Modelling and Experimenting with ITER: the MHD Challenge

by

F. Turco[1]

with

J.M. Hanson[1], A.D. Turnbull[2], G.A. Navratil[1], F. Carpanese[3], C. Paz-Soldan[2], C.C. Petty[2], T.C. Luce[2], W.M. Solomon[4], J.R. Ferron[2], C.T. Holcomb[5], T.N. Carlstrom[2]

[1]Columbia University
[2]General Atomics
[3]Politecnico di Milano-General Atomics
[4]PPPL
[5]Lawrence Livermore National Laboratory

New York,

January 23rd, 2015

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Columbia University

Contents

- **Introduction to DIII-D development of ITER and FNSF scenarios**
- **Making progress by integrating experiments and modelling**
  - Understanding and projecting MHD stability limits
  - MHD spectroscopy to measure the approach to a limit
- **The ITER Baseline Scenario:** moderate β_N, zero torque
- **The path to high β_N and steady-state conditions**
  - Modeling the approach to the no-wall limit with non-ideal effects (MARS-K)
- **The steady-state hybrid scenario: high β_N, high torque**
  - Enhance the ideal and resistive limits with profiles and shape changes
- **Low torque at high β_N**
  - Validation of MARS-K description of the rotation effects
- **Discussion**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Goals and Needs of a Fusion Reactor

Large $nT\tau_E$	Need high T_e, T_i
Good confinement (τ_E)	To have high fusion gain $Q = P_{fus}/(P_{input}-P_{\alpha})$
Fully non-inductive conditions	For continuous operation (no transient J_{ohm})
High pressure (β_N)	For large J_{boot}, low P_{input}
Long stable plasmas	Avoid disruptions, loss of confinement

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

How Do We Project Present Experiments to Future Machines?

- **Produce demonstrations of relevant conditions in present machines**
- **Extrapolate to conditions not presently attainable**

	PRESENT	FUTURE
EXPERIMENT	- Plasmas on 1 machine - Multi-machine campaigns	- Scaling laws
MODELS	- Benchmark - Validation	- Predictive capability

How Do We Project Present Experiments to Future Machines?

- **Produce demonstrations of relevant conditions in present machines**
- **Extrapolate to conditions not presently attainable**

	PRESENT	FUTURE
EXPERIMENT	- Plasmas on 1 machine - Multi-machine campaigns	- Scaling laws
MODELS	- Benchmark - Validation	- Predictive capability

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

One of the Issues for All the Present Plasmas is Duration at Peak Performance

MHD instabilities cause pressure and rotation collapses, disruptions

- **Ideal kinks, RWMs** → large β_N and rotation collapses, disruptions
- **Tearing (resistive) instabilities** → loss of confinement, disruptions
- **High frequency modes (fishbones, TAEs…)** → loss of confinement, triggering of other modes

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

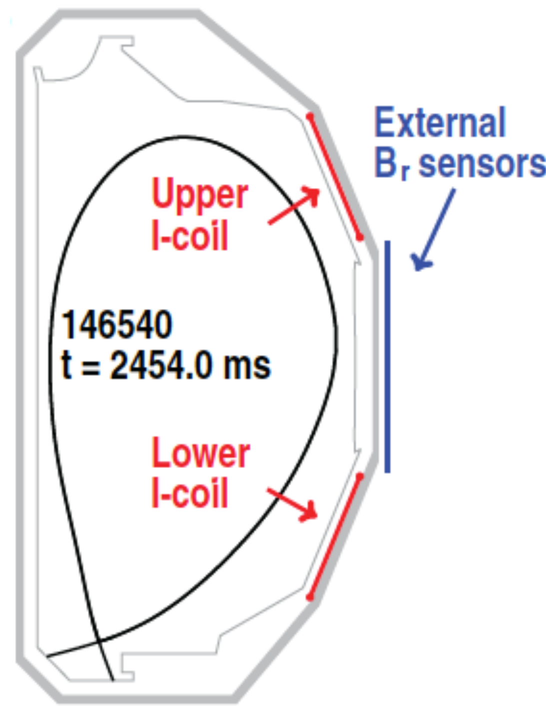
Measure the Approach to Instability: MHD Spectroscopy

EXP

MHD spectroscopy*: probe the stable side of the RWM

A rotating kink-resonant n=1 field is applied with a set of "internal coils" (I-coils), at f=10 Hz or f=20 Hz ← *rotation frequency of the RWM*

- **The plasma response amplitude increases close to a stability boundary**
  - Used to probe the proximity to an ideal stability limit (high β_N pressure limit, low q current limit)
  - Resistive stability is strongly correlated to ideal limits*(acquire information on tearing modes)



Expand the analysis and modeling space to the "stable" side of the modes

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

* Reimerdes PRL 2004
* Brennan PoP 2007, Turco PoP 2012

Rwms as Kink Limit Measured and Modelled With Plasma Response

MOD

- **The ideal kink instability, with a realistic (non-ideal) wall model, is described by the RWM branch of the dispersion relation**
  - **→ slow growth rate of the order of τ_{wall}**

- **MHD spectroscopy measures the approach to this stability boundary**

- **The RWM is influenced by**
  - Pressure and current profile gradients (ideal MHD)
  - Resonances between the plasma rotation and the thermal particles drift frequencies
  - Non-resonant contributions from fast-particles (NBI ions in DIII-D)

- **In DIII-D, RWMs**
  - Cause rotation and β_N collapses in the high-q_{min}, high-β_N SS plasmas
  - Provide the hard disruptive limit in the q<2 scenarios

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Drift Kinetic Effects Are Needed to Describe the Experimental Observations

MOD

- **RWMs do not usually appear in fast-rotating, low q_{min} plasmas → kinetic damping of the RWM [Hu et al, PRL2004]**

$$\gamma\tau_W = -\frac{\partial W_{no-wall}}{\partial W_{ideal-wall}}$$

Ideal MHD RWM dispersion relation

$$\gamma\tau_W = -\frac{\partial W_{no-wall} + \partial W_{kinetic}}{\partial W_{ideal-wall} + \partial W_{kinetic}}$$

Kinetic damping physics

- **The rotation, the thermal and fast-ion dependences may extrapolate unfavourably to machines with low external torque and lower fraction of fast beam-generated ions, such as ITER**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MARS-K Model is Being Validated to Predict the Stability in Unexplored Regimes

MOD

Eigenvalue code, modified to solve for the response to an inhomogeneous forcing function ← *External field from the I-coils*

$\xi(\gamma + i\Omega) = v + (\xi \cdot \nabla\Omega)R$	**Plasma displacement**
$\rho(\gamma + i\Omega)v = -\nabla \cdot p + j \times B + J \times \tilde{B} - \rho(\Omega \times v + v \cdot \nabla\Omega)$	**Momentum (with rotation)**
$(\gamma + i\Omega)\tilde{B} = \nabla \times (v \times B) + (\tilde{B} \cdot \nabla\Omega)R$	**Faraday's law**
$j = \nabla \times \tilde{B}$	**Ampère's**
$(\gamma + i\Omega)p = -v \cdot \nabla P$	**Perturbed pressure**
$p = pI + p_{//} + p_{\perp} \quad \leftarrow \quad \int M v^2 f \, d\Gamma$	**Drift kinetic pressure tensors**

The model includes
- resistive DIII-D wall geometry
- fast-NBI ions with a Maxwellian slowing down distribution function in v

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

*Y. Liu et al, Phys. Plasmas 15, 112503 (2008)

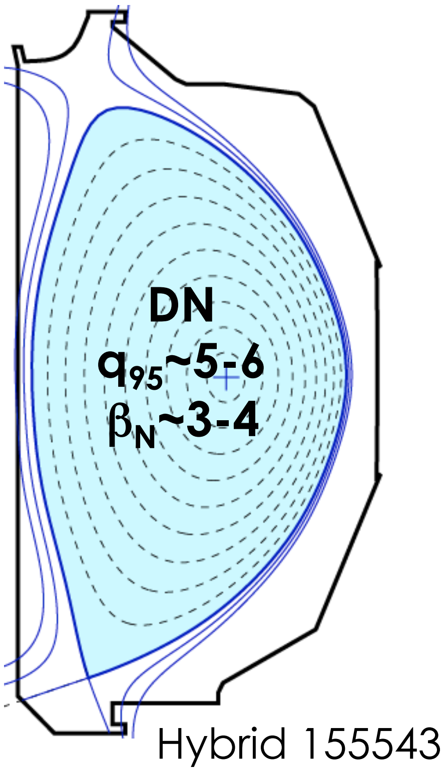
DIII-D is Tasked to Provide Demonstration Plasmas for ITER and FNSF

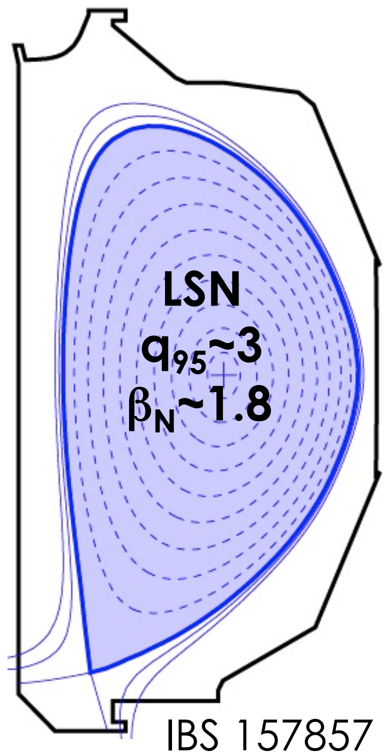
EXP

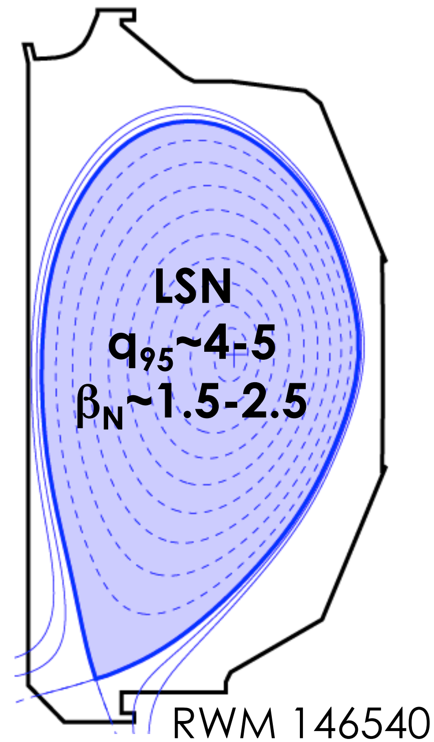
Experiments → platform to study the phenomena that the models describe

SCENARIO: a type of plasma, and plasma evolution, that has specific requirements for

- **plasma shape, q_{95}, Q, torque, collisionality, T_e/T_i, etc**







DIII-D NATIONAL FUSION FACILITY SAN DIEGO

I Am Going to Discuss the Work Towards These Scenarios:

ITER	**ITER Baseline Scenario (IBS)** Q=10, 15 MA (q_{95}~3), q_0<1, P_{fus}=500 MW, LSN shape
	Steady-State Q=5, 9 MA (q_{95}~5), LSN shape, f_{NI}=1
FNSF*	**Steady-state** Q < 5, 6.7 MA, q_{min}>1, DN, high neutron fluence

***Fusion Nuclear Science Facility** **for FDF (future US machine) → the mission is to develop fusion blankets and test materials**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

IBS: MHD Stability Below The No-wall Limit, At Zero Torque

ITER	**ITER Baseline Scenario (IBS)** Q=10, 15 MA (q_{95}~3), q_0<1, P_{fus}=500 MW, LSN shape
	Steady-State Q=5, 9 MA (q_{95}~5), LSN shape, f_{NI}=1
FNSF*	**Steady-state** Q < 5, 6.7 MA, q_{min}>1, DN, high neutron fluence

← β_N~1.8-2.2

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

[IBS] Stable Solution Found At Moderate to High Torque

EXP

- **DIII-D IBS demonstration discharges match**
  - **plasma shape (LSN)**
  - **q_{95} = 3.1**

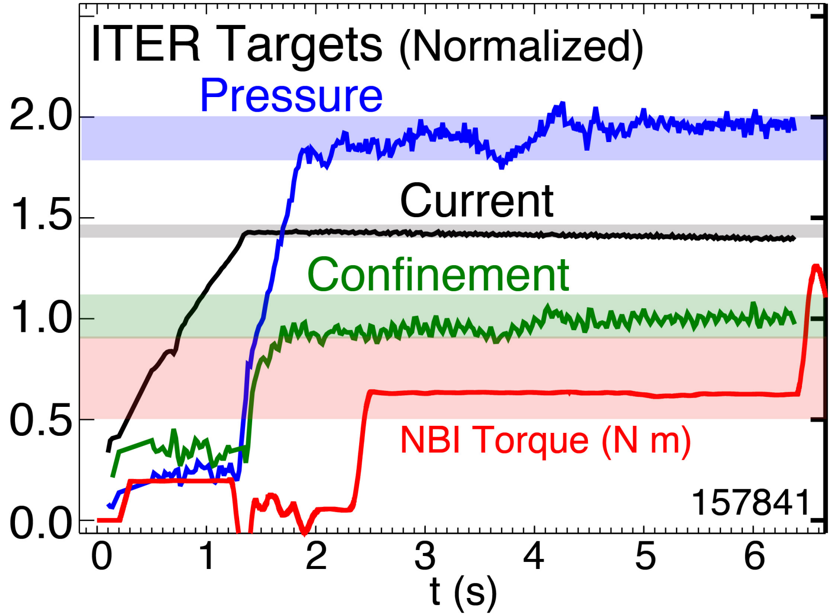
(ITER I_p=15 MA, Bt=5.3 T, R=6.2 m)

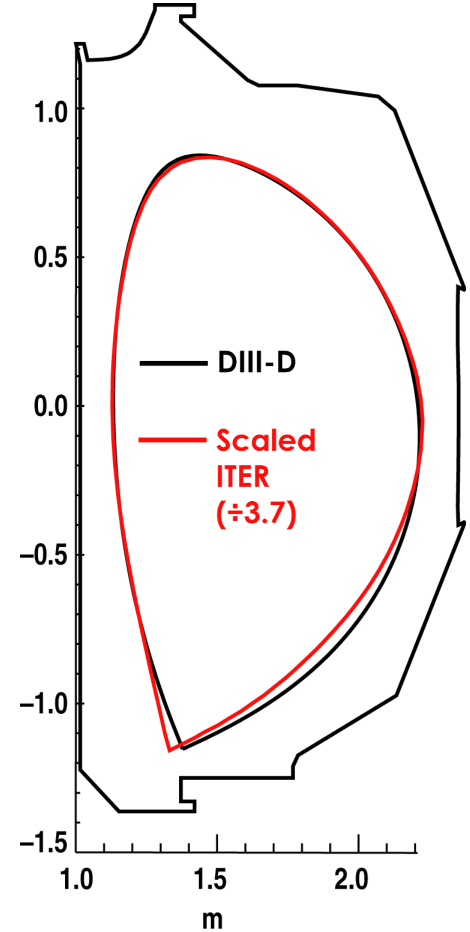
  - **Q = 10 ← β_N=1.8, H_{98}=1 at q_{95}=3**

DIII-D can match the predicted torque → 0-0.7 Nm

- **Not matching with the present heating systems:**
  - **T_e/T_i ~ 0.6-0.9 at ρ=0**
  - **collisionality**

Solution not very reproducible





DIII-D NATIONAL FUSION FACILITY SAN DIEGO

[IBS] At Low Torque Life is Even Harder

EXP

- Narrow operating point found at ≥1 Nm
- Operation at 0 Nm remains elusive
- Modes appear after several τ_E at constant β_N

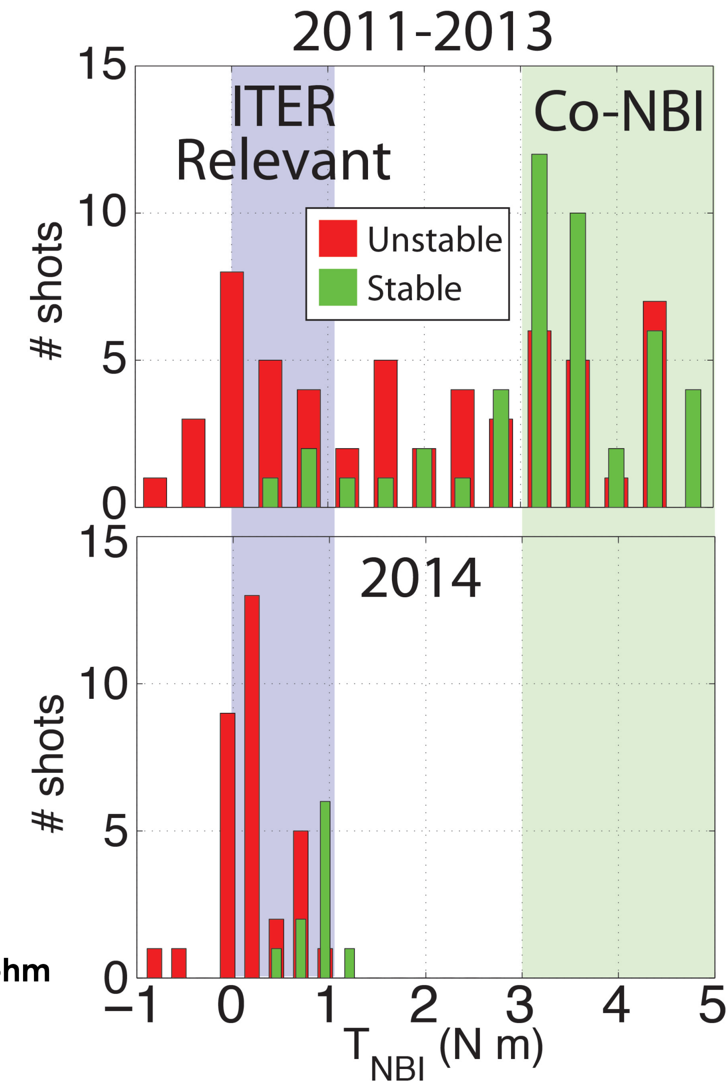
Operating on a marginal point
→ sensitive to small perturbations

Ideal no-wall limit β_{NW}~2.8-3.1
Ideal with-wall limit β_{WW}~3.2-3.5
IBS constant β_N~1.8-2.2

Non-ideal effects → current profile, rotation

Low rotation → more mode coupling, less wall stabilization

Rotation → transport → T_e → indirectly impacts J_{ohm} → current profile more unstable?

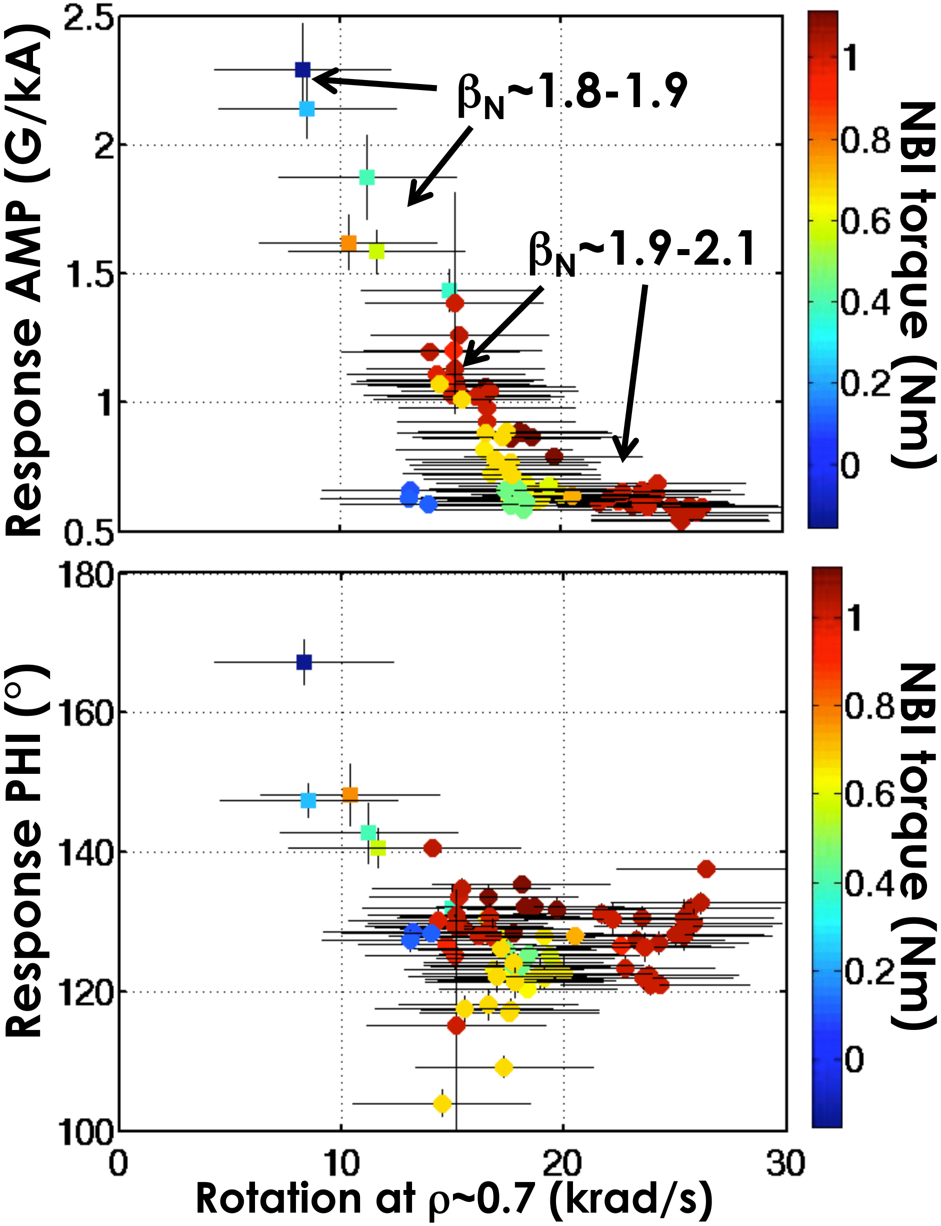


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MHD Spectroscopy Can Measure the Proximity to A Stability Limit

EXP

Response amplitude increase



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MHD Spectroscopy Can Measure the Proximity to A Stability Limit

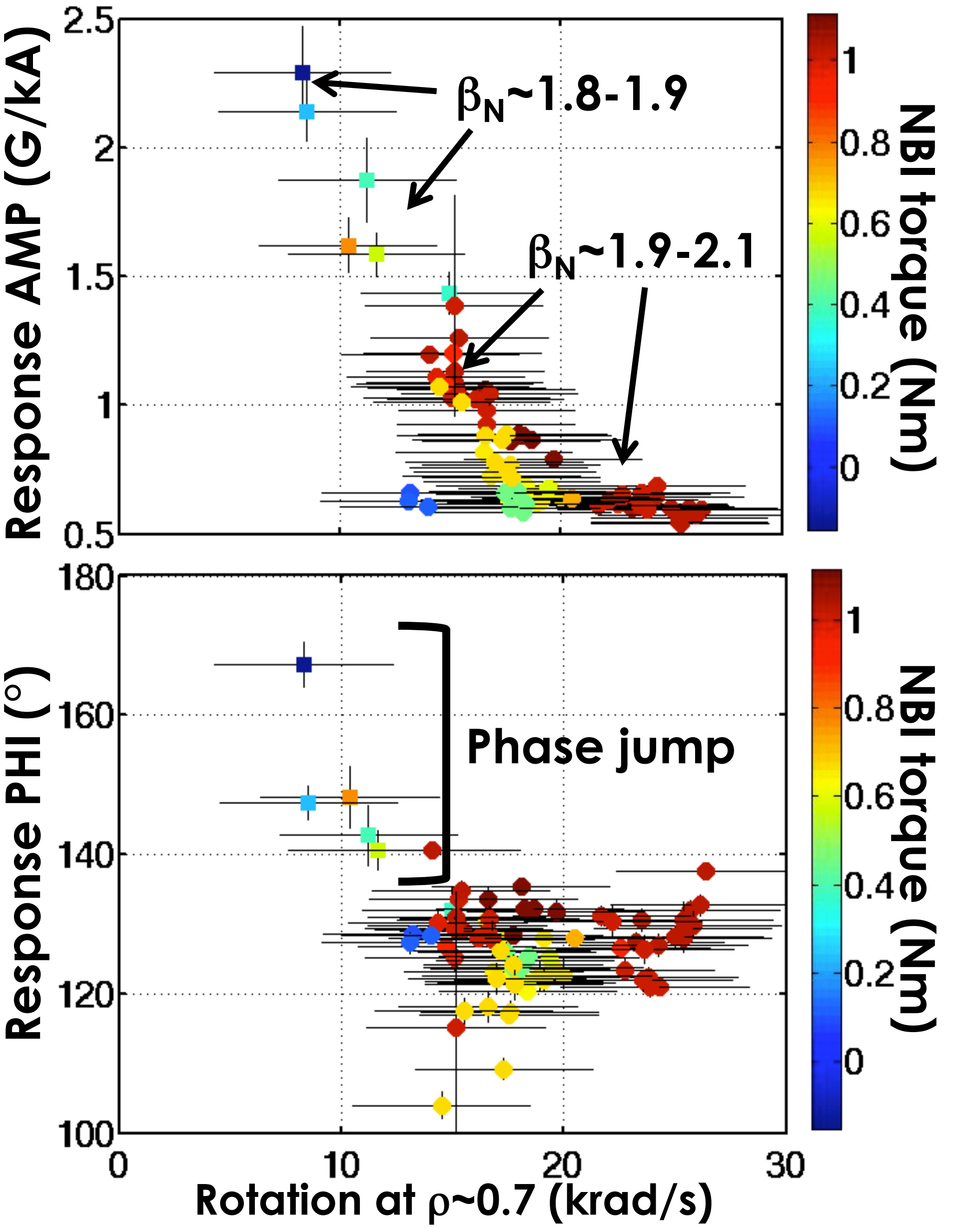
EXP

Response amplitude increase

Non-ideal effects ←→ Lower limits

Phase jump at ~12-15 krad/s

→ Typical of no-wall limit crossing

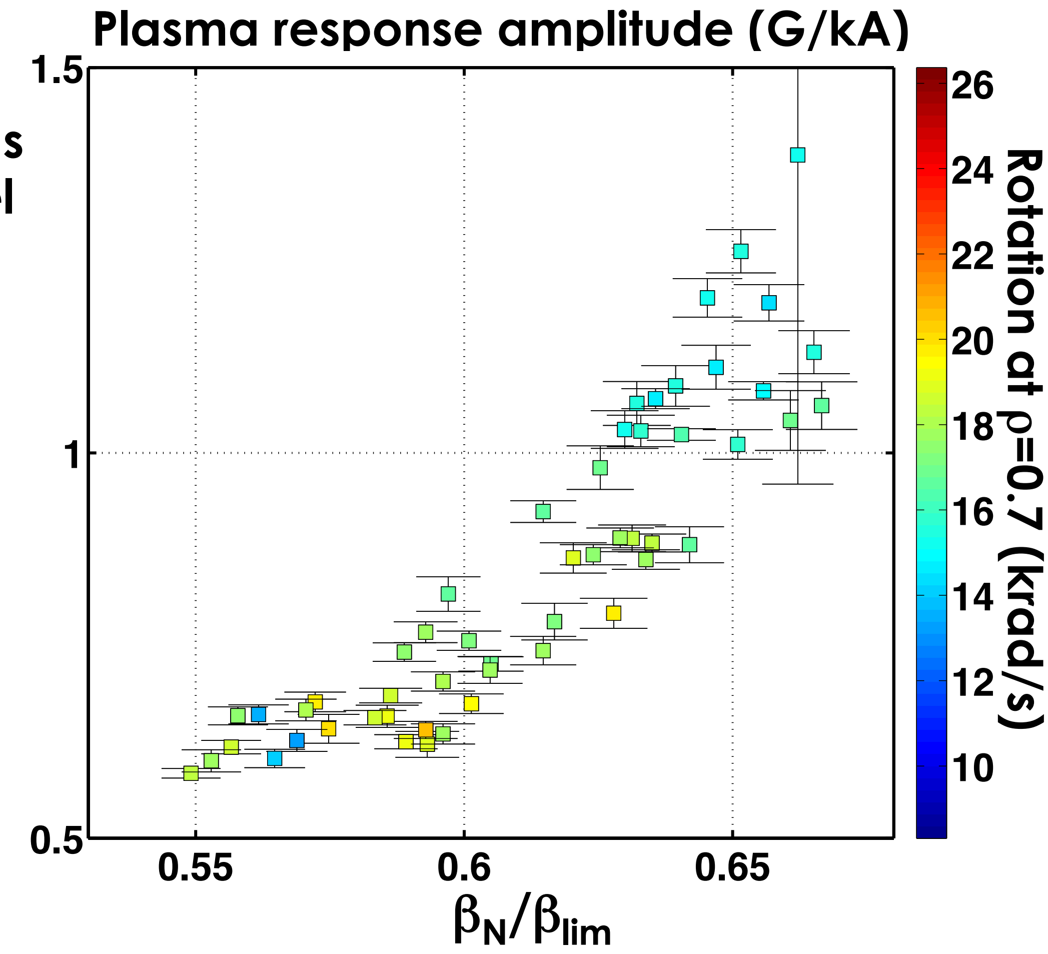


DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

MHD Spectroscopy Can Measure the Proximity to A Stability Limit

EXP

- At "moderate" rotation, the trends are consistent with the ideal model



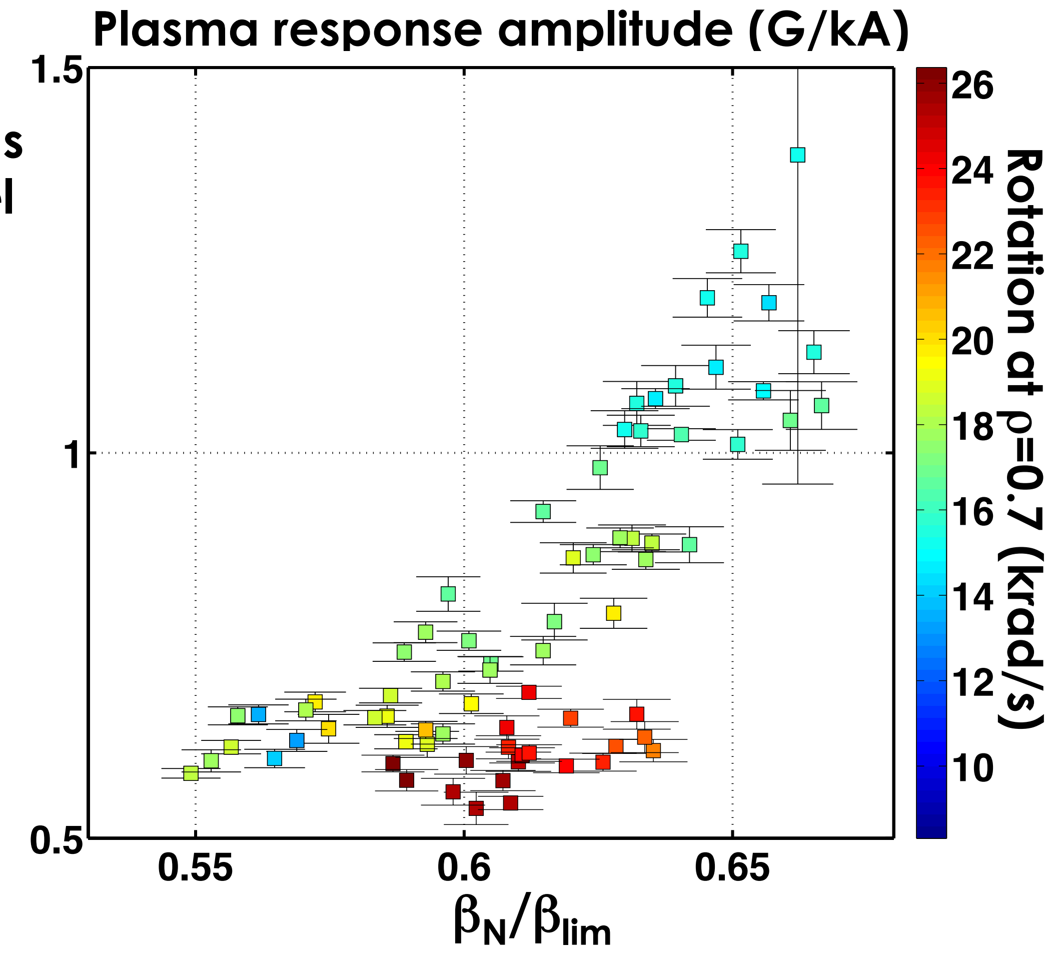
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MHD Spectroscopy Can Measure the Proximity to A Stability Limit

EXP

- At “moderate” rotation, the trends are consistent with the ideal model

- At higher rotation the response is off trend → kinetic damping?



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MHD Spectroscopy Can Measure the Proximity to A Stability Limit

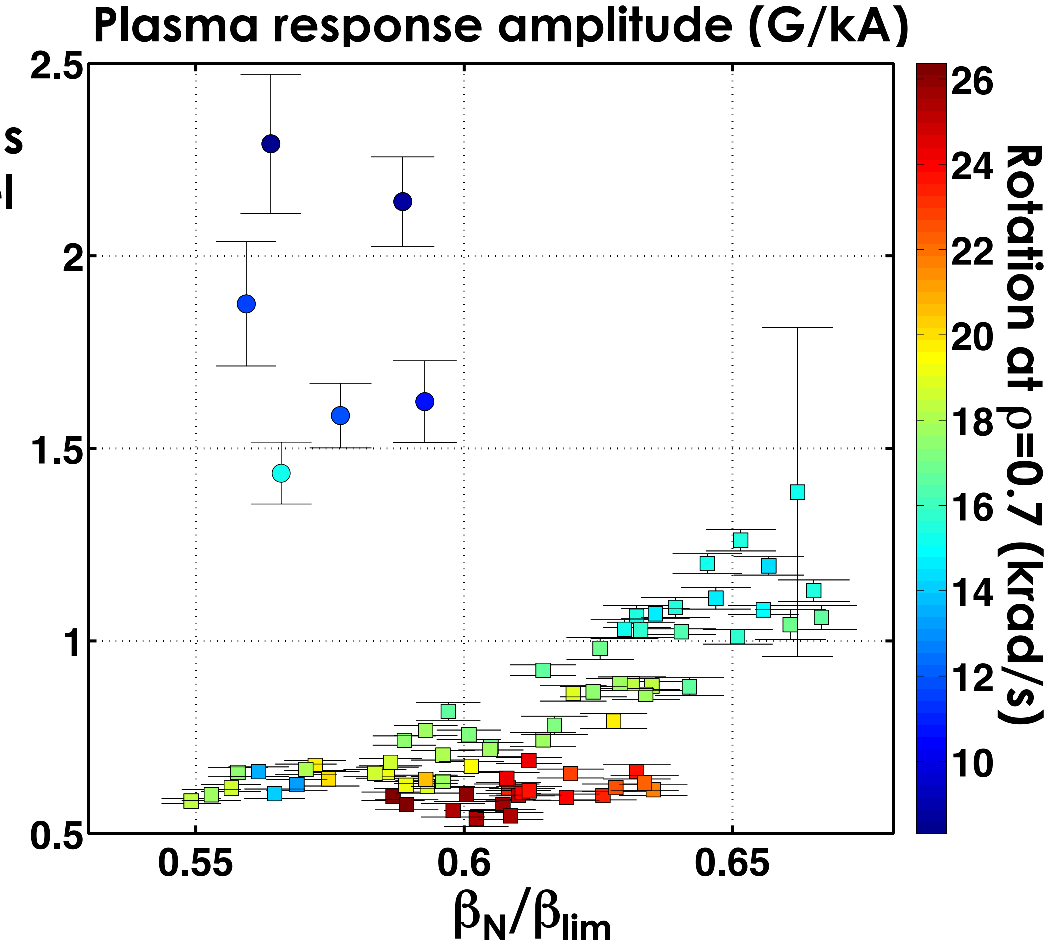
EXP

- At "moderate" rotation, the trends are consistent with the ideal model

- At higher rotation the response is off trend → kinetic damping?

- At very low rotation, with ECH, higher response → collisionality effect?

Ideal MHD likely not sufficient to explain the trends



Modeling of rotation and kinetic damping effects → **Understand instability at low torque**

The Path to High β_n is A Good Platform to Validate Models

ITER	**ITER Baseline Scenario (IBS)** Q=10, 15 MA (q_{95}~3), q_0<1, P_{fus}=500 MW, LSN shape
	Steady-State Q=5, 9 MA (q_{95}~5), LSN shape, f_{NI}=1
FNSF*	**Steady-state** Q < 5, 6.7 MA, q_{min}>1, high neutron fluence

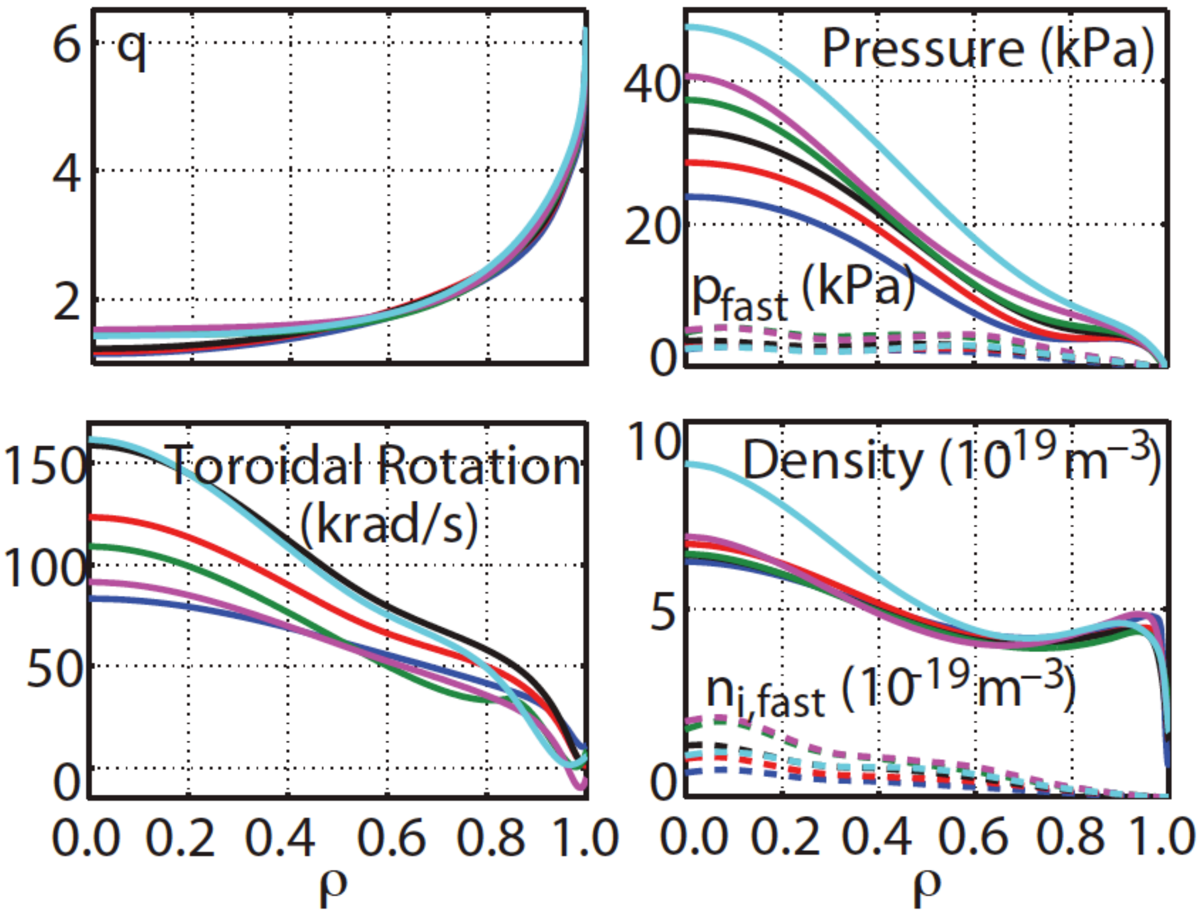
Higher β_N
Higher q_{95}
RWM plasma

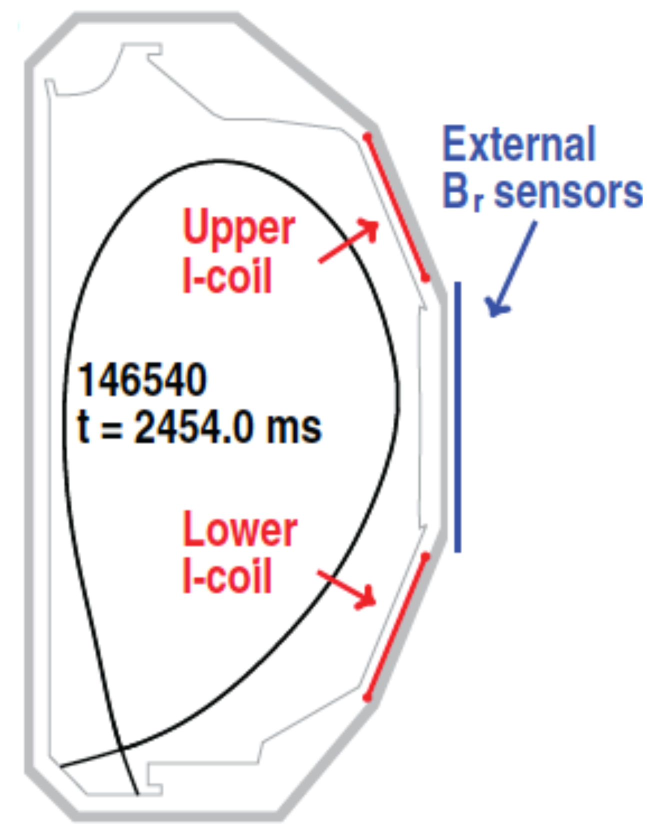
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Experiments: Pressure (β_n) Scan to Cross the No-wall β_n Limit

EXP

Increase the pressure with NBI power → Measure the plasma response





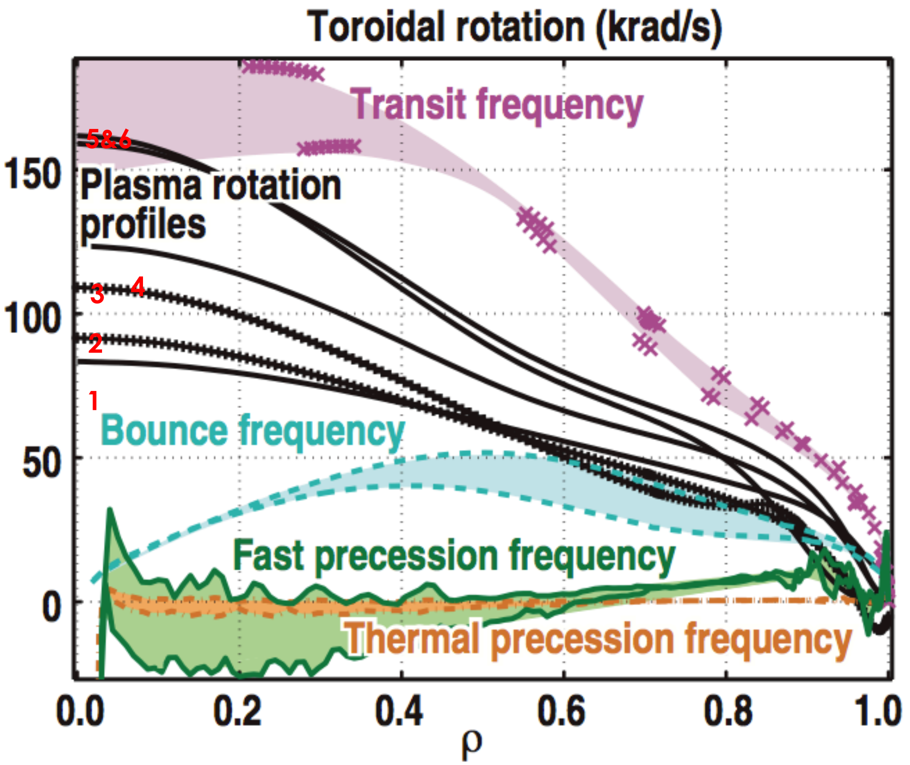
ELMing H-modes, moderate β_N, LSN shape, q_{95}~4-5, q_{min}>1

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

β_n Scan: It's Crucial to Assess the Validity of the Modeling Results

MOD

- Rotation has an impact on the response amplitude
- The rotation is not constant across the β_N values



→ Some of the variations may be due to the rotation!

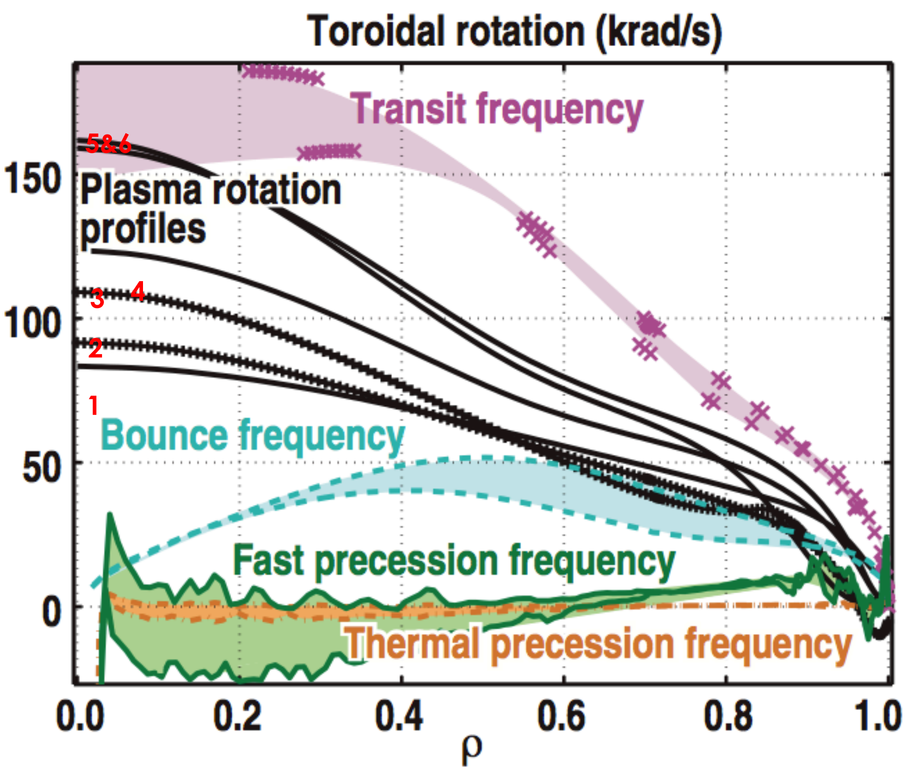
→ Understand the validity of the results (sensitivity to other variables)

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

β_n Scan: It's Crucial to Assess the Validity of the Modeling Results

MOD

- Rotation has an impact on the response amplitude
- The rotation is not constant across the β_N values



- Need to isolate the effect of β_N → keep rotation fixed
- ...for each β_N case:

Sensitivity study:

Ω→ β_N↓	1	2	3	4	5	6
1.18						
1.43						
1.67						
1.8						
2.05						
2.5						

fixed β_N

fixed Ω

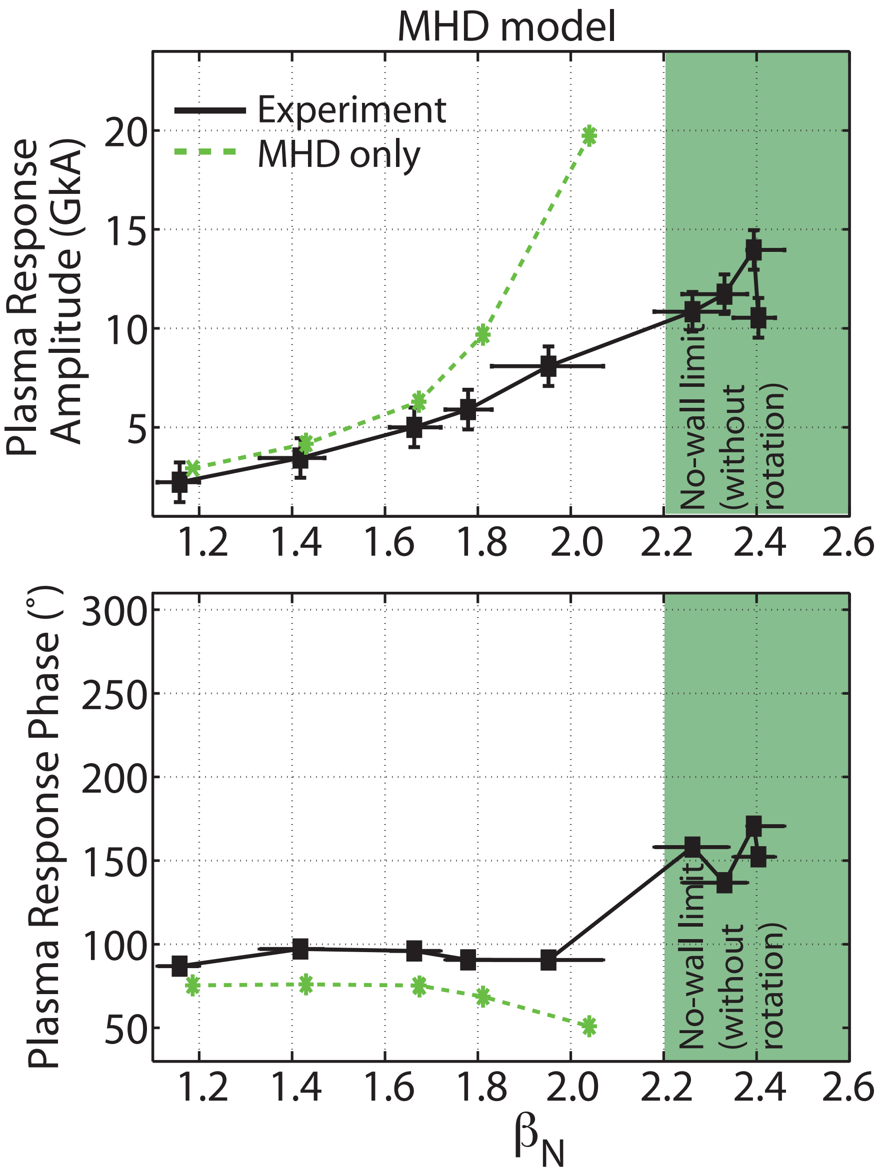
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Evaluated 36 cases: 6 rotation profiles for each of the 6 β_N points

β_n Scan: MHD-only Model Does Not Reproduce Approach to the No-wall β_n Limit

MOD

- **Previous modelling* showed the MHD model without rotation has a pole at the no-wall limit**



*Lanctot, PoP2010

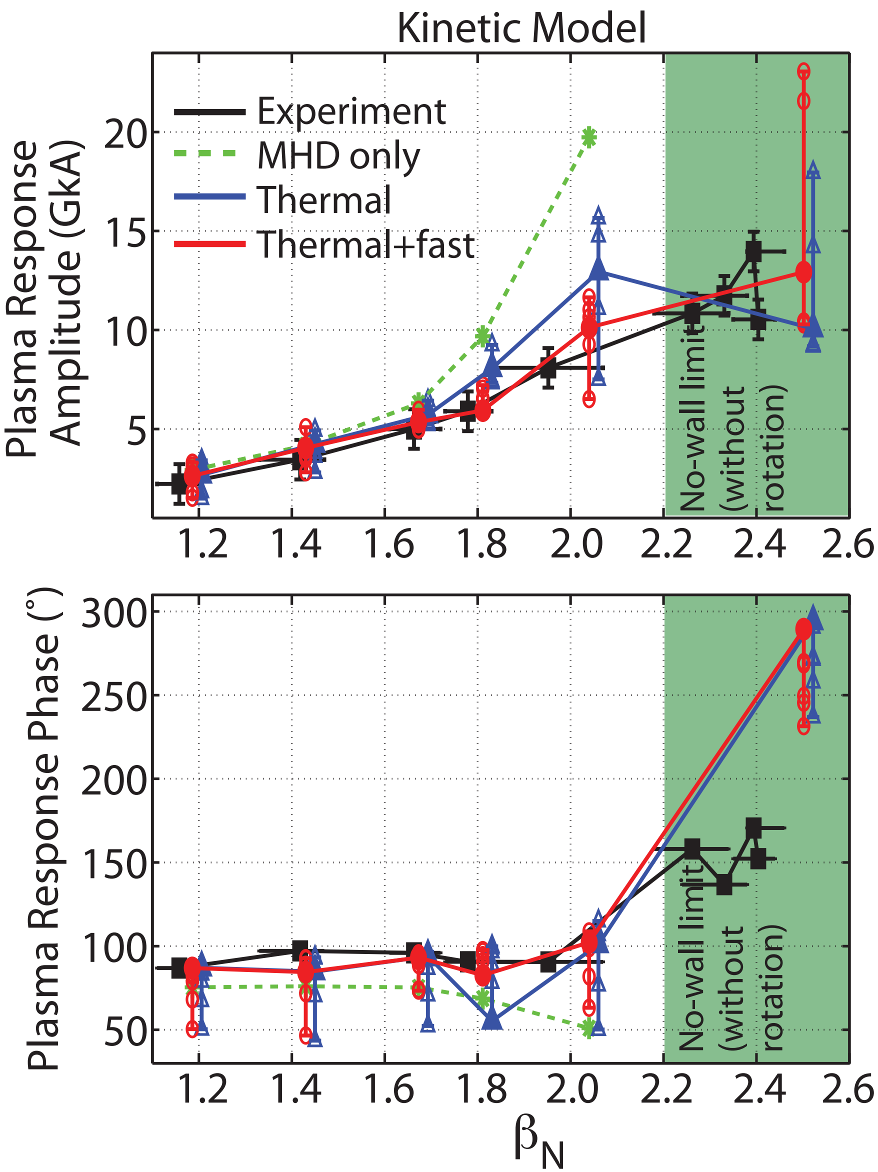
β_n Scan: Drift Kinetic Model Reproduces Approach to the No-wall β_n Limit Correctly

MOD

- **Previous modelling* showed the MHD model without rotation has a pole at the no-wall limit**
- **The pole is eliminated with the full kinetic model (thermal + fast ions)**
- **Without fast-ion damping the pole reappears → 45% higher than expt**
- **The phase shift is still overestimated above the no-wall limit**

The sensitivity study

- Shows how much of the trend is *not* due to the β_N
- Provides confidence in the results



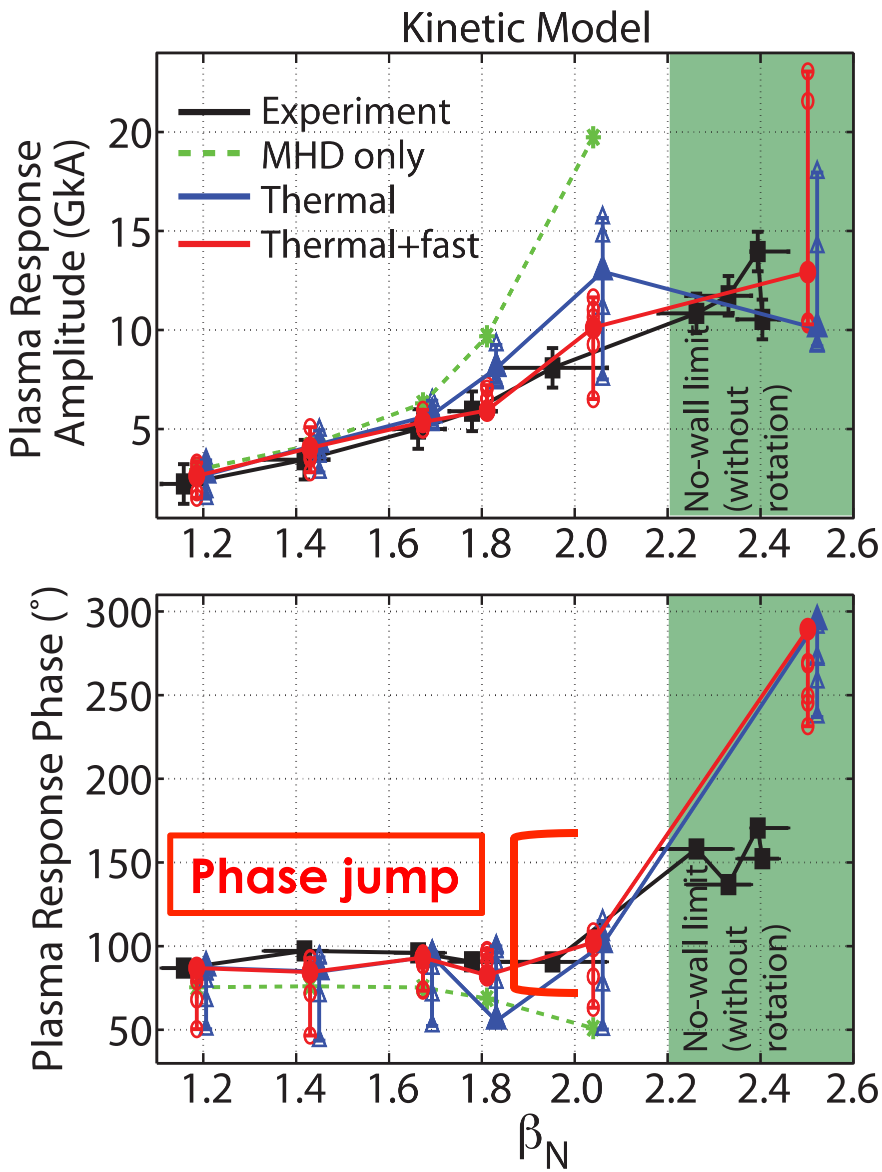
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

*Lanctot, PoP2010

β_n Scan: Drift Kinetic Model Reproduces Approach to the No-wall β_n Limit Correctly

MOD

- Previous modelling* showed the MHD model without rotation has a pole at the no-wall limit
- The pole is eliminated with the full kinetic model (thermal + fast ions)
- Without fast-ion damping the pole reappears → 45% higher than expt
- The phase shift is still overestimated above the no-wall limit



ITER: very small fast-ion β from NBI
→ will the plasmas be (45%) more unstable?
→ Will the fast α-particles be enough to stabilize them?

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

*Lanctot, PoP2010

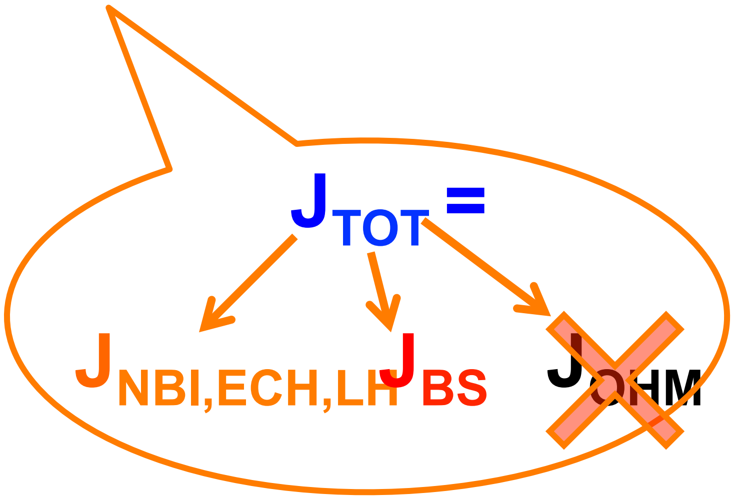
ITER	**ITER Baseline Scenario (IBS)** Q=10, 15 MA (q_{95}~3), q_0<1, P_{fus}=500 MW, LSN shape
	Steady-State Q=5, 9 MA (q_{95}~5), LSN shape, f_{NI}=1
FNSF	**Steady-state** Q < 5, 6.7 MA, q_{min}>1, high neutron fluence

β_N~3-4

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Steady-state: Fully Non-inductive Current Drive, Where the Plasma Current and Pressure Have Stopped Evolving (Reached A Stable State)

- Current must be composed of bootstrap and externally driven NBI, ECH...
- Large J_{boot} is associated to high β_N



- MHD stability can be an issue even at high torque

- Standard high-β_N, steady-state scenario → high q_{min}~1.5-2.5, zero/reversed shear, broad profiles with off-axis CD

...or not!

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Alternative Approach: the Hybrid Scenario

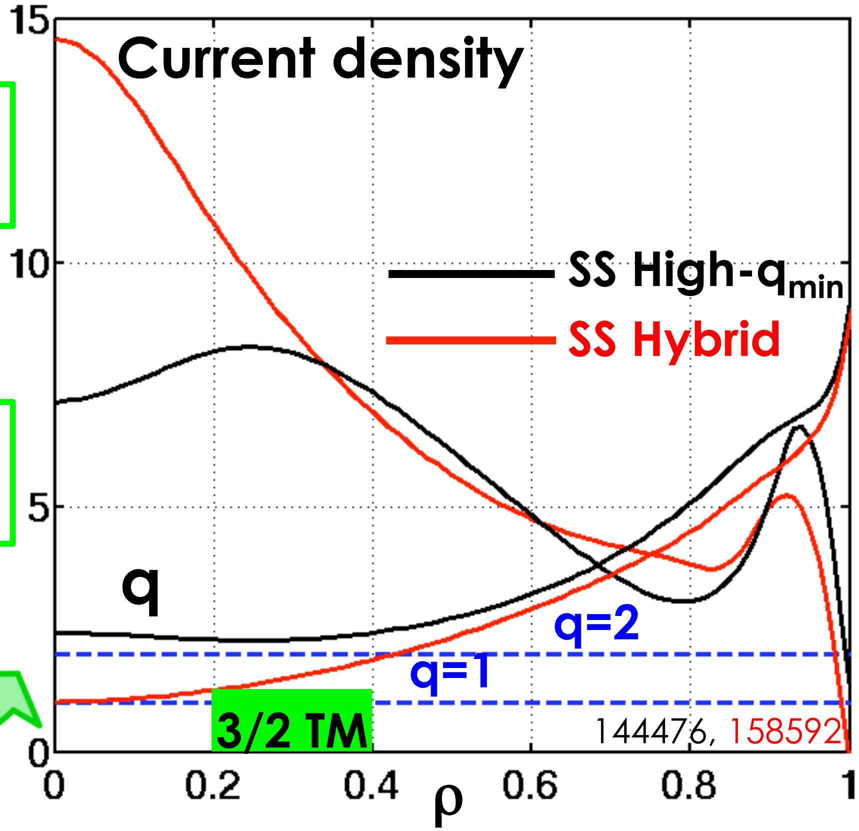
What is a hybrid? → **Long duration, high confinement H-mode**

→ **More stable to 2/1 tearing modes**

Final J independent from sources

↓

q relaxes to "hybrid" state – $q_{min} \geq 1$



Alternative Approach: the Hybrid Scenario

What is a hybrid? → Long duration, high confinement H-mode

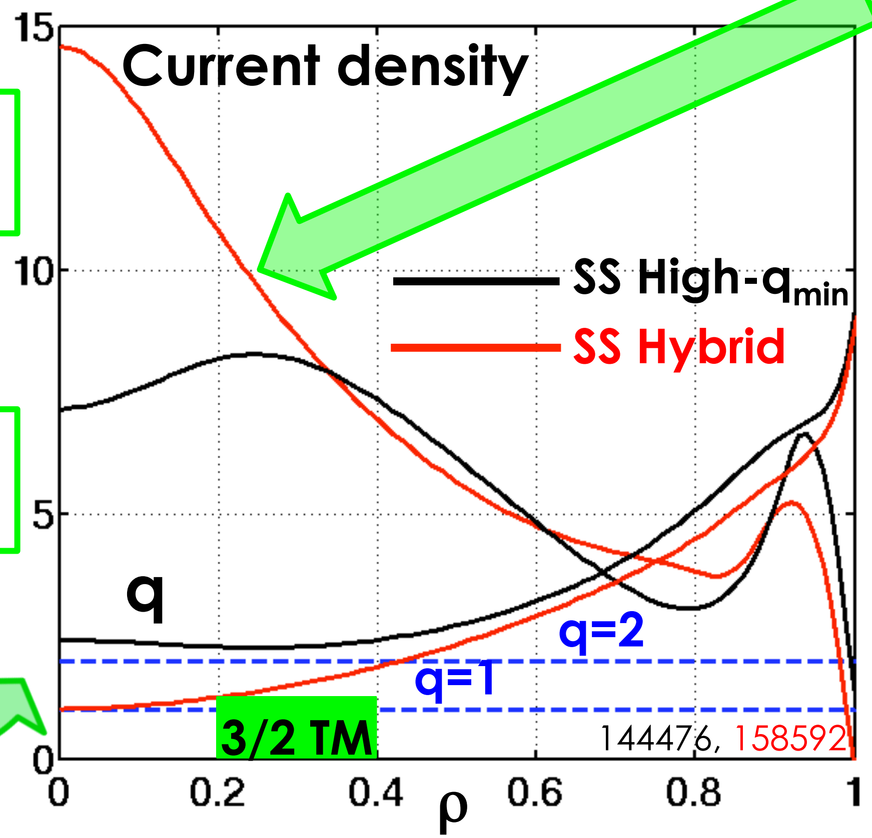
→ More stable to 2/1 tearing modes

All external current driven in the plasma centre

No alignment issues
Most efficient CD

Final J independent from sources

q relaxes to "hybrid" state – q_{min}≥1



- Benign m=3/n=2 or m=4/n=3 mode causes "flux pumping" out of ρ~0.35
- q naturally stays above 1 → no sawteeth

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Alternative Approach: the Hybrid Scenario

What is a hybrid? → **Long duration, high confinement H-mode**

→ **More stable to 2/1 tearing modes**

All external current driven in the plasma centre

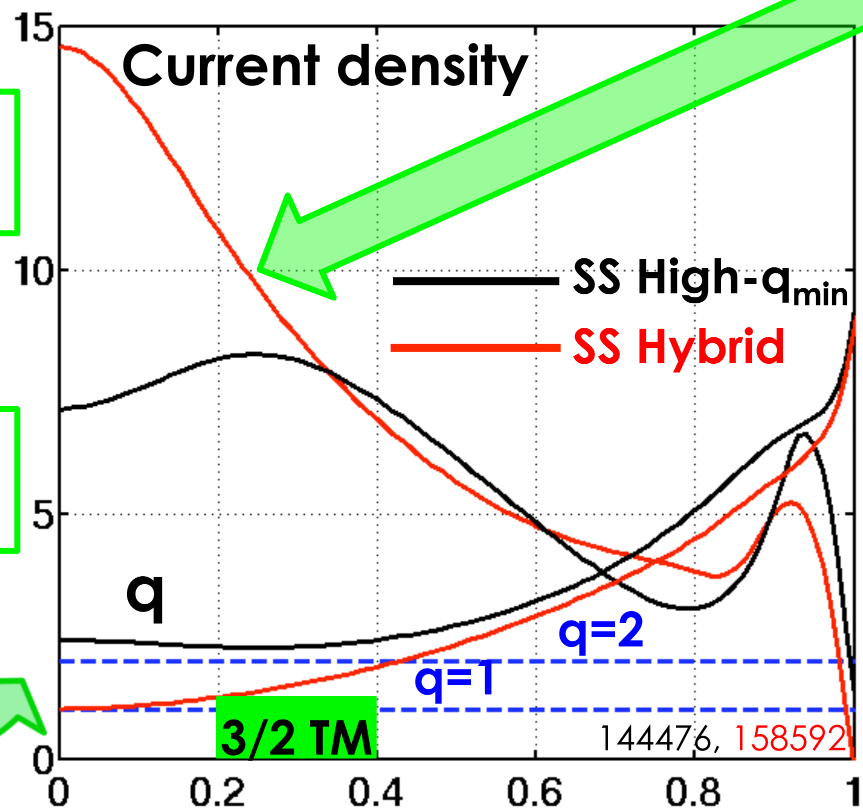
↓

No alignment issues
Most efficient CD

Final J independent from sources

↓

q relaxes to "hybrid" state – $q_{min} \geq 1$



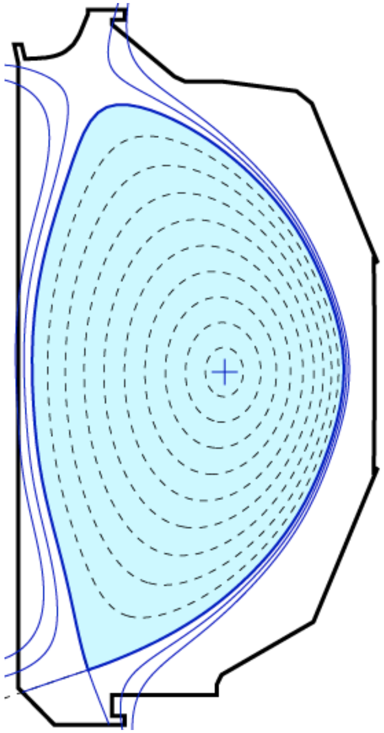
Ideal MHD with-wall limits are $\beta_{limit} \geq 4.5$

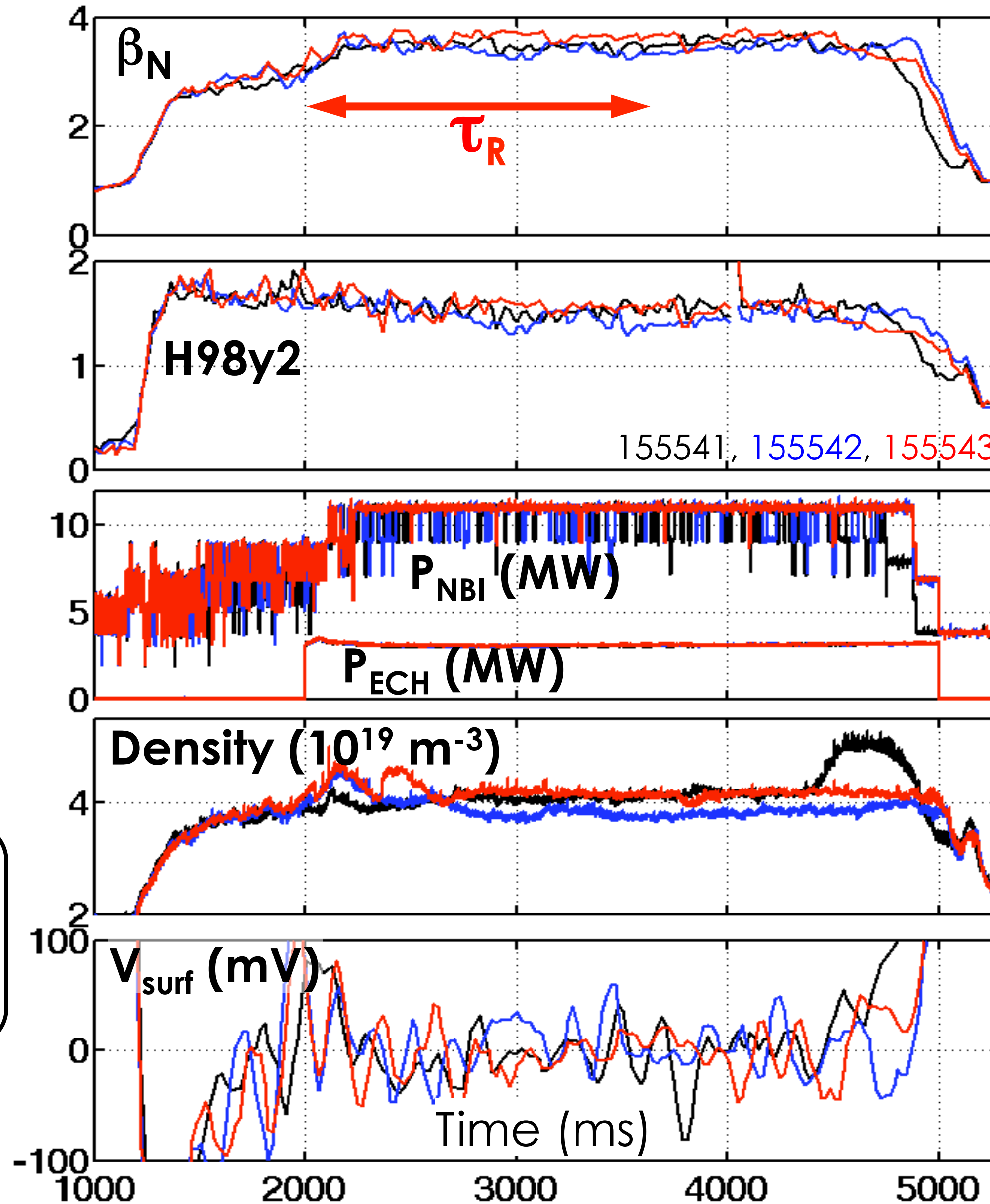
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Hybrid Plasmas Reach Fully NI Conditions and β_n=3.6 for ~2 τ_r

EXP

Double null plasma shape





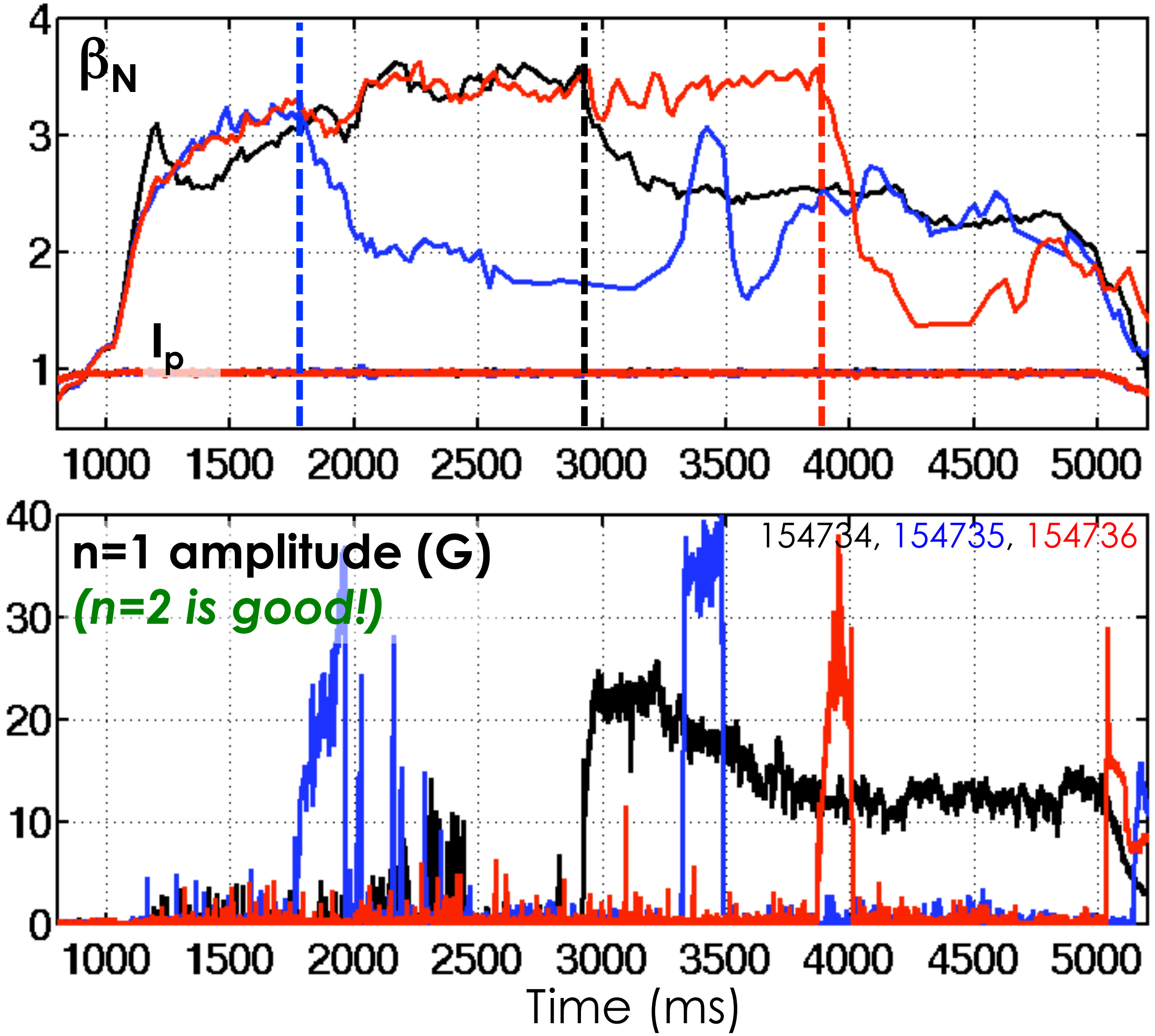
- Stable to the 2/1 TM at β_N~3.6
- Loop voltage ~ 0 for ~2 τ_R
- Limited by NBI pulse duration

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MHD Stability is the Main Challenge for High-β_n Hybrids

EXP

- 2/1 tearing modes arise on β_N>3.5 flattop
- They degrade the confinement significantly → loss of 20-50% β_N



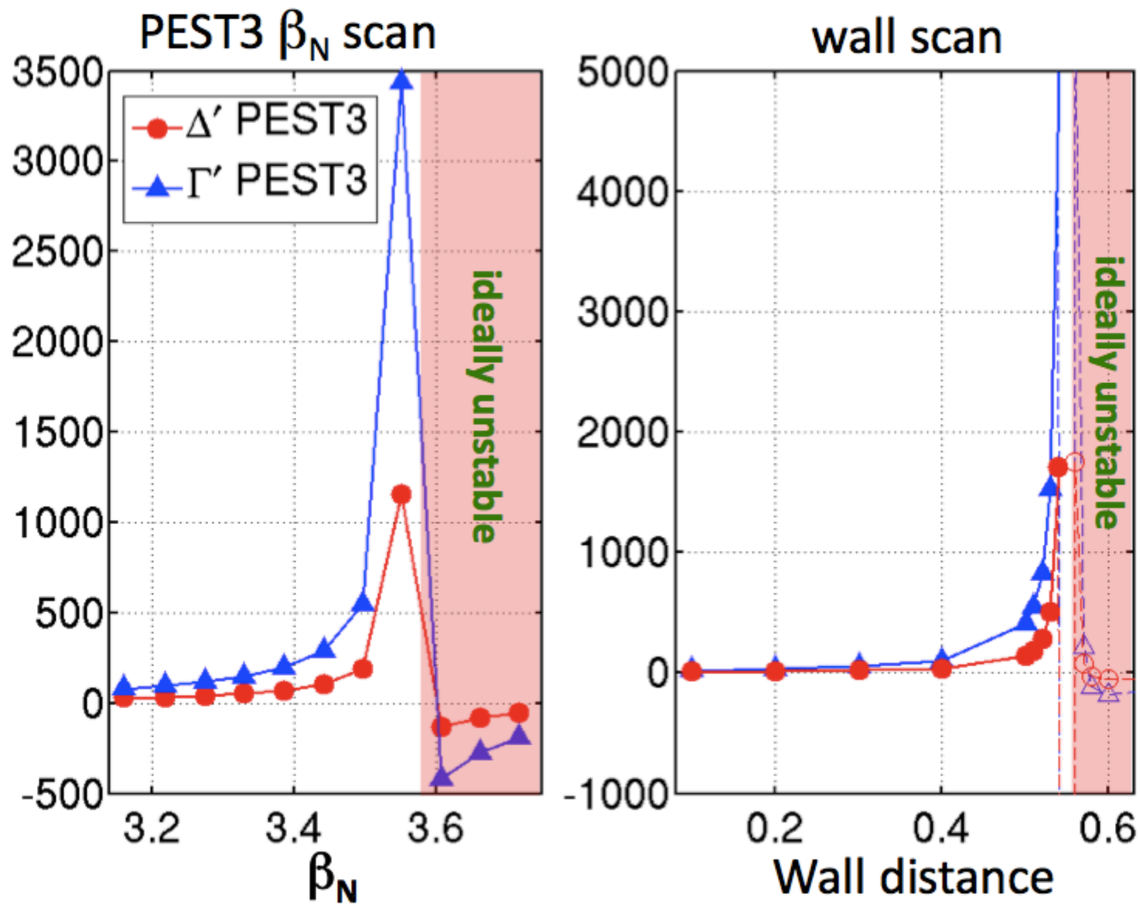
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Tearing Limits Are Strongly Correlated With the Ideal With-wall Limit

MOD

- **The tearing index Δ' increases sharply at the ideal wall limit**

Modelling of the approach to the ideal limit:



DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

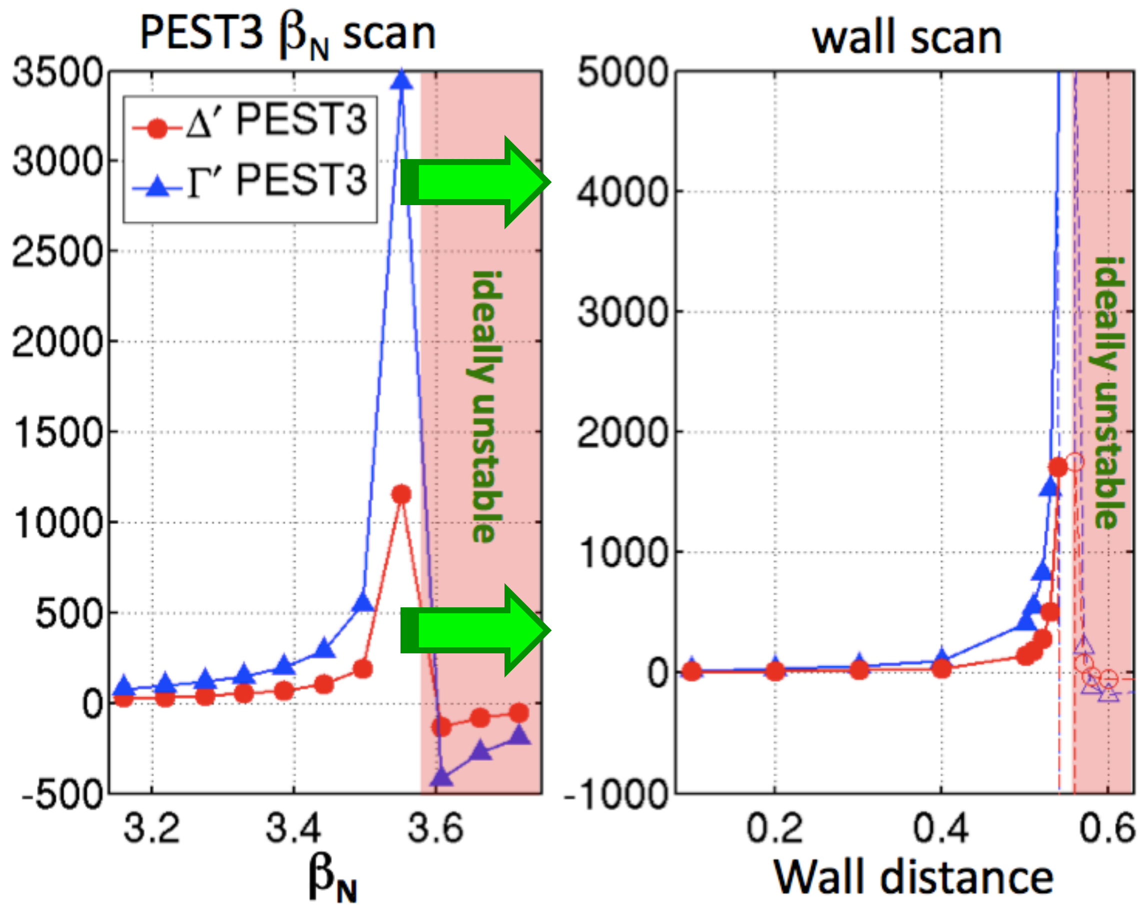
Tearing Limits Are Strongly Correlated With the Ideal With-wall Limit

MOD

- **The tearing index Δ' increases sharply at the ideal wall limit**
- **High β_N operation ⟺ Operate with very large, very sensitive Δ'?**

Modelling of the approach to the ideal limit:

One solution is to increase the ideal limit:
- **broaden J and p**
- **change the plasma shape**

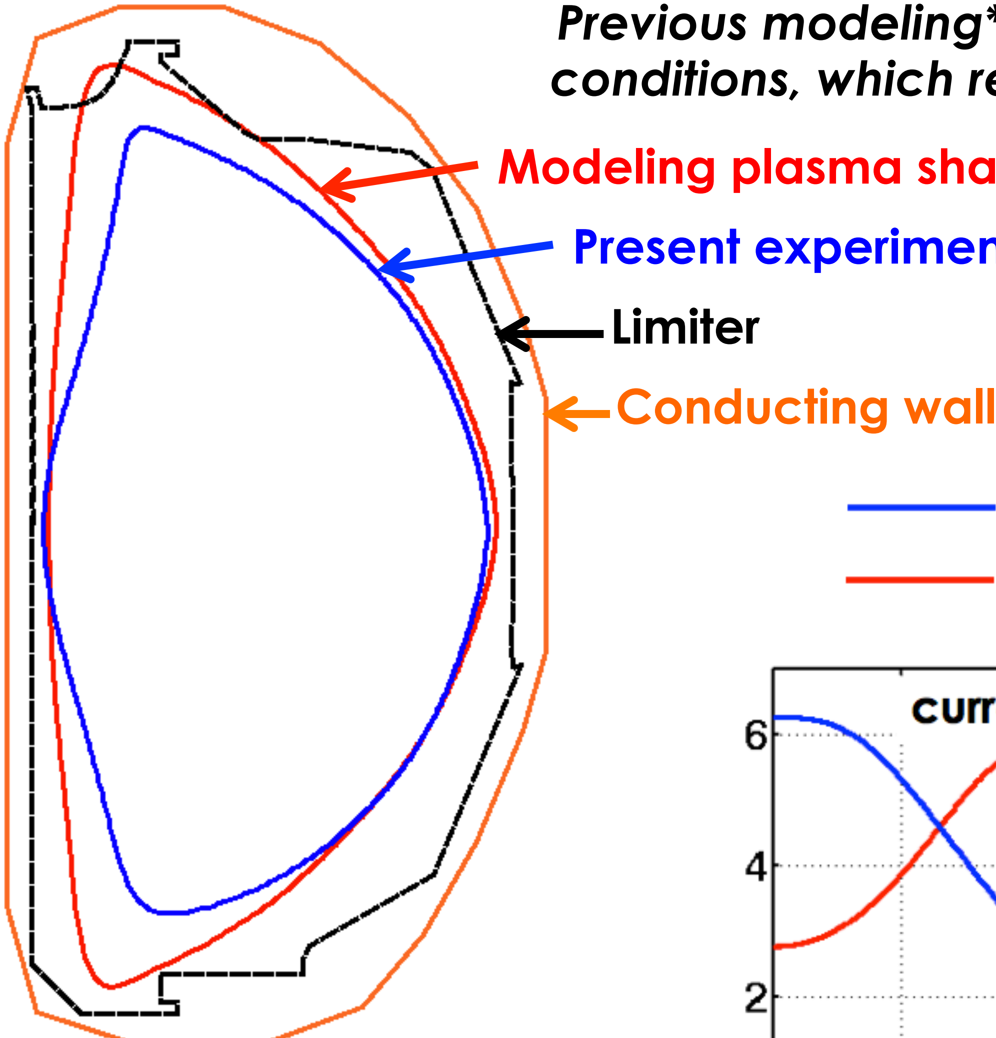


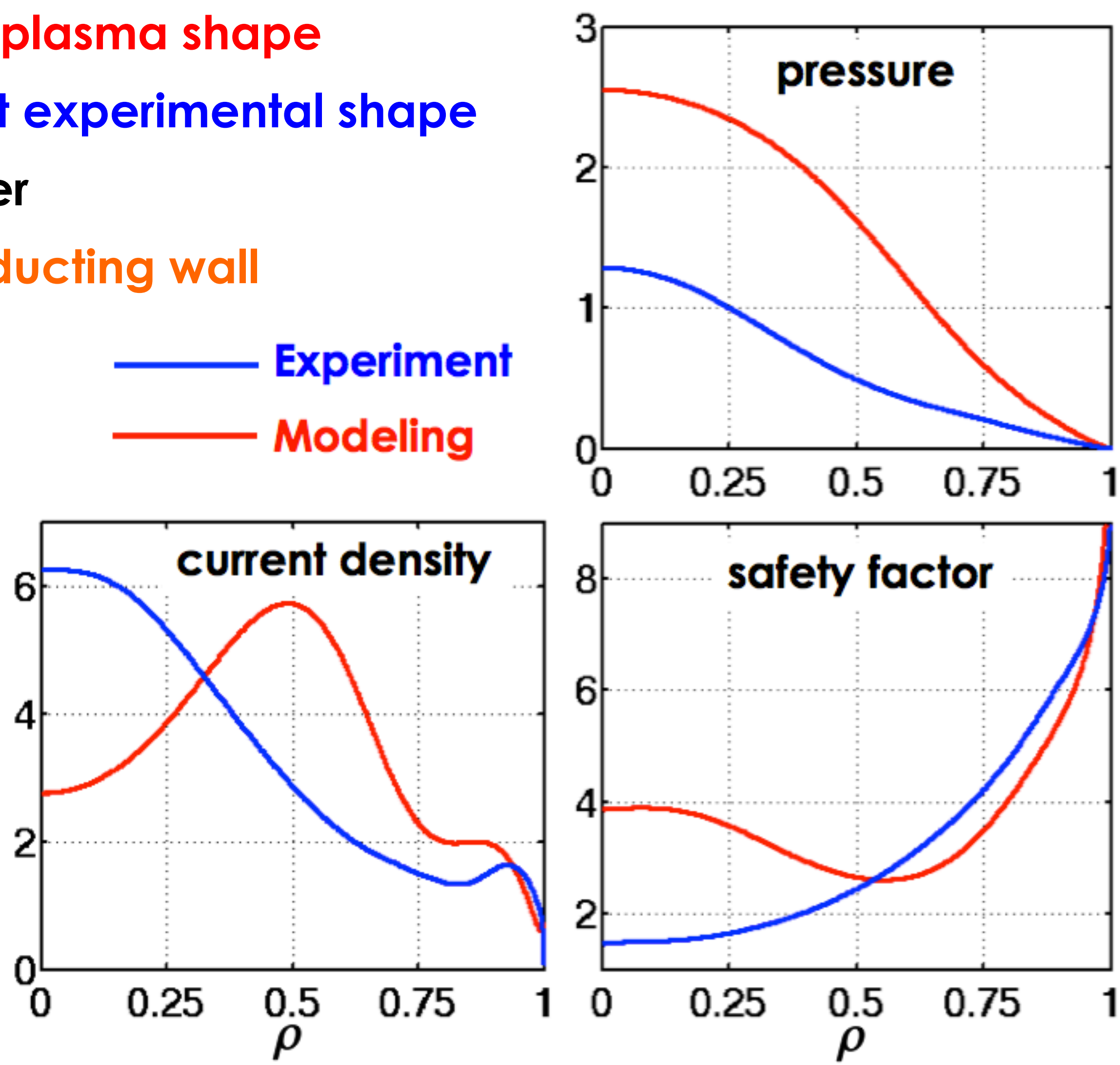
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Push the Ideal Limit Up to Improve Tearing Stability Conditions

MOD

Previous modeling* provides an example of extreme conditions, which realize very high ideal stability limits





DIII-D NATIONAL FUSION FACILITY SAN DIEGO

*Turnbull PRL 1995

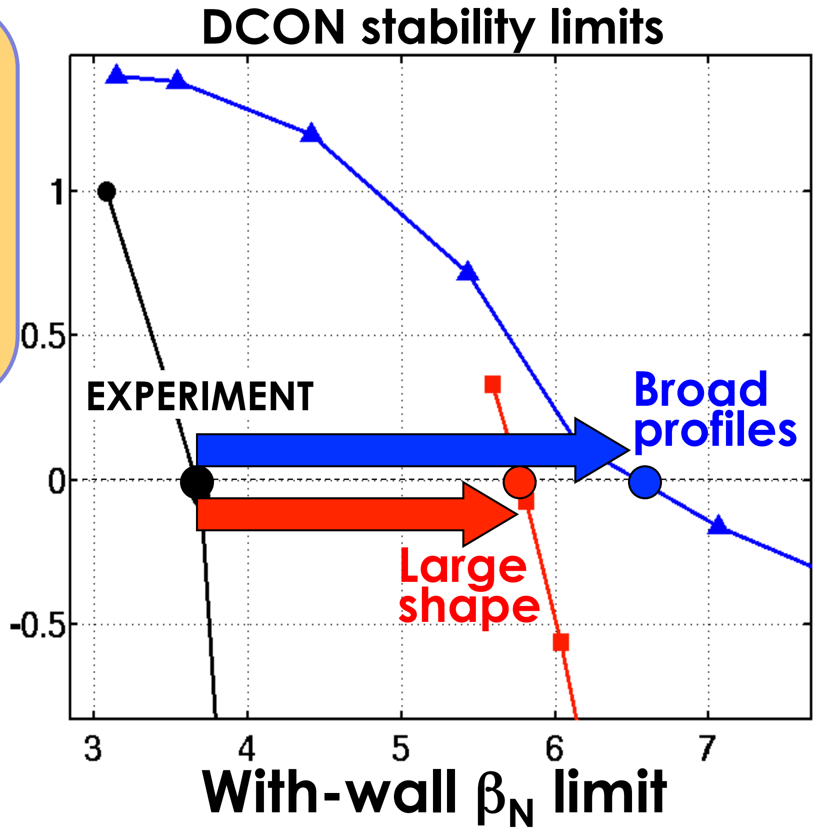
How Much of the Increase is Due to the J and p Profiles?

MOD

New modelling to decouple the effects:

- Experimental profiles + larger shape
- Experimental shape + broad profiles

Each makes β_{lim} ↗ +60%



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

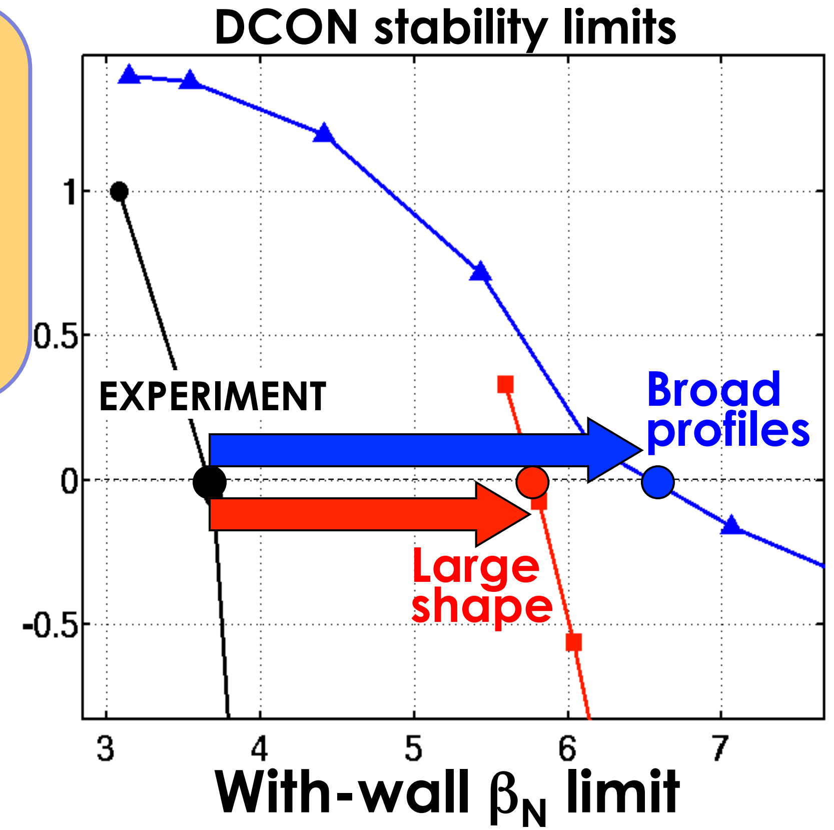
How Much of the Increase is Due to the J and p Profiles?

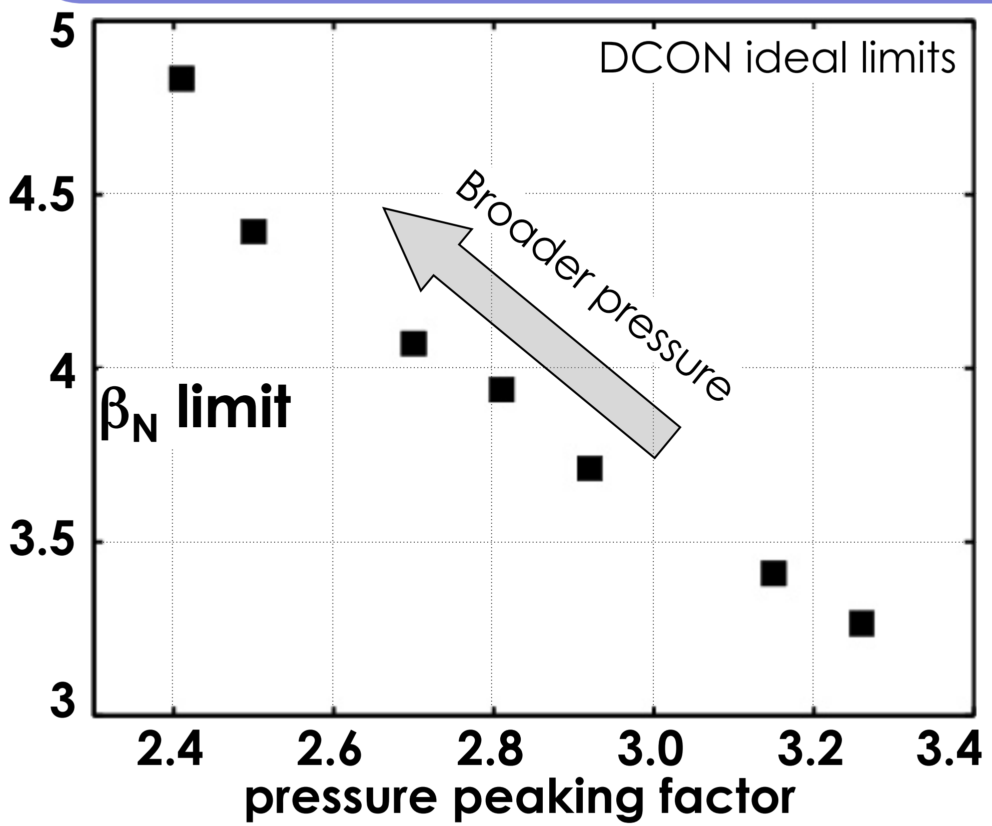
MOD

New modelling to decouple the effects:

- Experimental profiles + larger shape
- Experimental shape + broad profiles

Each makes β_{lim} ↗ +60%





Pressure peaking factor alone:

- Ideal β_{lim} ↗ +45%

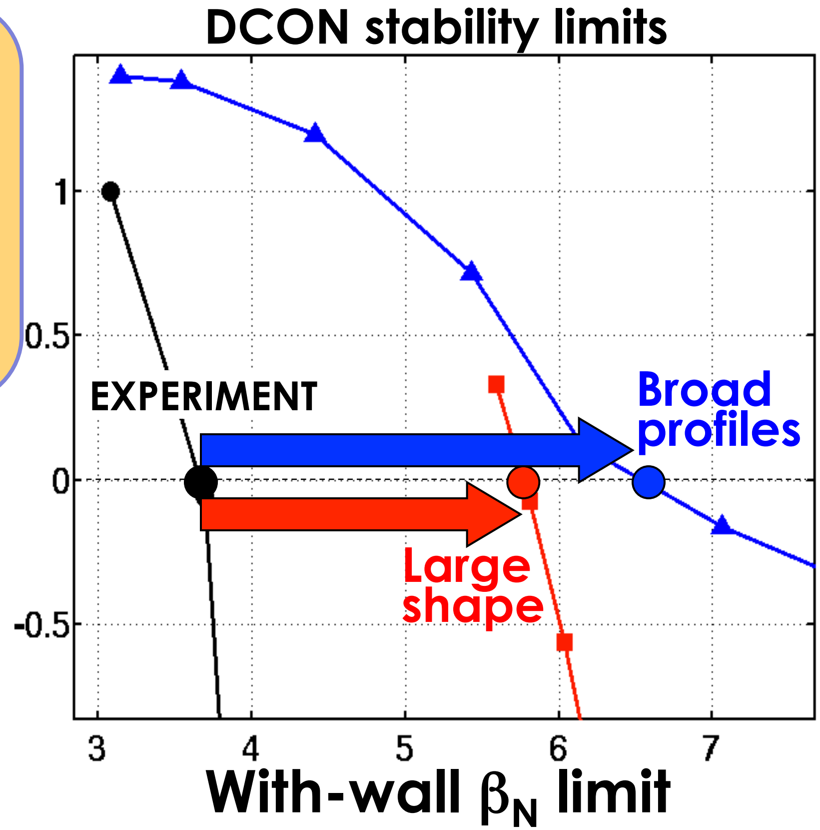
How Much of the Increase is Due to the J and p Profiles?

MOD

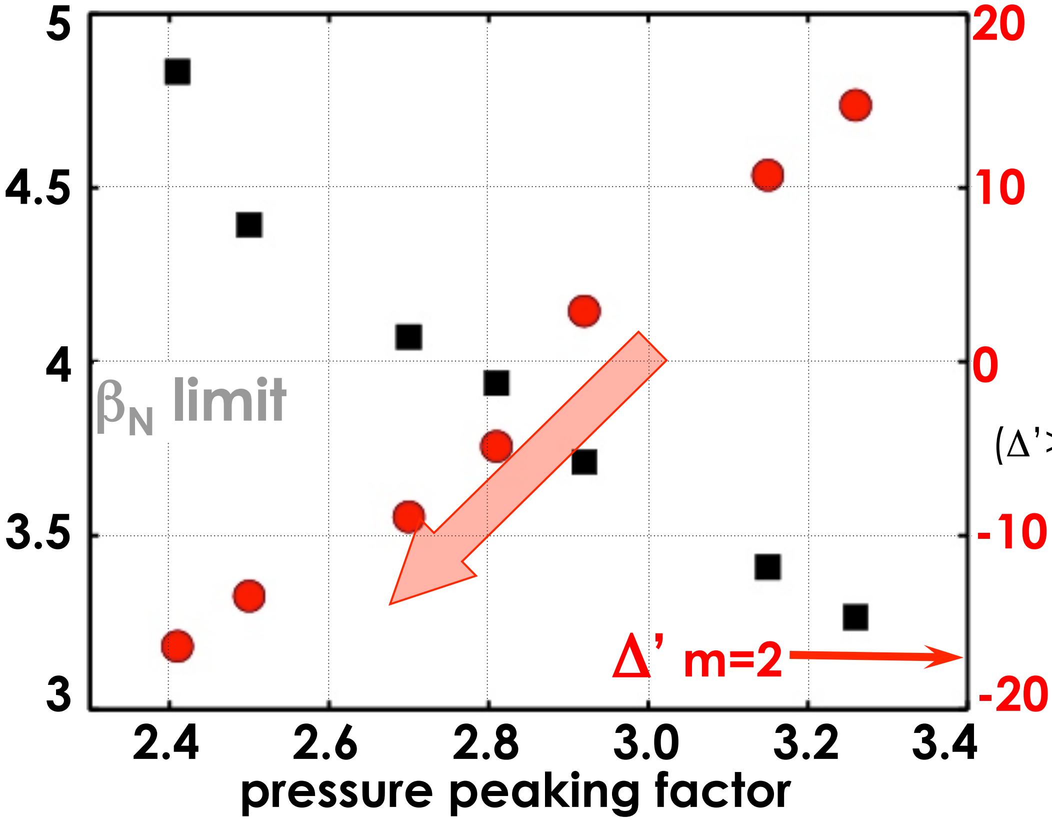
New modelling to decouple the effects:

- Experimental profiles + larger shape
- Experimental shape + broad profiles

Each makes β_{lim} ↗ +60%



(Δ'>0 necessary but not sufficient for instability)



Pressure peaking factor alone:

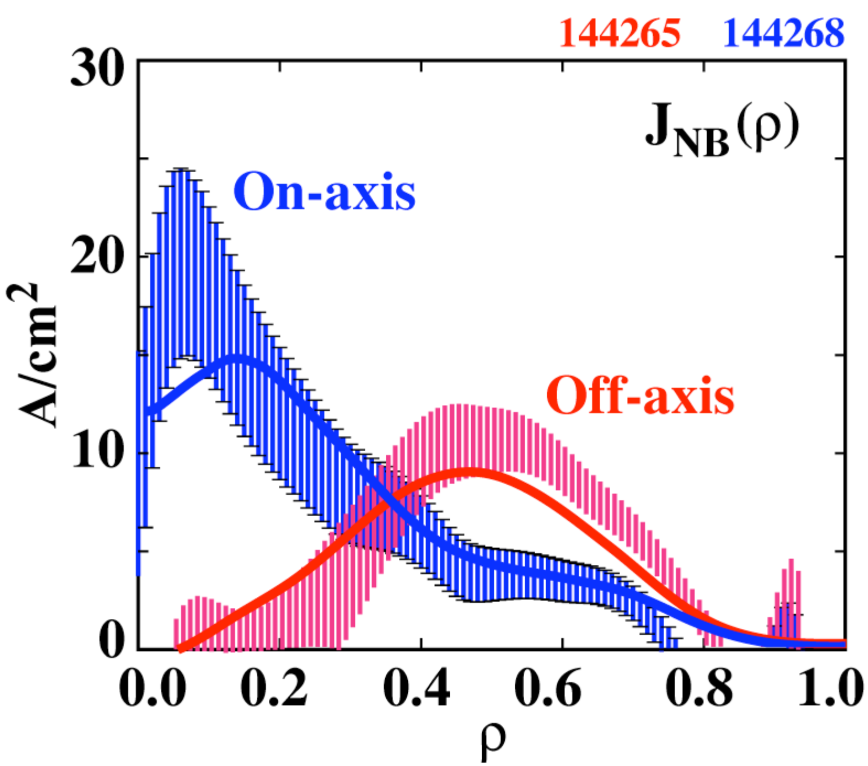
- Ideal β_{lim} ↗ +45%
- Tearing stability increases m=2

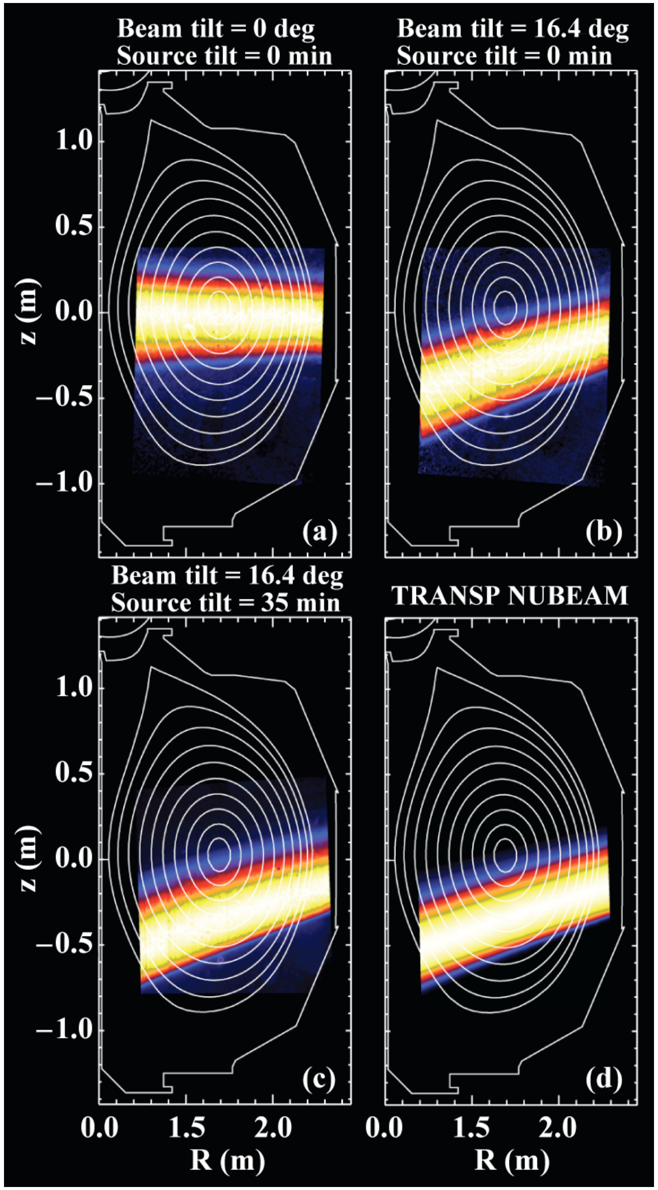
Use the Modelling Results to Design More Stable Plasmas

EXP

OFF-axis NBI to broaden the hybrid current and pressure profiles

(1 neutral beam line is tilted → ~4 MW off-axis power)



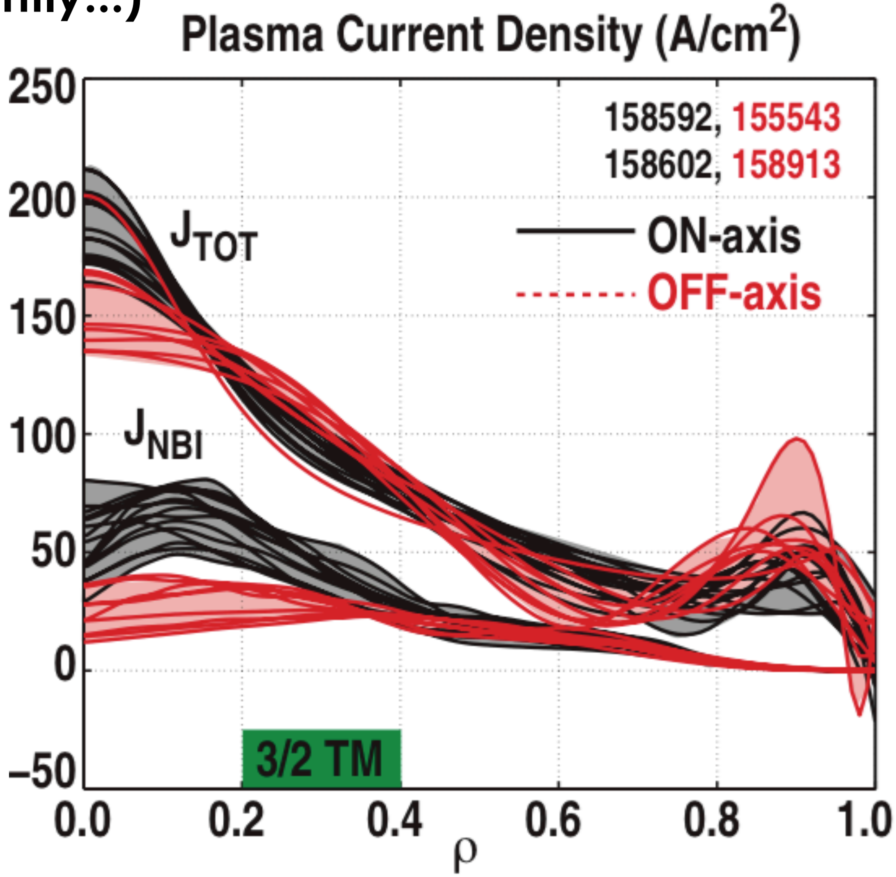


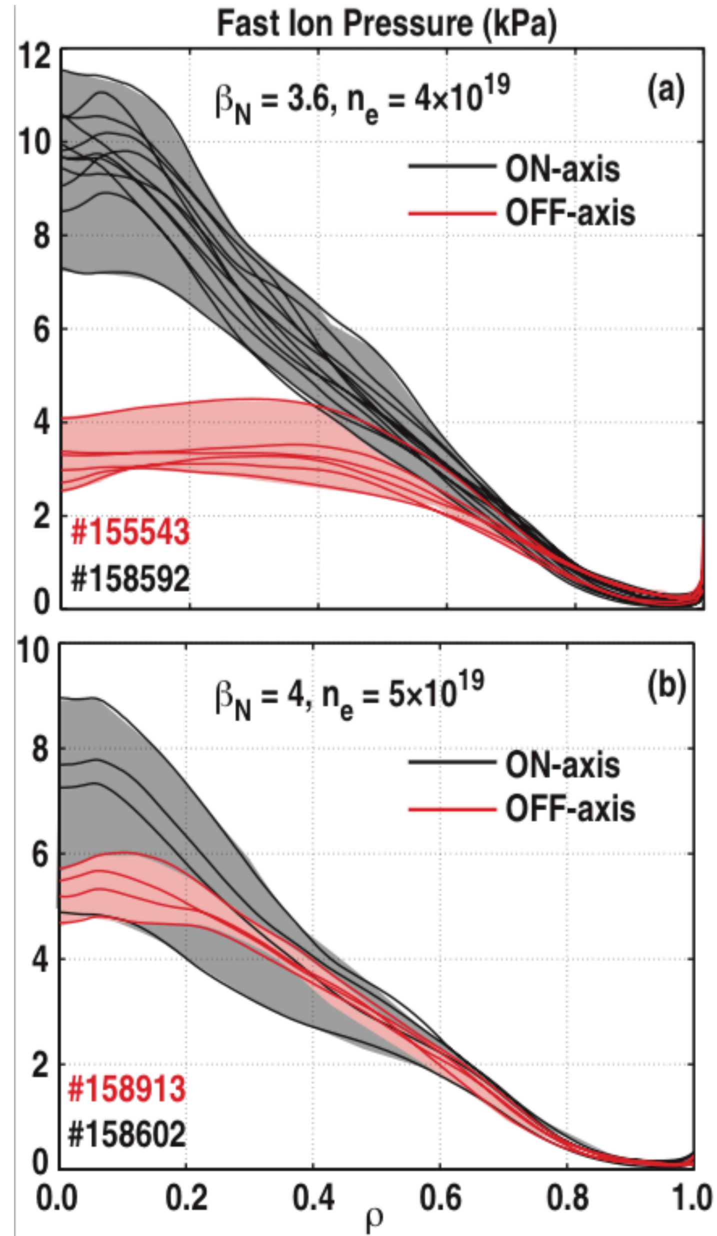
Courtesy of JM Park (IAEA 2013)

Apply this Concept to the q_{min}~1 Hybrid Plasmas

EXP

Despite the anomalous current diffusion in hybrids, 4 MM of off-axis NBI broaden J and p (slightly…)



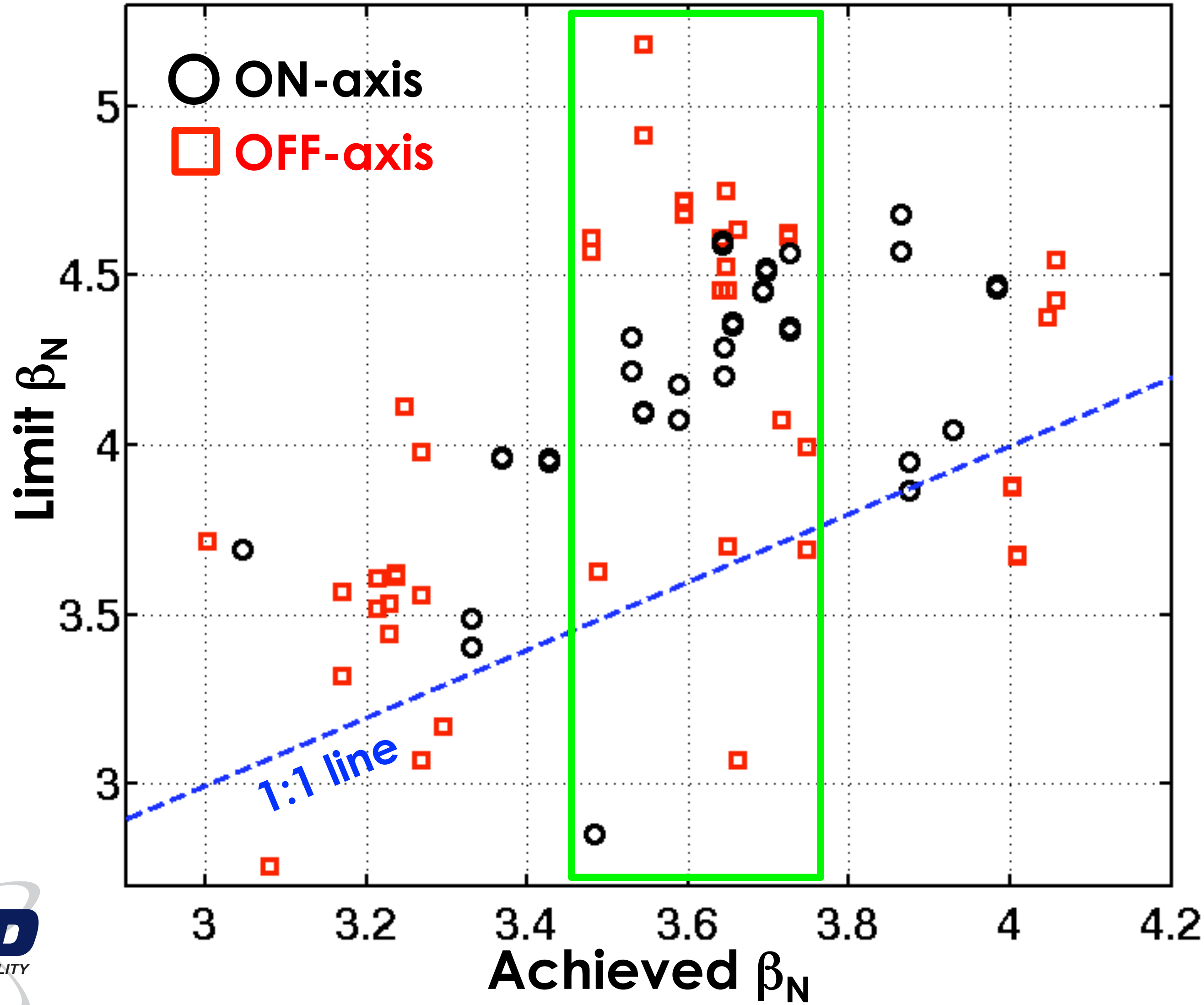


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Plasmas with Off-axis NBI Have Similar Ideal Limits as the On-axis Cases

EXP

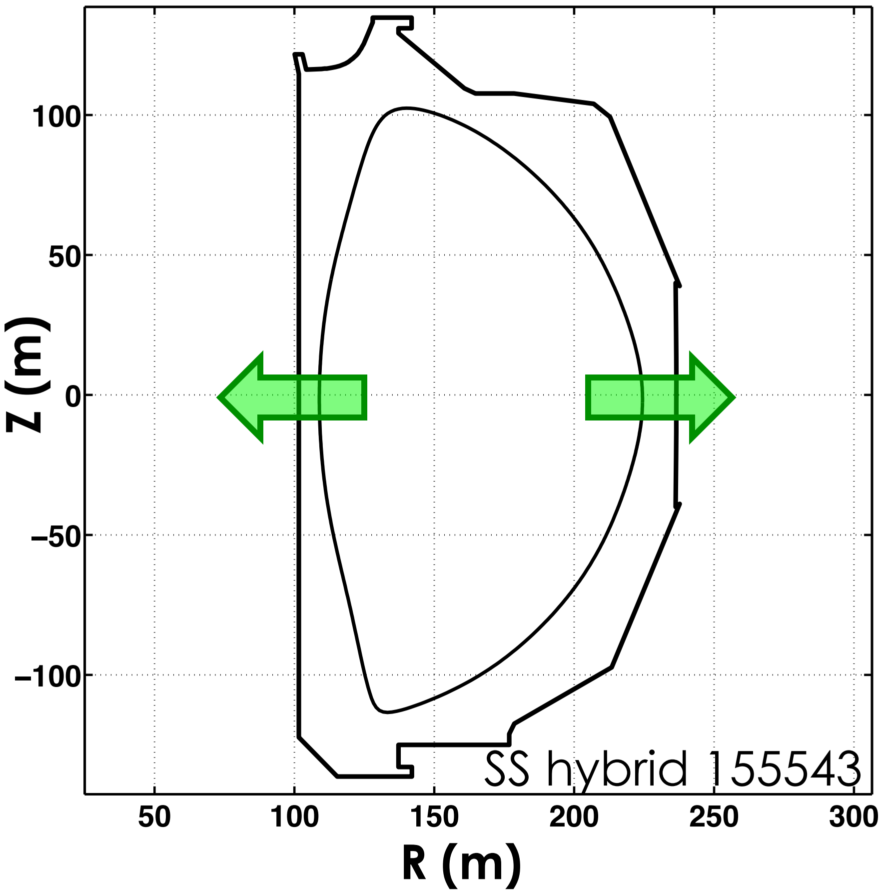
- The with-wall β_N limits of the OFF-axis cases are ~10% higher



The Plasma Shape Can Be Optimized to Yield Higher Ideal Limits

MOD

The modelling will guide the design of the next hybrid experiment



Increase the minor radius

Decrease the inner and outer gaps

Increase the degree of wall stabilization
(within the new wall geometry limits)

Kink structure is localised on the LFS
Does the inner gap matter?

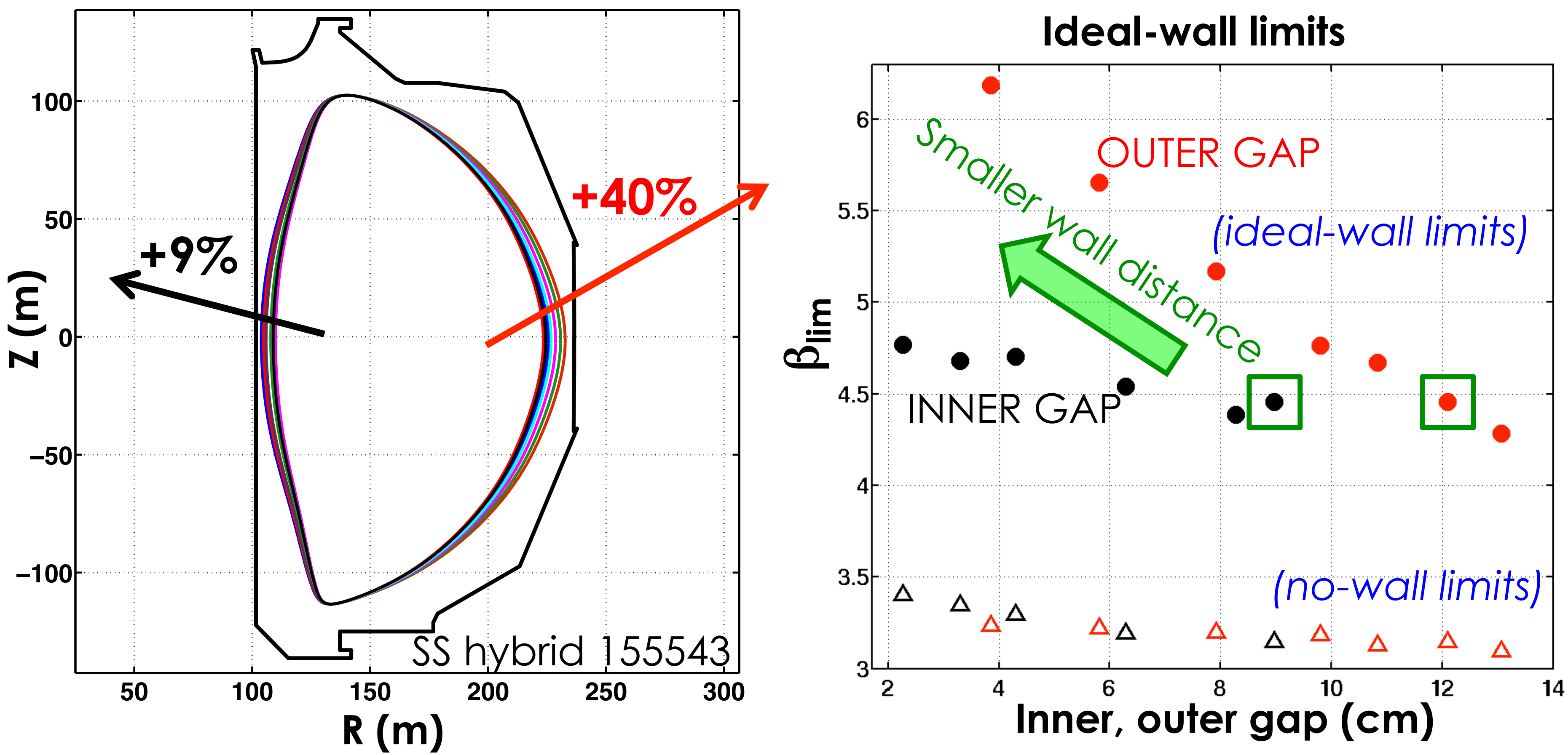
F. Carpanese, Politecnico di Milano

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Wider Shape, with Larger Squareness, will be Proposed for the Next Hybrid Experiments

MOD

The LFS wall stabilization (outer gap) is stronger than the HFS (inner gap)



F. Carpanese, Politecnico di Milano

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Higher order changes → squareness affects the stability

All the High-β_n Plasmas Have High NBI Torque

MOD

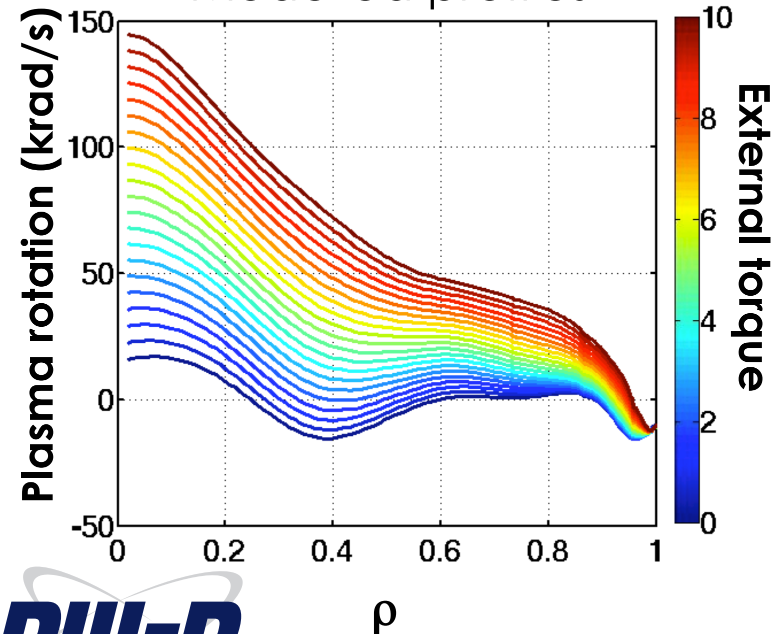
What happens at low rotation, high β_N?

- **Experiment → decrease the rotation at fixed β_N, q_{95}**
- **Model → capture the rotation effects to extrapolate what we can't do**

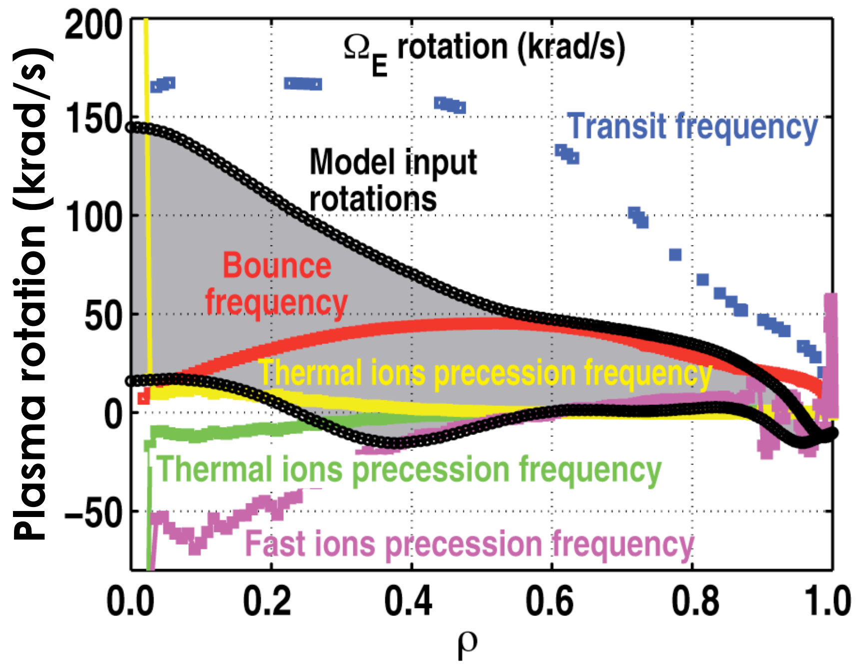
To eliminate perturbations due to equilibrium and profile details, the model uses:

- **A <u>fixed equilibrium</u> and n_e, T_e, n_i, P_{NBI}, etc, from a DIII-D plasma**
- **A self-similar rotation profile series**

Modelled profiles



Comparison with drift frequencies

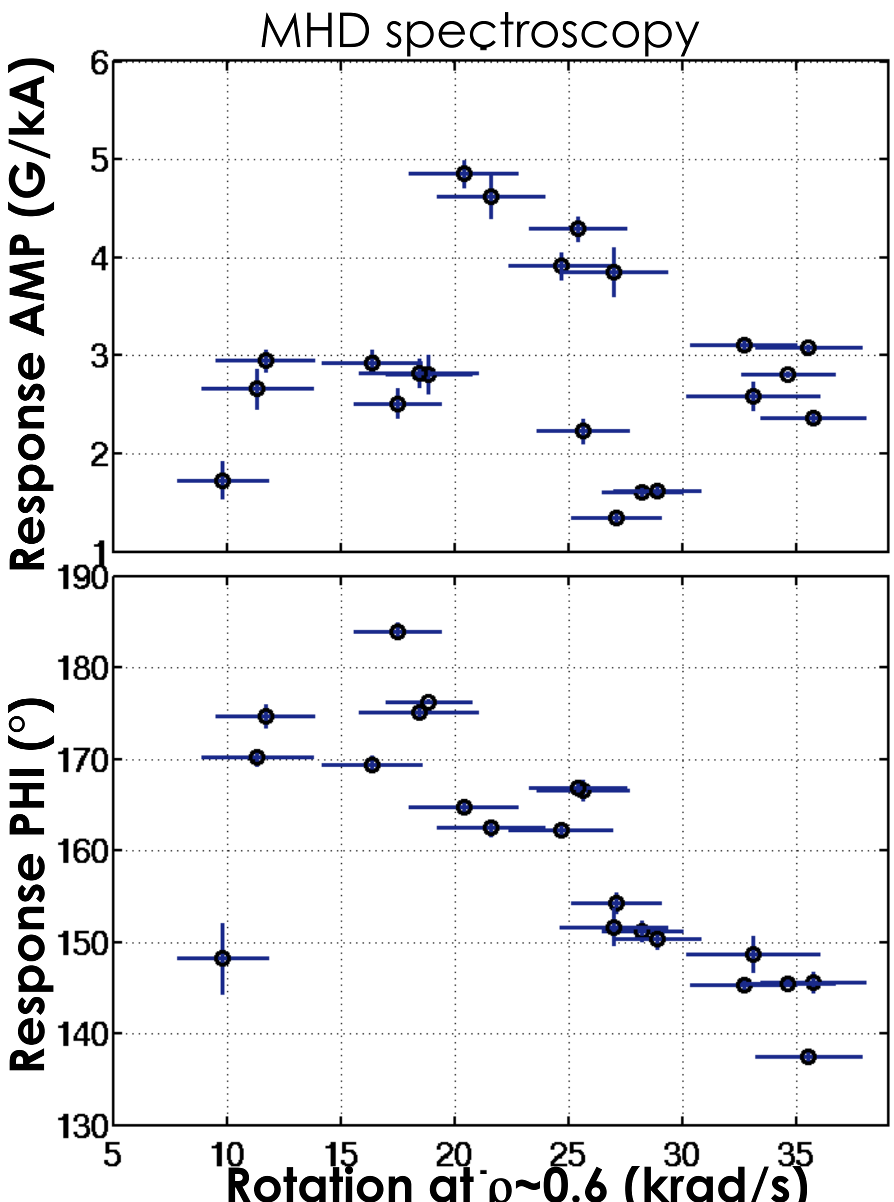


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Rotation Effects Above the No-wall β_n Limit

EXP

- **Broad peak in the response at 20-25 km/s (~1% of the Alfvén velocity)**
- **Below the no-wall limit (IBS) the trend is increasing**

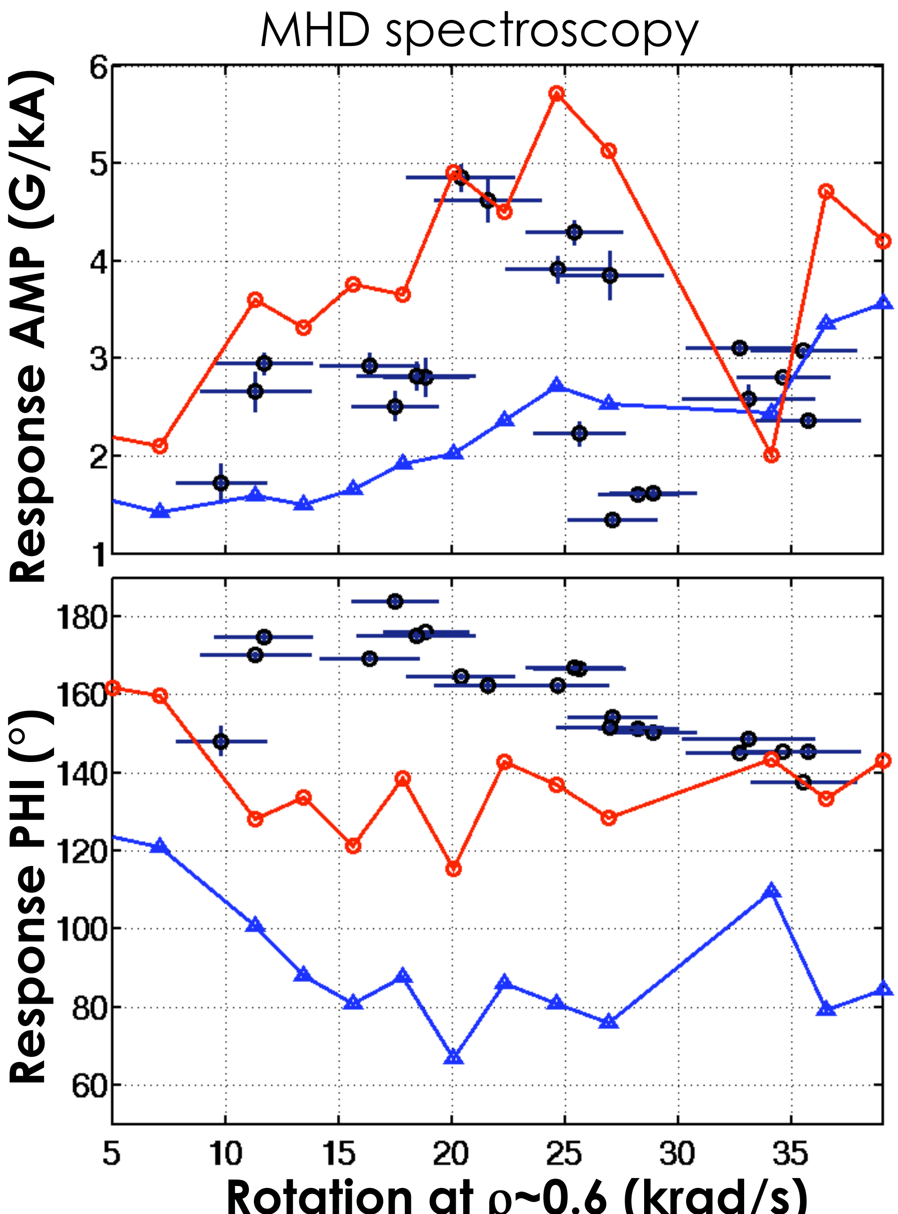


DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Rotation Scan: MARS-K Reproduces the Response Amplitude with Fast-ions

MOD

- With thermal and fast ions the amplitude results are in the ball-park
- *...but the phase is underestimated by ~25%*
- If the fast-ions damping is neglected, the results diverge (more) from the measurements



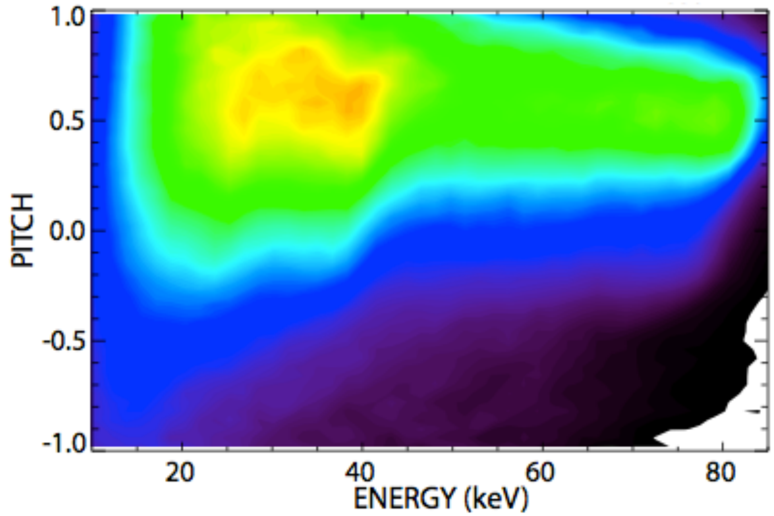
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

No Model is Perfect — the Way Forward

Identify what physics is not present and could be relevant:

- **Zero collisionality → New MARS-Q: energy dependent collisionality operator**
- **The present version of MARS-K assumes a Maxwellian fast-ion distribution**
  (experimental profile in ρ, but no $v_{//}$, v_{perp} dependence)
- **Neutral beam ions in DIII-D are strongly anisotropic:**

Experimental beam-ion distribution (NUBEAM)



New MARS-Q version with more realistic distribution
→ resolve the rotation scan discrepancy?

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Discussion and Conclusions

- **The development of viable scenarios for ITER and FNSF is based on experiments and modelling efforts**
- **The ITER Baseline Scenario:** the zero torque regime operates on a marginal stability point
- **MHD spectroscopy can measure the approach to a stability limit**
  - Warning tool for disruption avoidance?
- **The MARS-K model reproduces the plasma response measurements up to the no-wall limit**
  - Fast NBI-ion damping is crucial above 90% of the limit
- **The steady-state hybrid scenario:** attractive solution for ITER and FNSF, **the ideal and tearing limits can be increased**
- **The rotation dependence at high β_N is challenging**
  - New version of MARS-K includes more physics

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Columbia University