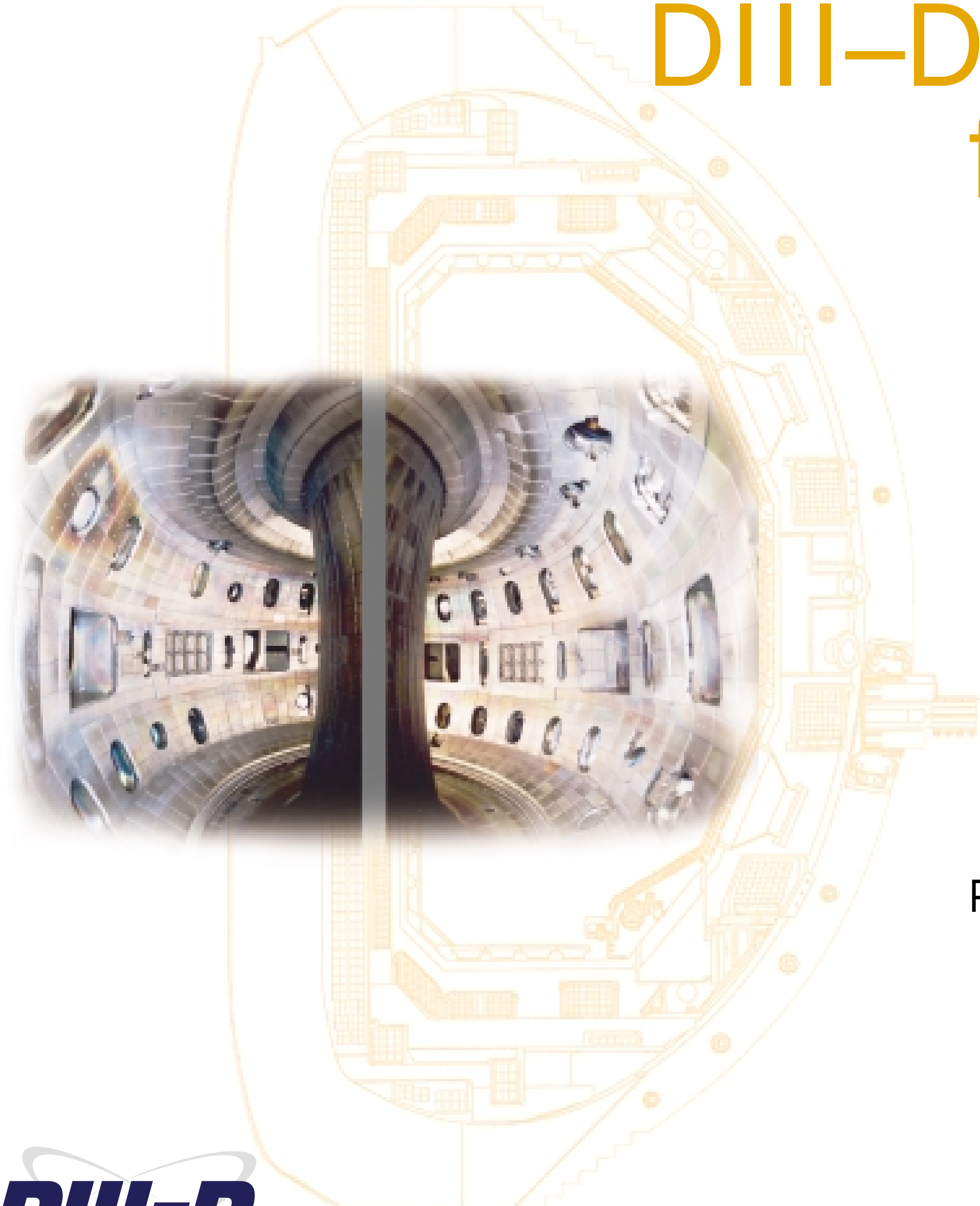
DIII–D Program Plan for 2004–2008



by
T.C. Luce

for
The DIII–D Team

Presented at
NSTX Five-Year Plan Ideas Forum
Princeton Plasma Physics Laboratory
Princeton, New Jersey

June 24-26, 2002

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THE DIII–D RESEARCH PROGRAM WILL MAKE MAJOR CONTRIBUTIONS IN THREE FOCUS AREAS

- **Advanced Tokamak: in-principle steady-state, high performance discharges**
  - Scientific understanding of key elements
    - ★ MHD stabilization
    - ★ Profile optimization
  - Plasma control
  - Integrated self-consistent scenarios

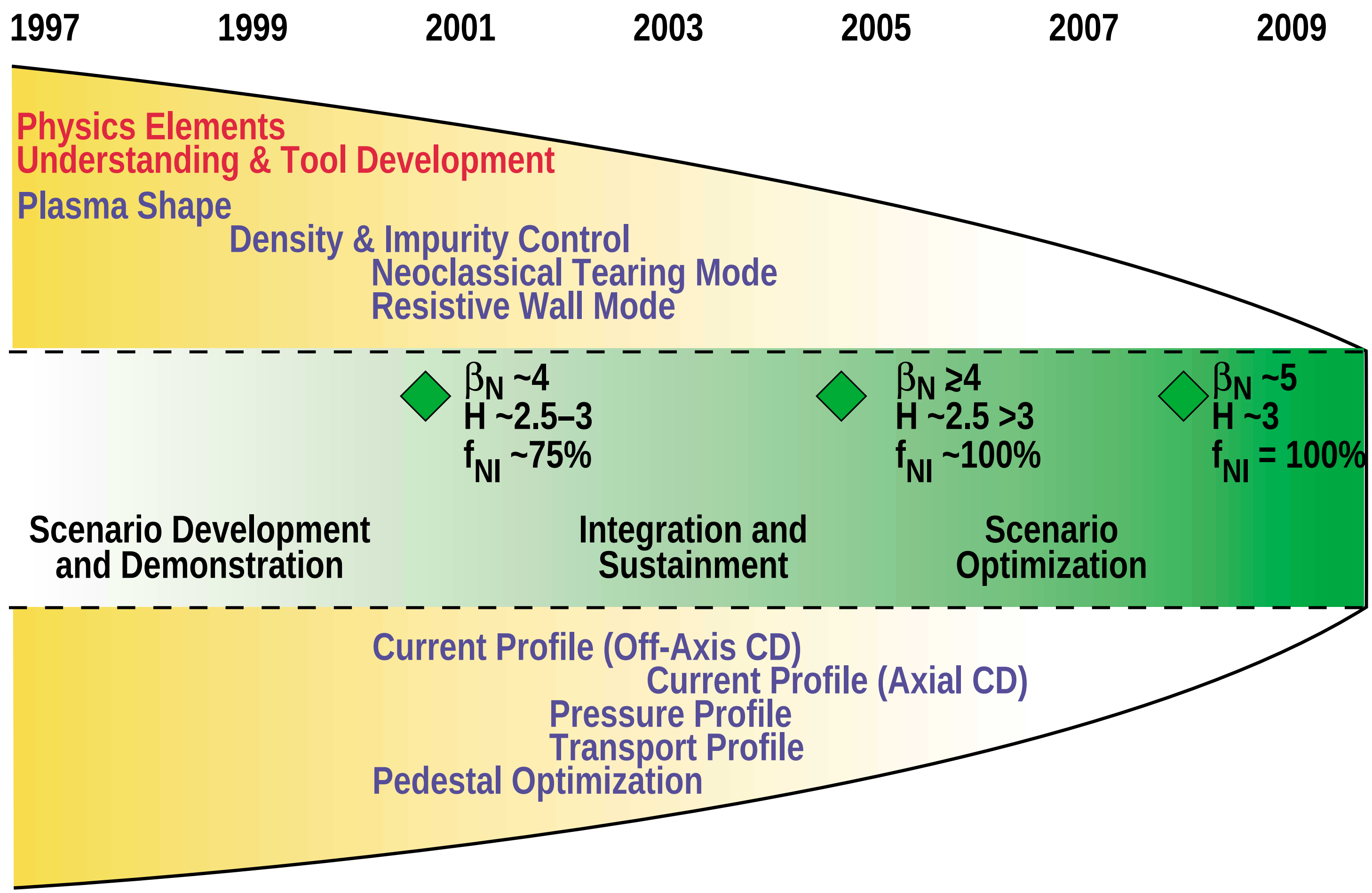
- **Transport: major advance in turbulent transport understanding**
  - Develop state-of-the-art simulations and models
  - Measure turbulence generated flows
  - Measure short wavelength turbulence (electron transport)

- **Mass transport in the boundary**
  - Integrated modeling of the boundary
  - Measure flow of primary ions
  - Measure erosion and redeposition (tritium retention issue)

DIII–D progress over a broad range of science issues will support these accomplishments

THE DIII–D ADVANCED TOKAMAK PROGRAM

- The heart of the program is scenario development, integration, and optimization
- Essential to the AT program and the AT optimization is plasma control



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THREE CLASSES OF ADVANCED SCENARIOS

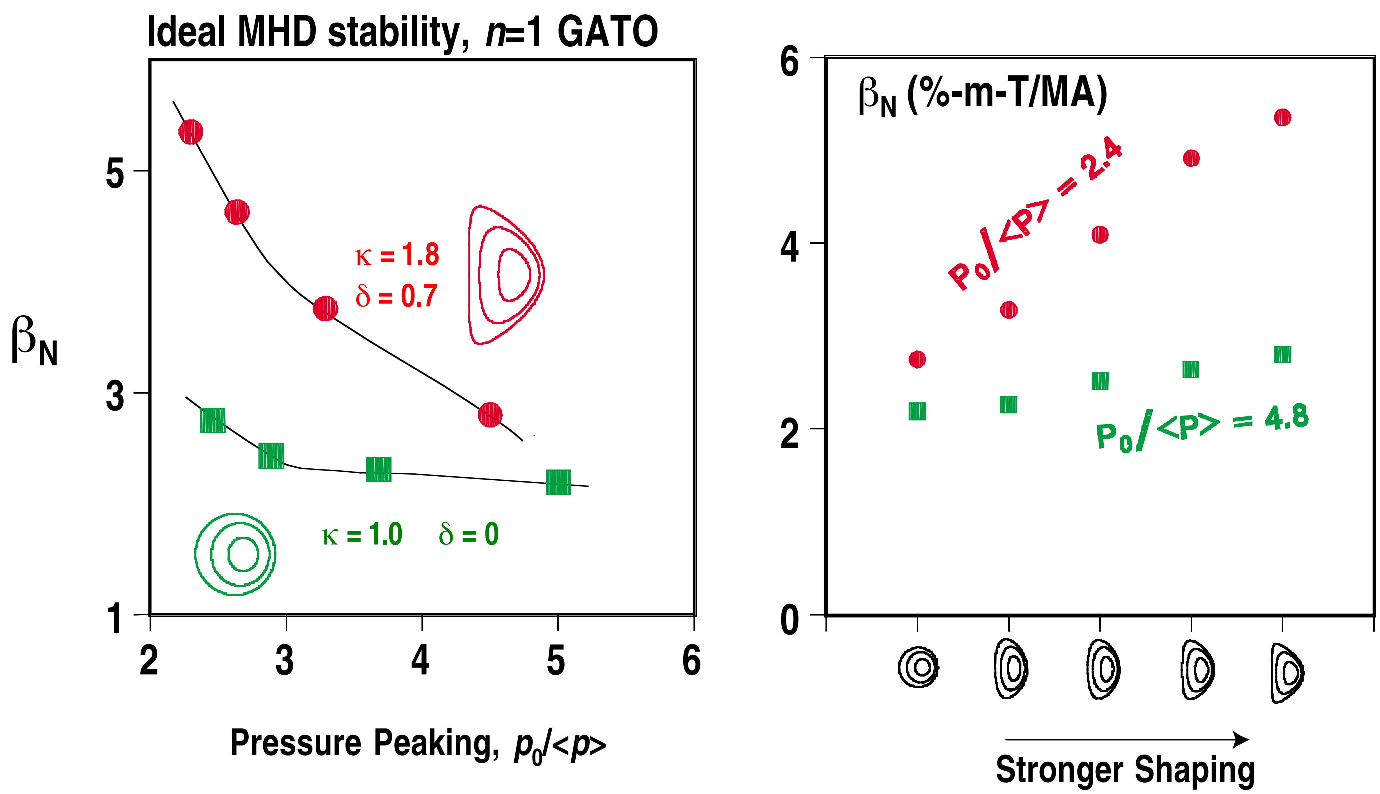
- **Transient high performance**
  - Possibility of significantly larger α power or fusion gain than ELMing H–mode.
  - Platform for testing diagnostics and materials for reactor environment.

- **Stationary high performance**
  - Active control of MHD allows operation at increased fusion performance.
  - Lower plasma current per unit fusion power $\Rightarrow$ reduced risks.

- **Steady-state**
  - 100% noninductive current drive required.
    - > Advantage to maximized fraction of well-aligned bootstrap current.

Emphasis of DIII–D Advanced Tokamak research is steady-state high performance.

BETA LIMIT IN STRONGLY SHAPED PLASMAS CAN BE INCREASED BY BROADENING THE PRESSURE PROFILE



- **MHD stability favors:**
  - Strong shaping (high elongation κ and triangularity δ).
  - Broad pressure profile
    - > *Need to establish firm understanding of transport.*
    - > *Profile control tool development.*

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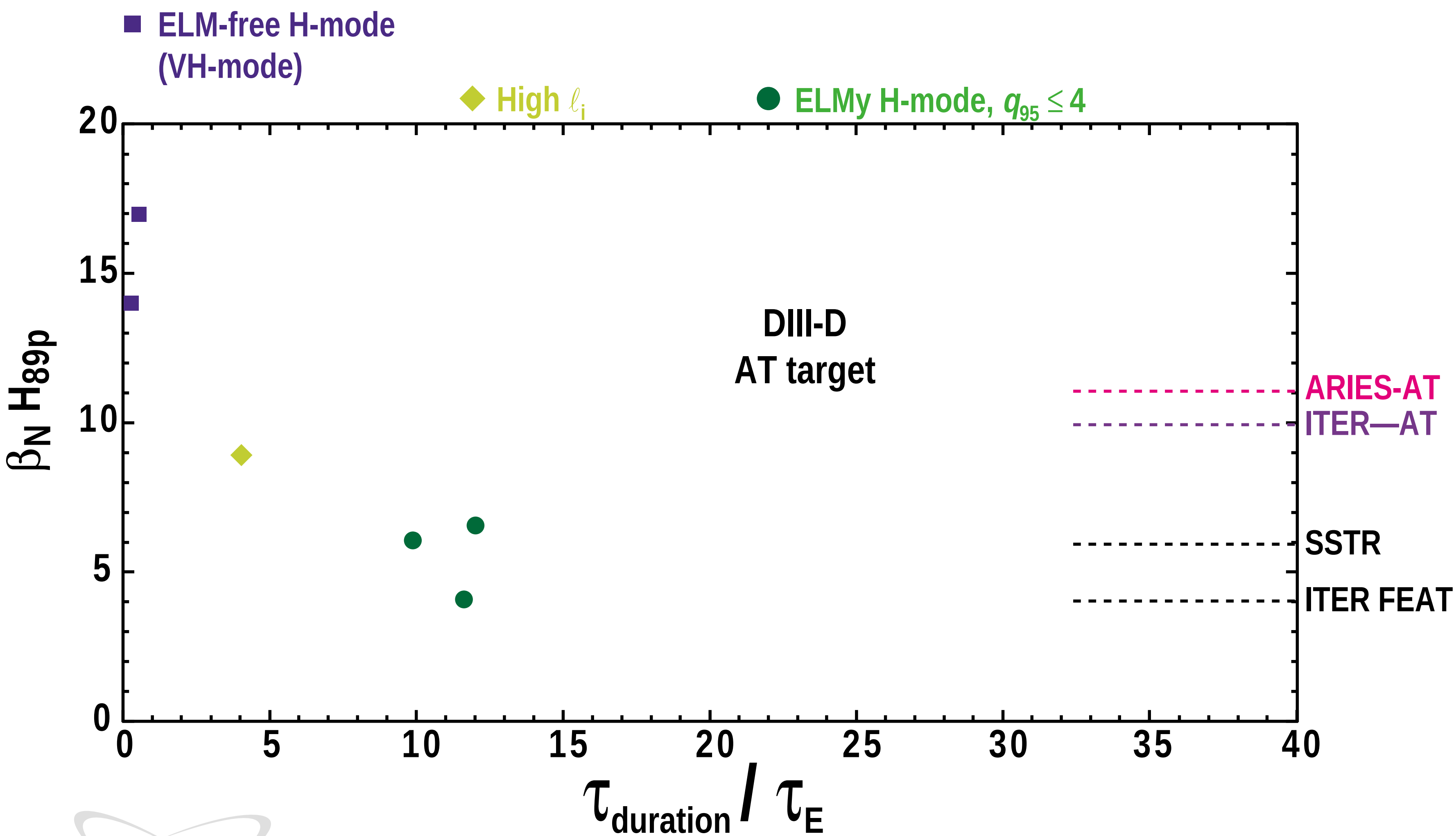
SIGNIFICANT PROGRESS TOWARD LONG-PULSE HIGH PERFORMANCE

- Advanced performance found in many operating regimes



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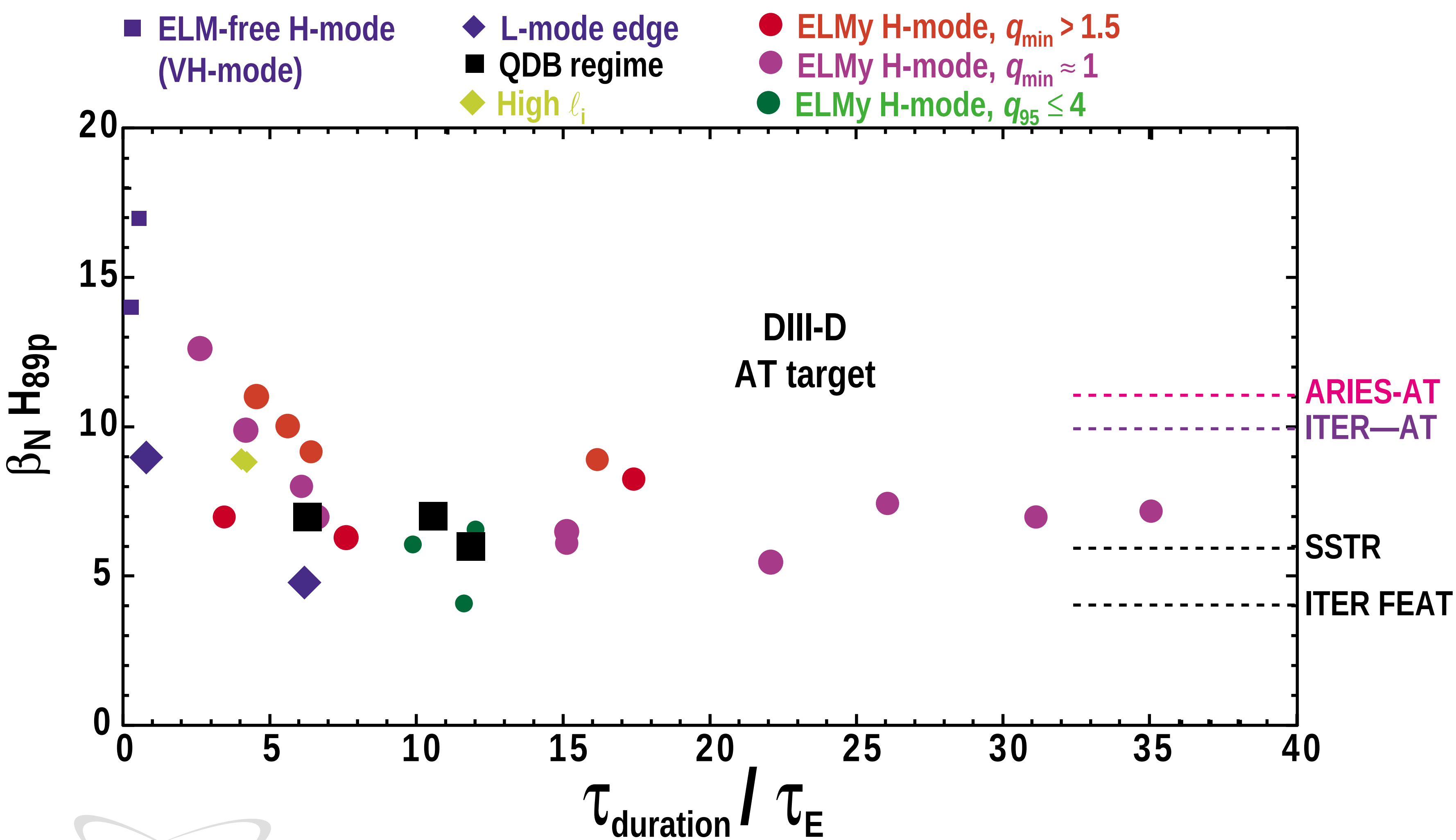
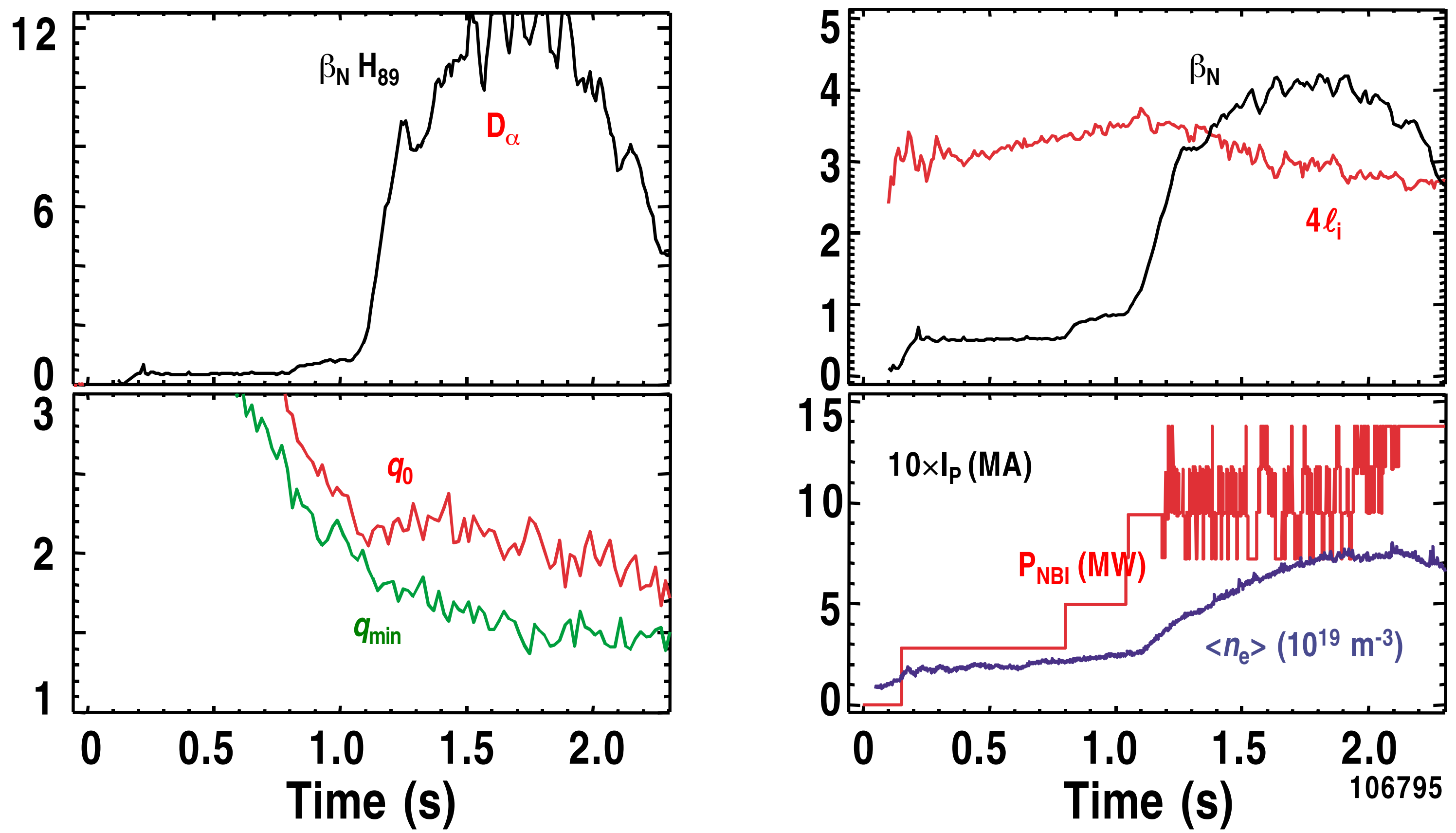
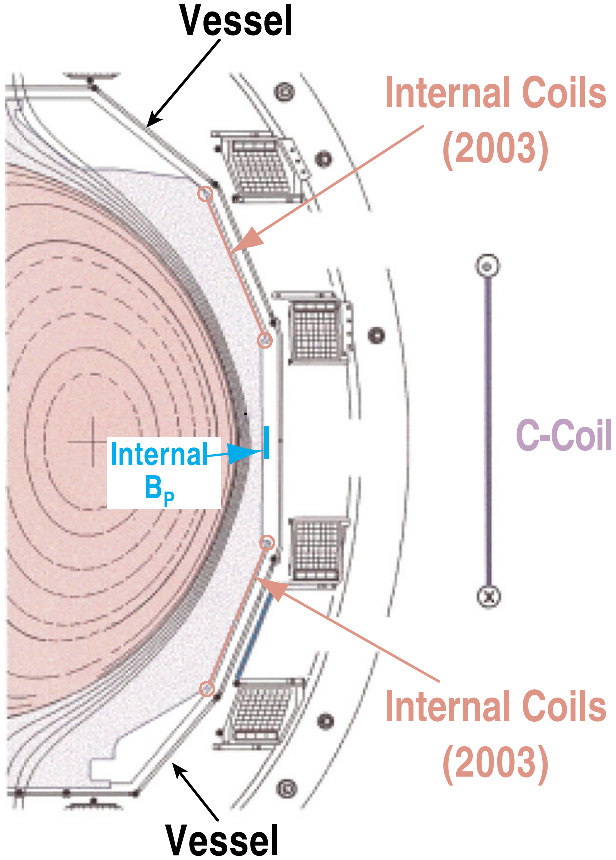


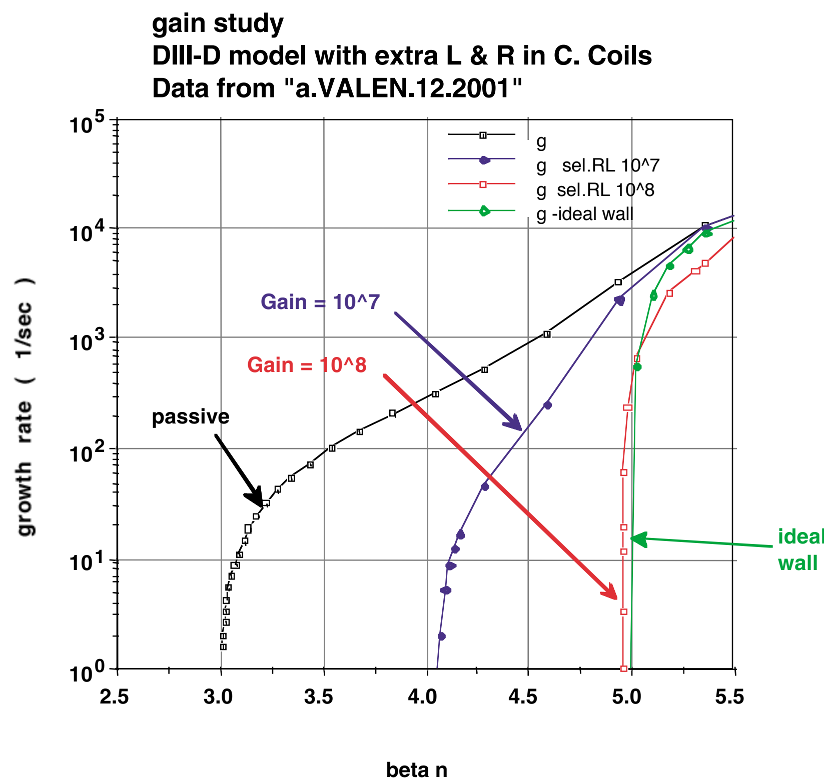
ERROR FIELD CORRECTION WITH PRESENT COILS ALREADY ALLOWS OPERATION ABOVE NO-WALL LIMIT



- Achieved through rotational stabilization of resistive wall mode.
- Dynamic error field correction is used during AT experiments.

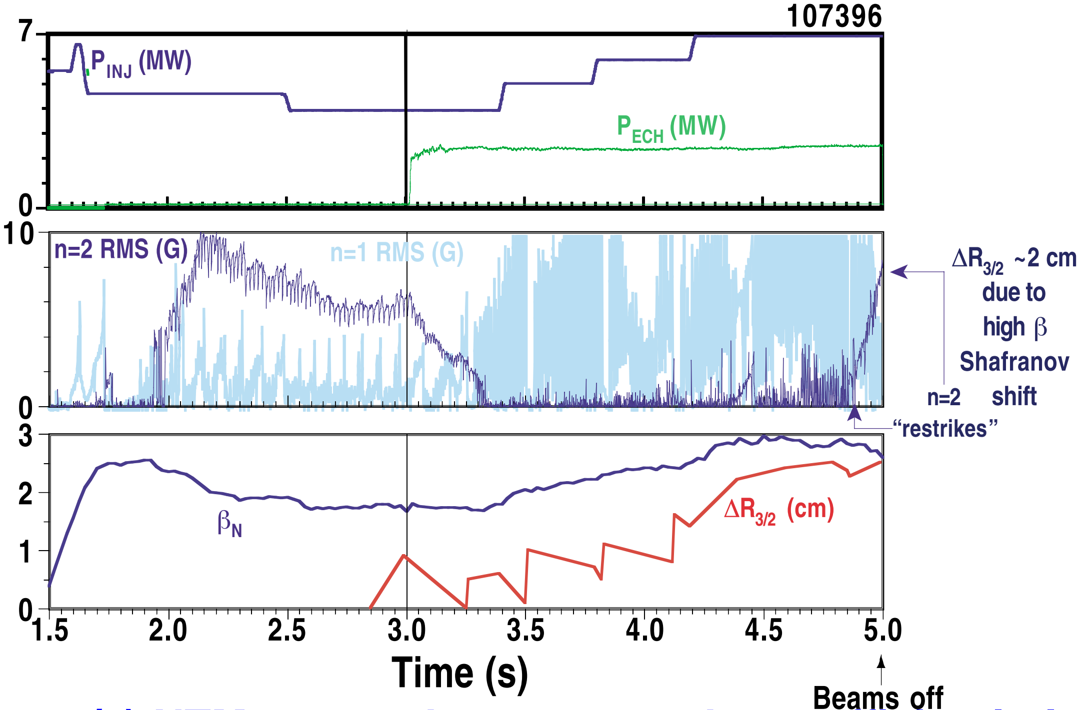
NEW INTERNAL COILS WILL ALLOW OPERATION EVEN CLOSER TO IDEAL WALL LIMIT





- **12 internal control coils being installed during 2002 vent.**
  - Will work in combination with existing 6 segment C-Coil to allow operation near ideal wall limit.
- **Sensors with high S/N required for maximum gain.**

NEOCLASSICAL TEARING MODES LIMIT DURATION OF PRESENT DAY AT EXPERIMENTS



- **Low order (2/1 or 3/2) NTM onset when q_{min} reaches sufficiently low values.**
  - Suppression of both modes demonstrated with ECCD in DIII–D.
- **Avoidance is the preferred approach: steady-state AT scenarios with high $q_{min} > 2$ not susceptible to these modes.**
  - ...but (3/1) mode has been seen in such discharges.

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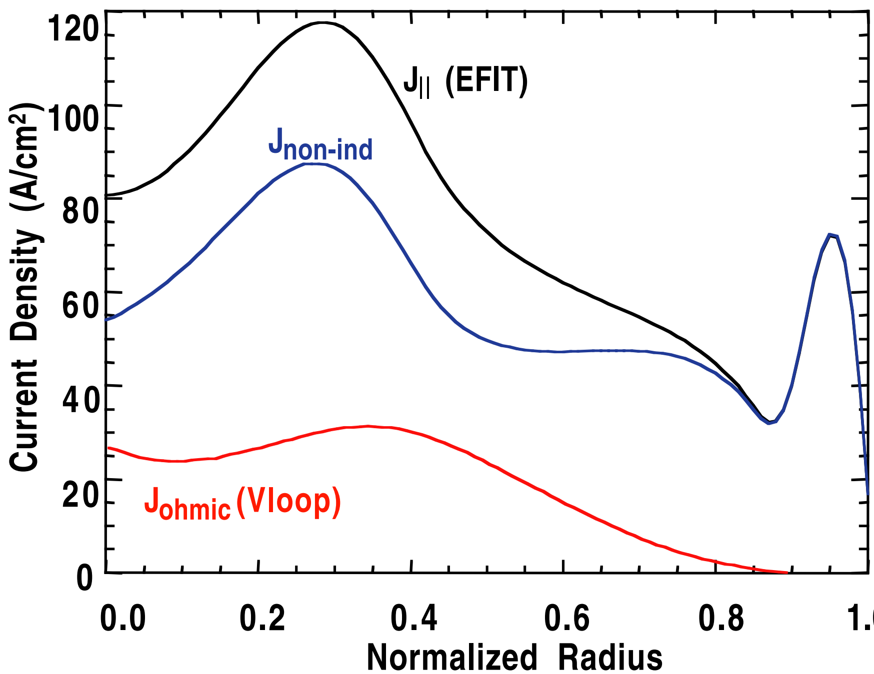
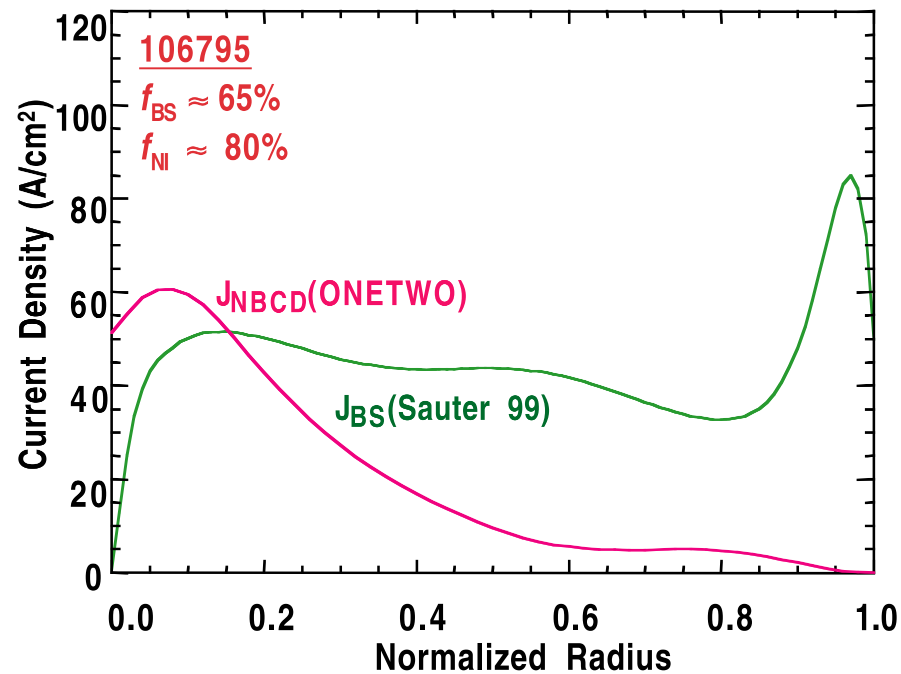
CURRENT PROFILE CONTROL NEEDED FOR STEADY-STATE

Provided Primarily by Bootstrap and ECCD





- **Steady-state goal of *AT* requires 100% noninductive current drive.**
  - Increased bootstrap contribution ($f_{BS} > 60\%$) minimizes current drive requirement.
    - Beam-driven current typically $f_{NBCD} \approx 15\%$.
  - Ohmic current at time shown has penetrated to core.
    - *Replacing Ohmic current at mid-radius with localized ECCD earlier in evolution should help maintain favorable q profile.*

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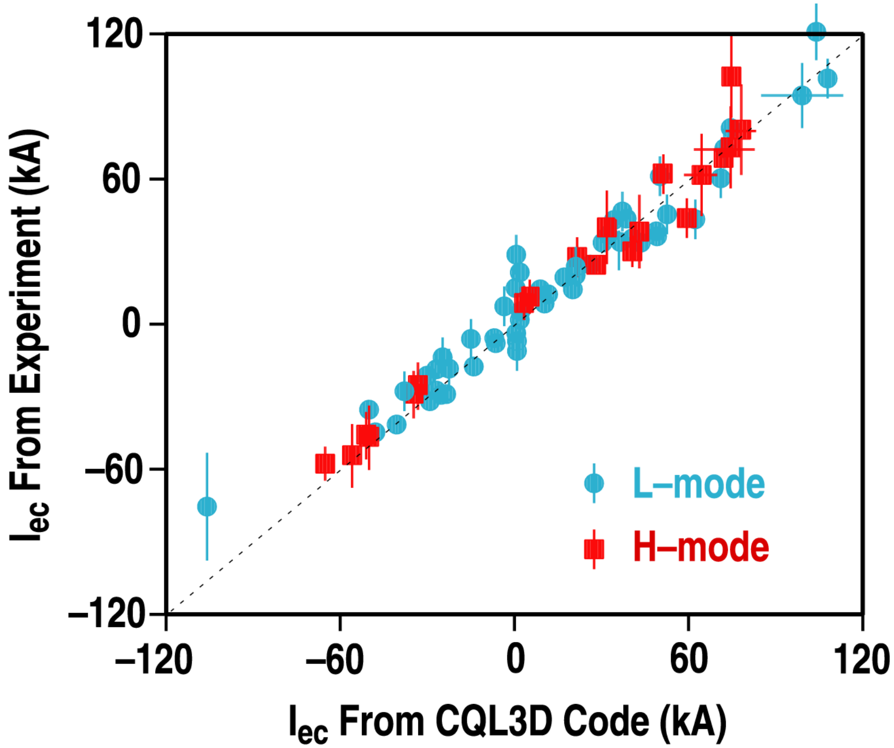
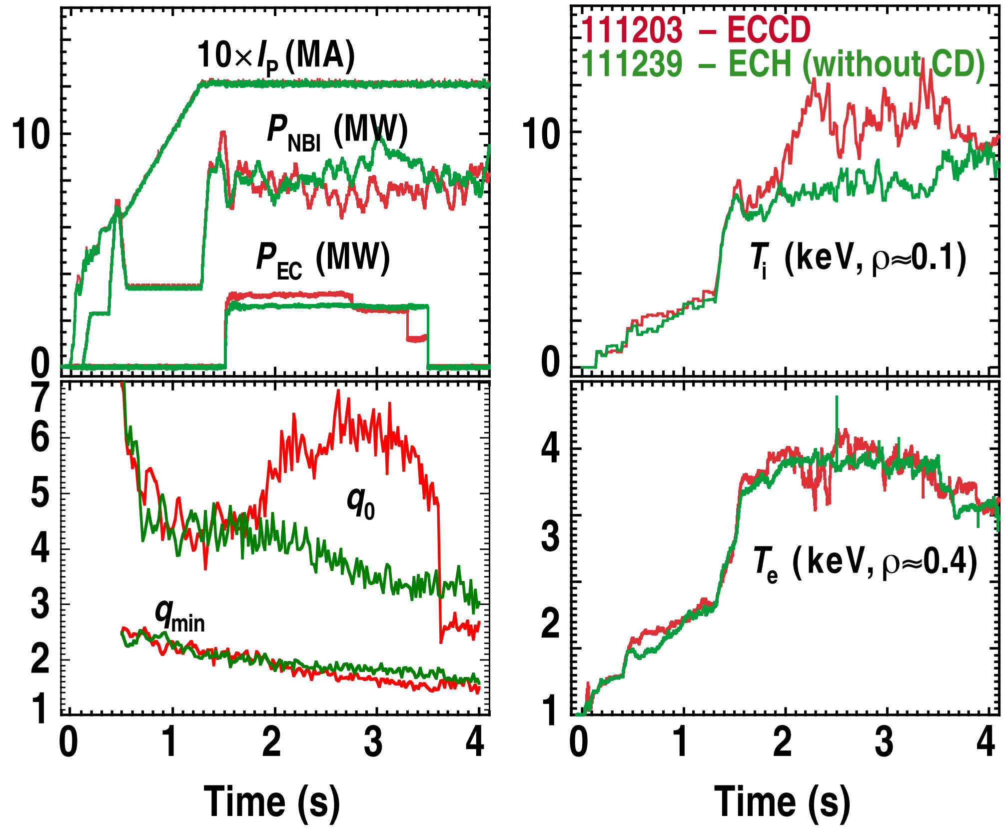
MEASURED ECCD IS IN GOOD AGREEMENT WITH THEORY



- Wide range of density, temperature, toroidal field, plasma current, H–mode or L-mode edge, minor radius (≤0.4), poloidal angle, parallel index of refraction
- Theory is evaluated using the CQL3D Fokker-Planck code, including effects of the dc toroidal electric field
- Sensitive test of theory
- Key dependence of off-axis ECCD on plasma beta validated

CLEAR DEMONSTRATION OF ECCD CURRENT PROFILE MODIFICATION IN A HIGH PERFORMANCE PLASMA

- **Current profile changes consistent with simulations.**
  - Cases without ECH (not shown) had similar current profile evolution to the ECH cases.
- **Transport affected as well: ITB appears in ion channel with ECCD.**
  - Both $T_i(0)$ and $T_e(0)$ larger with ECCD than radial launch.
- ***Similar results seen in QDB regime.***
  - *Current profile modification not specific to a single regime.*



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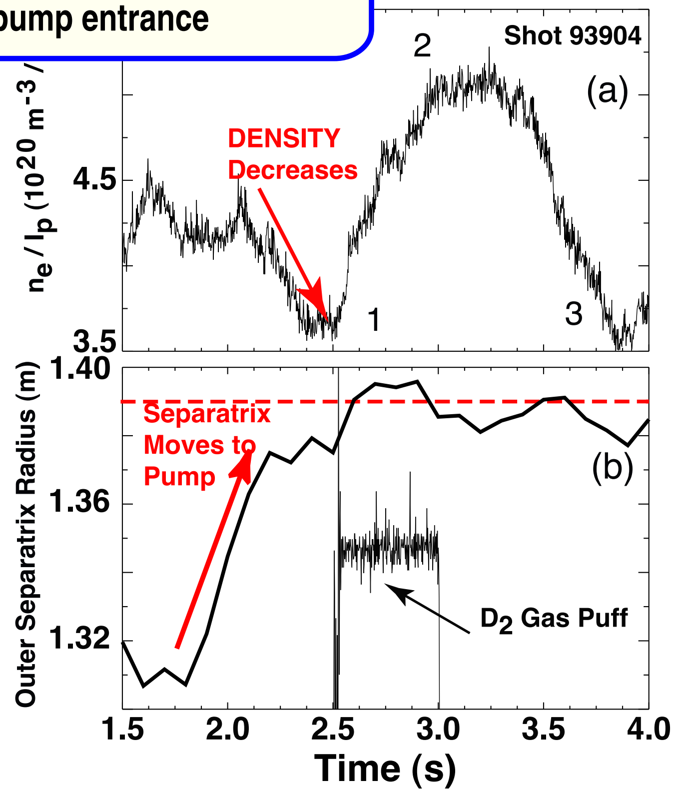
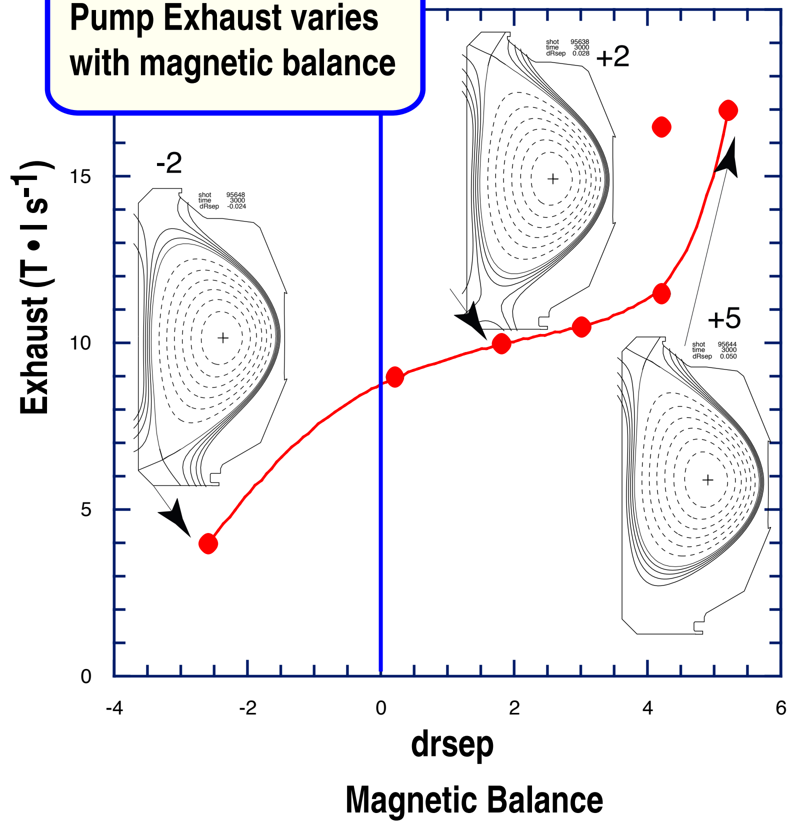
Density control is essential in AT plasmas: control achieved by strike point location and magnetic balance

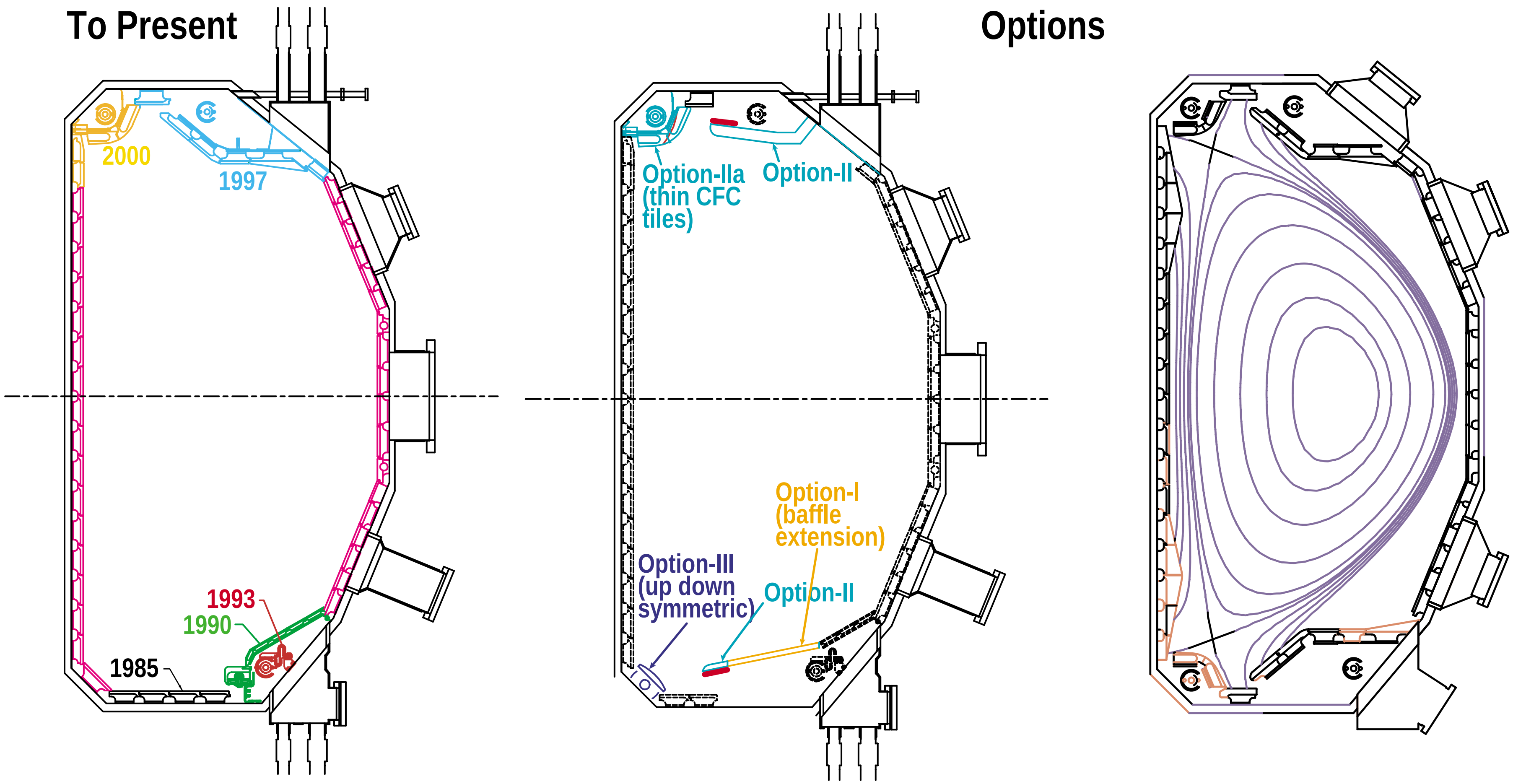
Core density decreases when strike point is moved to pump entrance



Pump Exhaust varies with magnetic balance



BOUNDARY CONTROL: EVOLVING DIVERTOR HARDWARE SUPPORTS BOUNDARY DIVERTOR PHYSICS AND ADVANCED TOKAMAK NEEDS



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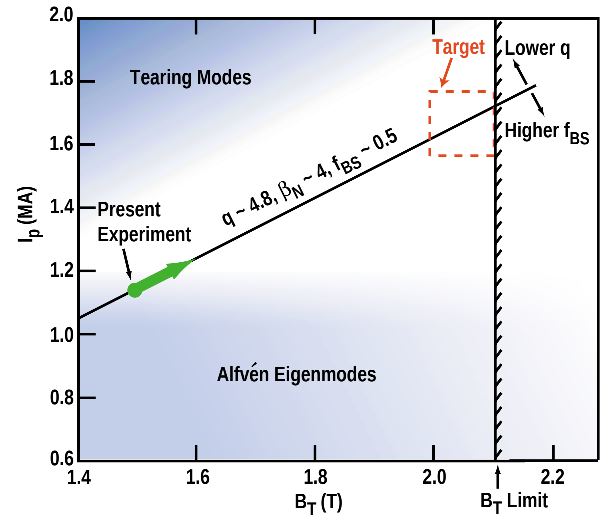
DIII–D LONG PULSE CAPABILITY PROVIDES FOR LEADING EDGE ADVANCED TOKAMAK PHYSICS IN SUPPORT OF FESAC/IPPA 10 YR GOAL

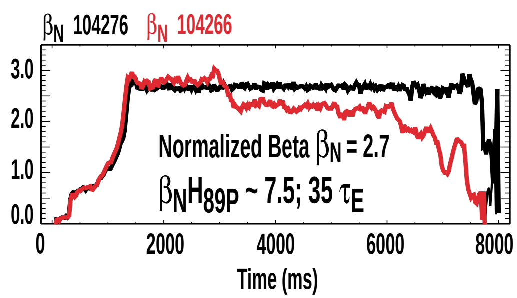
- FESAC/IPPA: Assess the attractiveness of extrapolable, long-pulse operation of the advanced tokamak for pulse lengths much greater than the current penetration time



- $\tau_{CR} \approx 1.4\, a^2\, \kappa/Z_{eff}\, T_e^{3/2}$
  - Near term: $\langle T_e \rangle \sim 4$ keV $\quad \tau_{CR} \sim 4$ s
  - Full field target: $\langle T_e \rangle \sim 6$ keV $\quad \tau_{CR} \sim 7.5$ s

Device	DIII–D	JET	KSTAR	JT–60SC	FIRE	ITER
τ_{CR}	7.5	50	9	25	13	250
τ_{pulse}	10	20	20/300	20/300	20	400

NEEDED IMPROVEMENTS



138 kV to 12.47 kV Transformer
84 MW Peak, 350 MW
Energy Throughput

Toroidal Coil
Beltbus

Toroidal Coil
Freewheeling Diodes

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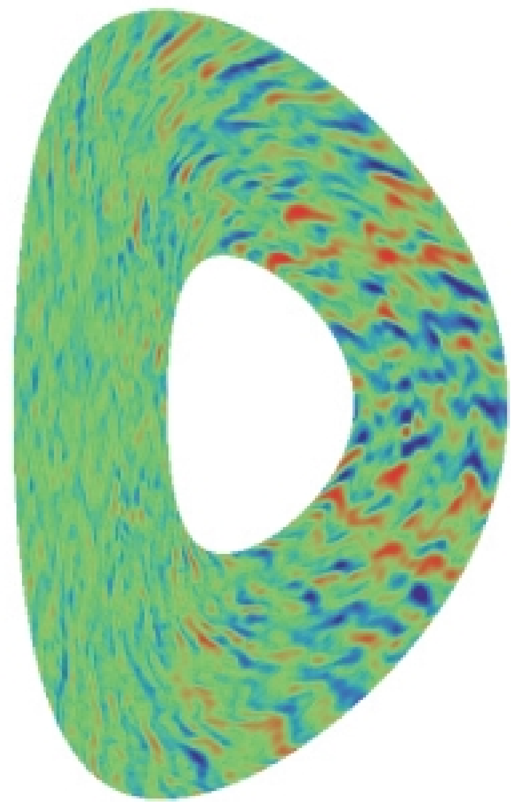
THE DIII–D PROGRAM PLANS A FOCUSED EFFORT ON UNDERSTANDING TURBULENT TRANSPORT OVER THE NEXT FIVE YEARS

— As part of a community-wide effort, in concert with TTF —

- **Lead goal is predictive understanding of transport**
  - **Five-Year Objective: Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems**
- **National cooperation and leadership (TTF)**

⇒ **Codes are on the verge of calculating essential physics needed for meaningful comparison with experiment**

- **New diagnostic measurements essential for this comparison**



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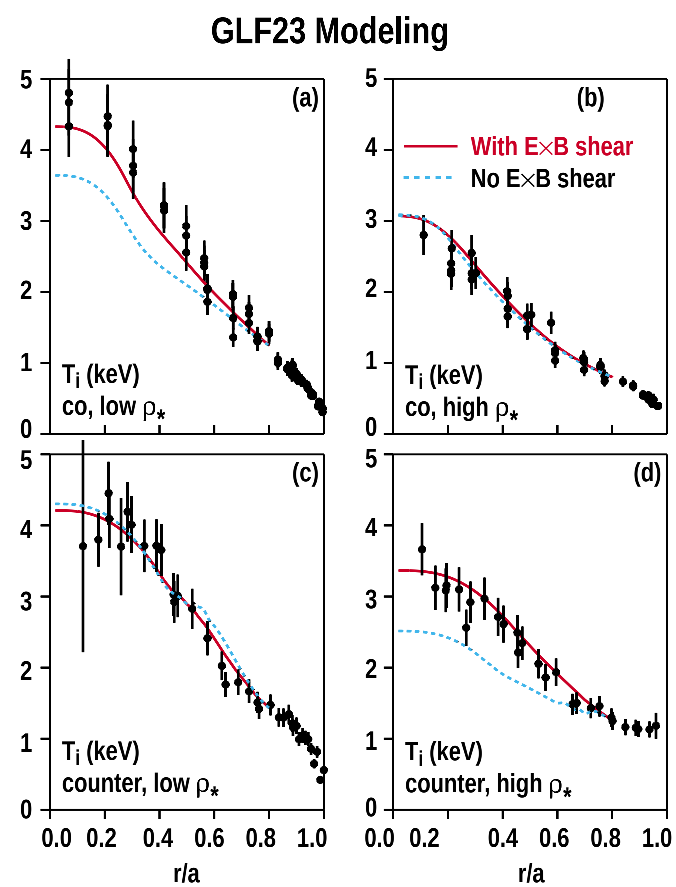
FIVE KEY ELEMENTS FOR UNDERSTANDING TRANSPORT IN THE TOKAMAK

1. **Strong partnership between experiment and theory/simulation/modeling**
   - Theory and modeling guide the experiments
   - Experiments test and validate theory
2. **State-of-the-art modeling and simulation capability**
   - New GYRO code (simulation), multi-processor computer
   - Synthetic diagnostic visualization — code modules that calculate exactly what diagnostics measure
   - Integrated modeling — new transport models to interpret plasma profile response
3. **Complete set of physics measurements — measure theoretically relevant quantities**
   - High k turbulence
   - Zonal flows
   - Turbulent imaging
4. **Plasma and transport control tools**
   - Spatially and temporally localized ECH
   - Versatile plasma shaping
   - Rotation control $\Rightarrow$ co-counter beams
5. **Innovative experiments**

STATUS OF PHYSICS UNDERSTANDING: ION THERMAL TRANSPORT

- There is general agreement that the ITG physics included in present-day modeling codes describes the ion thermal transport well
  - ExB shear stabilization can turn off ITG modes
  - In transport barriers, ion thermal transport at neoclassical level has been seen



- The key question in this area is whether the theoretically predicted zonal flows exist
  - Zonal flows regulate the turbulence amplitude and, hence, the magnitude of the transport
  - Need improved diagnostics to measure zonal flows

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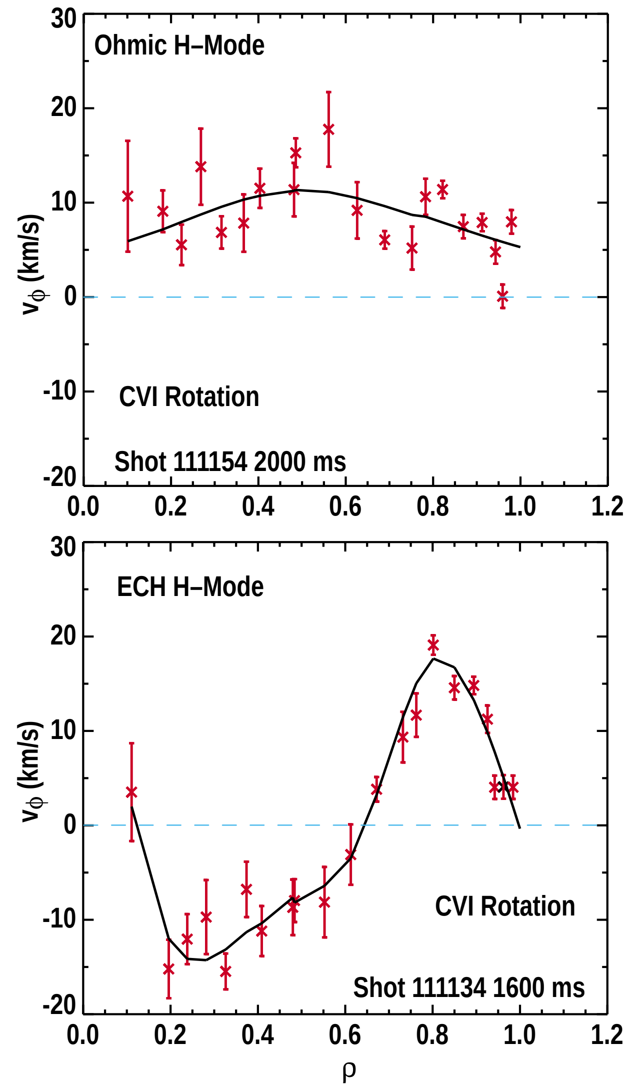
UNDERSTANDING OF PARTICLE, MOMENTUM, AND ELECTRON ENERGY TRANSPORT IS MUCH LESS ADVANCED

- **Particle transport**
  - Inclusion in theory calculations and models is needed
  - Measurement of sources is needed
  - Impurity transport is qualitatively consistent with neoclassical predictions in improved confinement regimes
- **Electron energy transport**
  - Measured level from power balance is nearly always above neoclassical values
  - Inclusion in theory calculations on an equal footing with ions is difficult due to disparate space and time scales
  - Measurements of fluctuations is difficult for similar reasons
- **Angular momentum transport**
  - Little systematic work experimentally
  - May be subtle connections to particle transport

PLASMAS WITHOUT ANGULAR MOMENTUM INPUT ROTATE

- Extensive work on C–Mod in ICRH and Ohmic H–mode shows significant rotation in direction of plasma current
- Recent DIII–D measurements show same result in Ohmic H–mode but more complex radial rotational structure in ECH H–mode
- What is the mechanism that produces this rotation?



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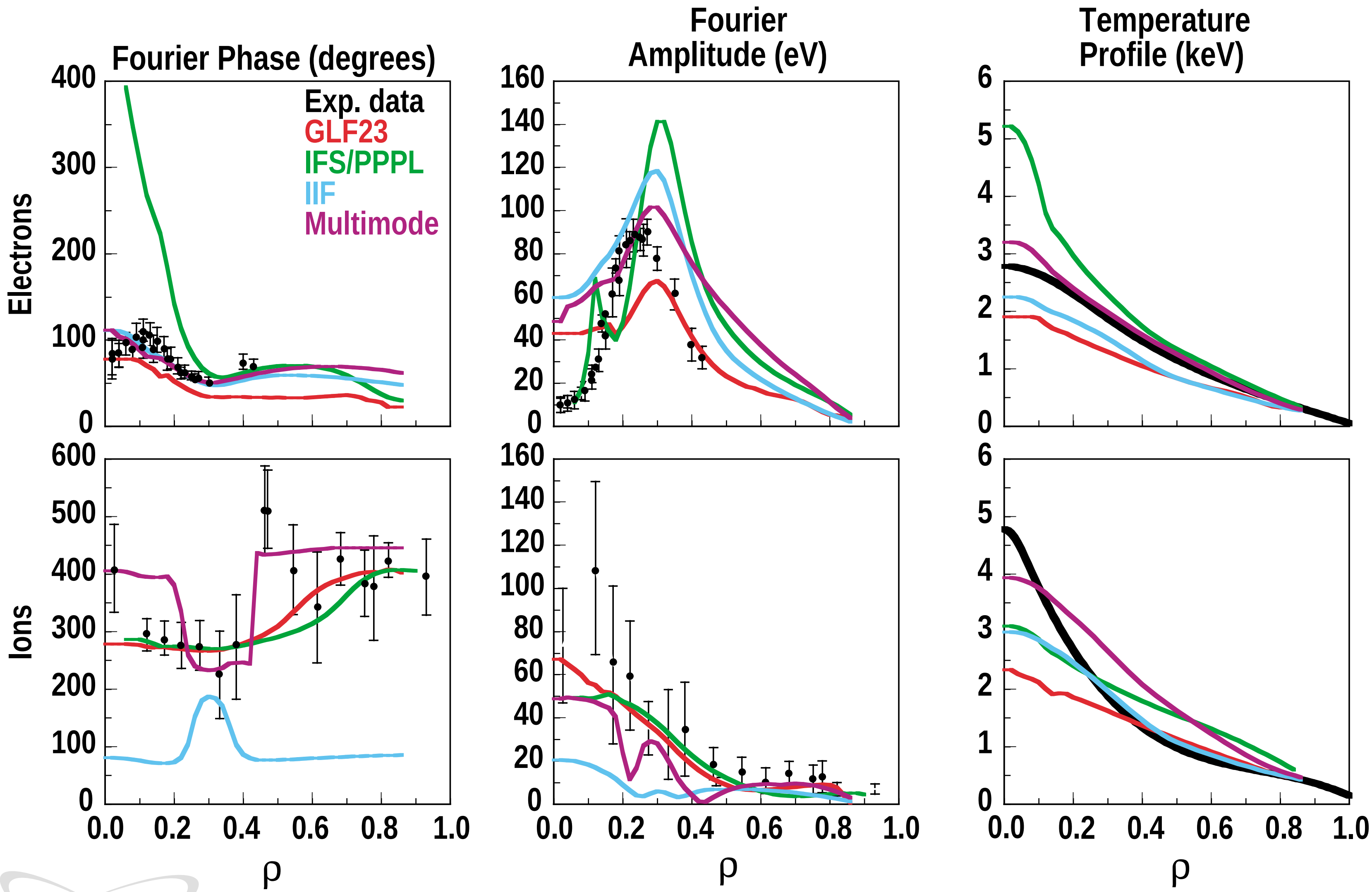
MODULATED TRANSPORT STUDIES PROVIDE KEY TOOL FOR TESTING THERMAL TRANSPORT

- ECH modulation at 25 Hz at ρ = 0.3



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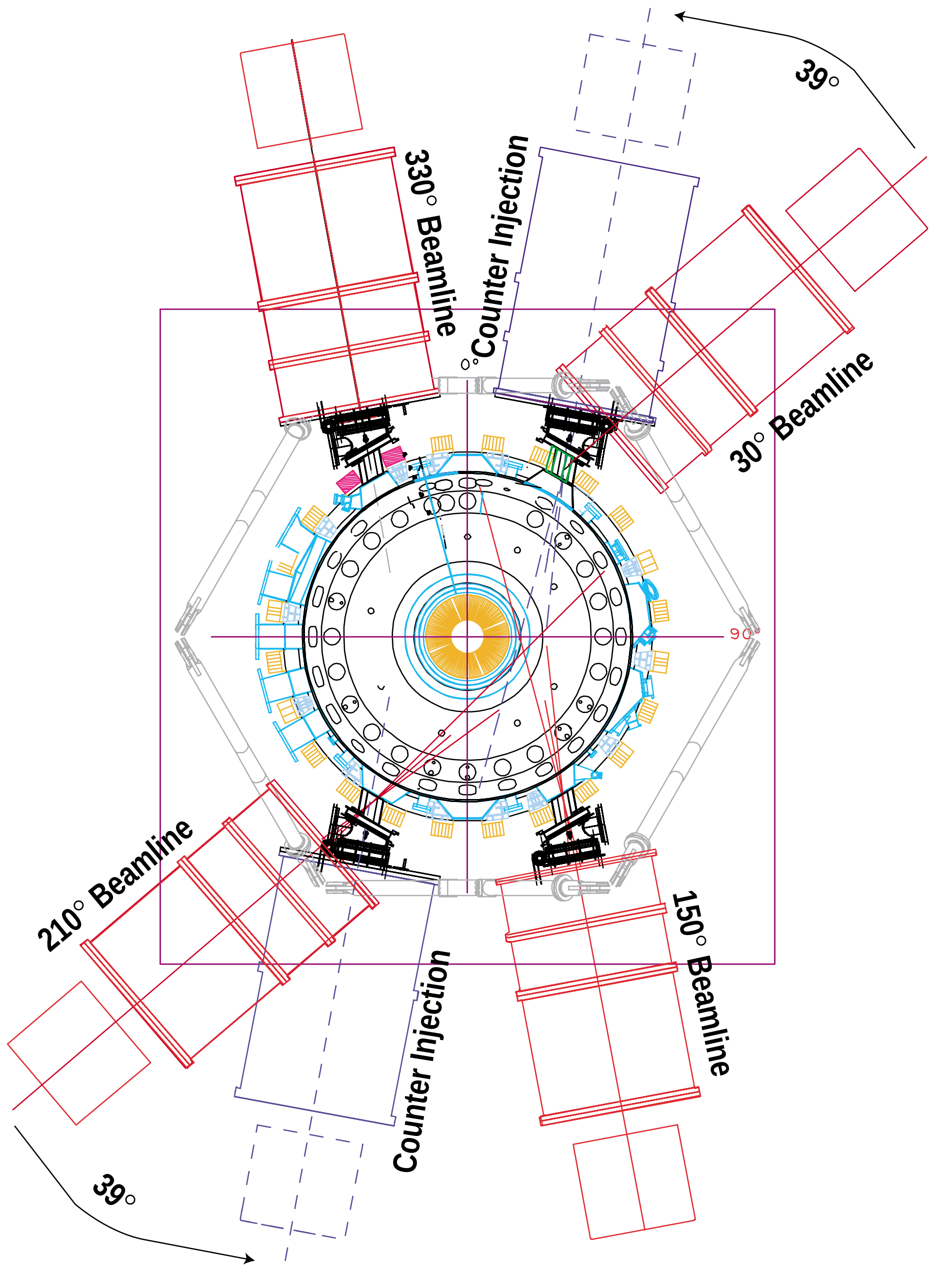
PLAN FOR CO PLUS COUNTER NBI ON DIII–D



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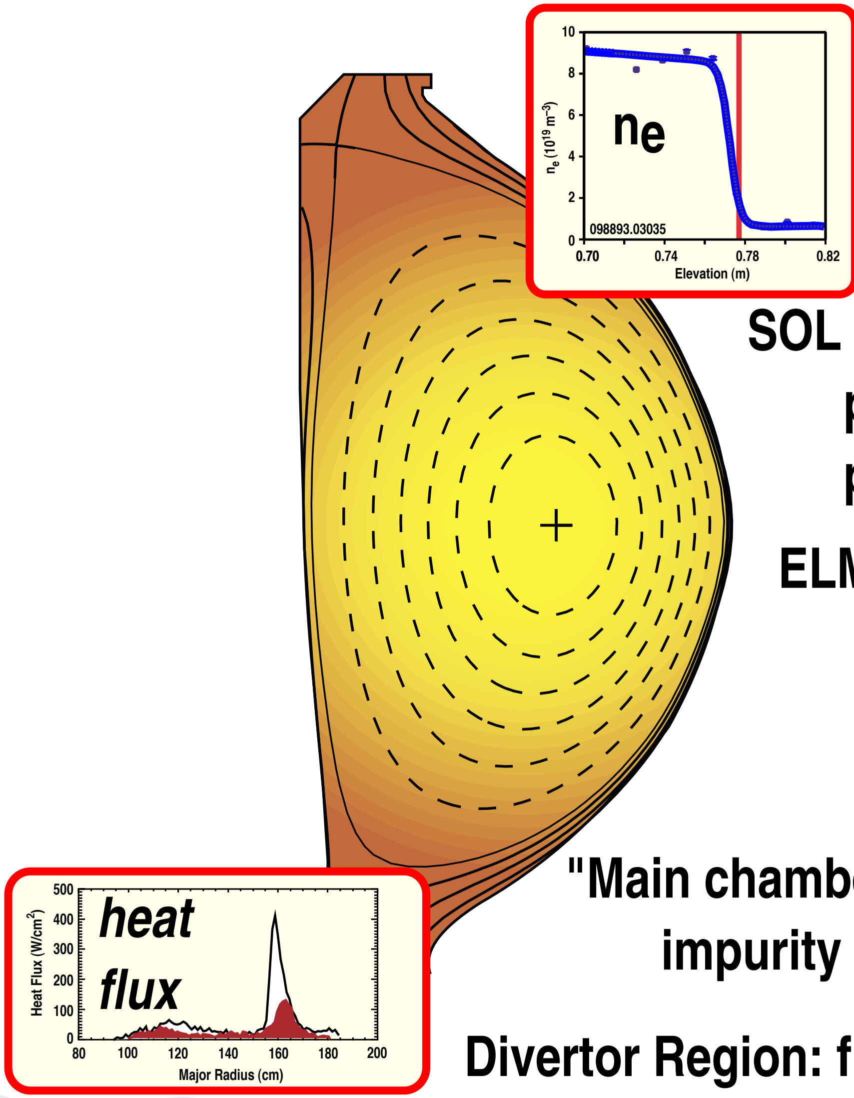
Mass Transport in the boundary:
Physics processes from the top of the pedestal to the divertor plate



Pedestal Physics: what determines
the width and height of the pedestal?

SOL transport: need to understand both
parallel (convection, conduction) and
perpendicular (transport coefficients)

ELMS: scaling and control

"Main chamber" and divertor impurity sources, and
impurity transport

Divertor Region: flows near the x-point, density control
Plate: erosion and redeposition, heat and particle loads

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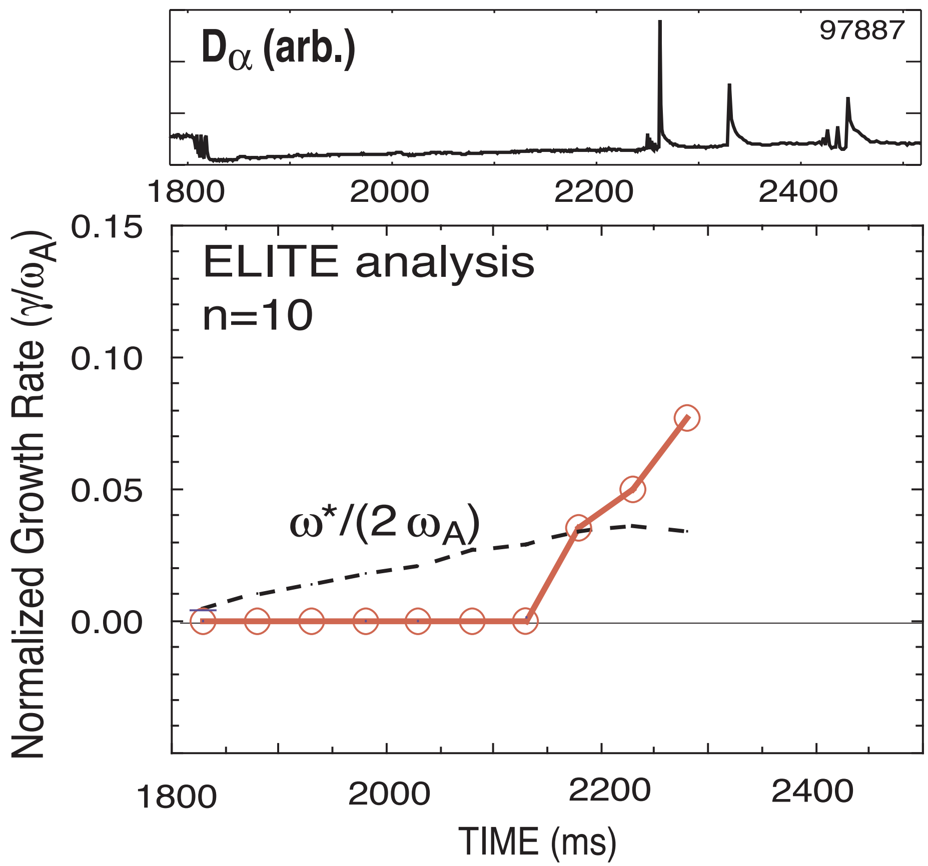
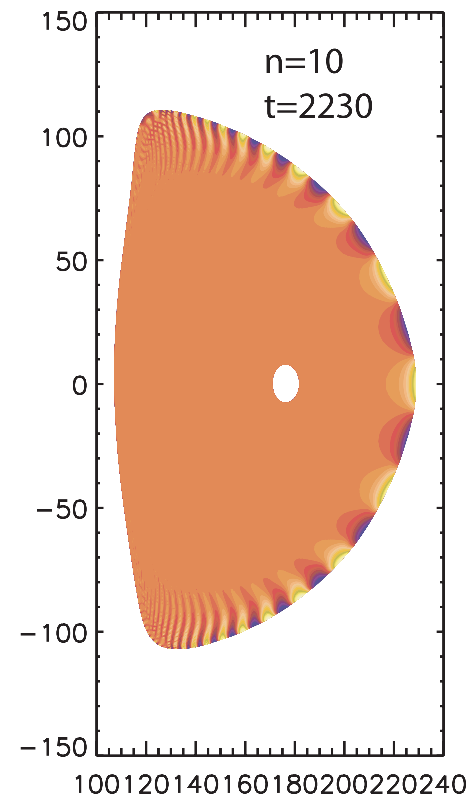
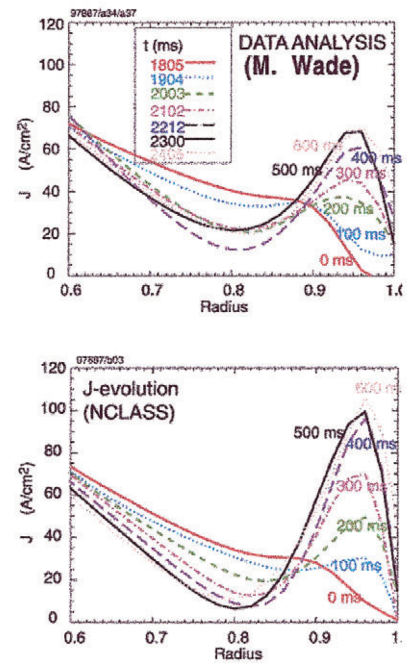
INTERMEDIATE n PEELING-BALLOONING MODES ARE A SOLID CANDIDATE FOR ELMs: CASE STUDY IN DIII–D







- DIII–D shot analyzed using experimental reconstruction of equilibria
- n=10 growth rate attains significant value just before ELM observed
- Edge current remains an important uncertainty ⇒ Li beam diagnostic

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UKAEA Fusion Working with Europe

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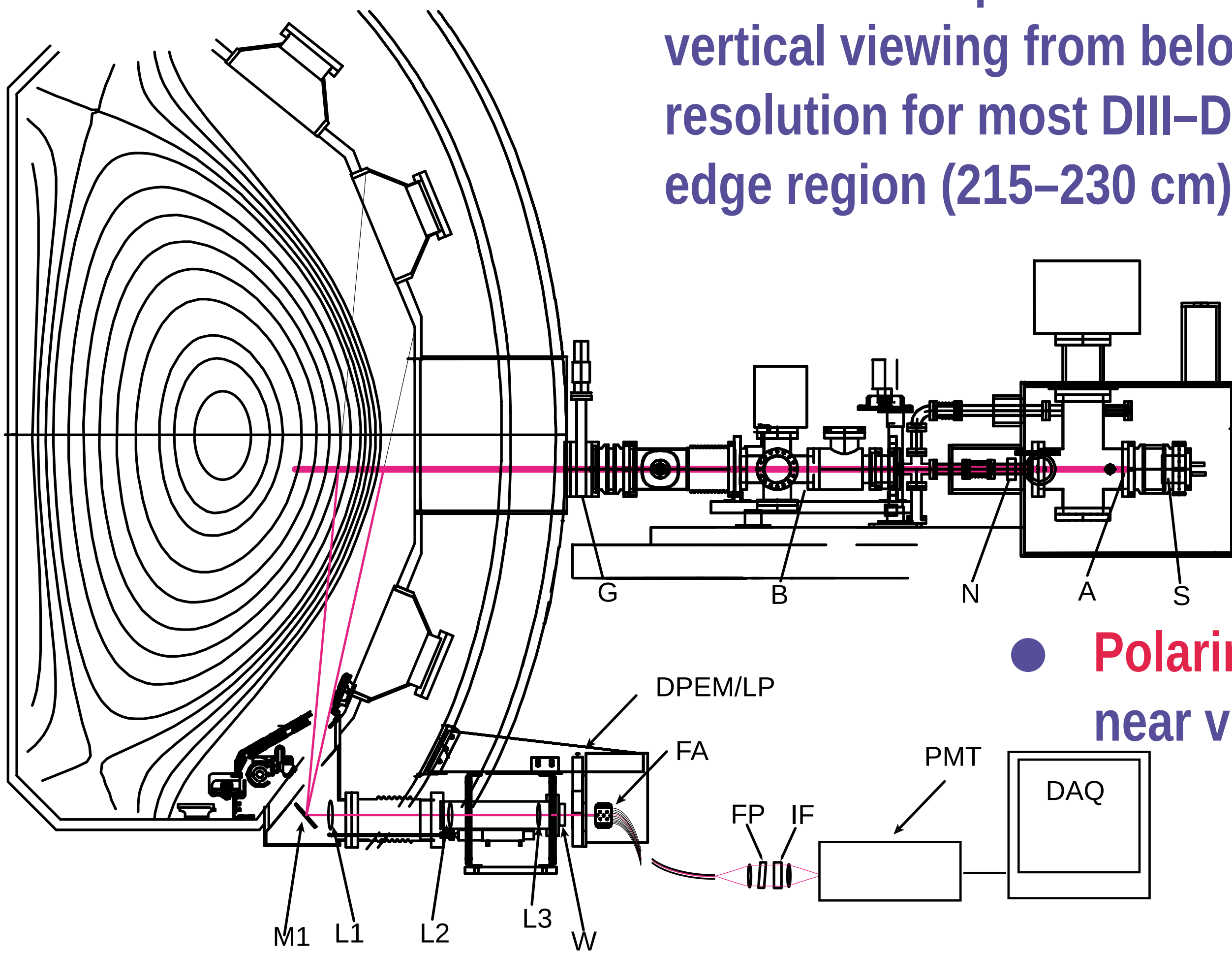
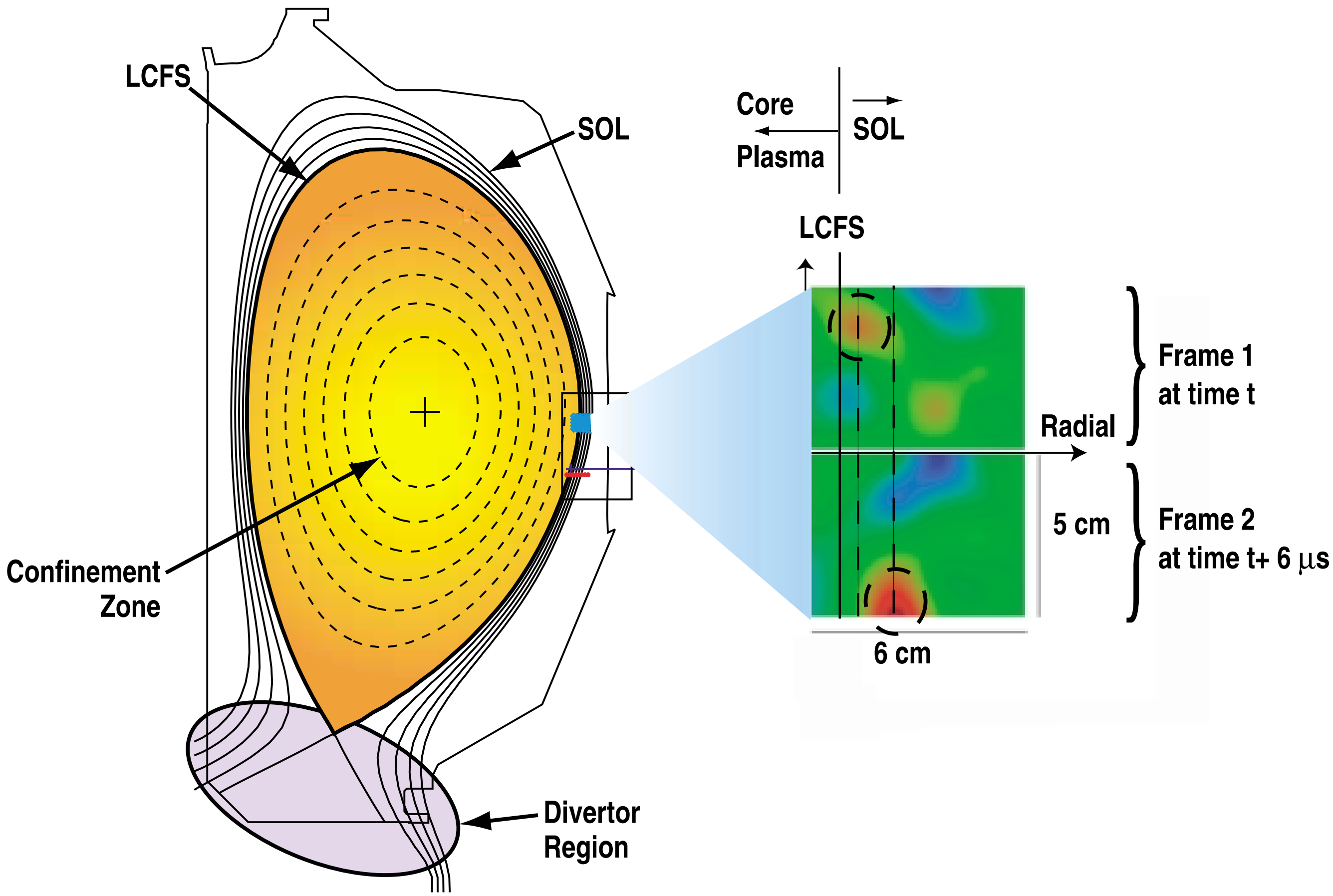
LITHIUM BEAM POLARIMETRY WILL PROVIDE HIGH RESOLUTION MEASUREMENTS OF EDGE J(r)

- **LiBEAM:** Neutral lithium beam is injected just below the midplane. This geometry along with vertical viewing from below gives best radial resolution for most DIII–D shapes. Good view of edge region (215–230 cm)



- **Polarimeter:** View from below, near vertical viewchord fan

INTERMITTANT CONVECTIVE TRANSPORT OBSERVED IN DIII–D PLASMAS



- Divertor solution critical challenge for ITER
- Measurement provides new insight into transport at the edge of the plasma

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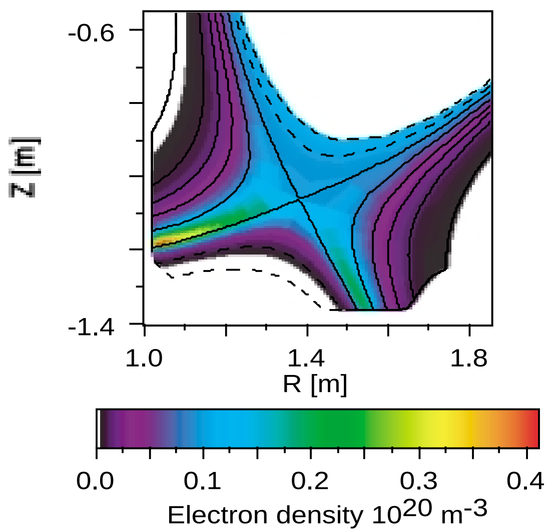
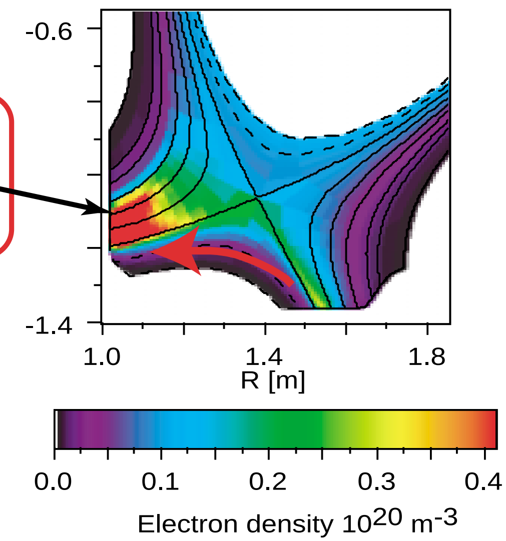
BOUNDARY SCIENCE KEY PHYSICS TOPIC: PARTICLE DRIFTS AND FLOWS

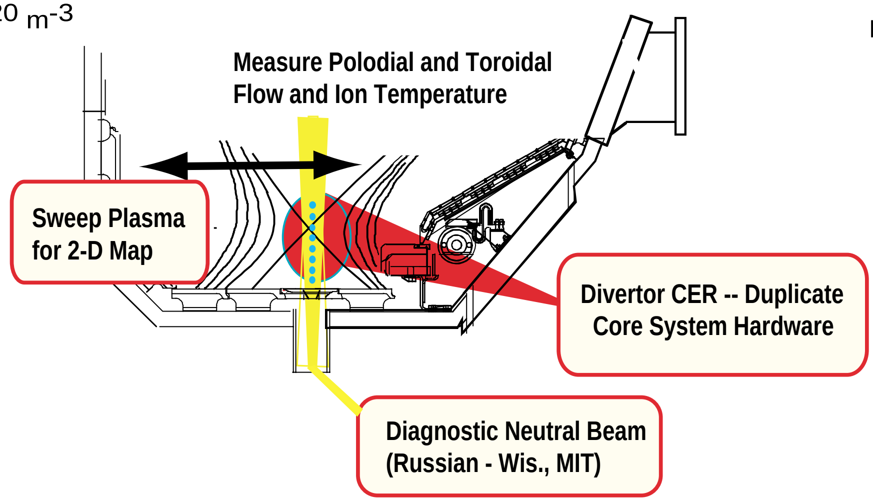
- UEDGE fluid modeling shows particle drifts increase density at inner strike point
- Measurements of particle drifts are a key component for physics understanding

n_e *Without* Drifts UEDGE Fluid Code



n_e *With* Drifts UEDGE Fluid Code





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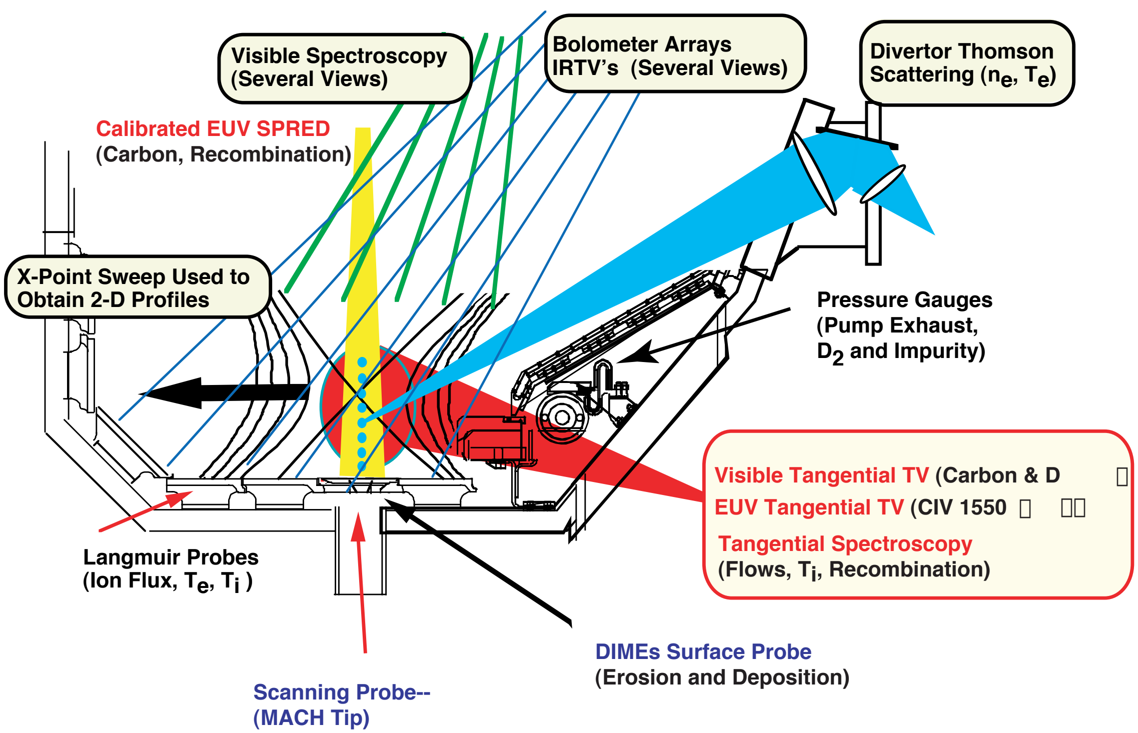
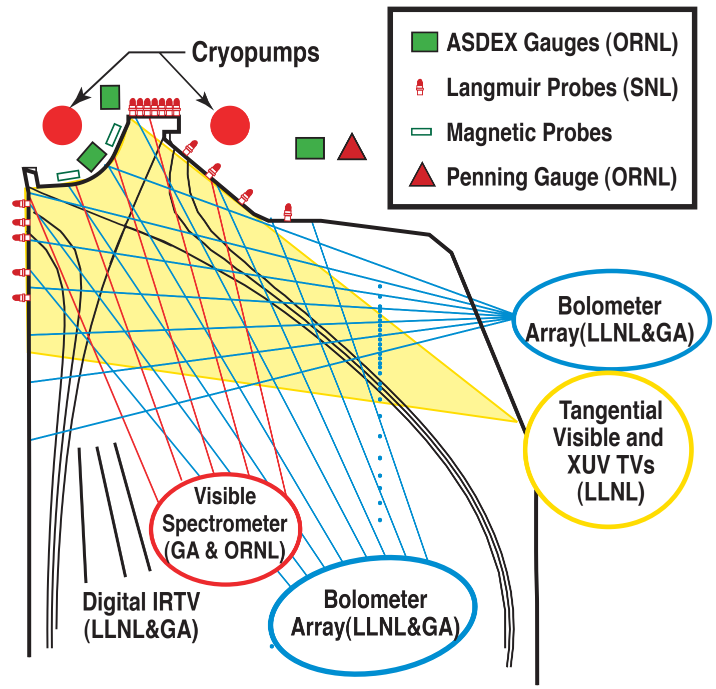
KEYS TO UNLOCKING THE PHYSICS ARE CONFIGURATION FLEXIBILITY AND COMPREHENSIVE DIAGNOSTICS





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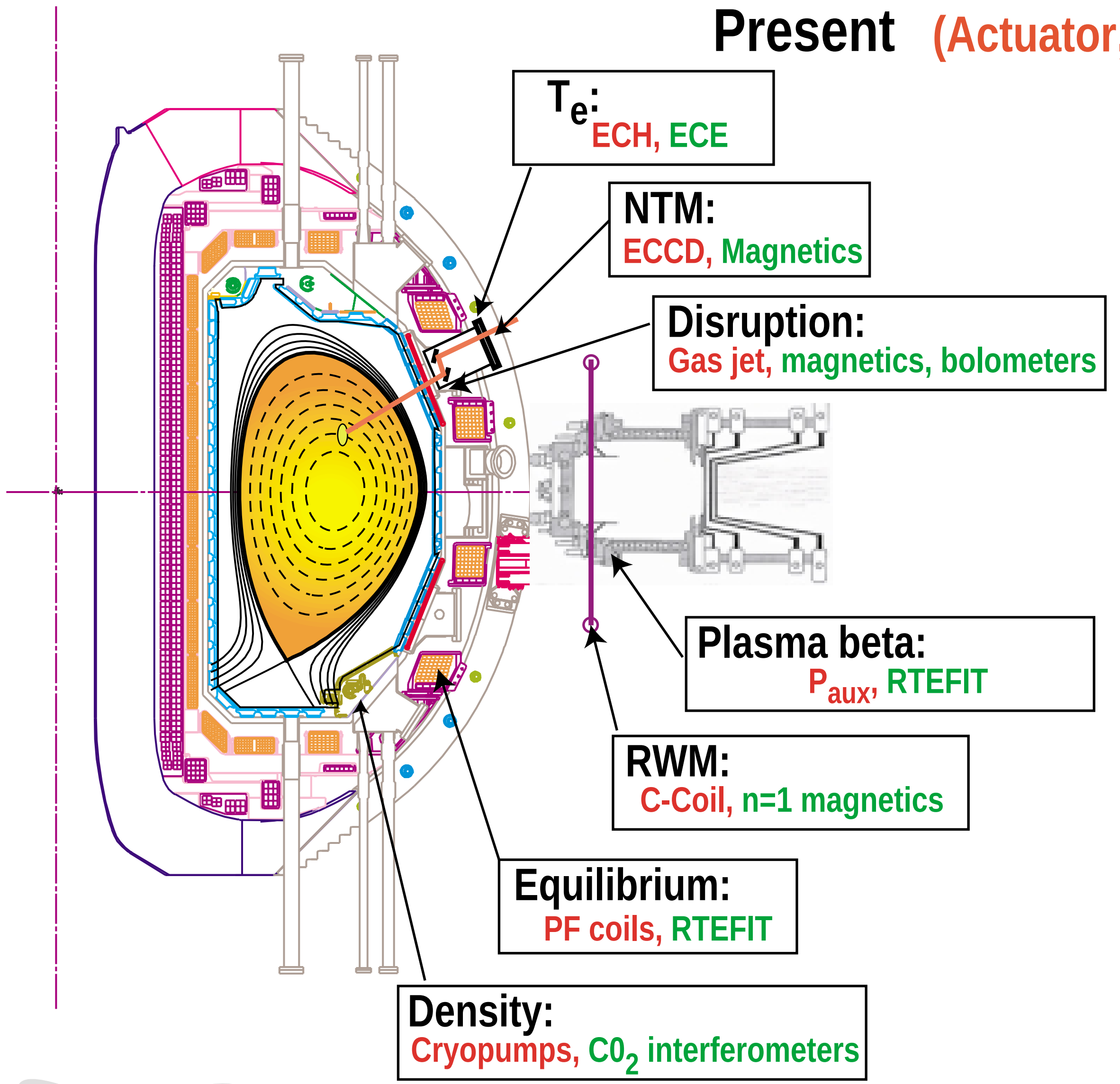
PLASMA CONTROL:
KEY TO THE SUCCESS OF THE DIII–D AT PROGRAM

Present (Actuator, Sensor) **Planned**



Integrated control:
Validated models
Expanded PCS

Current profile control:
ECCD/FWCD, MSE

Optimized RWM control:
I-Coil
Expanded magnetics

Disruption detection, correction, mitigation:
MHD regulation — PCS
Expanded magnetics

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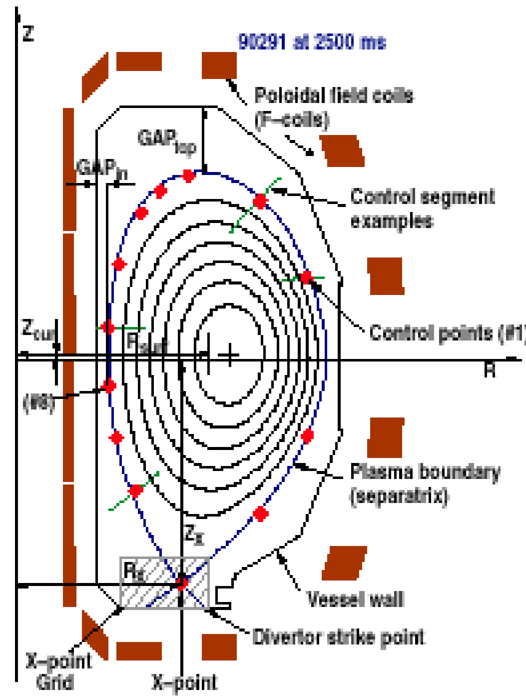
THE PCS IS THE ESSENTIAL ENABLING SYSTEM ALLOWING THE MANY ACTUATORS TO BE CONTROLLED SIMULTANEOUSLY IN A COORDINATED AND EFFECTIVE WAY

- Plasma control has evolved from the simple control of basic plasma properties such as plasma current, density, shape and location to the need to control in real time
  - The plasma current density profile,
  - The electron density profile,
  - The formation and location of internal transport barriers,
  - Impurity migration,
  - The plasma β,
  - The power loading to the divertor and plasma facing components



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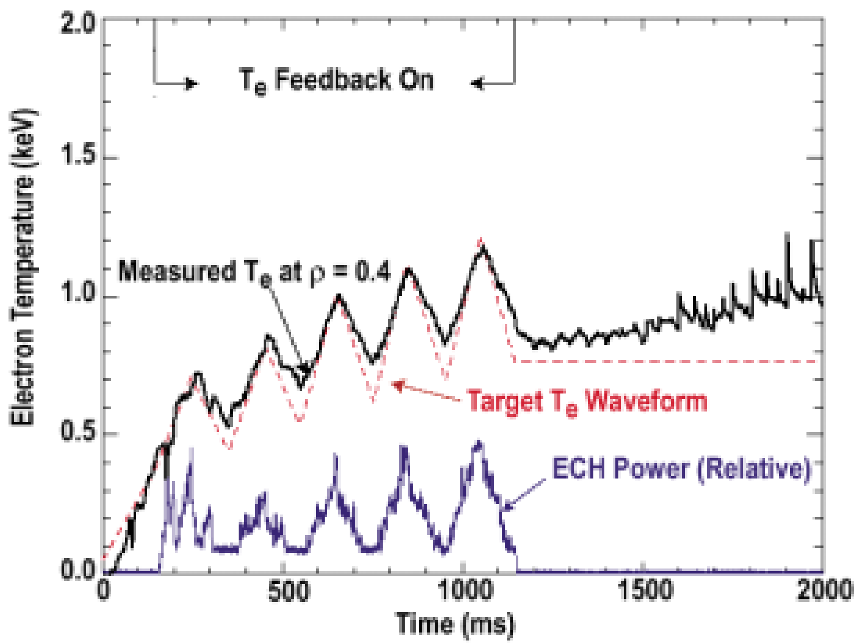
TO ACHIEVE ACTIVE CONTROL OVER THE PLASMA CURRENT DENSITY AND PRESSURE PROFILE, HEATING AND CURRENT DRIVE AT SELECTED LOCATIONS THROUGHOUT THE PLASMA IS REQUIRED

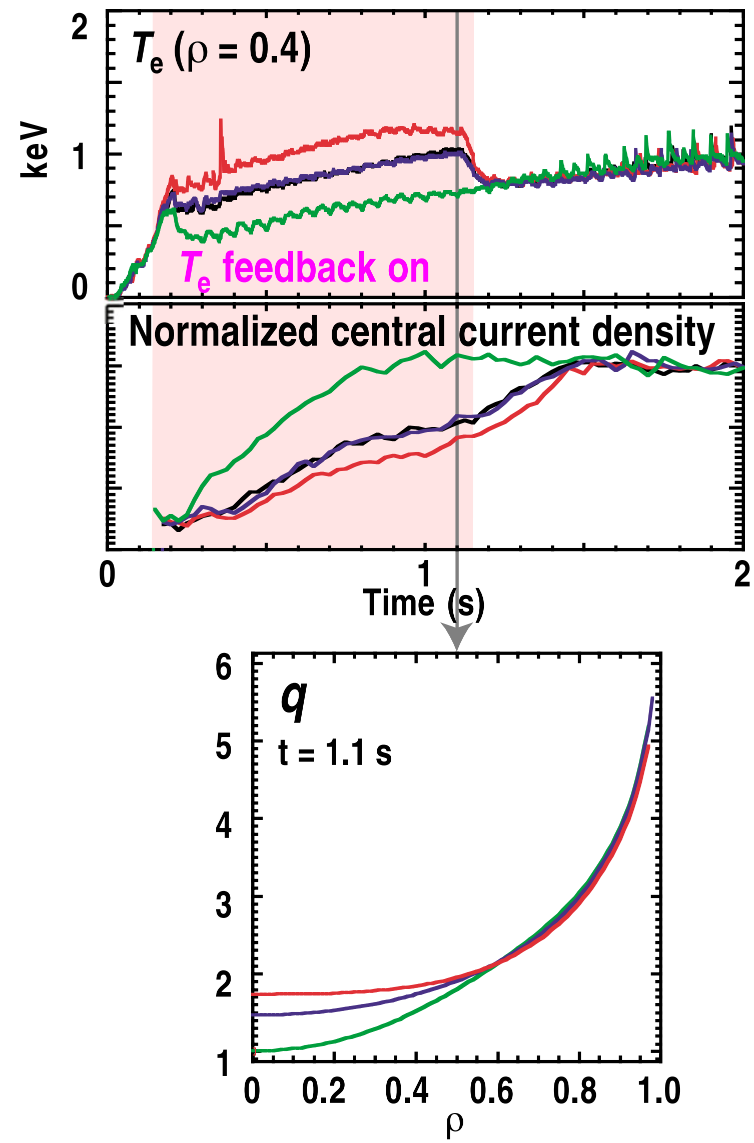
- The tool of choice for this function for the DIII-D program is electron cyclotron power due to the localization and flexibility, although ion cyclotron power and neutral beam injection can play a role

Fine control of T_e evolution has been demonstrated. With ECH deposition at $\rho = 0.4$ and PCS control of gyrotron power feedback on ECE measurement at $\rho = 0.4$



SIMULTANEOUS CONTROL OF MANY PARAMETERS REQUIRES A SOPHISTICATED PLASMA CONTROL SYSTEM

- Both optimization and physics understanding require real-time control.
- This implies development of:
  - Sensors
    - > Profile diagnostics measuring in real time temperature, density, rotation, current profile, etc.
    - > Diagnostics exist now but real-time analysis and data handling is needed.
  - Actuators: Systems which modify these quantities.
  - Control system:
    - > Existing plasma control system works well.
    - > Improvements needed to handle more data and control new tools.
- Example: Demonstration of real-time control of electron temperature to change the q profile.
  - Sensor is single ECE channel… ready to extend to use additional channels.
  - Similar control established using neutral beams.
  - Improves reproducibility of startup phase and allows operation at lower density.



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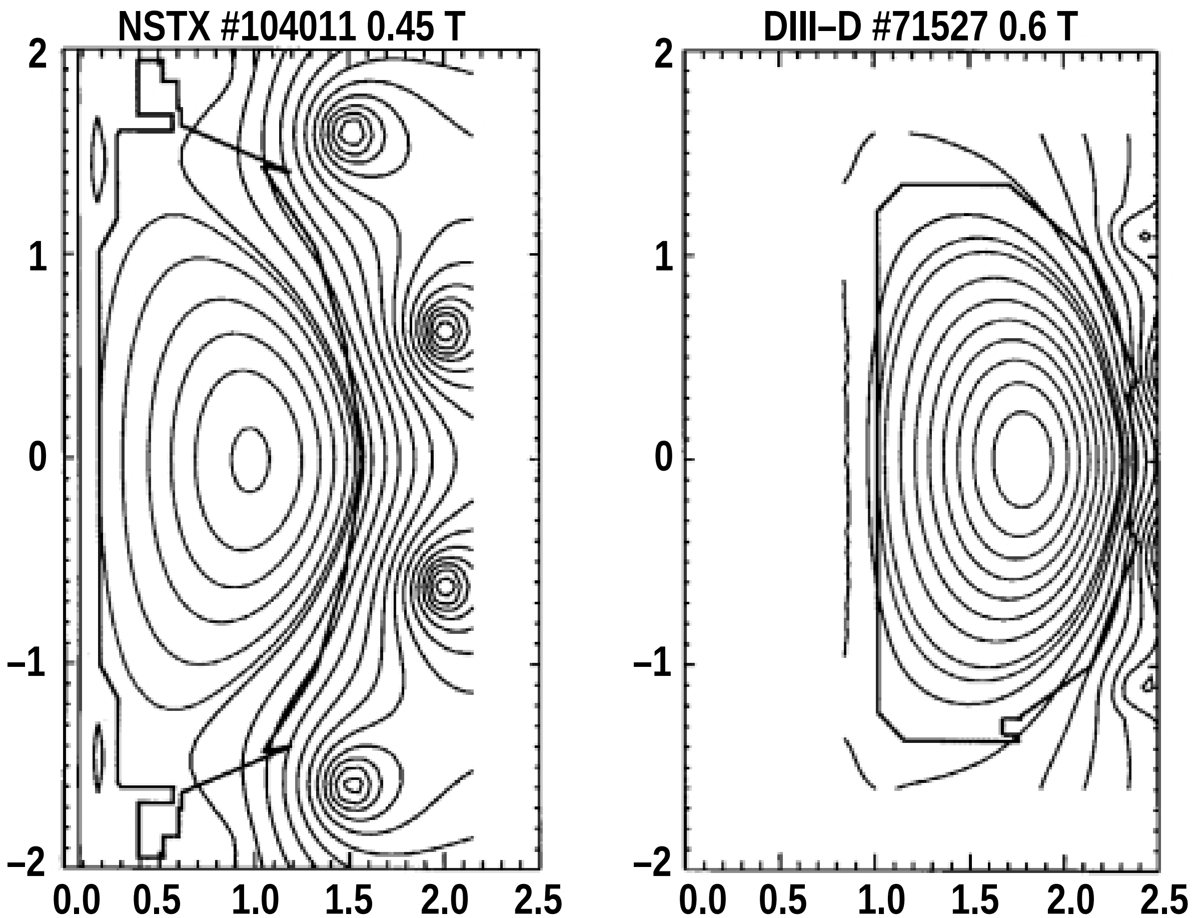
DIII-D WILL CONTINUE TO WORK TO ADVANCE THE FRONTIER OF PHYSICS UNDERSTANDING IN MANY AREAS

- MHD Stability
  - Fast ion instabilities and transport
    Sawtooth physics
    Disruption mitigation
- Heating and Current Drive
  - Basic physics of wave-particle interaction
  - Validation of bootstrap current models
- Divertor Physics
  - High density operation
  - Pellet fueling
- Transport
  - Dimensionless scaling
  - H-mode transition physics

NSTX/DIII–D COMPARISON ISOLATES TOROIDICITY EFFECTS ON ALFVEN EIGNMODES



- NSTX and DIII–D can match shape, toroidal field, and neutral beam energy
  - ⇒ Can match all Alfven mode parameters (V_f/V_A, for example)
- Goal: compare stability thresholds and mode structure with modeling predictions
  - Most unstable mode number
  - Multiple unstable modes
  - Kinetic effects
- Critical physics for next-step device

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SUMMARY

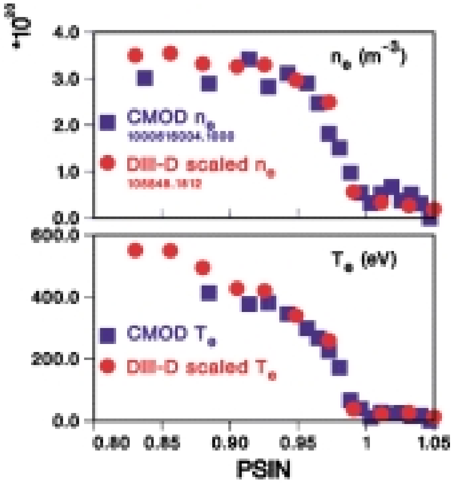
- **The DIII-D Research Plan for 2004-2008 proposes three major focal points:**
  - Tokamak optimization emphasizing demonstration and understanding of steady-state high-performance scenarios
  - Advancement of transport physics through coordinated development and detailed comparison of theory, modeling, and measurement
  - Understanding of the sources and sinks of particles and their transport across the boundary

- **Precision control will be essential to accomplishing each of these goals**

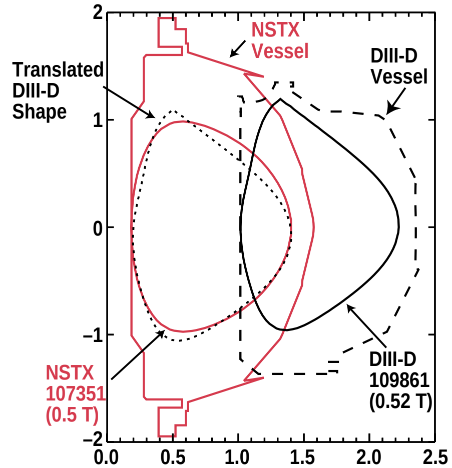
- **While maintaining these three focal points, the DIII-D program will continue to foster curiosity-driven research at the frontiers of plasma physics, especially in areas where DIII-D has unique capabilities**

COOPERATION/COLLABORATION AMONG DIFFERENT EXPERIMENTS PROVIDE INSIGHT/VALIDATION OF PHYSICS

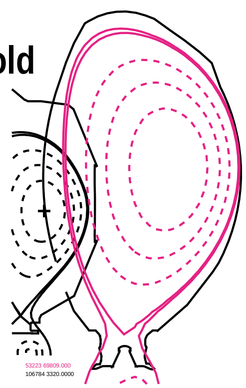
C–Mod/DIII–D Pedestal Similarity



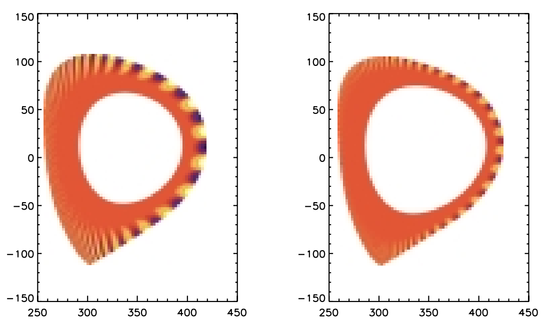
NSTX/DIII–D Alfvén Instabilities



JET/DIII–D NTM Threshold



JT–60U/DIII–D ELM Stability



Planned collaborations

- JT-60U
  - Steady-state, high performance
  - Divertor/edge
- JET
  - Optimized shear/ITB
  - NTM
  - RF and rotation
  - Edge physics
- ASDEX
  - NTM
  - Counter NBI, ITB
- TCV
  - H–mode
- C-MOD
  - Pedestal
  - SOL
  - NTM
- NSTX
  - Alfven
  - Transport
- HBT-EP*
  - RWM

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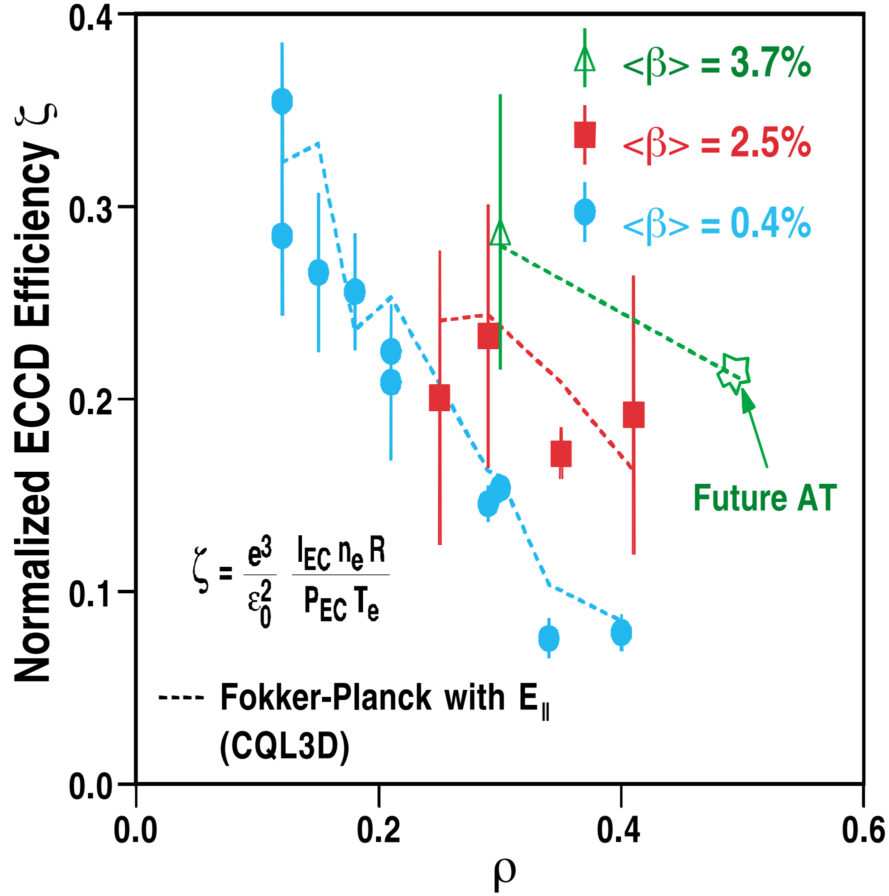
MODELS OF ECCD EFFICIENCY HAVE BEEN VALIDATED FOR APPLICATION IN *AT* CURRENT PROFILE CONTROL

- Good agreement between experiment and theory.
  - *ECCD is a well understood process.*
- Important parameters: High T_e and β_e.
  - Motivates investigation of recommissioning fast wave systems for electron heating to increase ECCD efficiency.



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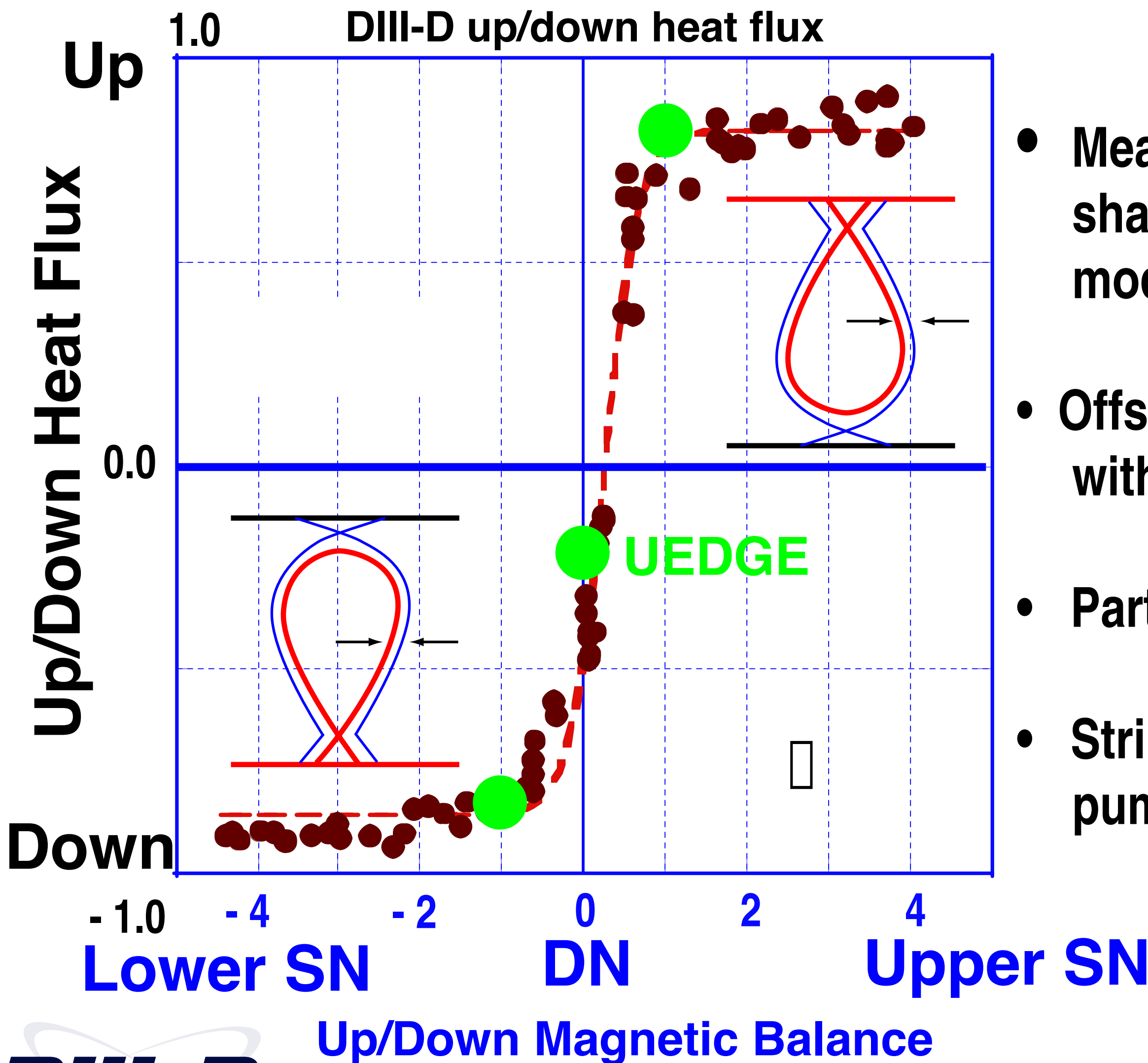
DN operation allows precise control of heat and particle fluxes



- Measured heat flux up/down sharing agrees well with UEDGE modeling
- Offset is explained in UEDGE with drifts turned on
- Particle flux profile is broader
- Strike point must be close to pump for exhaust

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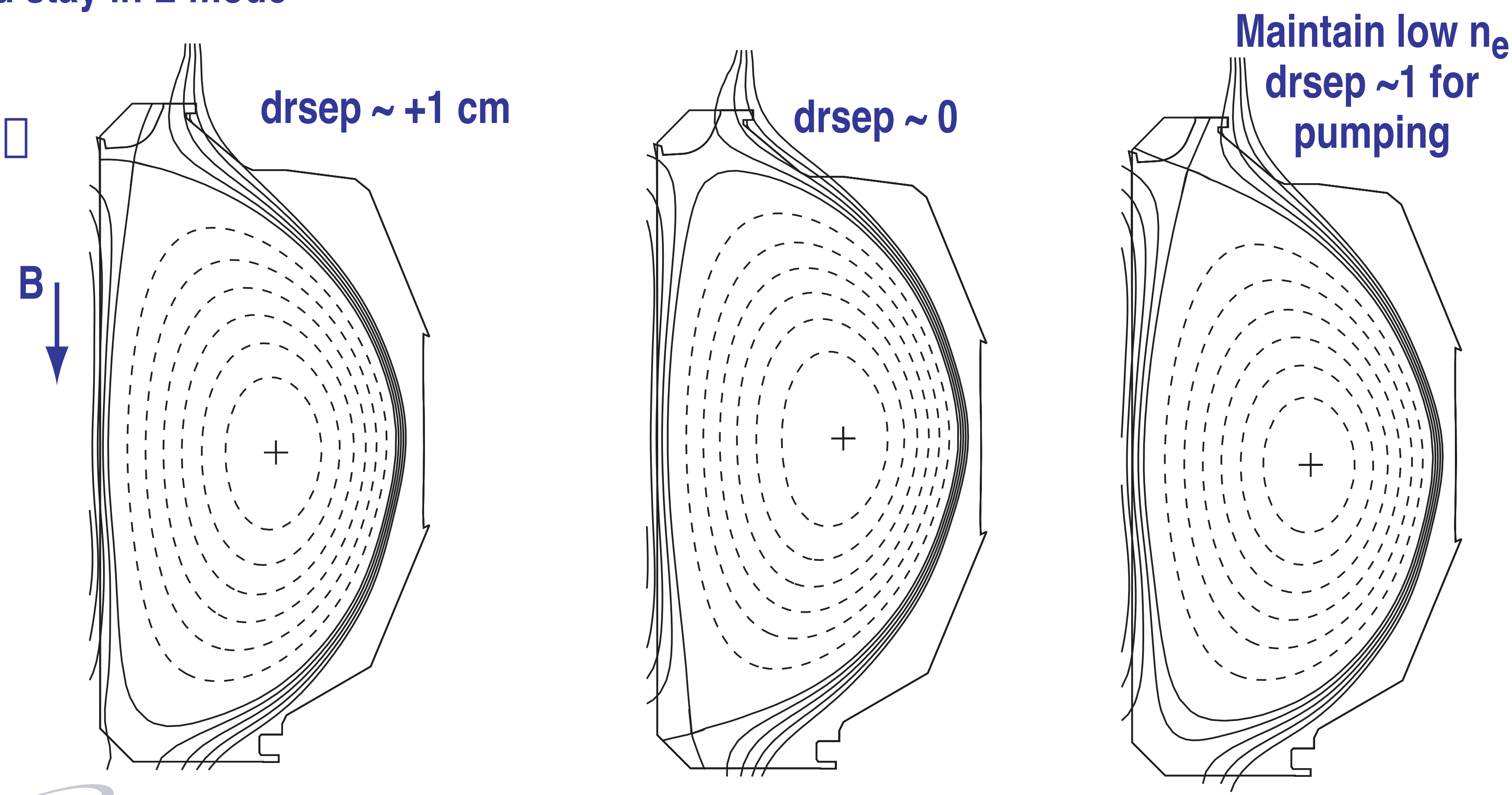
Magnetic balance (drsep) controls H-mode power threshold and particle exhaust rate

DN biased upward to raise L-H threshold and stay in L-mode → Balanced DN for H-mode transition → Pumped H–mode



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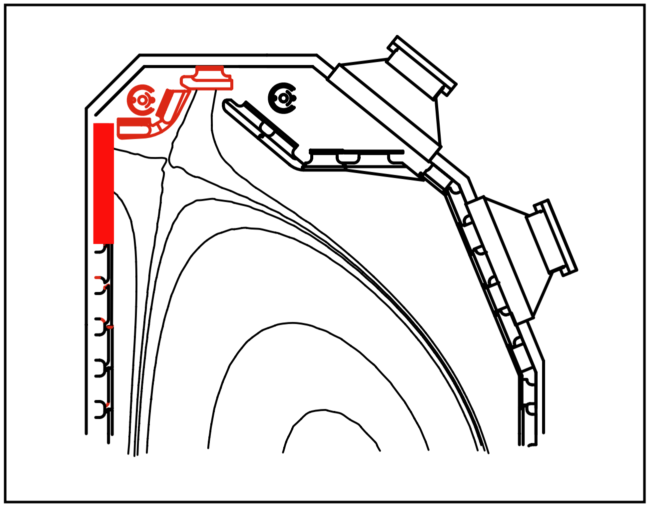
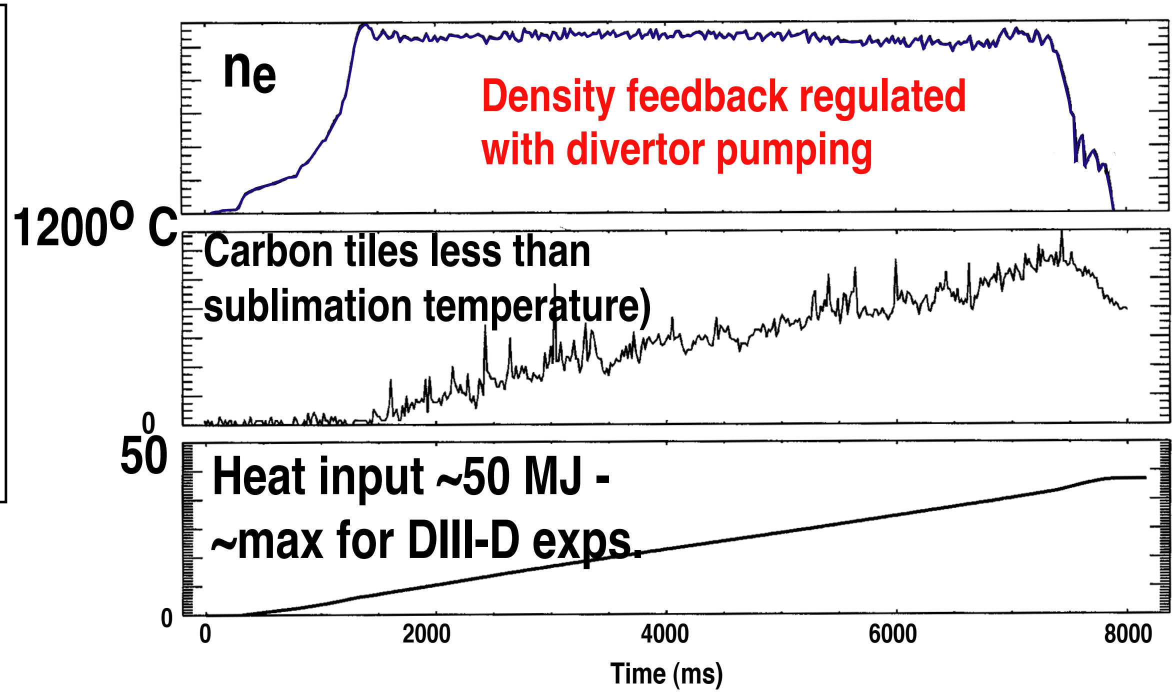
Present DIII-D divertor has demonstrated simultaneous 50 MJ, 5s heat flux control with particle control





- Divertor is matched to high-triangularity shape
- Cryopumps control the density

- Additional power handling will be accomplished with controlled DN, radiation, CFC if needed

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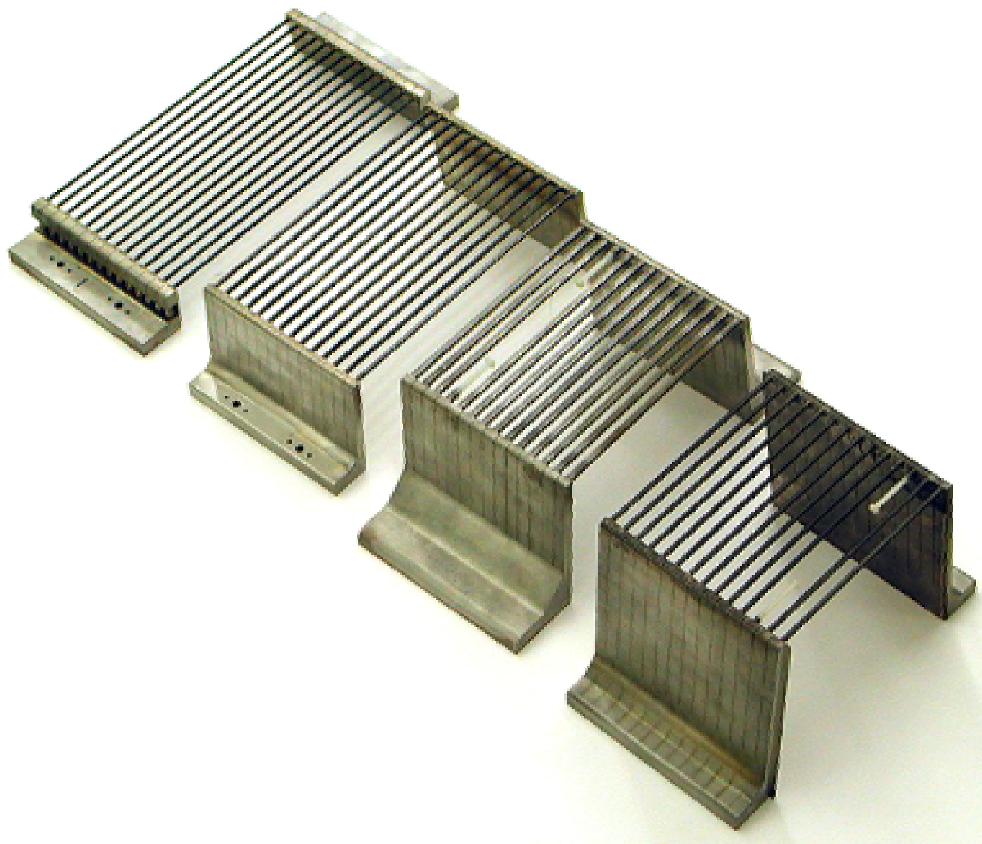
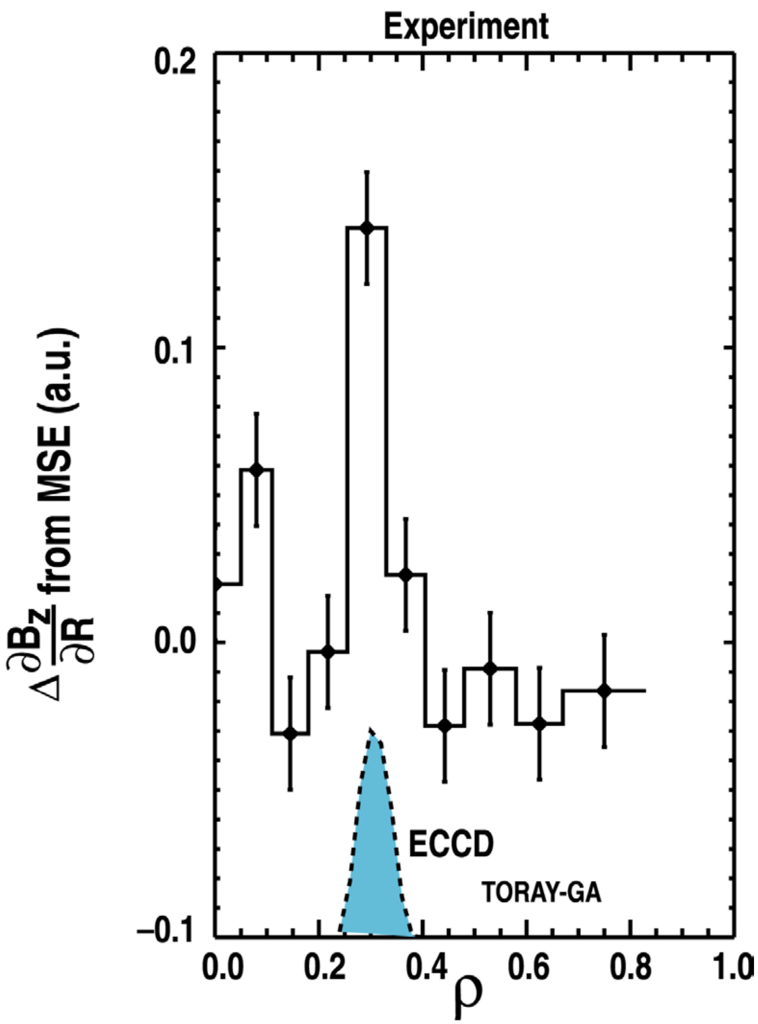
THE ION SOURCES USED ON DIII-D (AND ON NSTX) WERE DEVELOPED BY LBL/RCA ALMOST 20 YEARS AGO AND ARE WEARING OUT DUE TO EROSION OF THE WATER-COOLED GRIDS

- Unfortunately, the NB program is no longer supported by the fusion community and the technology developed to manufacture the grids has been lost. It is important to the fusion community that this technology be redeveloped so that a key heating resource remains available. GA has taken on this task



MSE MEASUREMENTS SHOW THAT THE INCREASE IN CURRENT DENSITY FROM ECCD IS HIGHLY LOCALIZED



- Key diagnostics for ECCD studies are MSE and ECE; continued development of diagnostics is desirable to improve resolution

- Further development of the MSE system is needed to provide simultaneous measurements of the pitch angles and the radial electric field with high radial resolution
  - Counter-NBI with new MSE views would provide this

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Physics understanding is necessary for active control of a radiative divertor

(High Core n_e) D_2 Detached Plasma

- Intrinsic carbon radiation reduces heat flux to divertor plate

"Controlled" Divertor

- "Puff and Pump" and injected impurity radiates in divertor