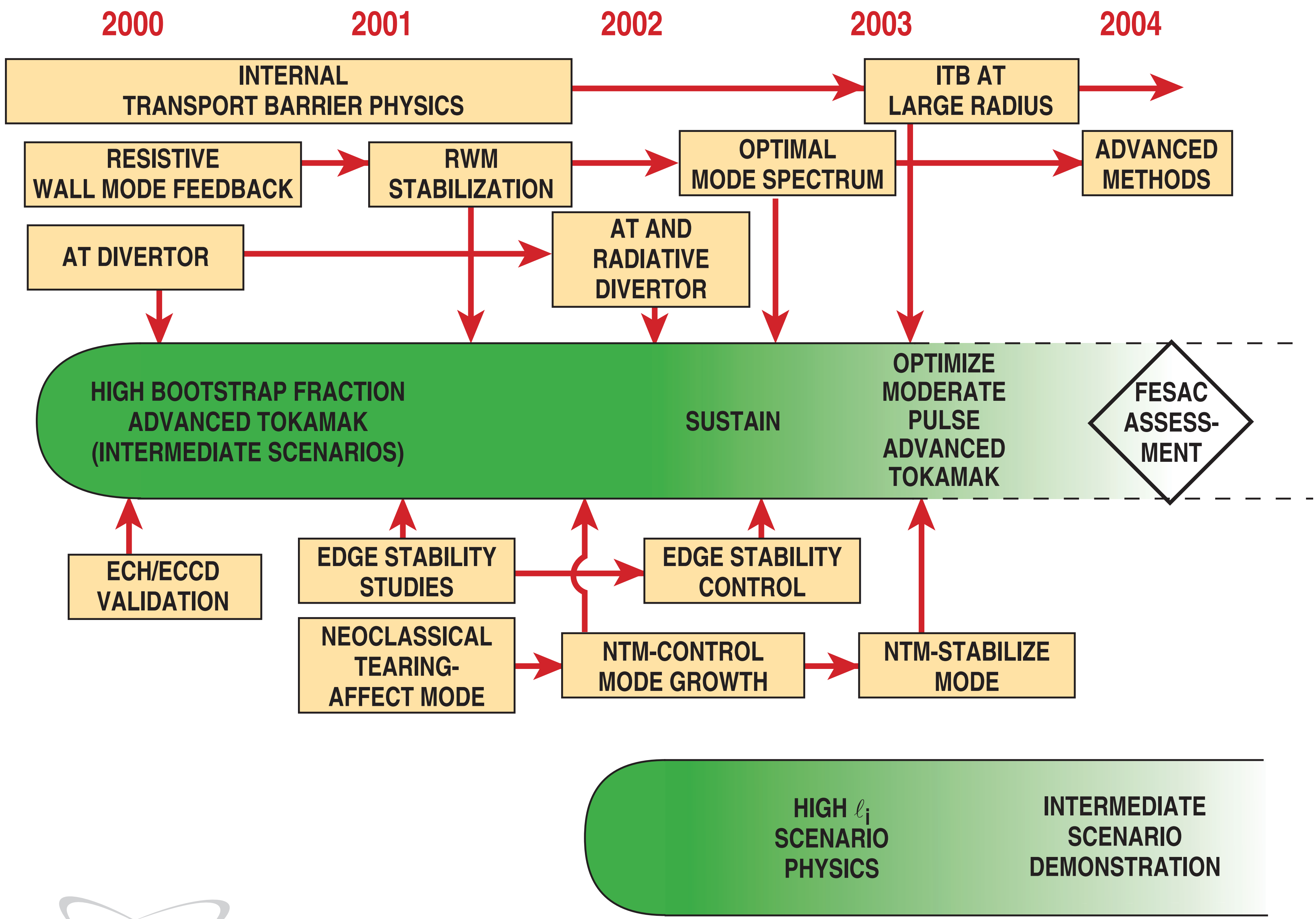
GENERAL ATOMICS

240-99/rs

THE 2000 DIII–D ADVANCED TOKAMAK RESEARCH THRUSTS FOR 2000–2004



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