Optimizing Stability, Transport, and Divertor Operation Through Plasma Shaping for Steady-State Scenario Development in DIII-D

by
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With

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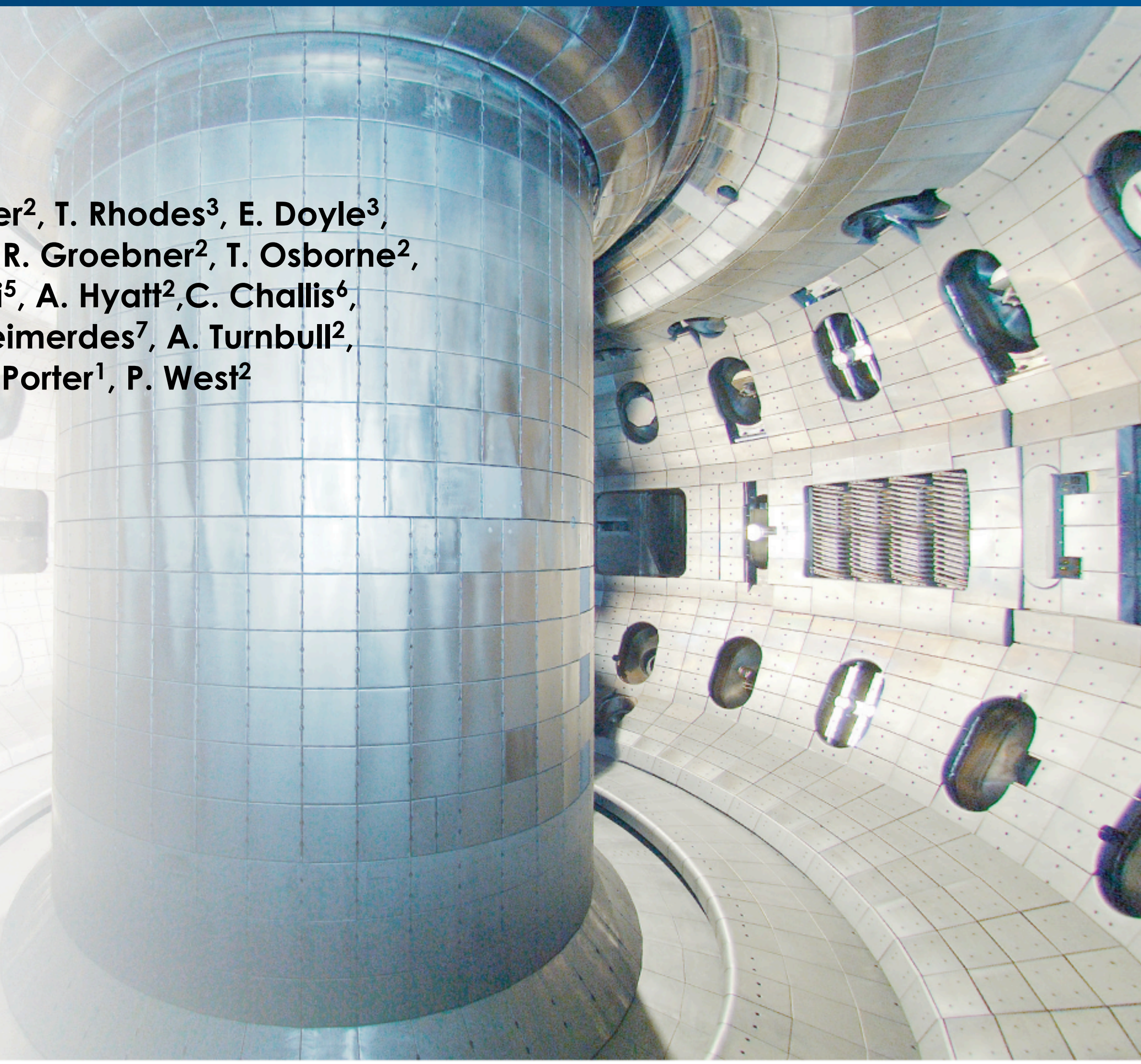

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Goal of Steady-State Tokamak Operation Requires the Integration and Optimization of Multiple Objectives

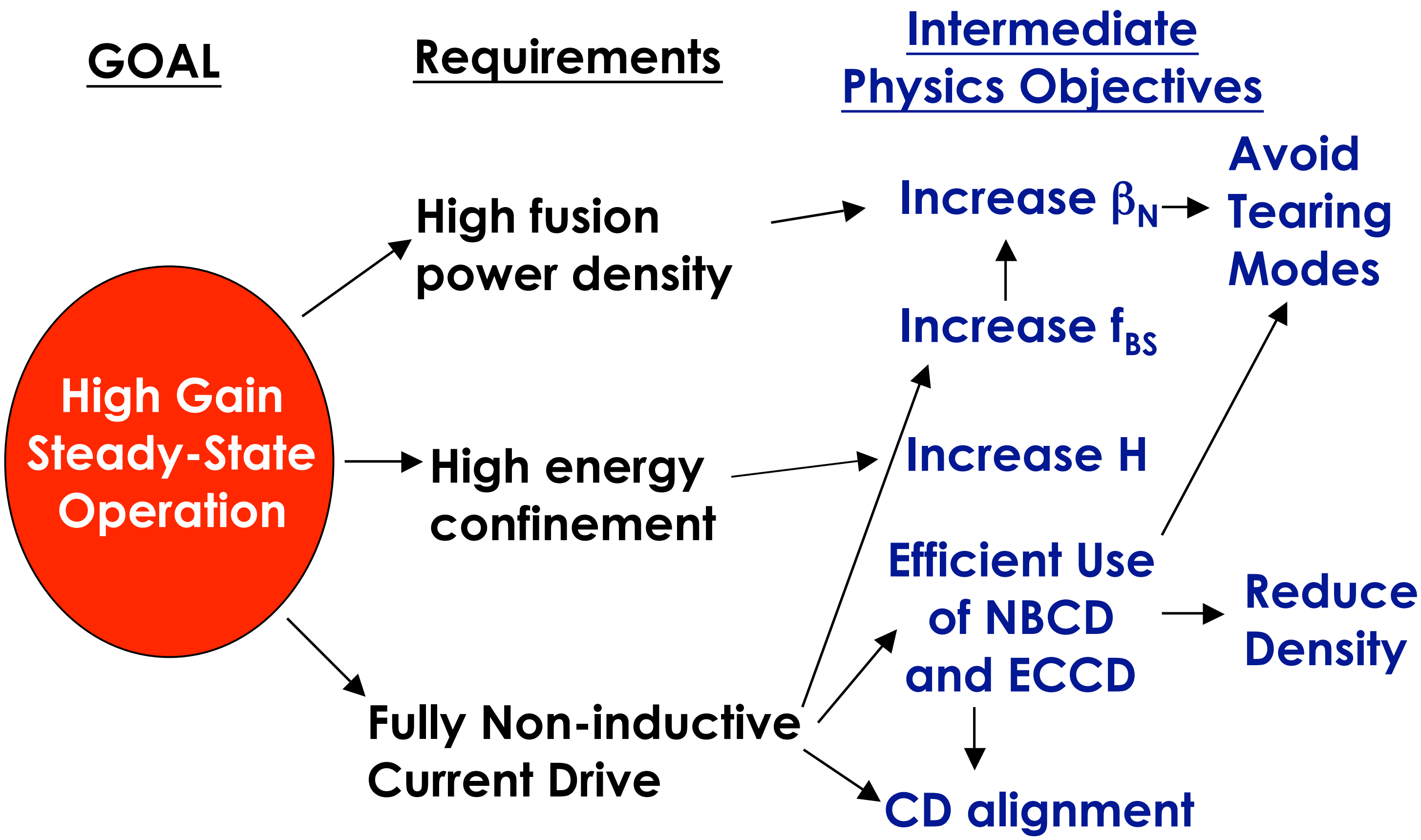
GOAL

High Gain Steady-State Operation

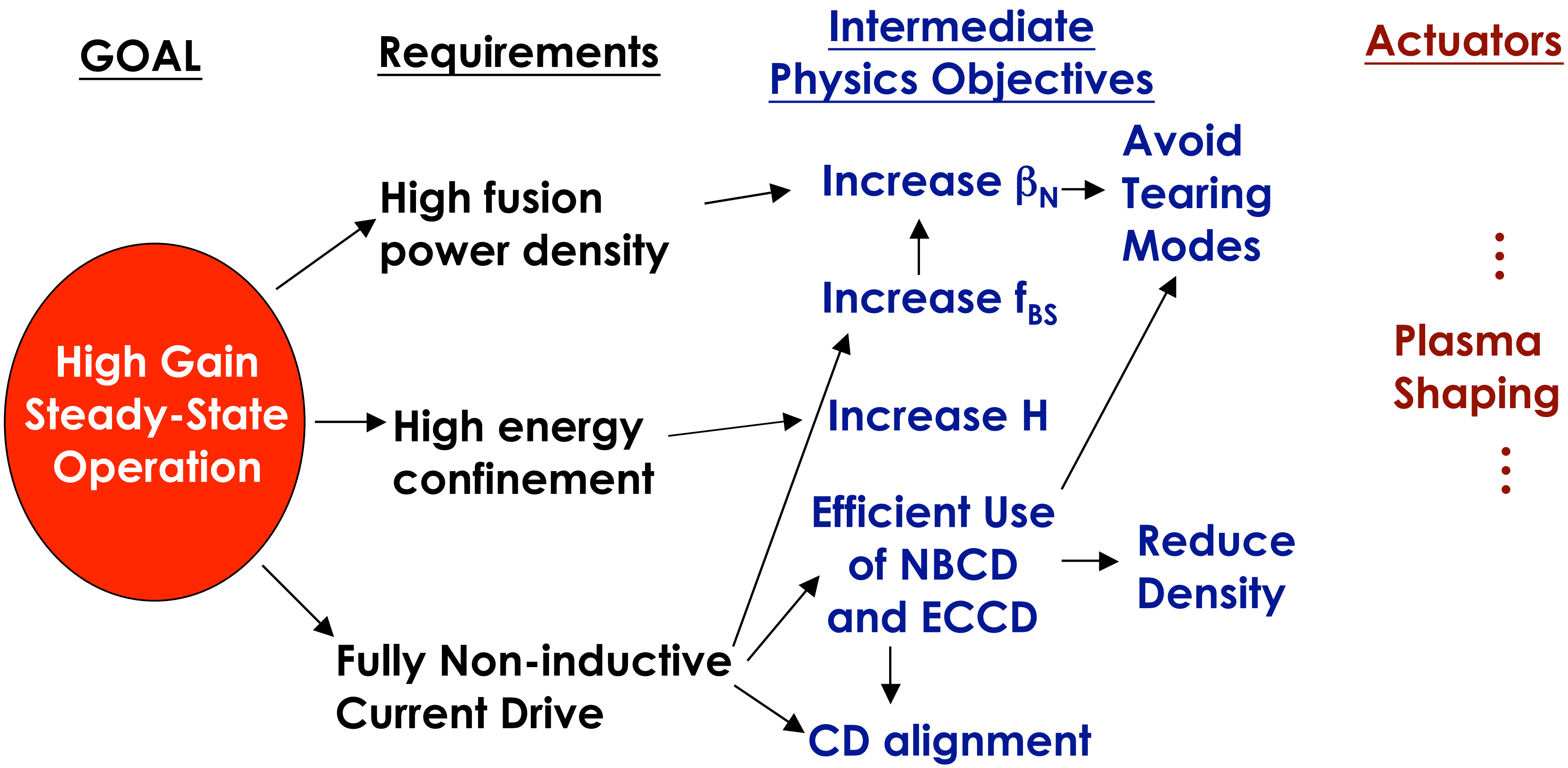
Requirements

- High fusion power density
- High energy confinement
- Fully Non-inductive Current Drive

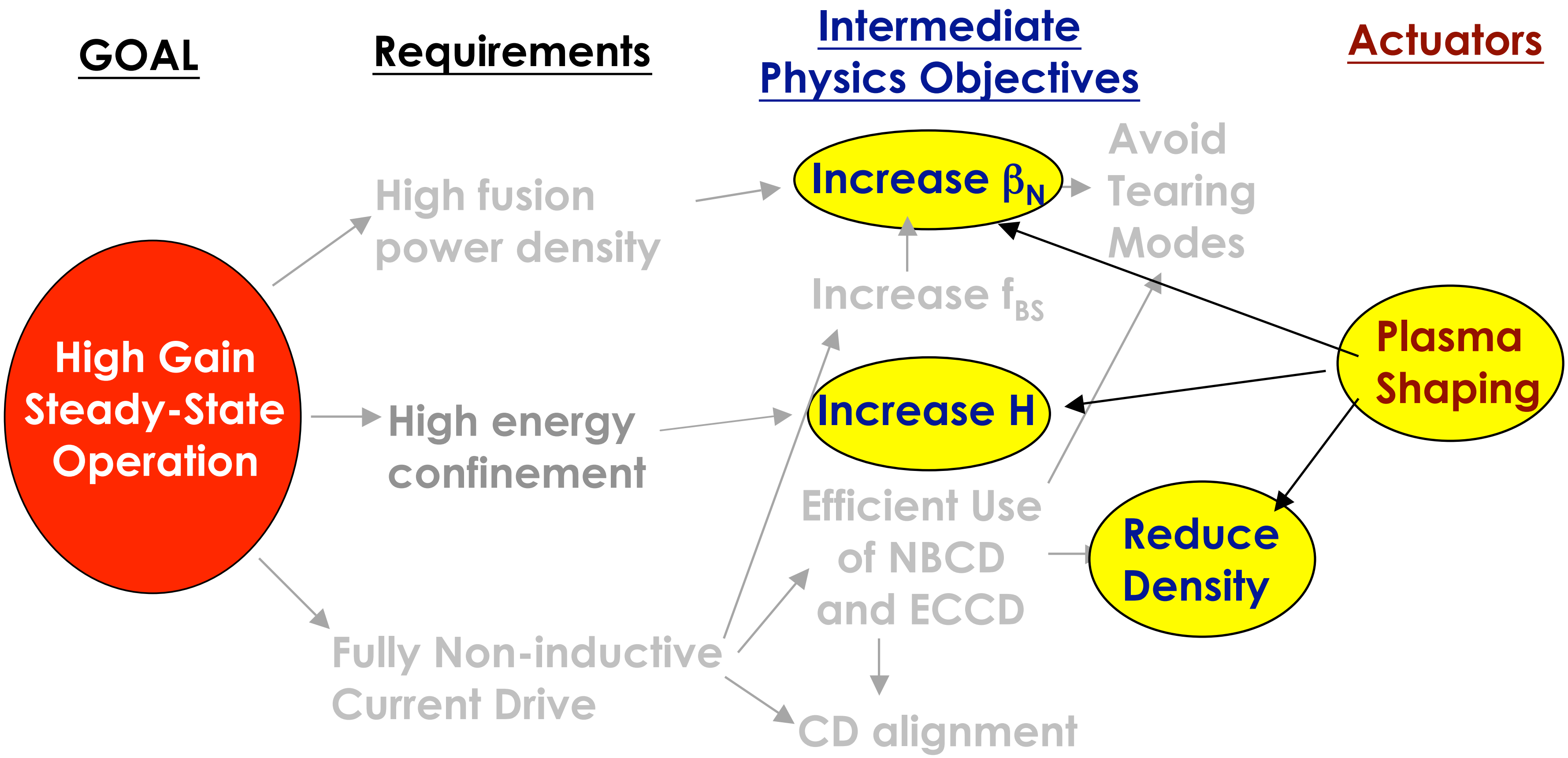
Goal of Steady-State Tokamak Operation Requires the Integration and Optimization of Multiple Objectives



Goal of Steady-State Tokamak Operation Requires the Integration and Optimization of Multiple Objectives

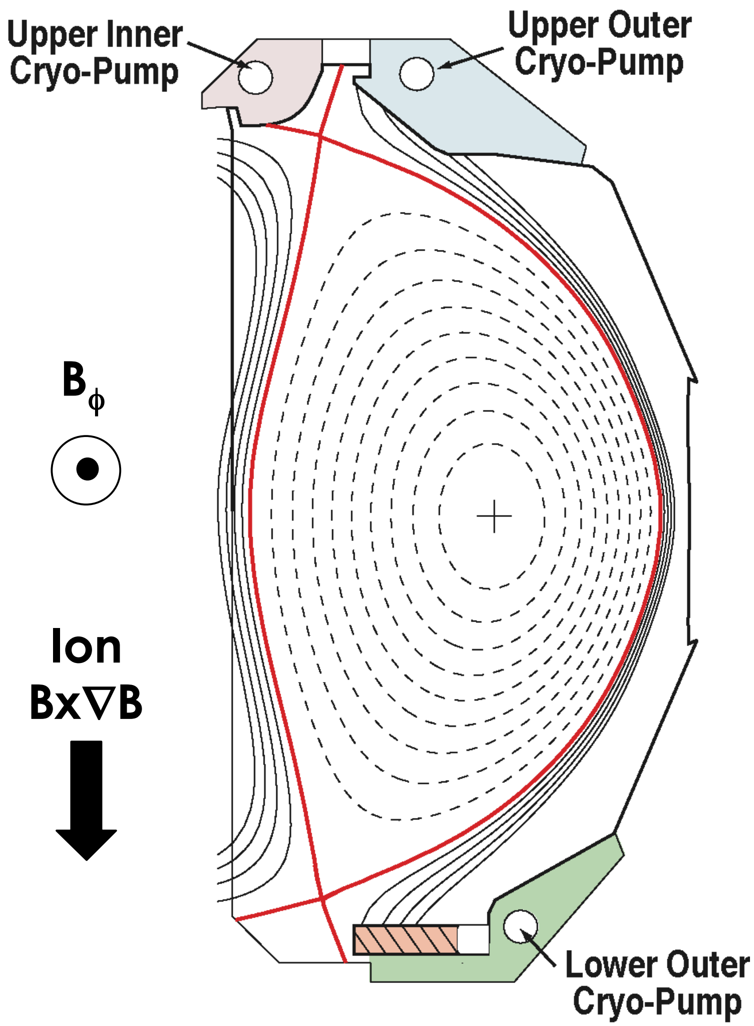


Goal of Steady-State Tokamak Operation Requires the Integration and Optimization of Multiple Objectives



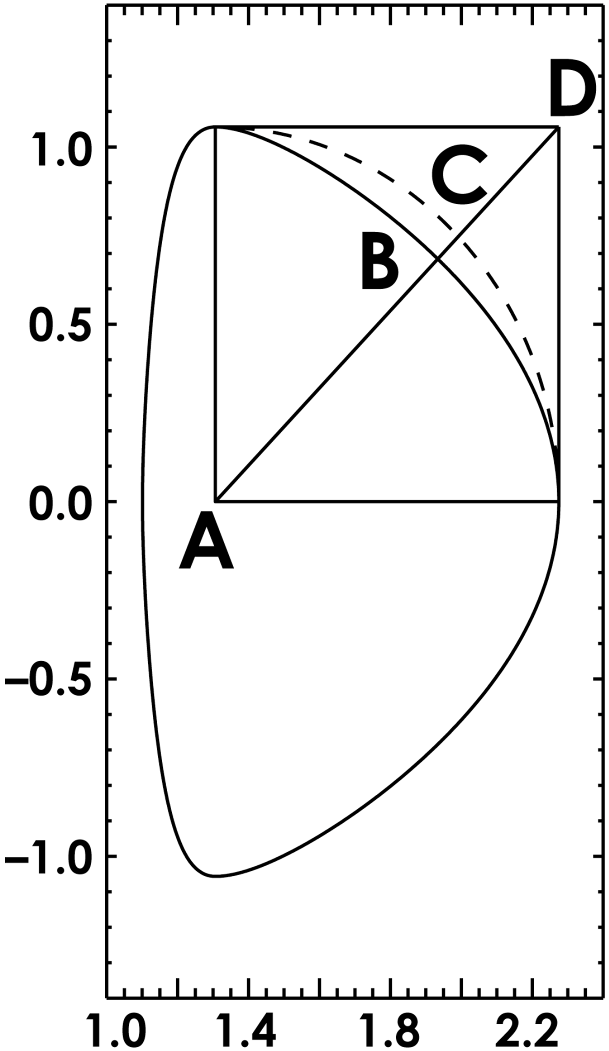
Using shape optimizations, we have extended the duration of $f_{NI} \equiv I_{NI}/I_p \sim 1$

In DIII-D Shape Flexibility is a Strong Optimization Tool

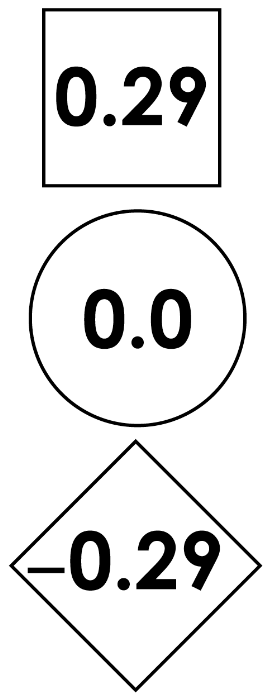


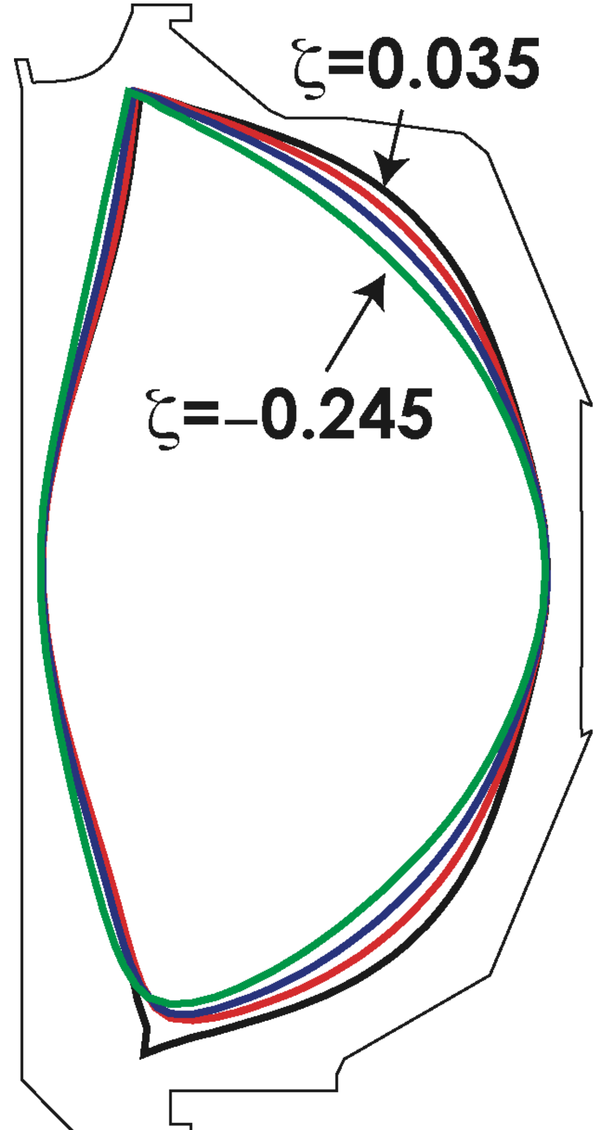
- Previous work optimized stability using double-null geometry, elongation and triangularity
- Squareness ζ is a higher order shape parameter that may be adjusted without impacting divertor coupling
- Adjusting double-null divertor balance allows pumping optimization

Squareness ζ is Defined Using an Ellipse Such That ζ=0 for a Circular Cross Section



$$\zeta = \frac{AB\text{-}AC}{CD}$$





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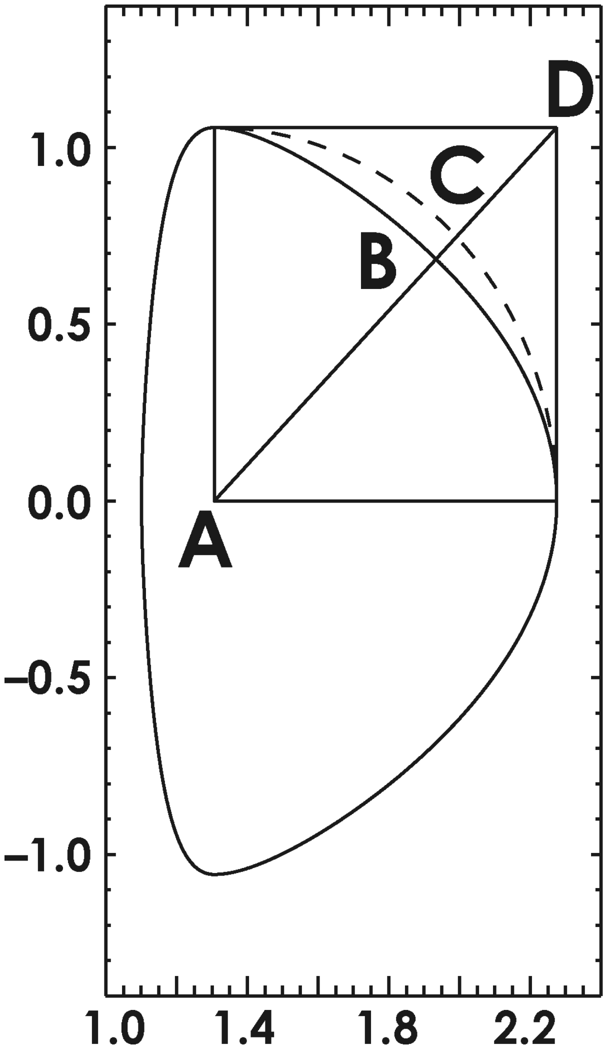
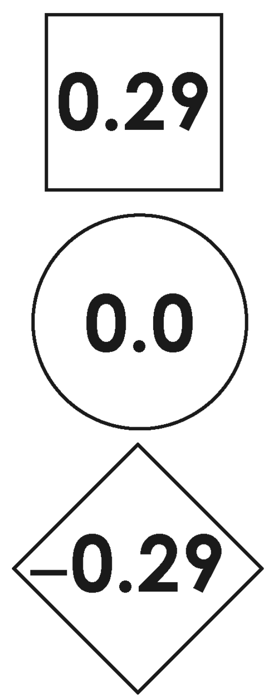
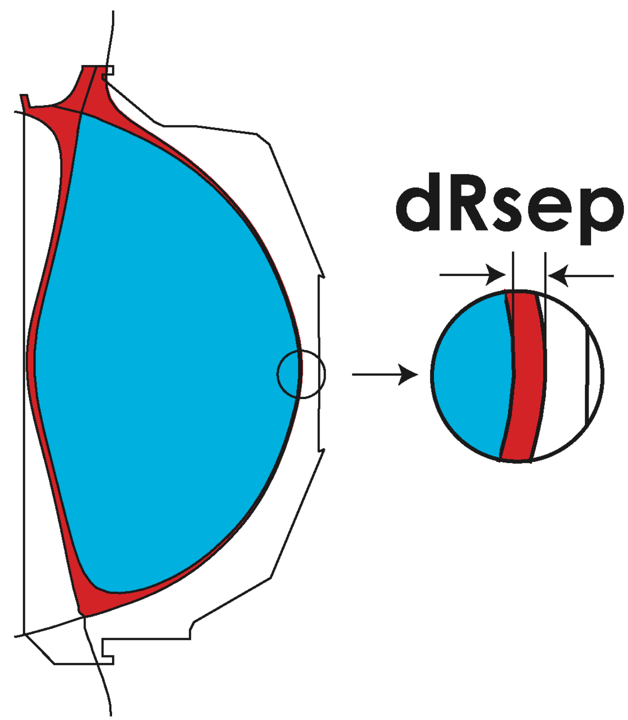
Divertor Balance is Described by dRsep Parameter



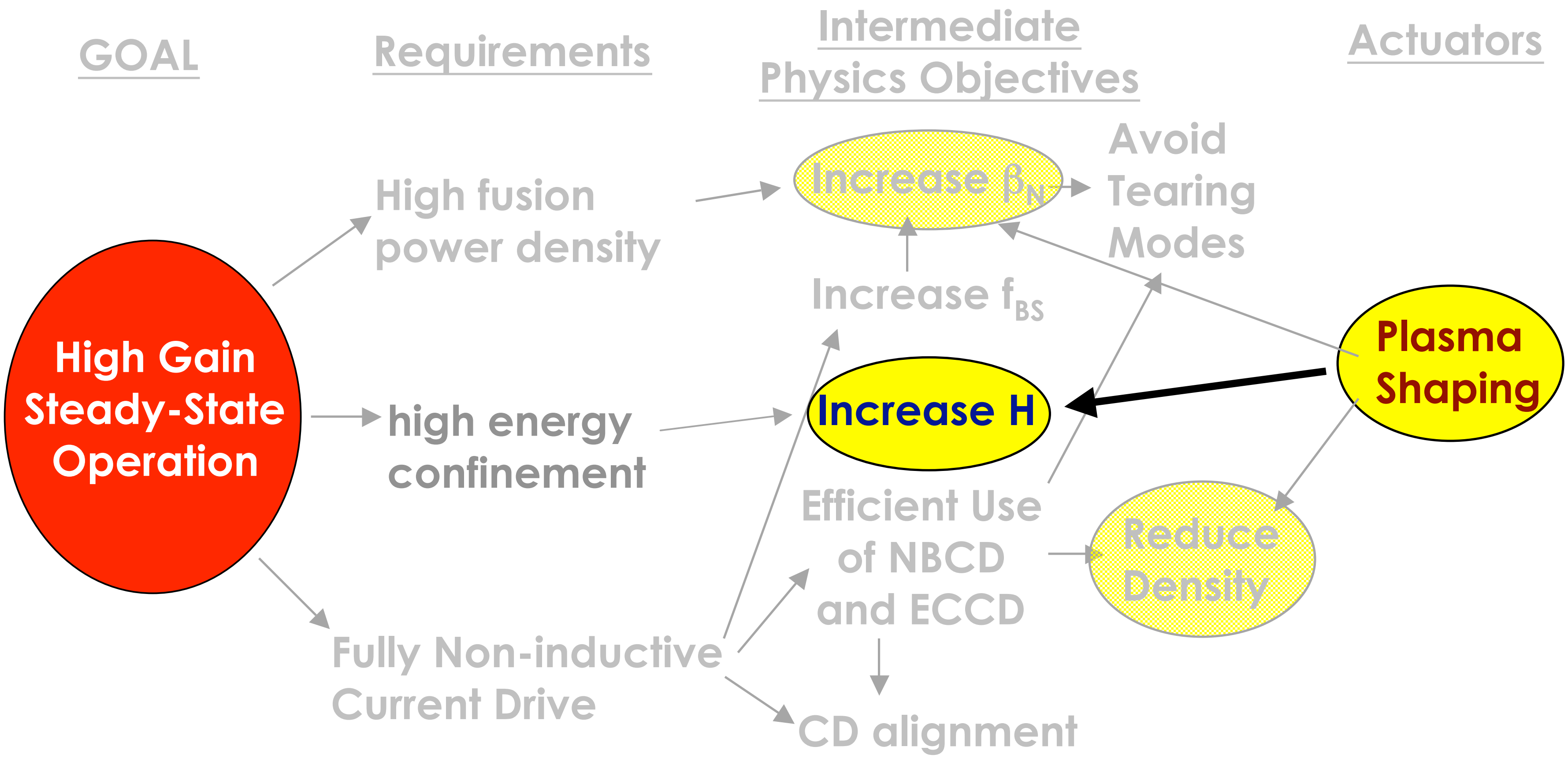
$$\zeta = \frac{AB - AC}{CD}$$



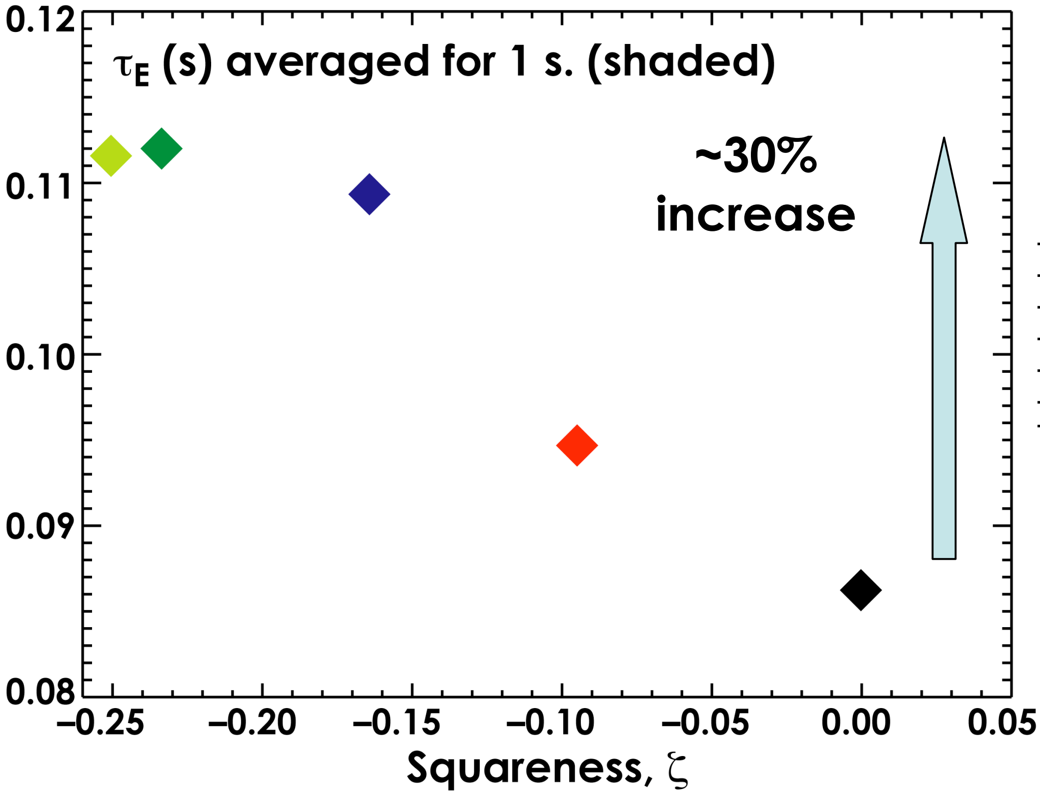


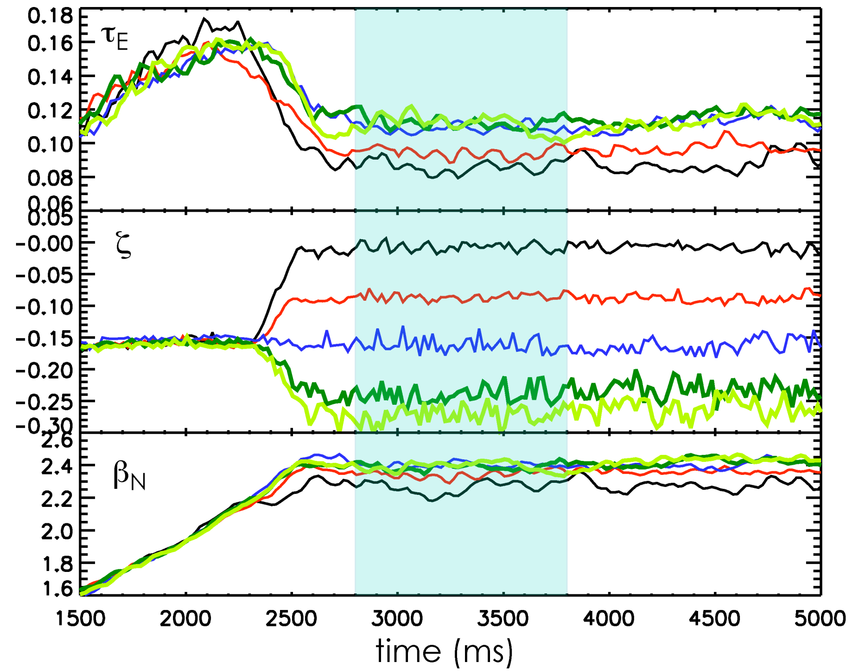
dRsep is the radial distance at mid-plane between flux surfaces connected to upper and lower X-pts.

Confinement



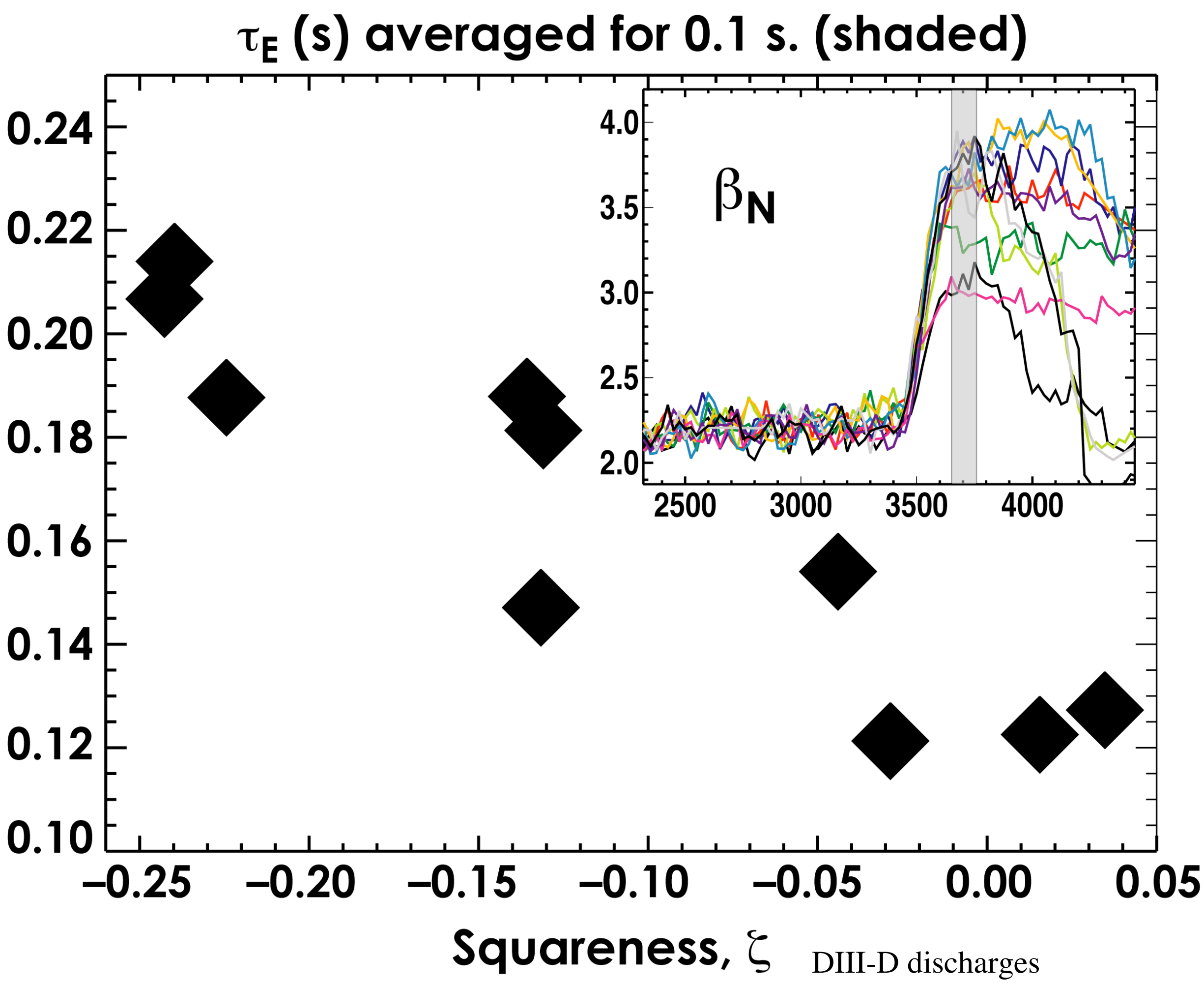
The Global Energy Confinement is Maximized at Low to Intermediate ζ at Low β_N





- Lower ζ has lower volume
- ζ not in confinement scaling laws that normally predict increased confinement with increased volume through *R*, *a*, and κ

The Trend of Better Confinement at Lower ζ is Also Observed at High β_N



DIII-D discharges
125202, 125206, 125209, 125215,
125214, 125186, 125205, 125208,
125213, 125201

- Compares first 100 ms of high β_N phase (q_{min} $\approx$1.5) before any MHD begins
- ~70% improvement in τ_E going from highest to lowest ζ
- H_{98} varies from 1.35 up to 1.85

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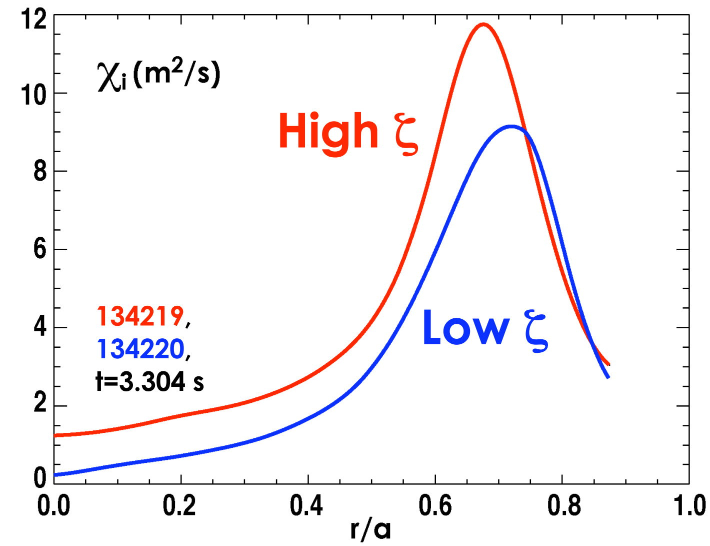
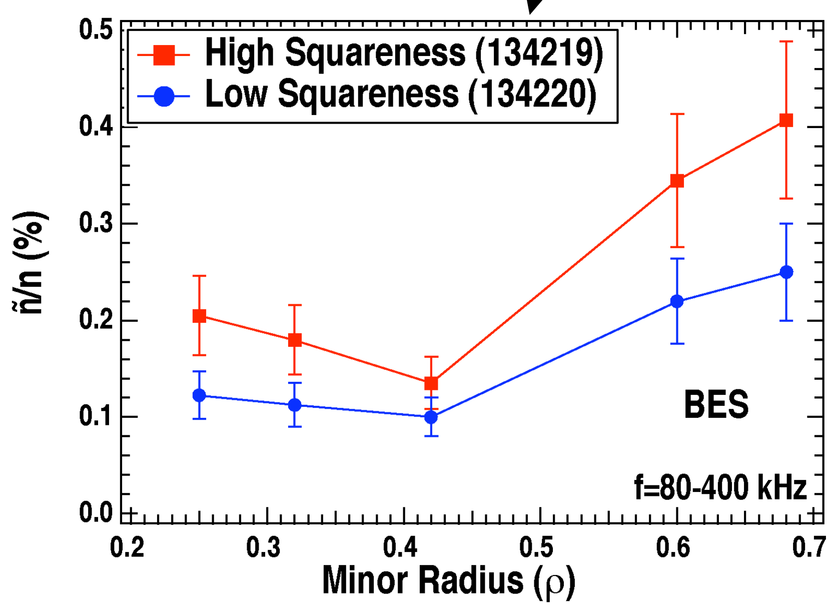
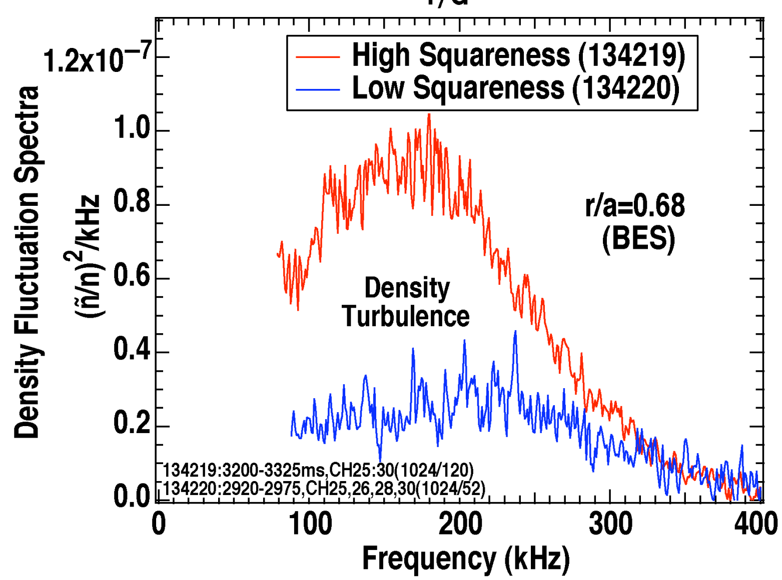
Core Transport and Density Fluctuations are Reduced at Low Squareness

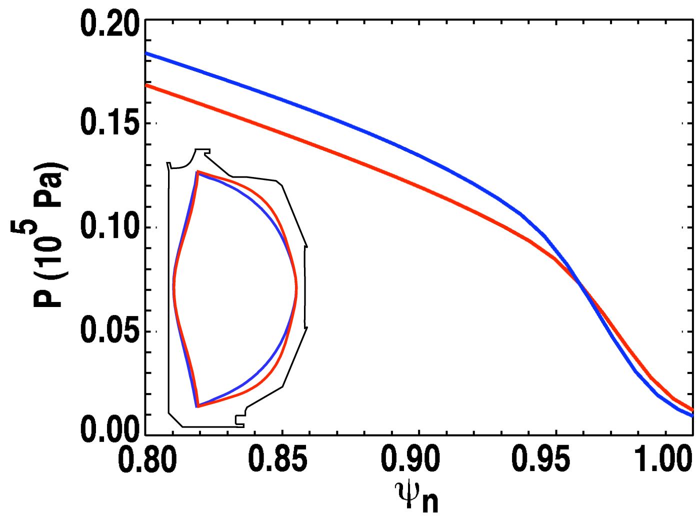
- **Calculated ion thermal diffusivities for high, low ζ**
- **Beam Emission Spectroscopy measurements ($k_\perp \leq 2.5\ cm^{-1}$) for these discharges**

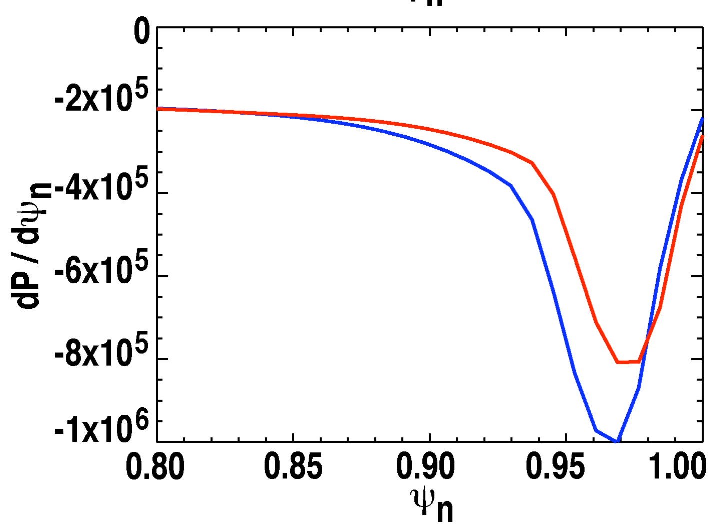




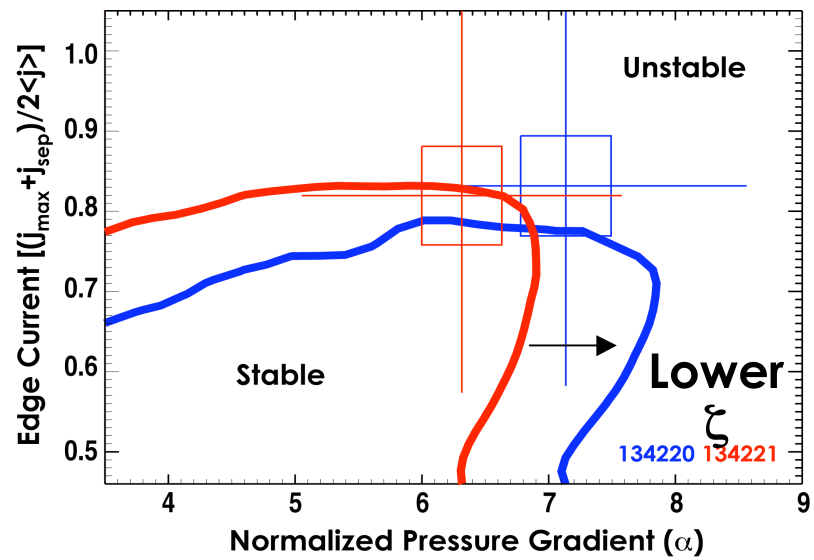


Larger Pedestal Pressure at Lower ζ Improves Confinement





- **Low ζ case** has ~10% greater pedestal pressure consistent with increased ELM Peeling-ballooning stability limit (ELITE calculation)
- **$\langle P \rangle_V$ is the same, but τ_E differs by ~19%, so core profiles and transport must change also**



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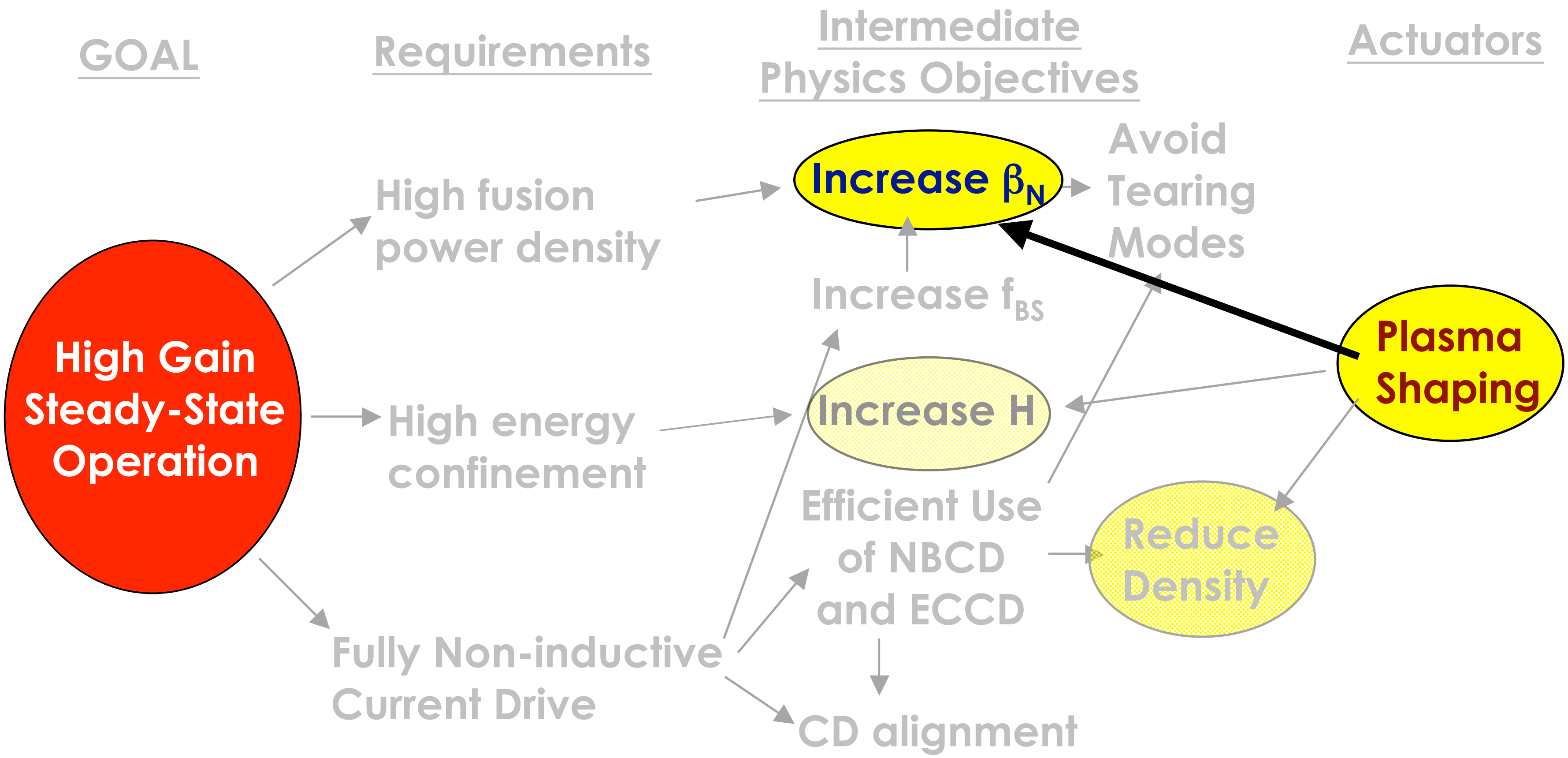
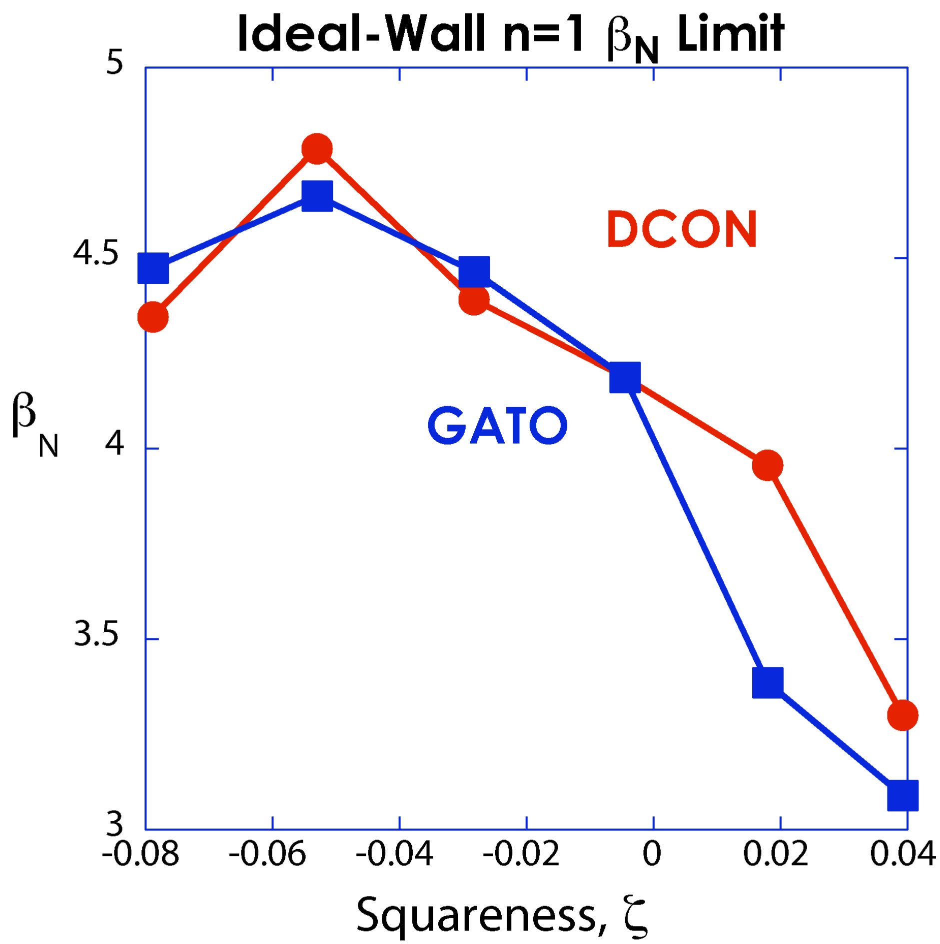
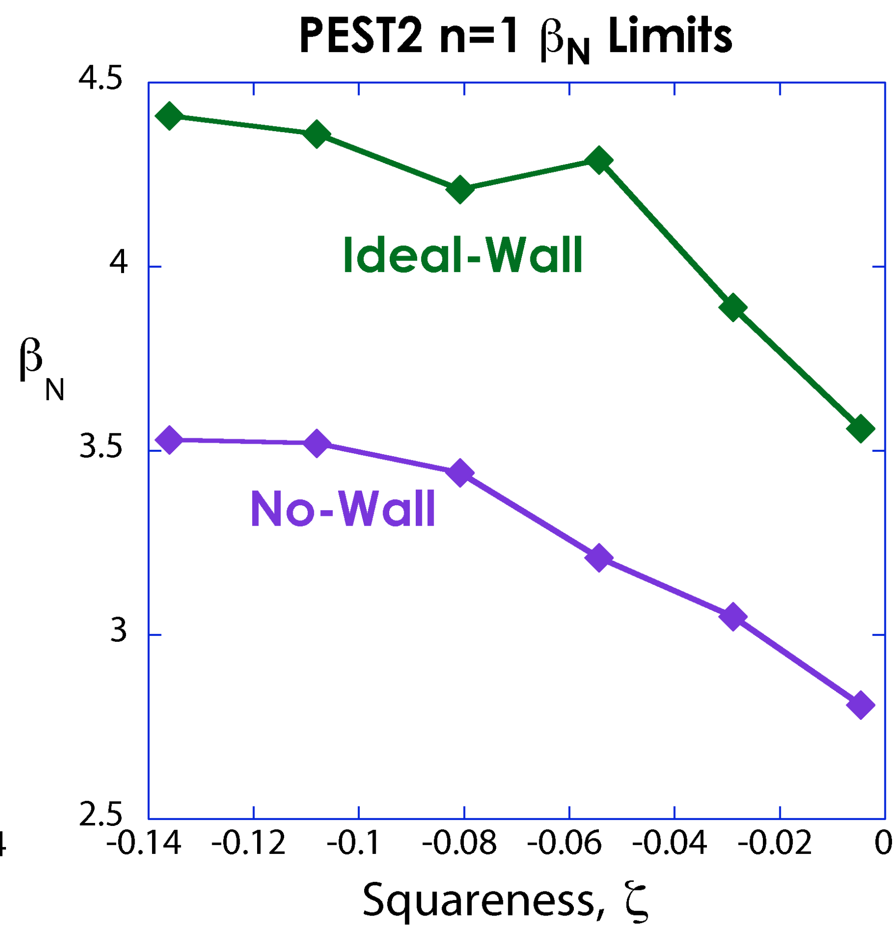
Stability


GOAL
Requirements
Intermediate Physics Objectives
Actuators
High Gain Steady-State Operation
High fusion power density
High energy confinement
Fully Non-inductive Current Drive
Increase β_N
Avoid Tearing Modes
Increase f_{BS}
Increase H
Efficient Use of NBCD and ECCD
CD alignment
Reduce Density
Plasma Shaping

Predictive Modeling Suggested n=1 Ideal-Wall and No-Wall Global β_N Limits Are Greater at Low to Intermediate ζ

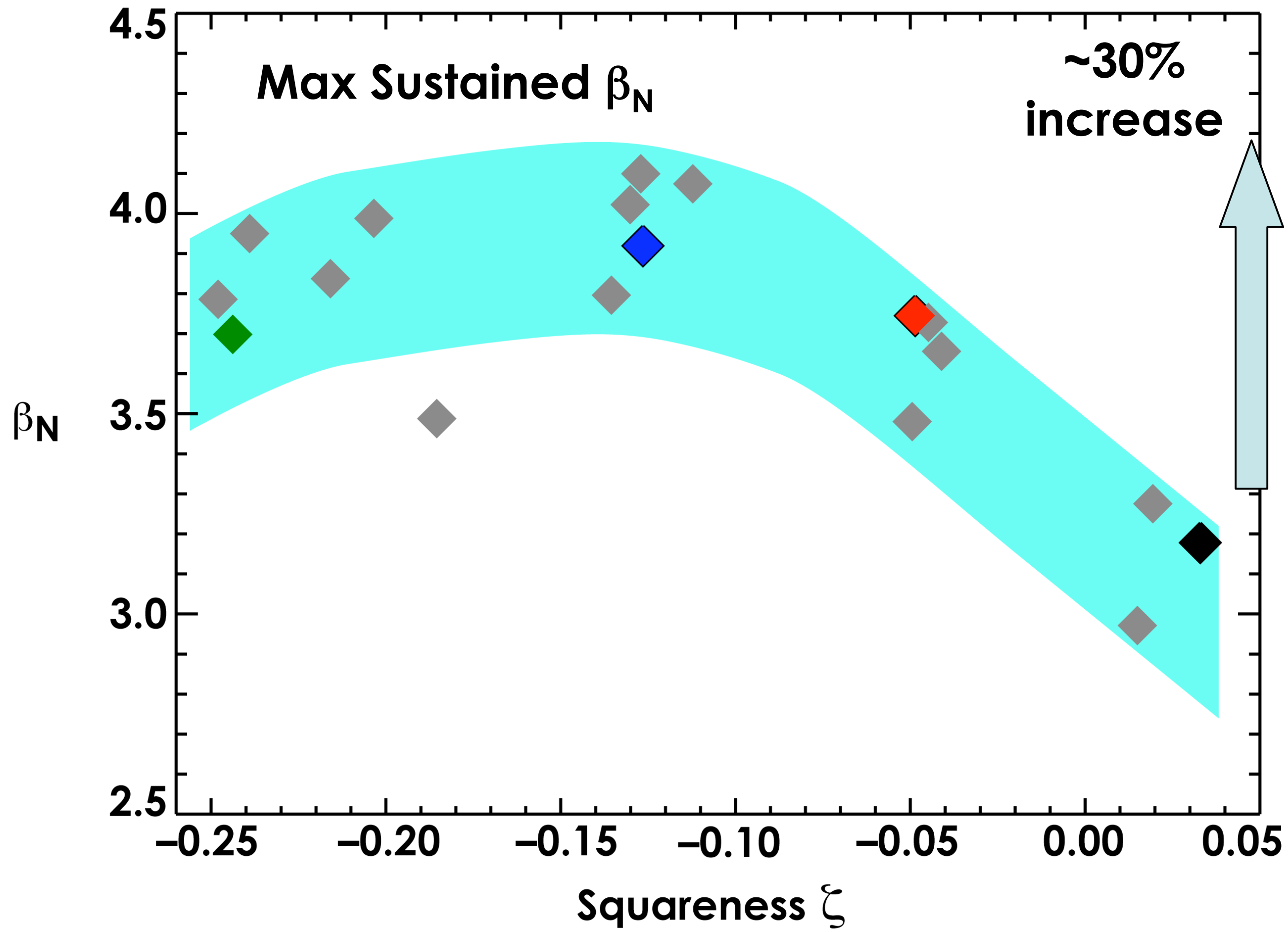


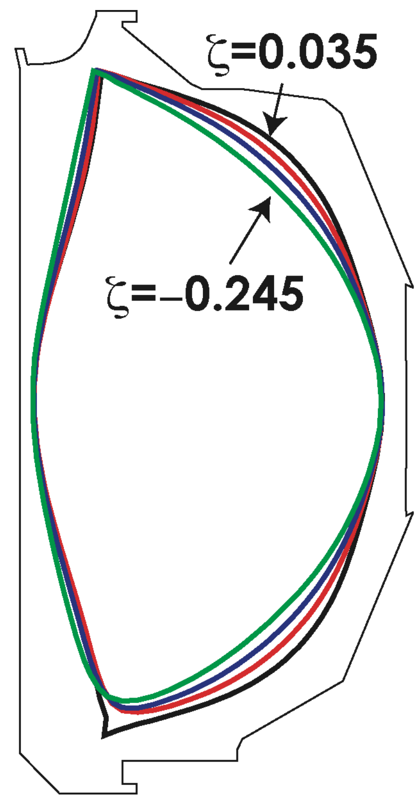
κ=1.90, δ=0.65,
P_0/<P>=2.5, q_{min}>2



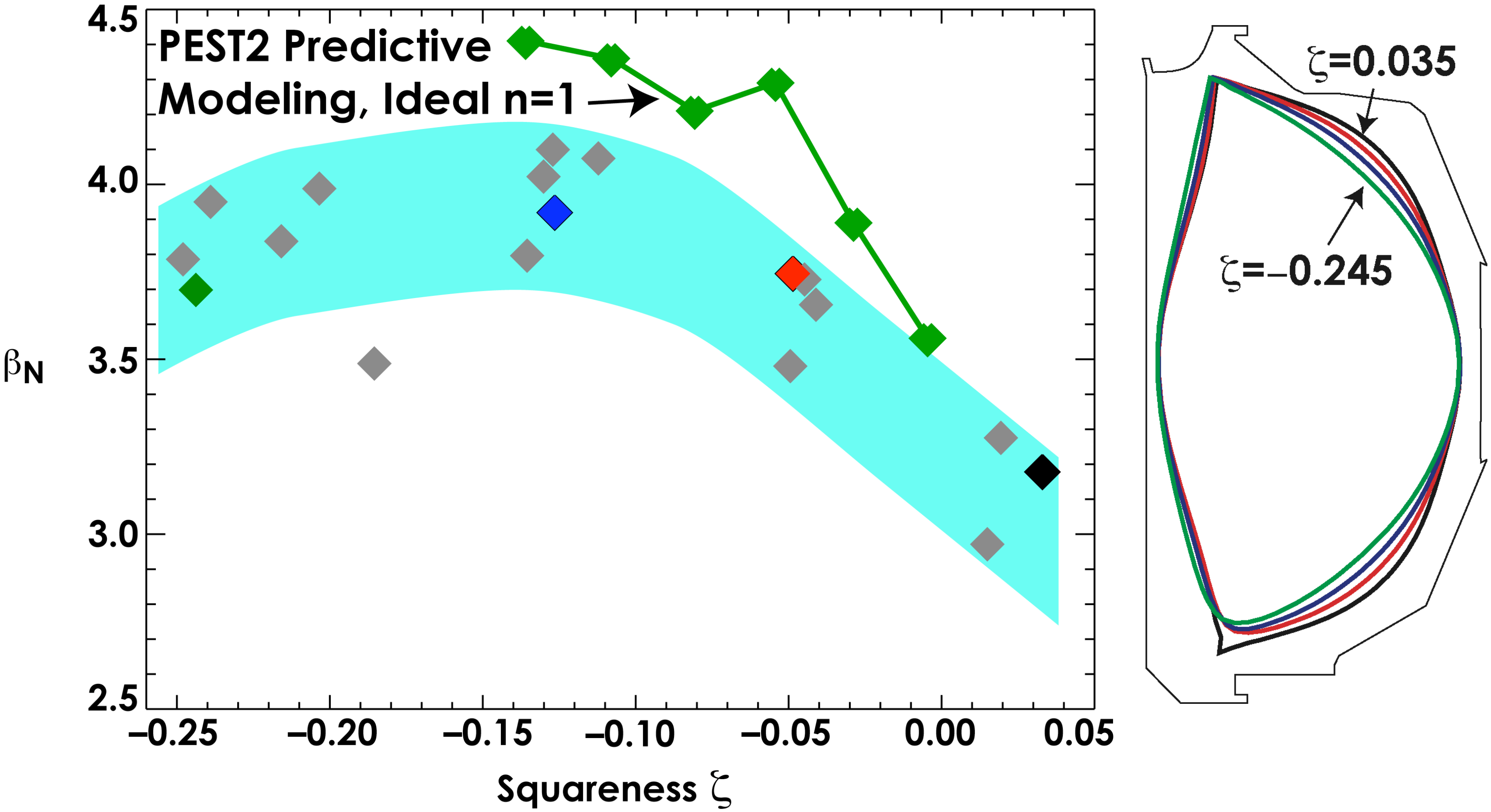
κ=1.8, δ=0.65,
P_0/<P>=2.72-2.85, q_{min}>2

Experimentally Obtained Peak Sustainable β_N With q_{min}~1.5 is Greatest at Intermediate ζ

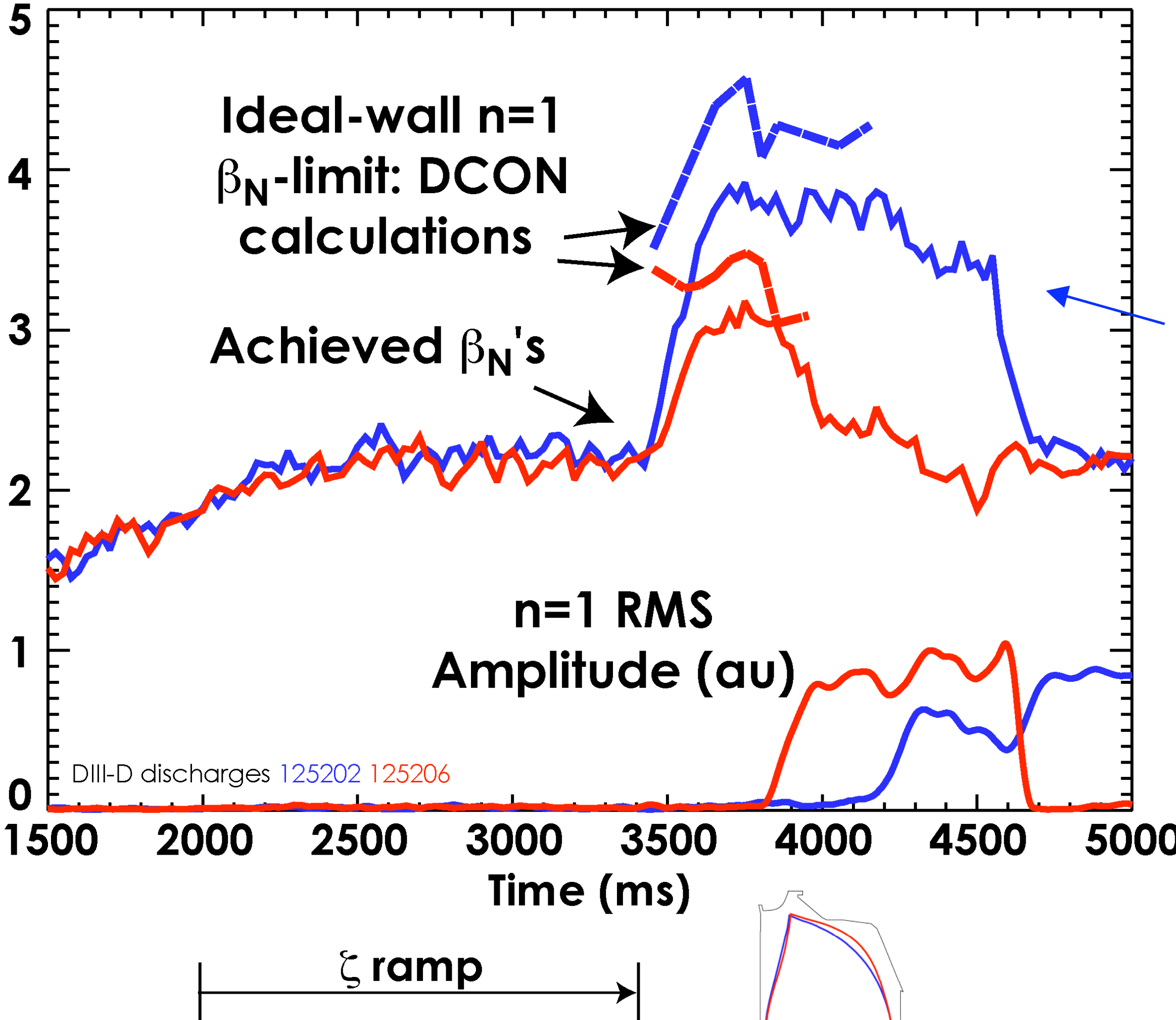


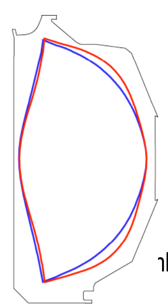


Experimentally Obtained Peak Sustainable β_N Validates Modeling Trend



Calculated Ideal-Wall Stability of Actual Discharges is Greater at Lower ζ





- Stability calculated using actual shapes and measured profiles as input
- Lower ζ typically has broader pressure profile - increases stability
- Disruptions not typically observed
- High β_N phase is terminated by 2/1 Tearing Mode when β_N nears ideal-wall n=1 limit

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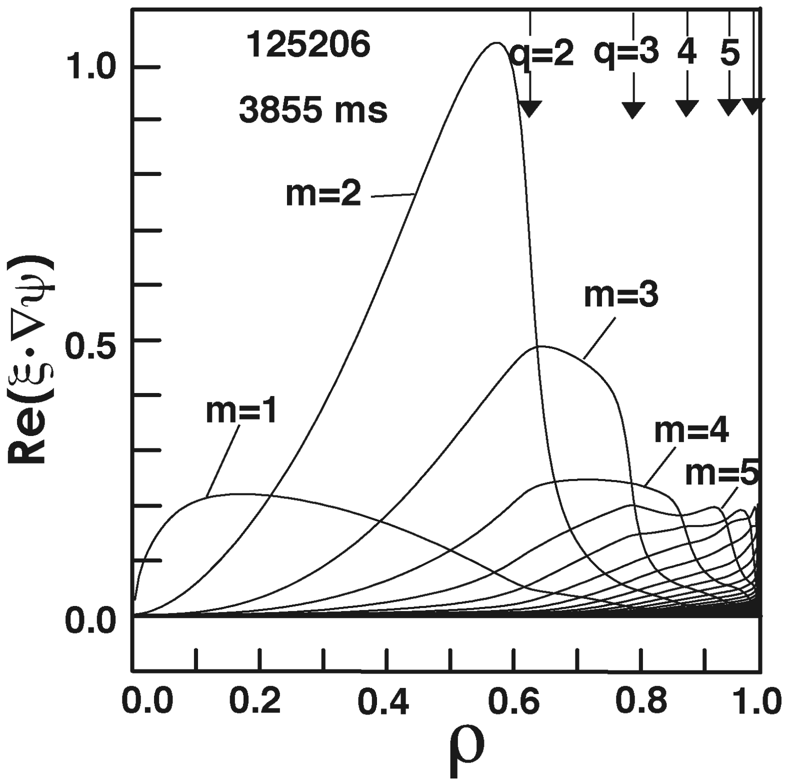
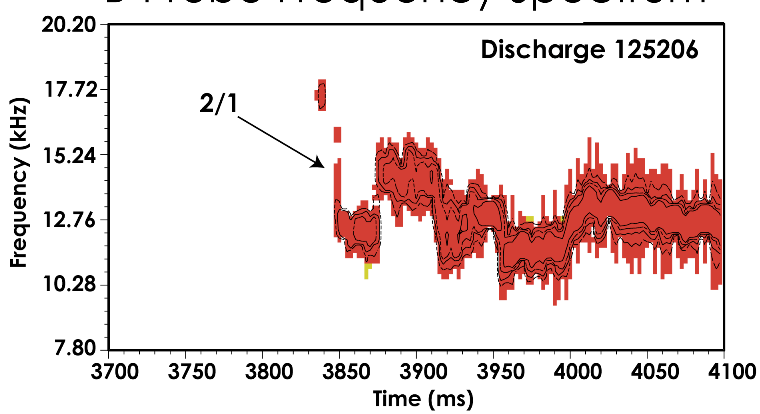
Appearance of Resistive Mode Near Ideal Limit is Consistent With Theory



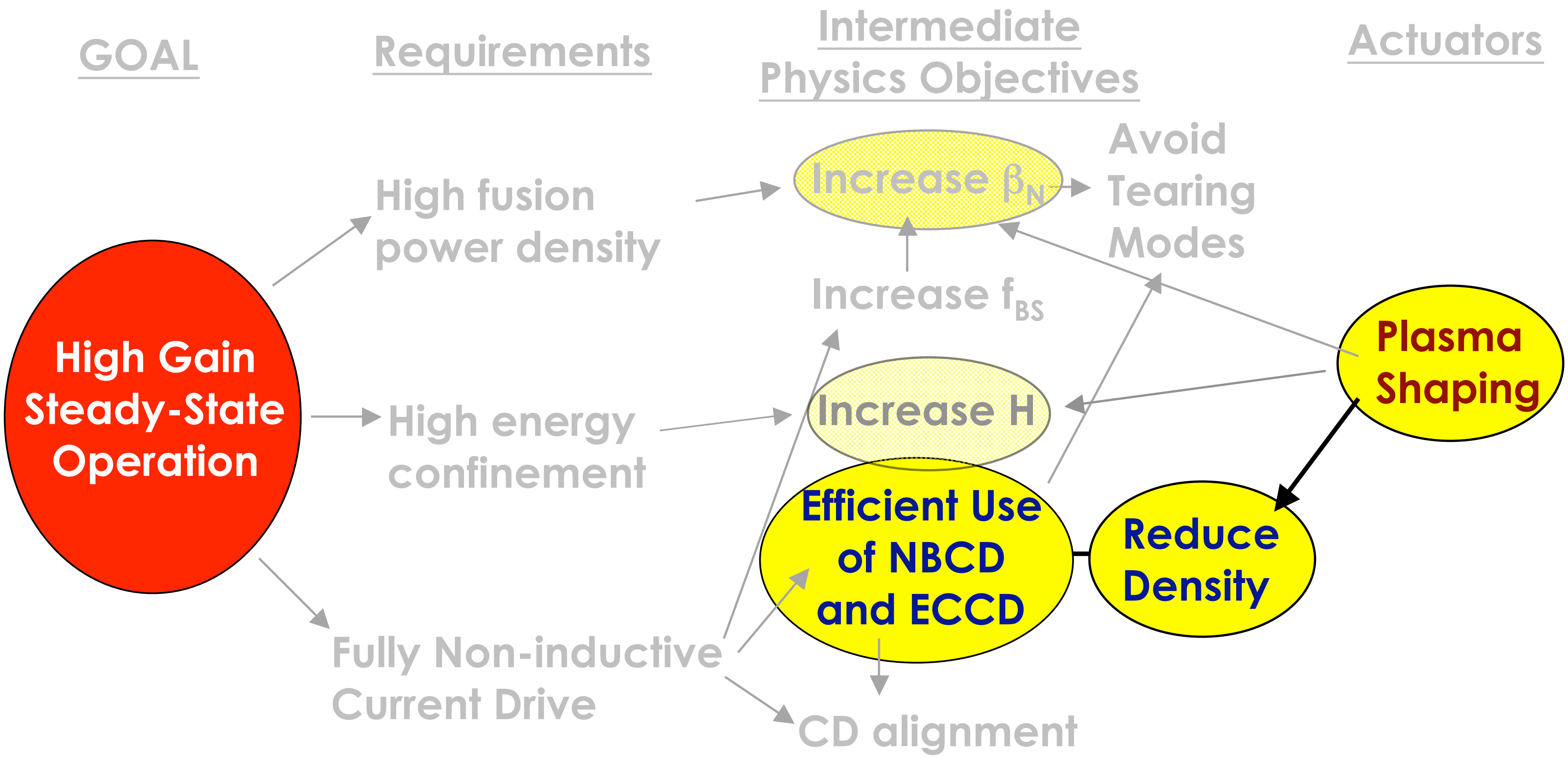
- **GATO predicts ideal-wall m/n=2/1 instability for high-ζ discharge at β_N~3**
- **Tearing mode stability index Δ'→∞ at ideal limit**
- **As ideal limit is approached, Δ' becomes large and positive, leading to Tearing Mode[1]**

B-Probe Frequency Spectrum

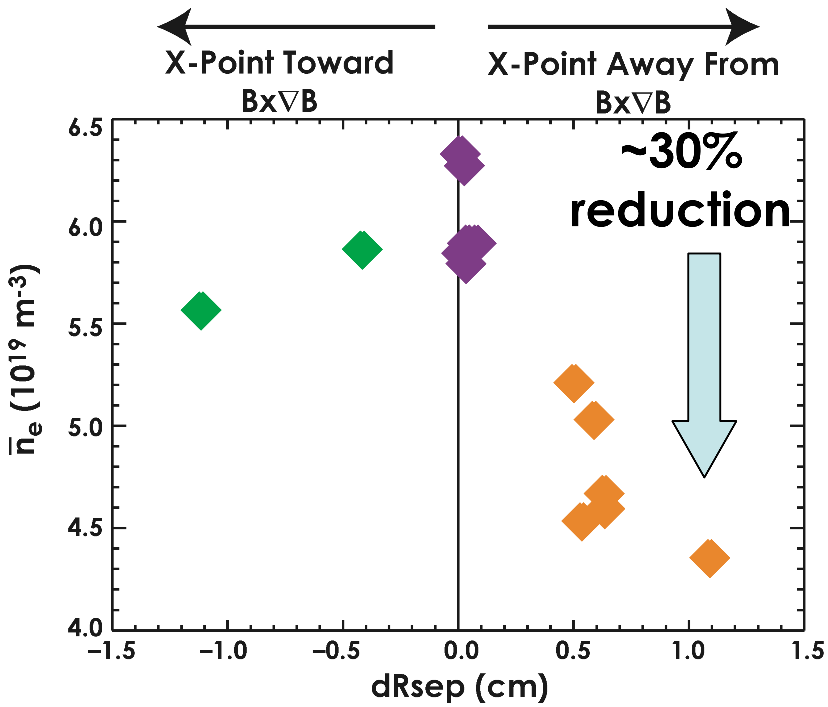


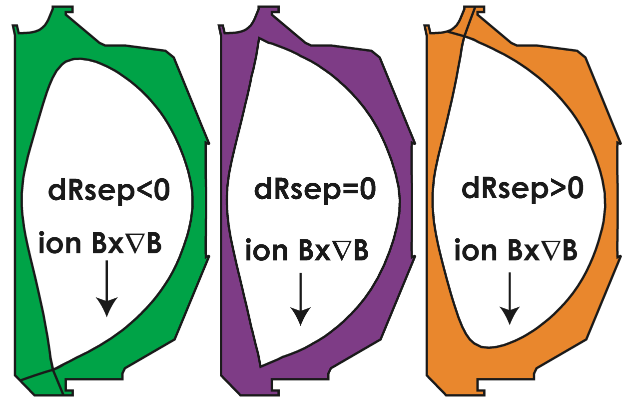
[1]Brennan et al., Phys. Plasmas, 10, 1643 (2003).

Density Control For Efficient Noninductive CD



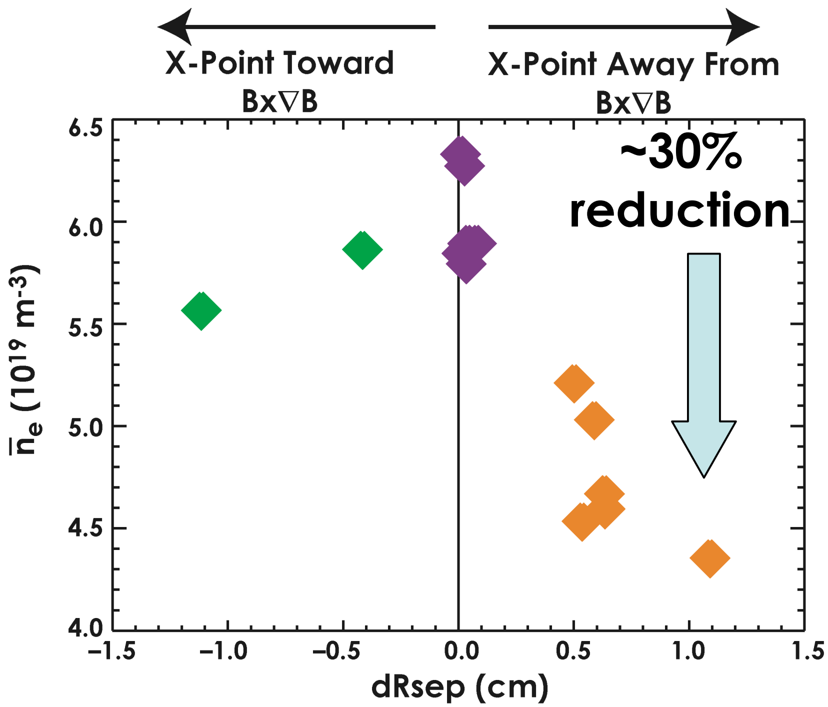
Unbalanced Double-Null Minimizes Density with Little Impact on Confinement

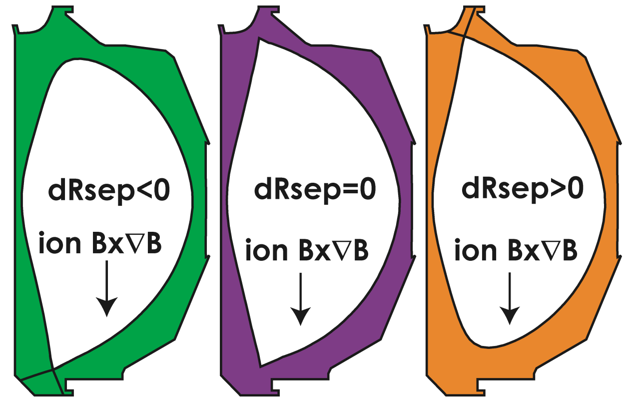




- **Small bias with ion Bx∇B drift directed away from X-pt. reduces density more than balanced or ion Bx∇B drift toward X-pt.**

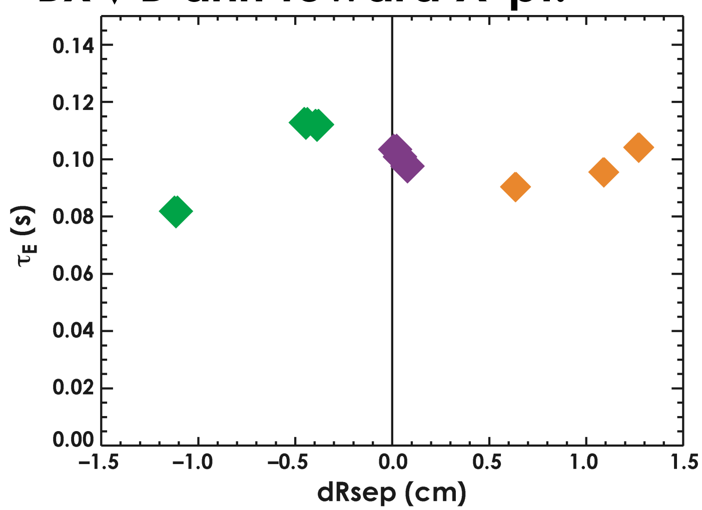
Unbalanced Double-Null Minimizes Density with Little Impact on Confinement





- Small bias with ion Bx∇B drift directed away from X-pt. reduces density more than balanced or ion Bx∇B drift toward X-pt.

- Confinement variation ≤ ~10% with dRsep change
- dRsep changes made with approximately constant squareness



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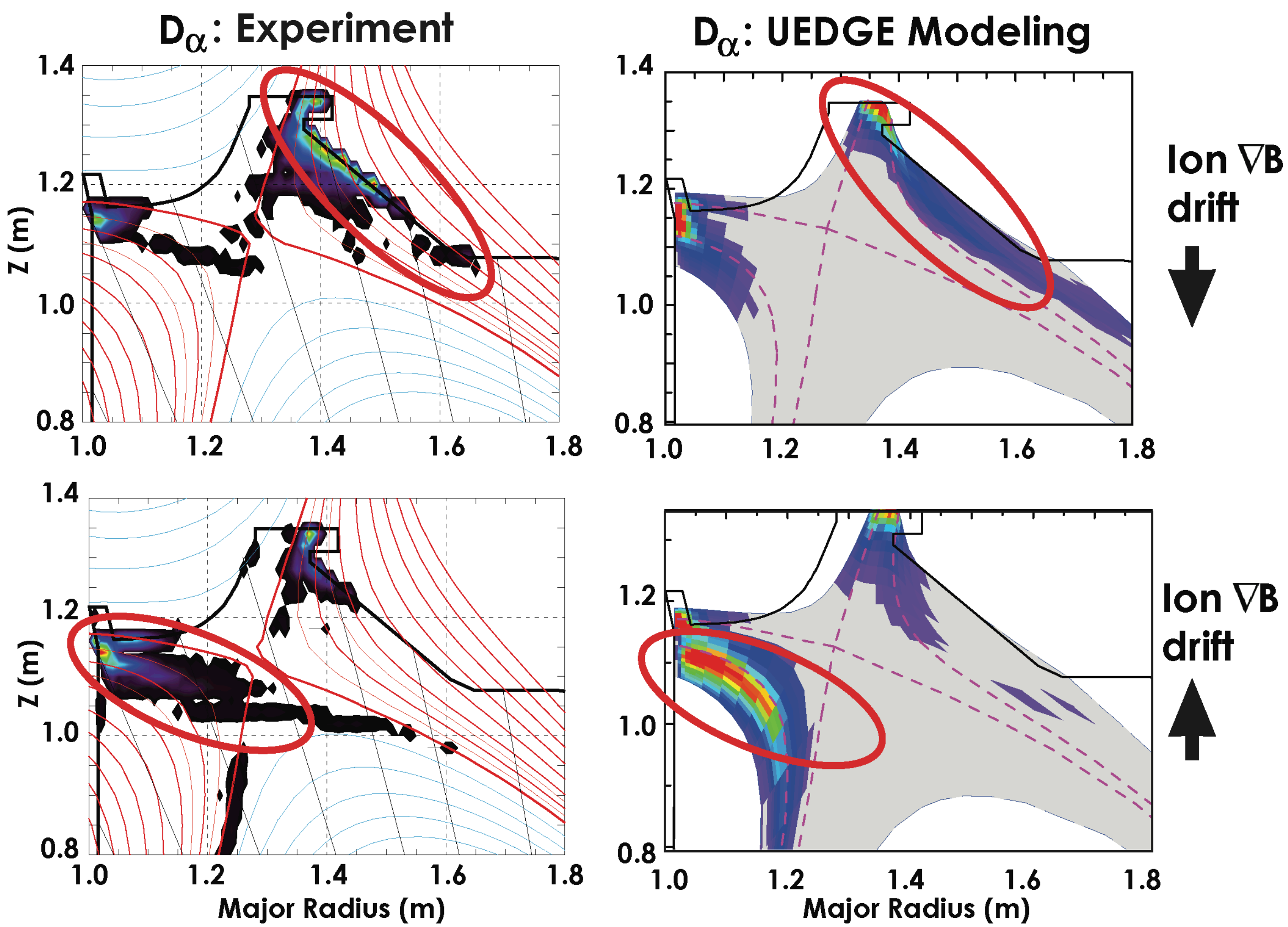
Modeling Suggests Better Density Control Assisted by More Favorable ExB Drifts Into Outer Pump

- ion B×∇B↓: recycling dominant in outer divertor
- ion B×∇B ↑: recycling dominant at inner divertor target



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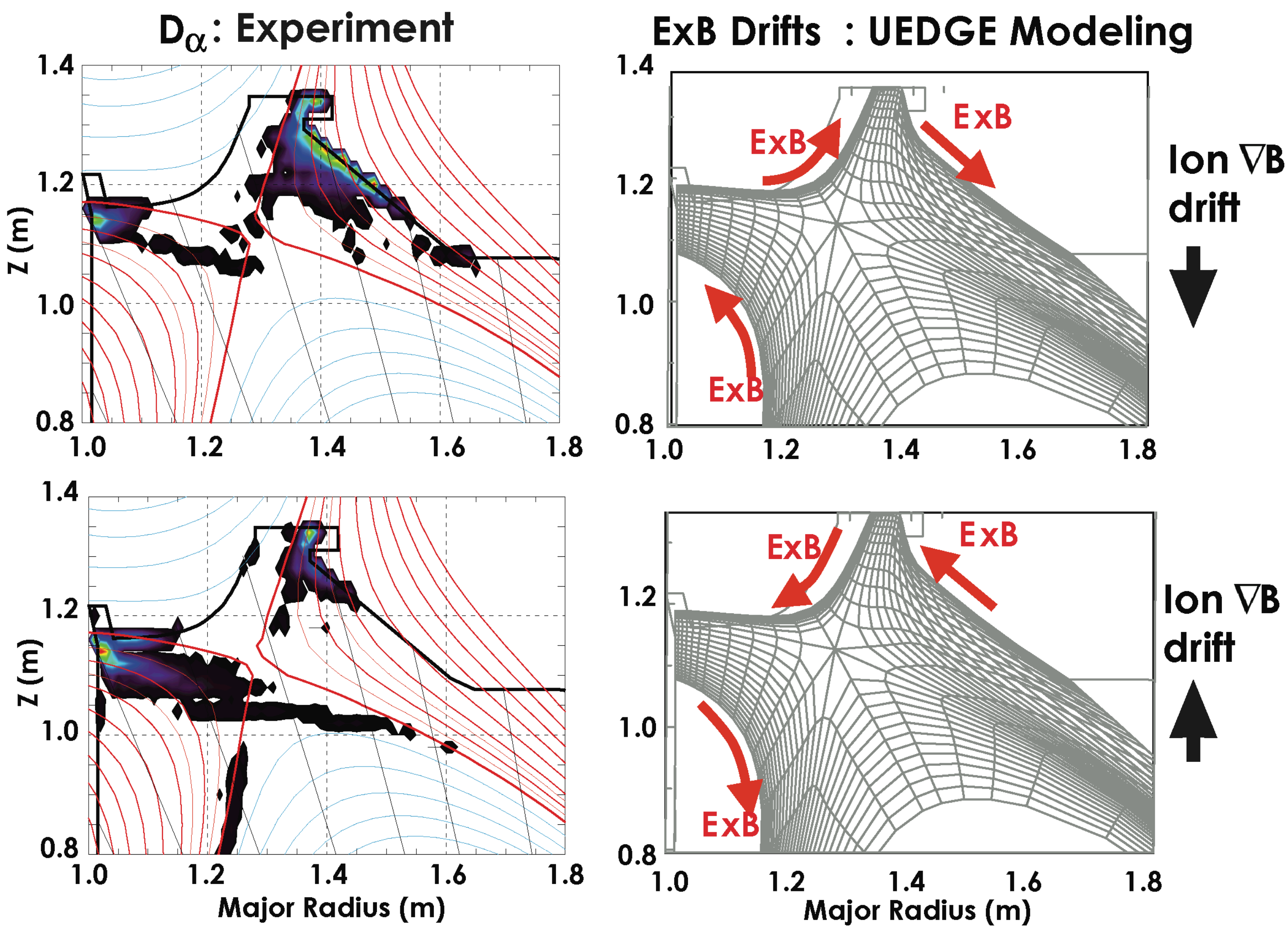
Modeling Suggests Better Density Control Assisted by More Favorable ExB Drifts Into Outer Pump

- ion B×∇B↓:

  ExB drifts push ions to more effective outer divertor

- ion B×∇B ↑:

  ExB drifts push ions to inner divertor that is susceptible to detachment



(Petrie, P03.00008)

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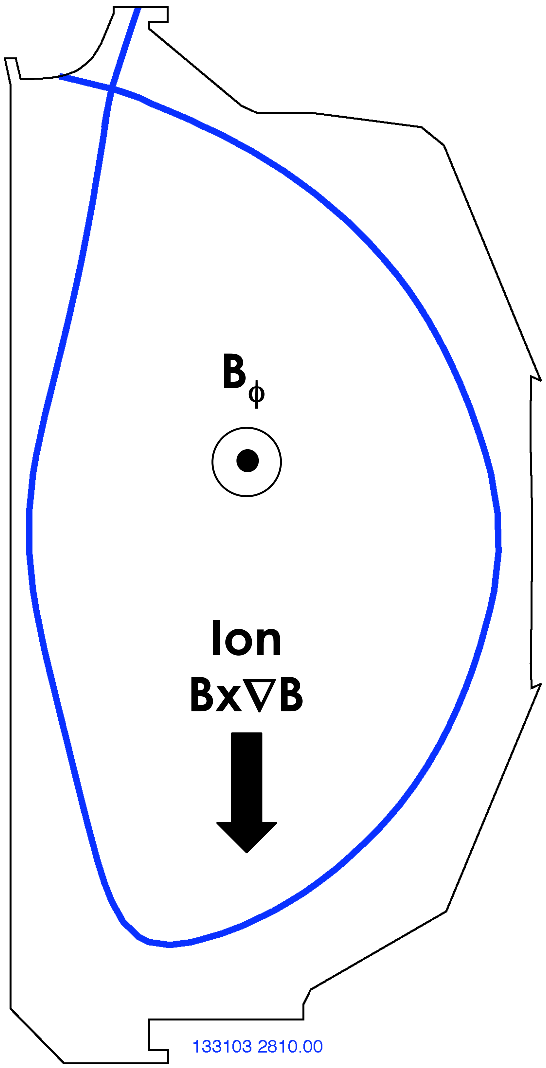
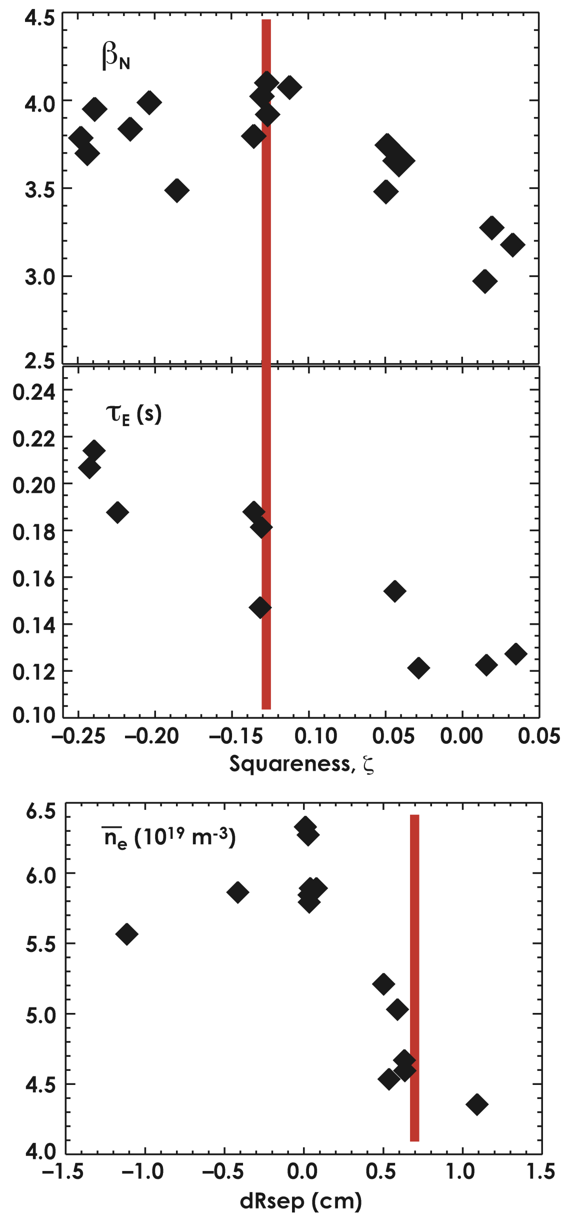
These Shape Studies Identify Moderate ζ With a Slight Divertor Imbalance as the Optimal for High f_{NI} Experiments





- **Pick squareness that has highest β_N, ζ≈-0.13**
- **Good confinement**
- **Bias divertor away from Bx∇B with dRsep 0.5-1.0 cm**

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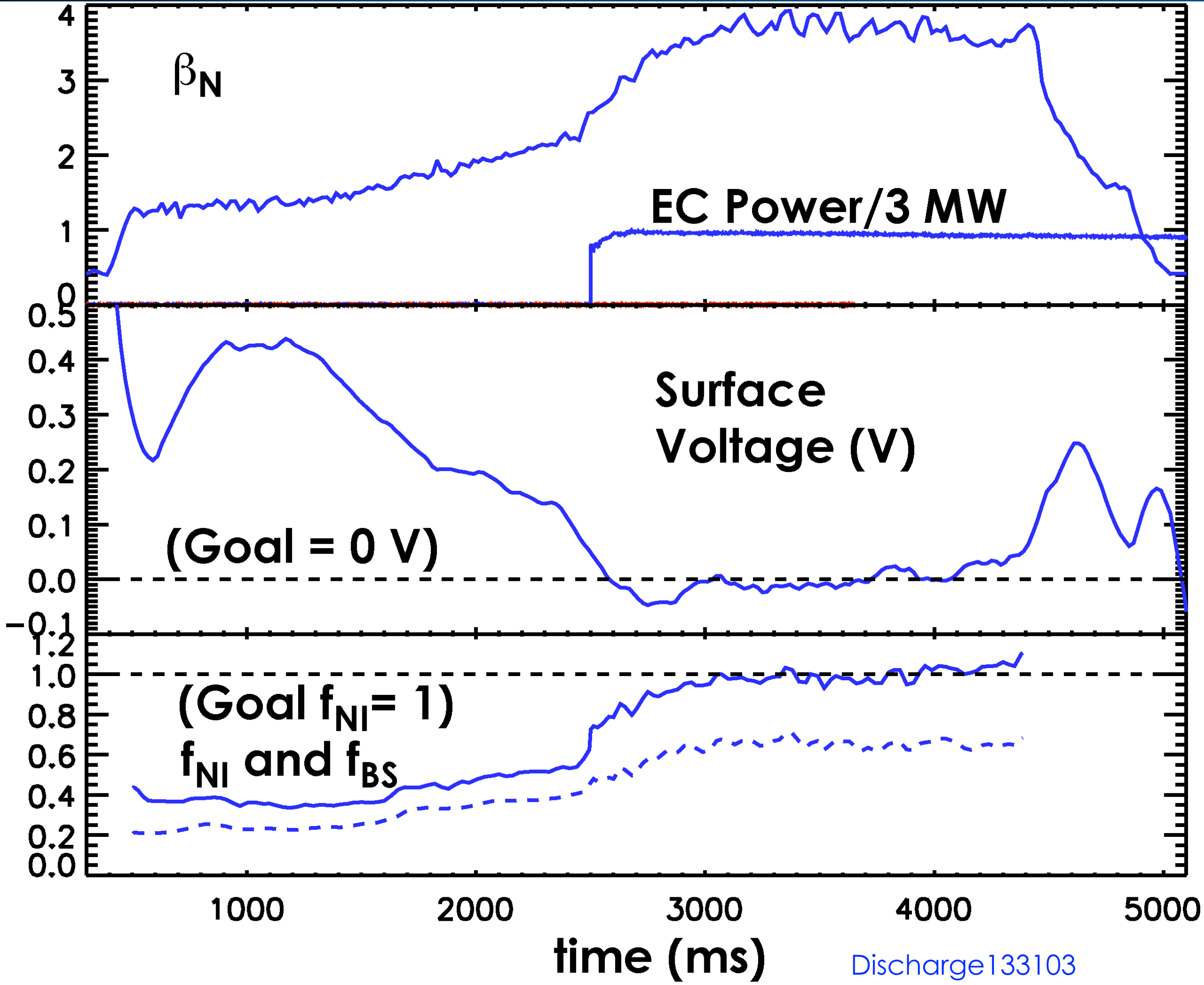
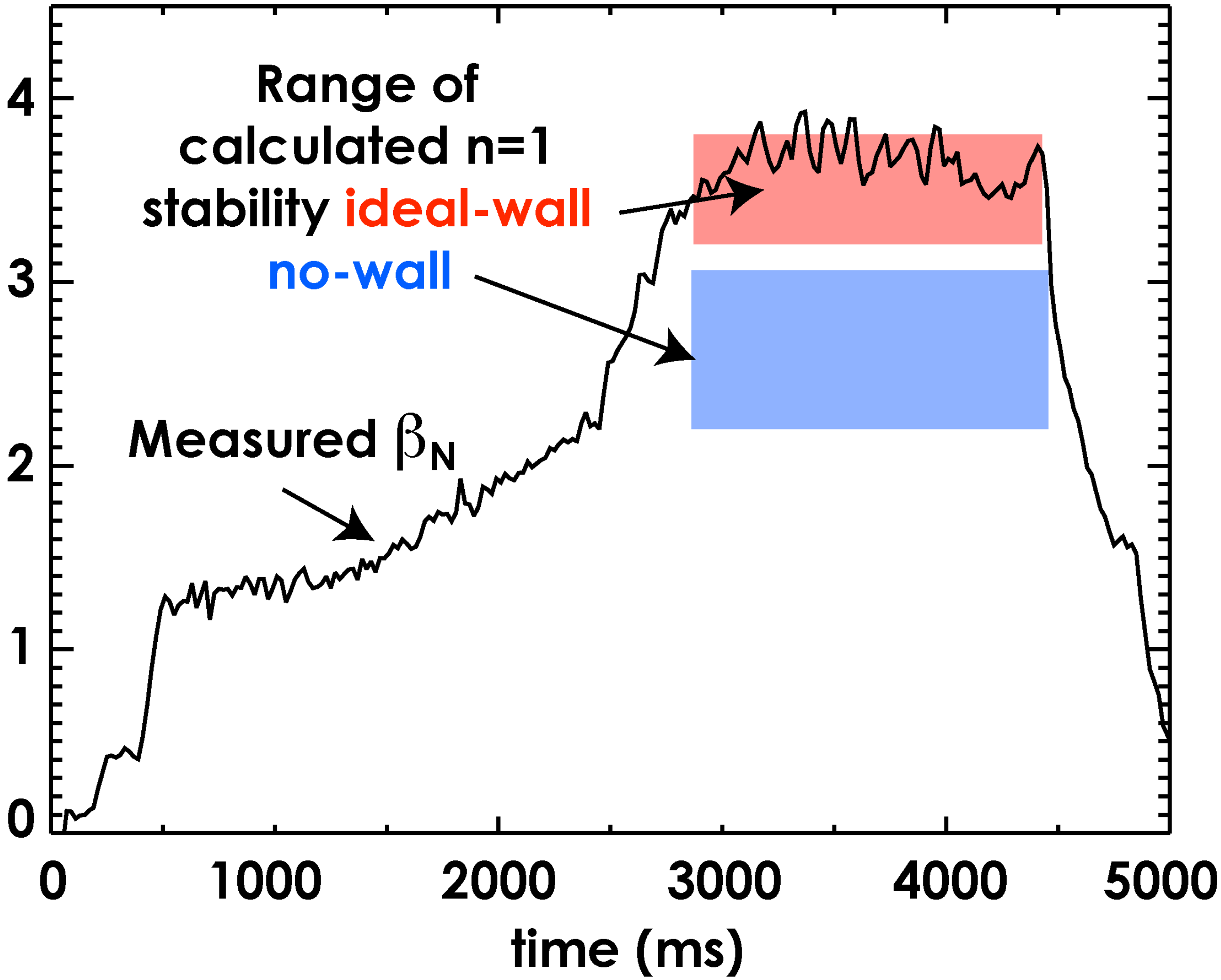
Using the Optimal Shape and Long-Pulse ECCD, We Have Extended the Duration of f_{NI}~1 at Higher β_N and f_{BS}



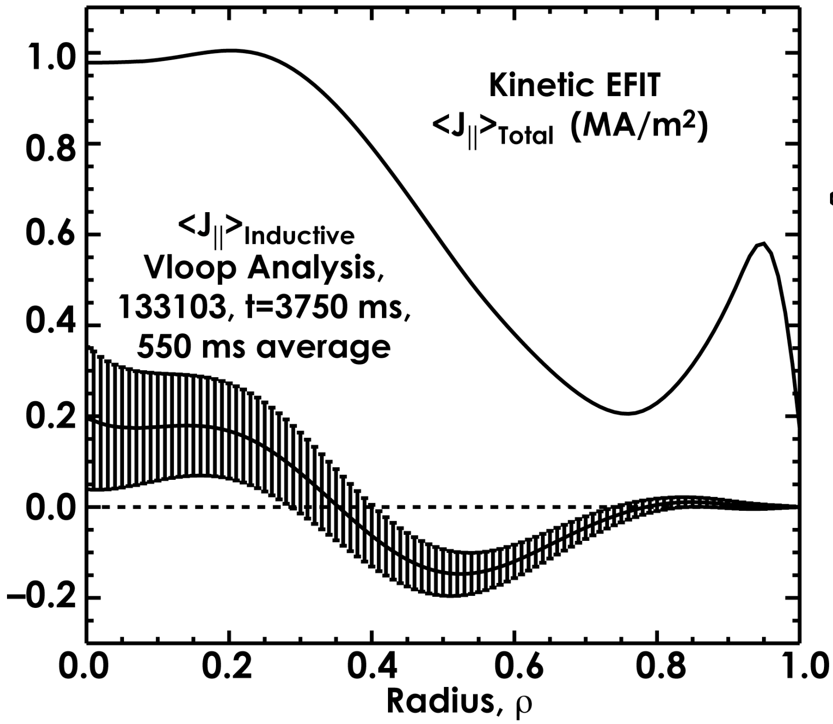
- - β_N~3.5-3.9
  - V_{surf}~0 for ~0.7τ_R
  - q_{min}~1.5, H_{98}~1.5 at start of high-β_N phase
- Transport code simulations predict f_{NI}~1 and f_{BS}~0.65
- Kinetic profiles as input and Sauter bootstrap current model
- Best previous β_N~3.2-3.6, with V_{surf}~0 for 0.4τ_R

β_N is ~30% Above the No-Wall n=1 Stability Limit and Approximately at the Ideal-Wall Limit

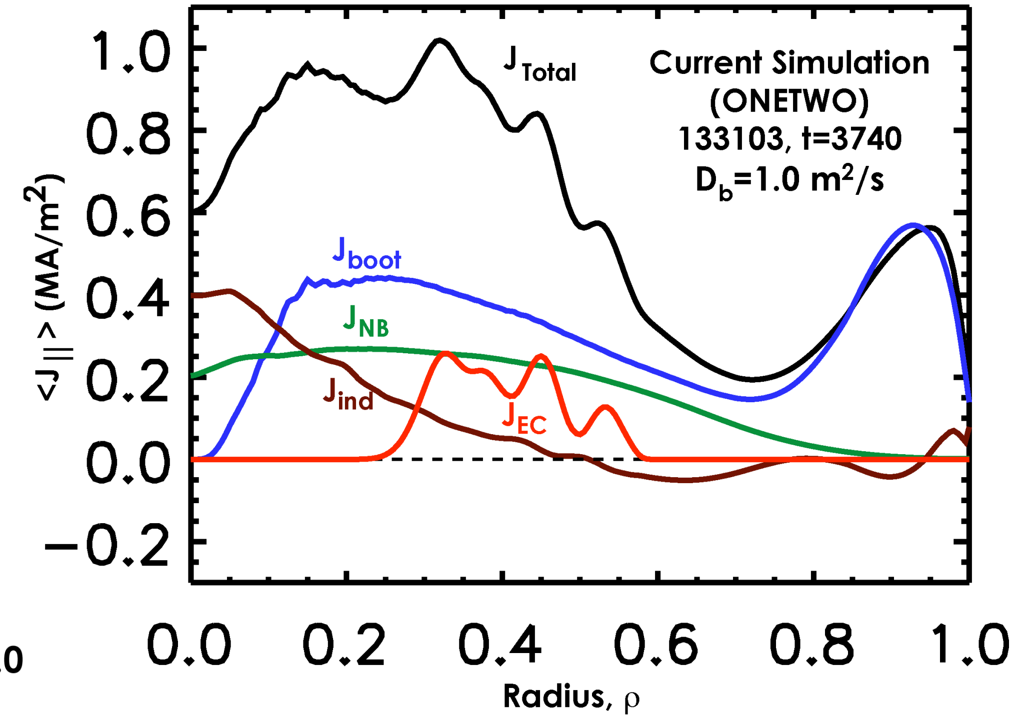


- Successfully avoiding 2/1 Tearing Mode
- Limit to high β_N duration is available beam energy
- 5/3 Tearing Modes are typically present
- Ideal n=∞ ballooning limit at β_N~4 (BALOO)

Measurement and Simulation Show The Inductive Current Density is Small Everywhere



Measurement of inductive current density - loop voltage analysis



Transport code simulation of current components agrees with measurement and provides a test of current models

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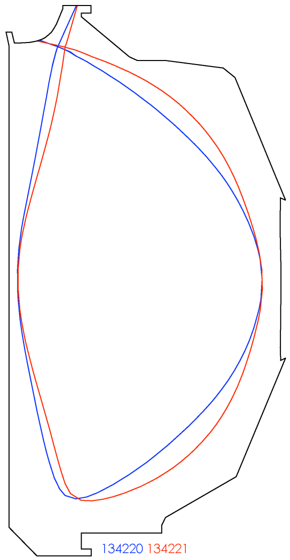
Summary

- Shape-optimized DIII-D discharges have achieved higher β_N (~3.7) and noninductive fractions (f_{NI}~1) for extended duration (~0.7τ_R)



- Squareness optimization (i.e. lower ζ) allows:
  - ~30% variation in achievable β_N

    due to n=1 ideal-wall dependence on ζ
  - ~70% variation in energy confinement time

    due to pedestal pressure and core transport

    changes with ζ
- Divertor balance optimization allows ~30% reduction in line-averaged density due to ExB drift into most effective pump
- n=1, pedestal, and particle control dependence on shape are all described by theoretical models that can be used to optimize future tokamaks