High Density as an Avenue towards High Confinement Quality and Core-Edge Integration in Advanced Tokamaks

S. Ding[1], A. M. Garofalo[1], X. Z. Gong[2], H. Q. Wang[1], L. Wang[2], W. Choi[1], J. P. Qian[2], J. Huang[2], M. Kotschenreuther[3], D. Hatch[3], S. Mahajan[3], D. B. Weisberg[1], Z. Y. Li[1], Z. Yan[4], X. Jian[2], S.-G. Baek[5], P. Bonoli[5], G. Wallace[5], D. Eldon[1], B. S. Victor[6], A. Marinoni[7], Q. M. Hu[8], I. S. Carvalho[1], T. Odstrčil[1], K. D. Li[2], A. W. Hyatt[1], T. H. Osborne[1], J. McClenaghan[1], C. T. Holcomb[6], J. M. Hanson[9], Y. X. Sun[2,10] and Z. H. Wang[2,10]

[1]General Atomics, P. O. Box 85608, San Diego, CA 92186-5608, USA
[2]Institute of Plasma Physics, Chinese Academy of Sciences, PO Box 1126, Hefei, Anhui 230031, China
[3]ExoFusion, Austin, TX, USA
[4]University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
[5]Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[6]Lawrence Livermore National Laboratory, Livermore, California 94551, USA
[7]University of California San Diego, La Jolla, CA, 92093, USA
[8]Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, 08543, USA
[9]Department of Applied Mathematics and Applied Physics, Columbia University, New York, New York 10027-6900, USA
[10]University of Science and Technology of China, Hefei, 230026, China

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Presented at the
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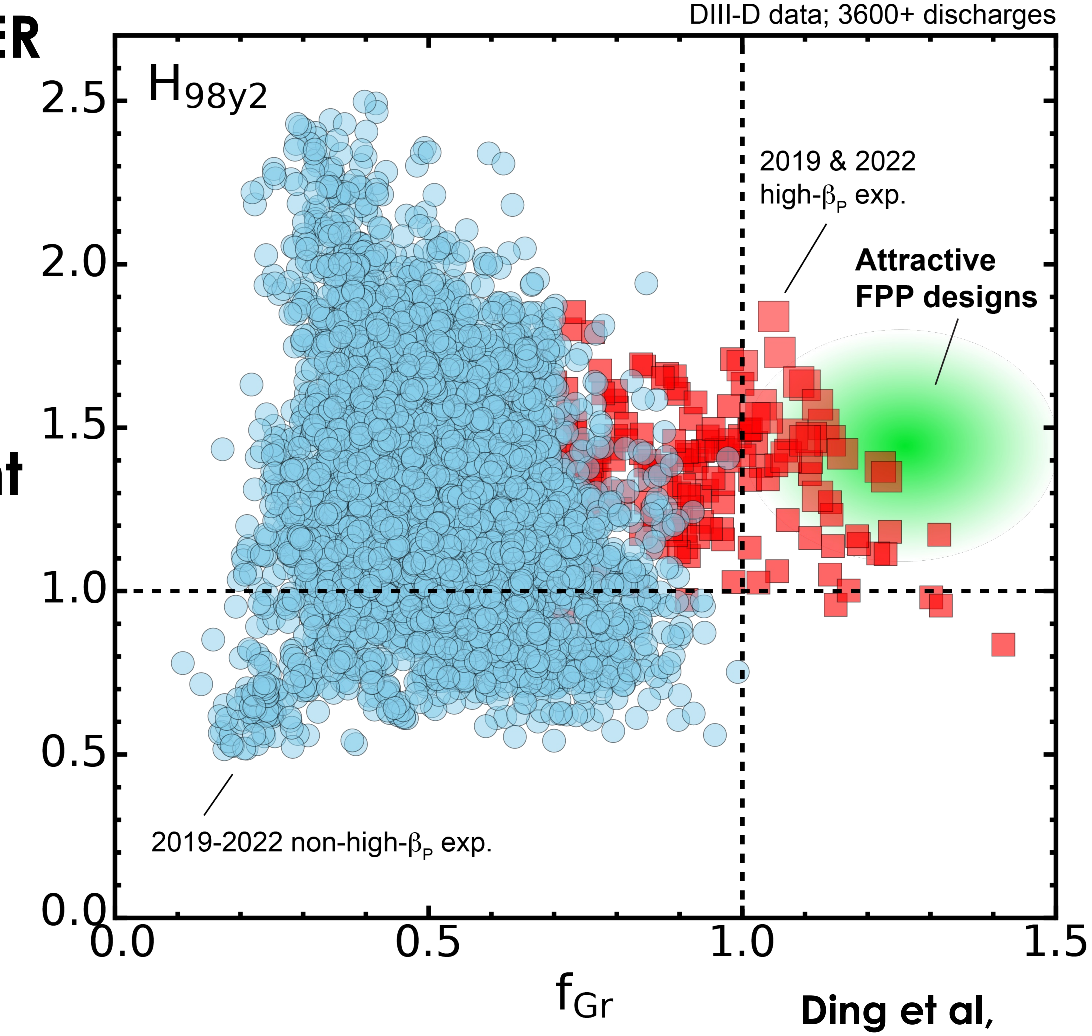
First demonstration of high β_P scenario with large radius ITB obtained on DIII-D with KSTAR operation constraints on June 14! [YoungMu Jeon, et al, APS 2024]

Takeaway: Breakthroughs Achieved for Improved Energy Confinement at Plasma Density near the Greenwald Value

- **Both steady-state fusion pilot plants (FPPs) and ITER Q=10 at significantly lower I_p require density Greenwald fraction (f_{Gr}) > 1 with H_{98y2} > 1**
- **High-β_P experiments on DIII-D achieve first such demonstration in a tokamak**
- **Key physics: enhanced α-stabilization of turbulent transport at high density gradient**
- **Same physics applied to EAST leads to nearly doubled T_i**
- **Excellent core-edge integration: small ELMs and divertor detachment also achieved at high H_{98y2} and high f_{Gr}**



Ding et al, Nature 2024

Outline

- On the performance requirements for steady-state fusion pilot plants (FPPs) and for ITER Q=10 P_{fus}=500 MW operation at reduced I_p
- DIII-D high-β_P experiments and transport analysis
- Simulations of EAST high-β_P plasmas and theory-guided experiments
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High Energy Confinement Quality and High Fuel Density are Two Key Elements for Economically Attractive Fusion

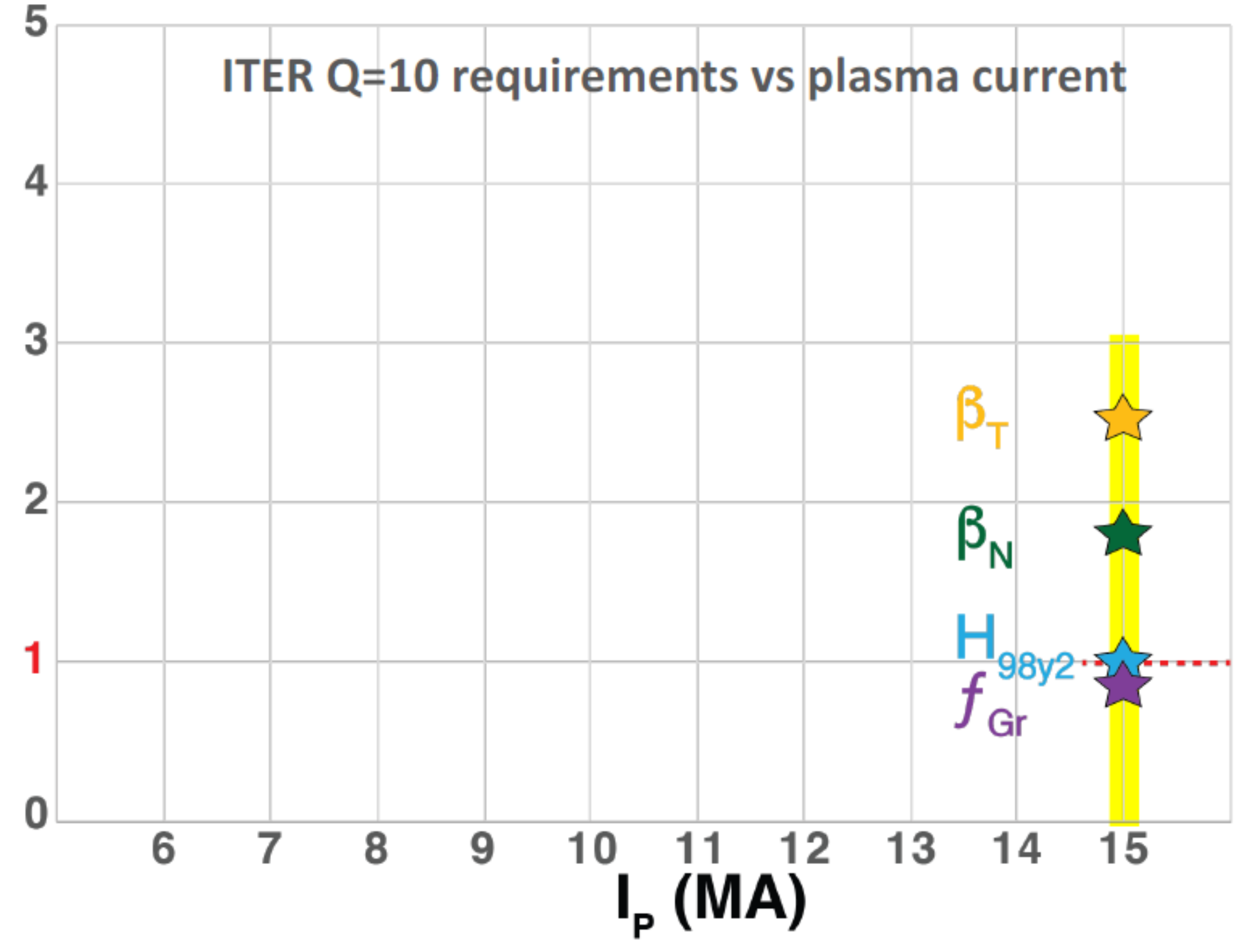
- **Energy confinement quality (H_{98y2}) is the highest leverage parameter for fusion capital cost** Wade, Fusion Sci. Technol. 2021 Hammett, Maxwell Prize Address, APS 2024
- **Thermonuclear power density $p \sim n_i^2 \langle \sigma v \rangle$** Wesson, Tokamaks 2004
- **Both f_{Gr} and H_{98y2} above unity proposed in steady-state FPP Designs**
  - f_{Gr}=line-avg n_e/n_{Gr}
  - $n_{Gr}=I_p/\pi a^2$, an empirical density limit on H-mode pedestal

FPP Device	f_{Gr}	H_{98y2}
CFETR	0.96	1.42
K-DEMO	1.0, 1.13	≥1.3
ARIES-ACT	1.0, 1.3	1.22 – 1.65
CAT-DEMO	>1.0	1.2 – 1.51
GA-FPP	1.2	≥1.5

Zhuang, Nucl. Fusion 2019
Yeom, Fusion Eng. Des. 2013
Kessel, Fusion Sci. Technol. 2015
Wade, Fusion Sci. Technol. 2021
Buttery, Nucl. Fusion 2021
Shi, APS 2022
Shi, APS 2023

ITER Operation at I_P Significantly Lower than 15 MA could Provide A Safer Path to Q=10 P_{fus}=500 MW, but Requires H_{98y2}>1.2 at $f_{Gr} \geq 1$

- **15 MA approach: q_{95}~3, H_{98y2}=1.0, f_{Gr}=0.85**
  - Risks: Disruption, MHD, divertor heat flux…



DIII-D NATIONAL FUSION FACILITY

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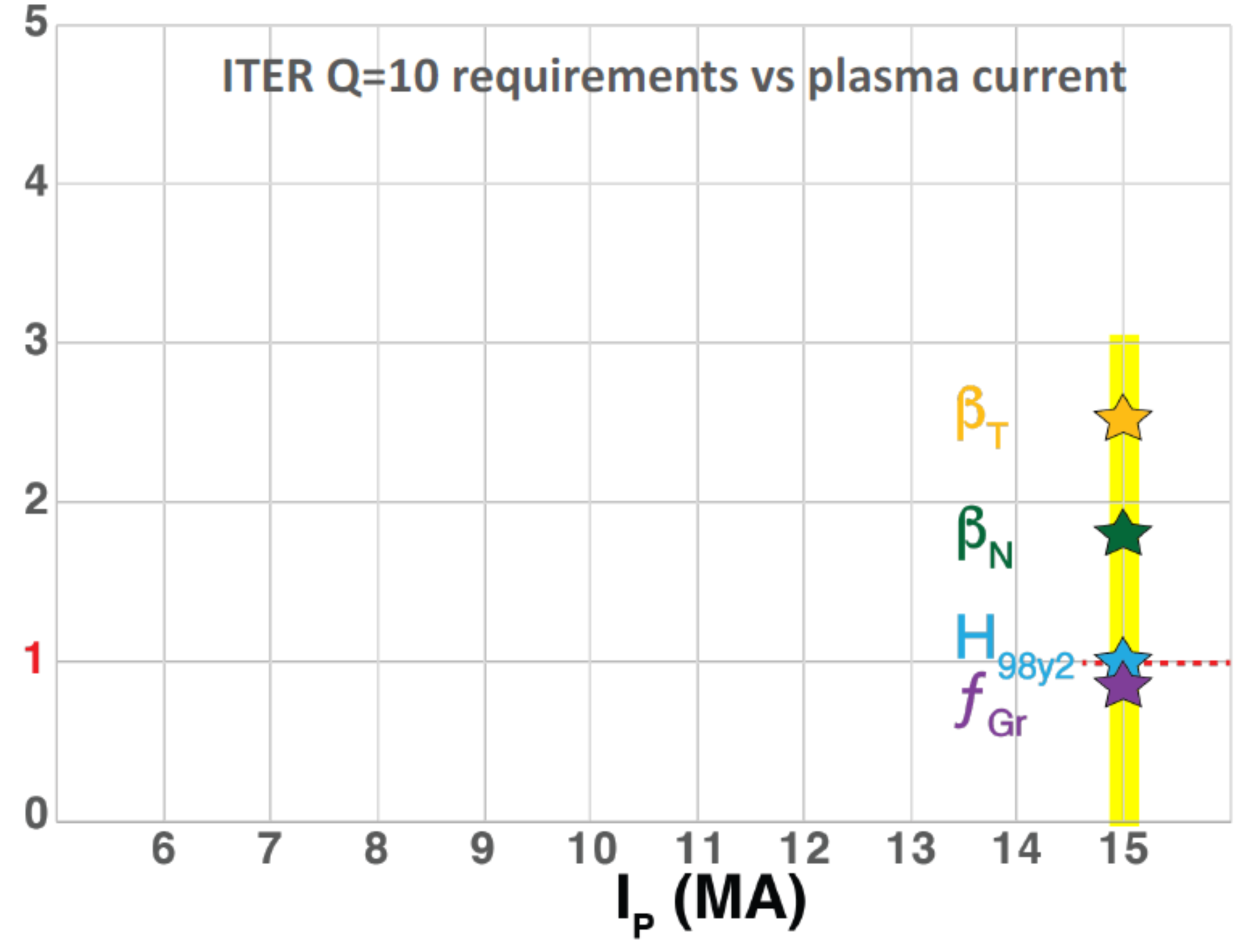
ITER is seeking an alternative higher q_{95} (≥6) plan for its Q=10 mission
- **Target I_p≥7.5 MA**

Loarte, ITR-24-004 (2024)



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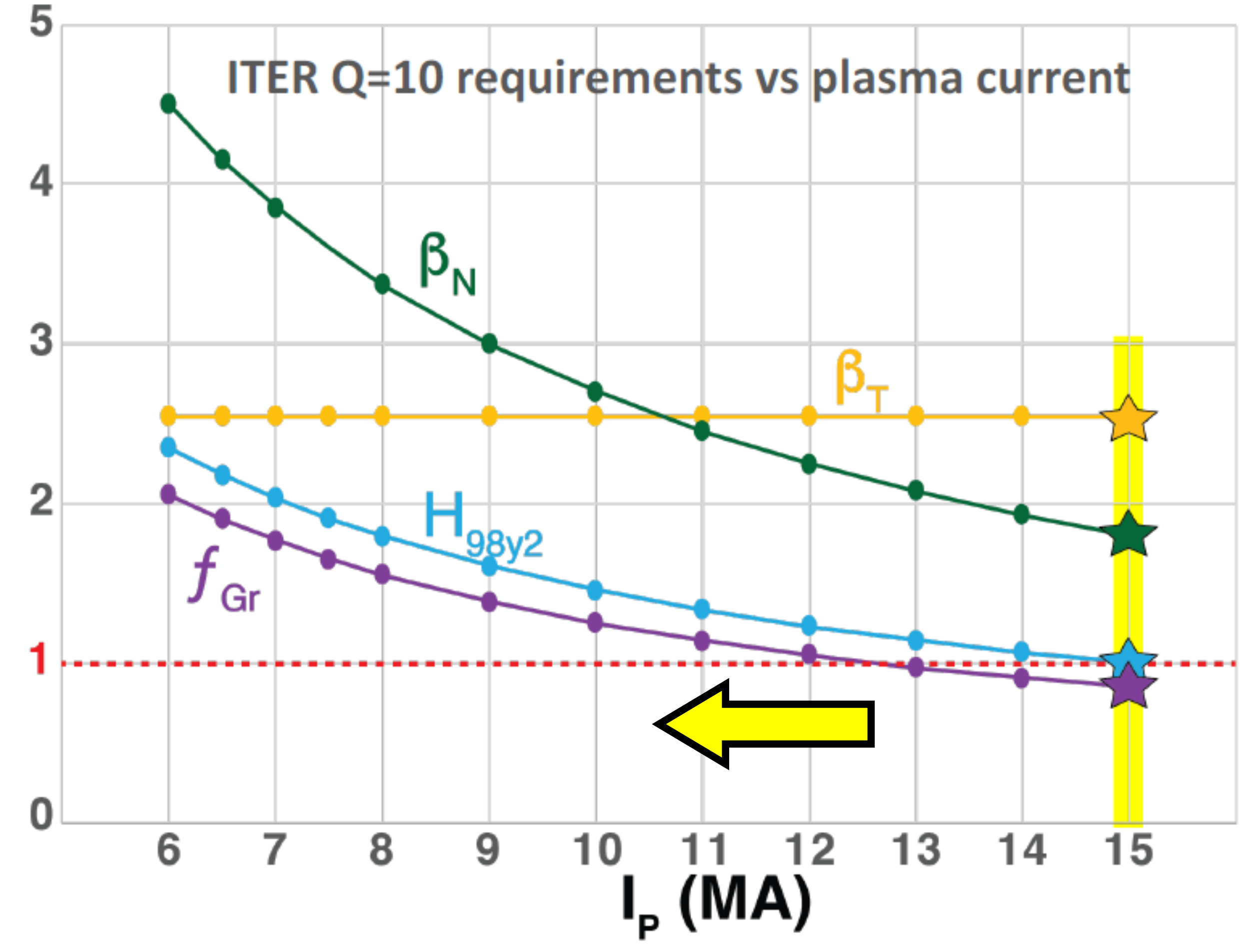
- **15 MA approach: q_{95}~3, H_{98y2}=1.0, f_{Gr}=0.85**
  - Risks: Disruptions, MHD, divertor heat flux…
- **Reduce I_p, while keeping constant B_T, P_{aux}, n and T in 0D modeling**
  - Constant τ_E
  - Constant Q and P_{fus}
- $\beta_T = nk_BT/(B^2/2\mu_0)$ = constant
- $\beta_N = \beta_T/(I_P/aB) \sim 1/I_P$
- $f_{Gr} = \langle n_e \rangle/(I_P/\pi a^2) \sim 1/I_P$
- $H_{98y2} = \tau_E/\tau_{98y2} \sim 1/I_P^{0.93}$



$$\tau_{98y2} = 0.0562\, I_P^{0.93} B_T^{0.15} n_e^{0.41} P_H^{-0.69} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa^{0.78}$$

Garofalo et al, APS 2024

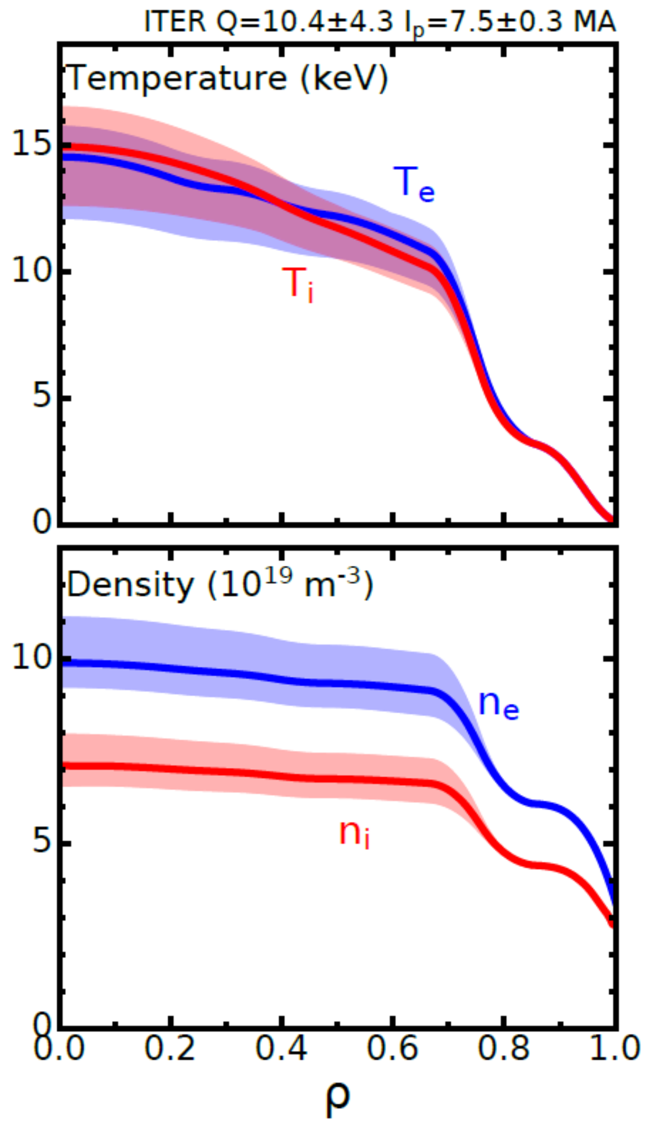
Theory-based High Fidelity Modeling Shows High β_P Scenario Can Enable ITER Q Goals

- **Self-consistent ITER modeling using high β_P scenario by STEP in OMFIT**
- **Q=5 steady-state predicted with f_{Gr}~1.3 and H_{98y2} >1 at I_p~8.3 MA (q_{95} ~7, β_N~3.0)**
  - Day-1 H&CD powers
  - P_{fus}~400 MW

McClenaghan et al, Nucl. Fus. 2020

- **Q=10 predicted with f_{Gr}~1.4 and H_{98y2}~1.7 at I_p~7.5 MA (q_{95} ~8, β_N~2.8)**
  - Day-1 H&CD powers
  - P_{fus}~ 350 MW

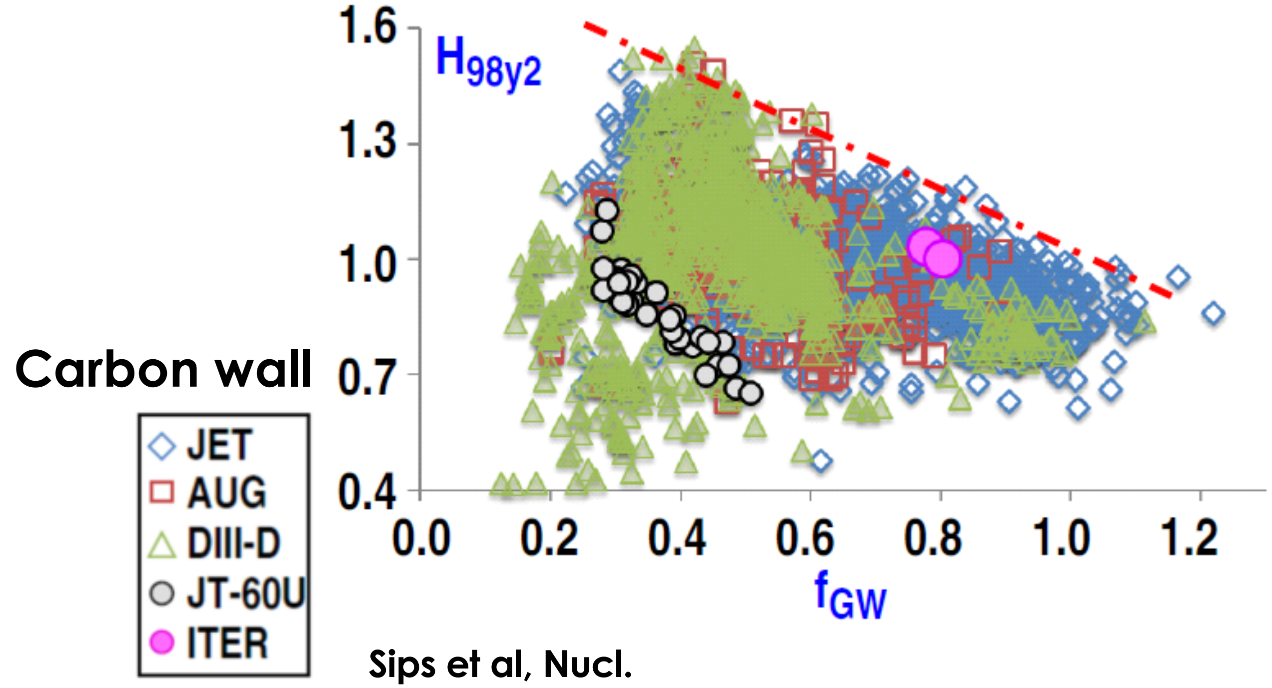
Ding et al, IAEA FEC 2021



Operating regimes with f_{Gr}>1 and H_{98y2}>1 need to be demonstrated in experiments

Simultaneous $f_{Gr}>1$ and $H_{98y2}>1$ is Difficult for Experiments in Present Tokamaks → a "Performance" Limit

- **ITPA database for ITER Q=10 H-mode q_{95}=2.7-3.3**
  - International tokamaks
  - No constraints on toroidal rotation/injected torque



Sips et al, Nucl. Fusion 2018

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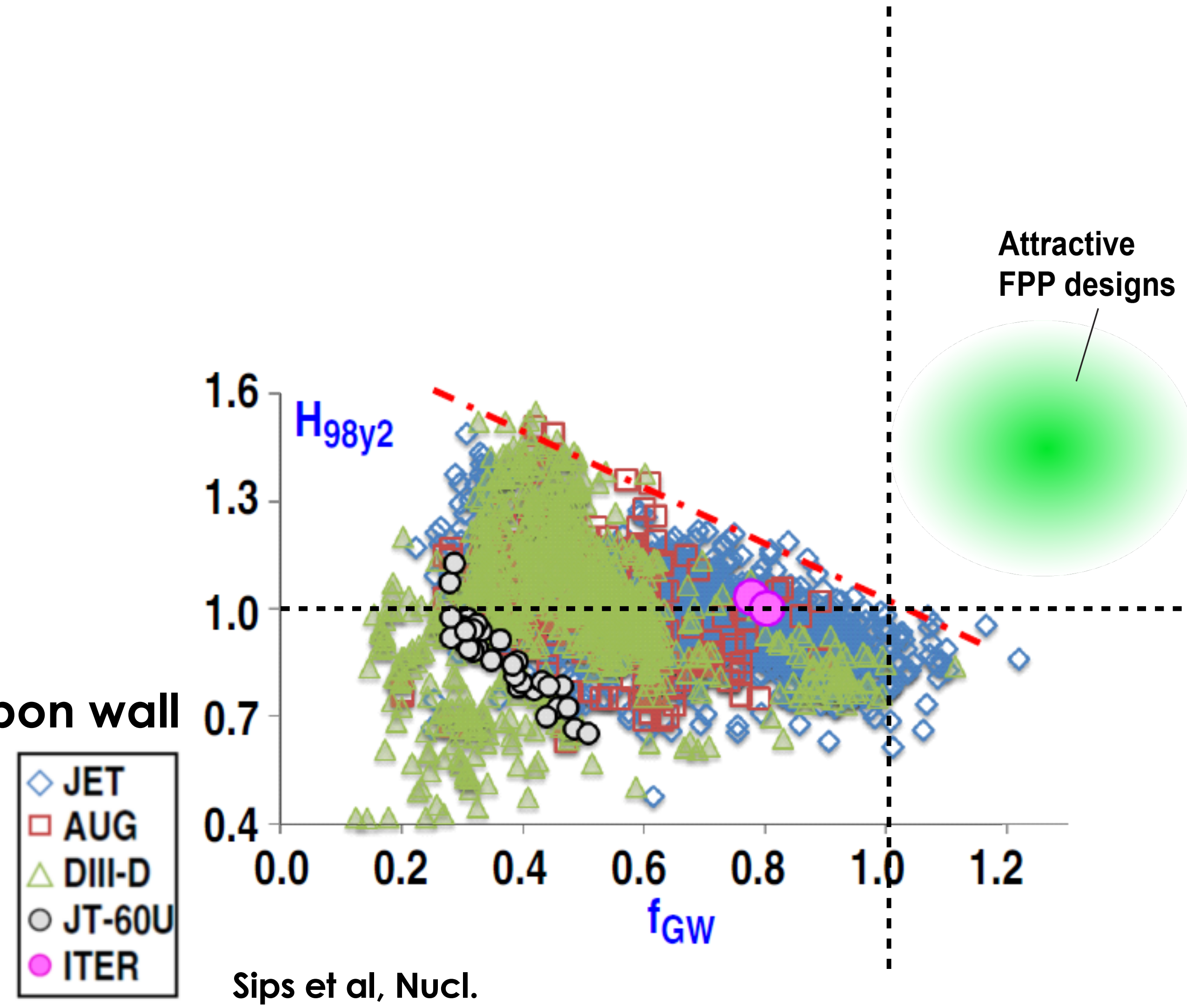
No experiment shows significant H_{98y2}>1 at f_{Gr}>1

Carbon wall



Sips et al, Nucl. Fusion 2018

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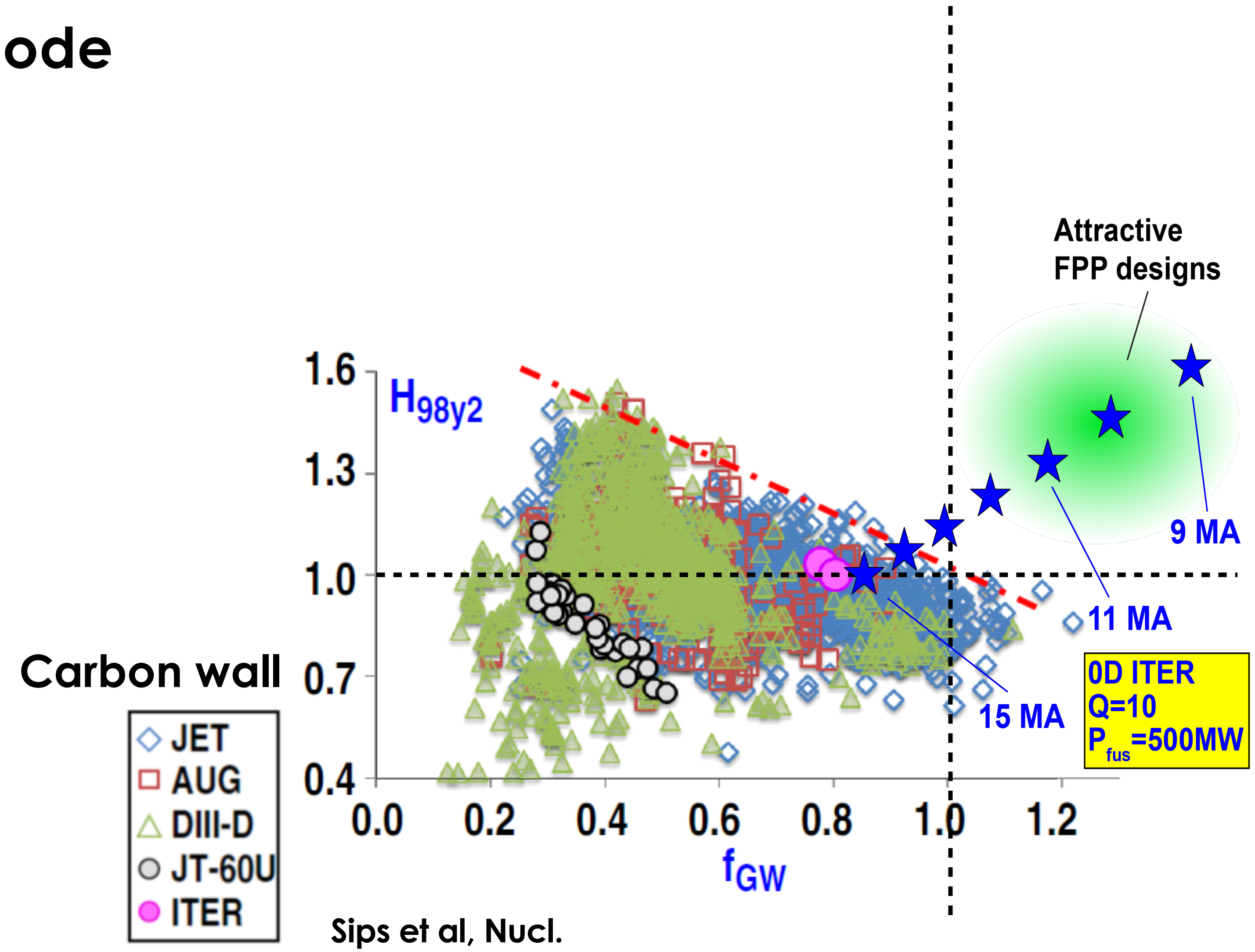

Sips et al, Nucl. Fusion 2018

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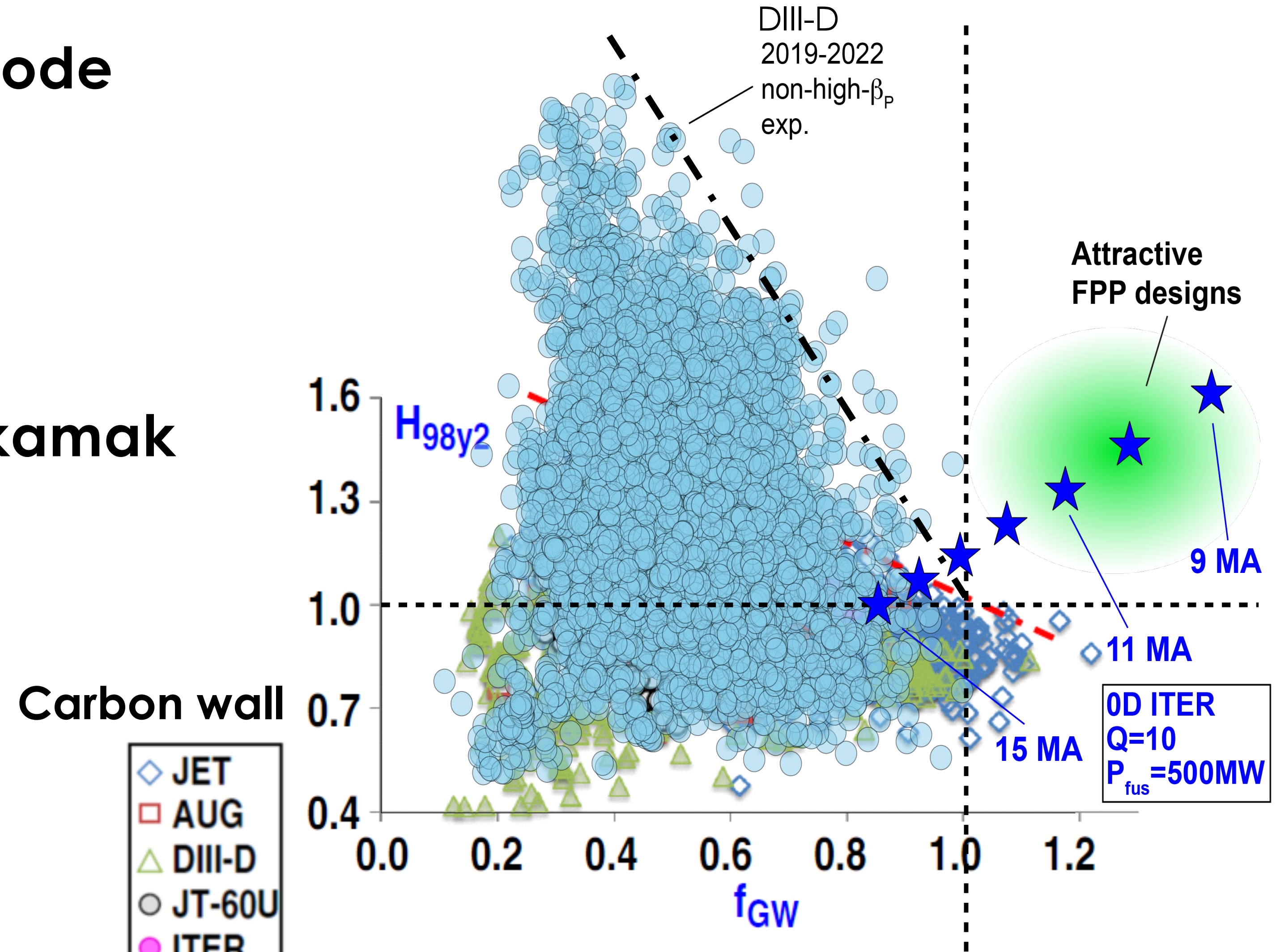
- **Remove q_{95} constraint, single tokamak (DIII-D)**

Still No experiment shows significant $H_{98y2}>1$ at $f_{Gr}>1$



Sips et al, Nucl. Fusion 2018

Ding et al, Nature 2024

Only High-β_P Scenario Has Overcome the Performance Limit

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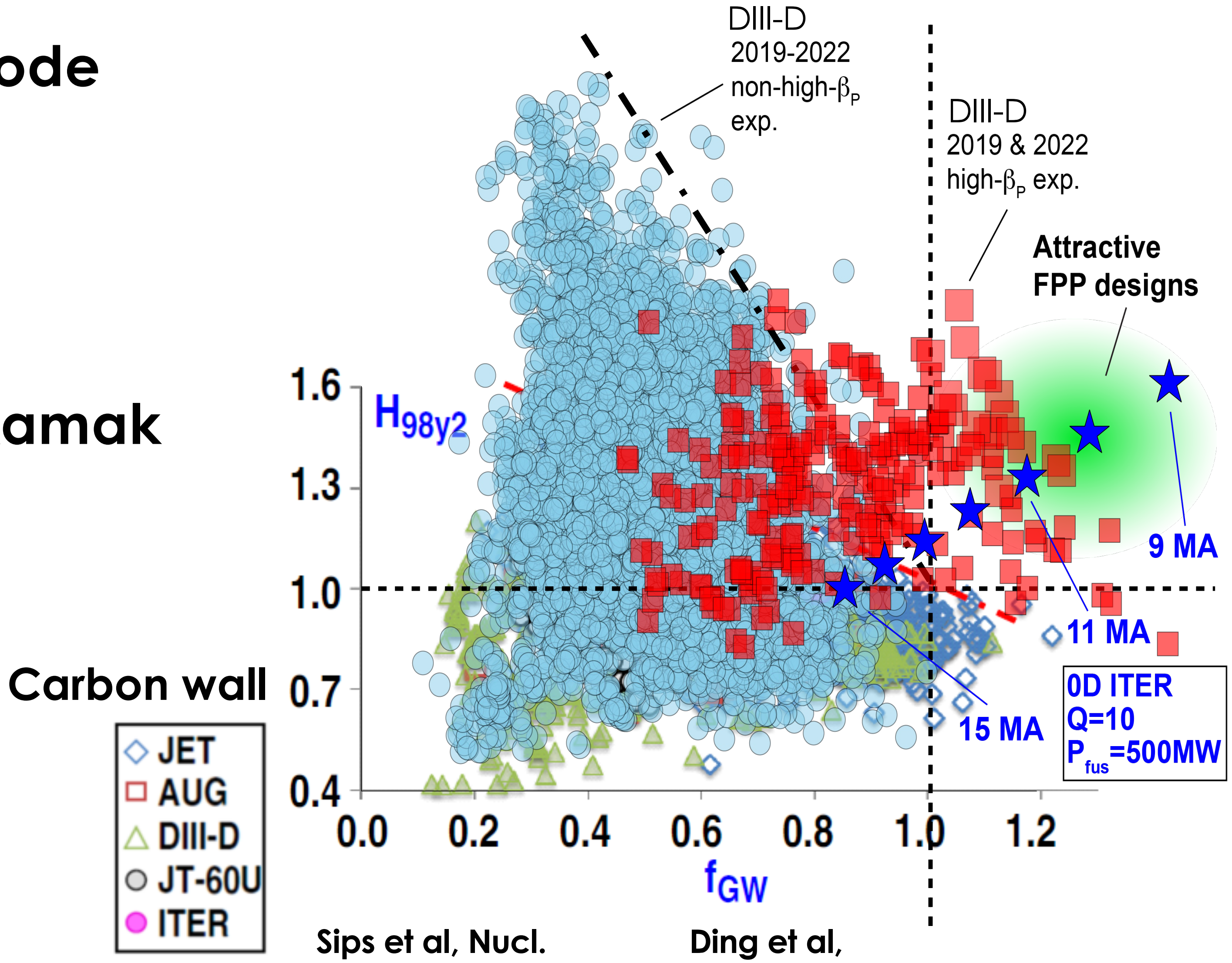
Until breakthrough from high-β_P experiments



Sips et al, Nucl. Fusion 2018

Ding et al, Nature 2024

Only High-β_P Scenario Has Overcome the Performance Limit, both on JT60-U and DIII-D

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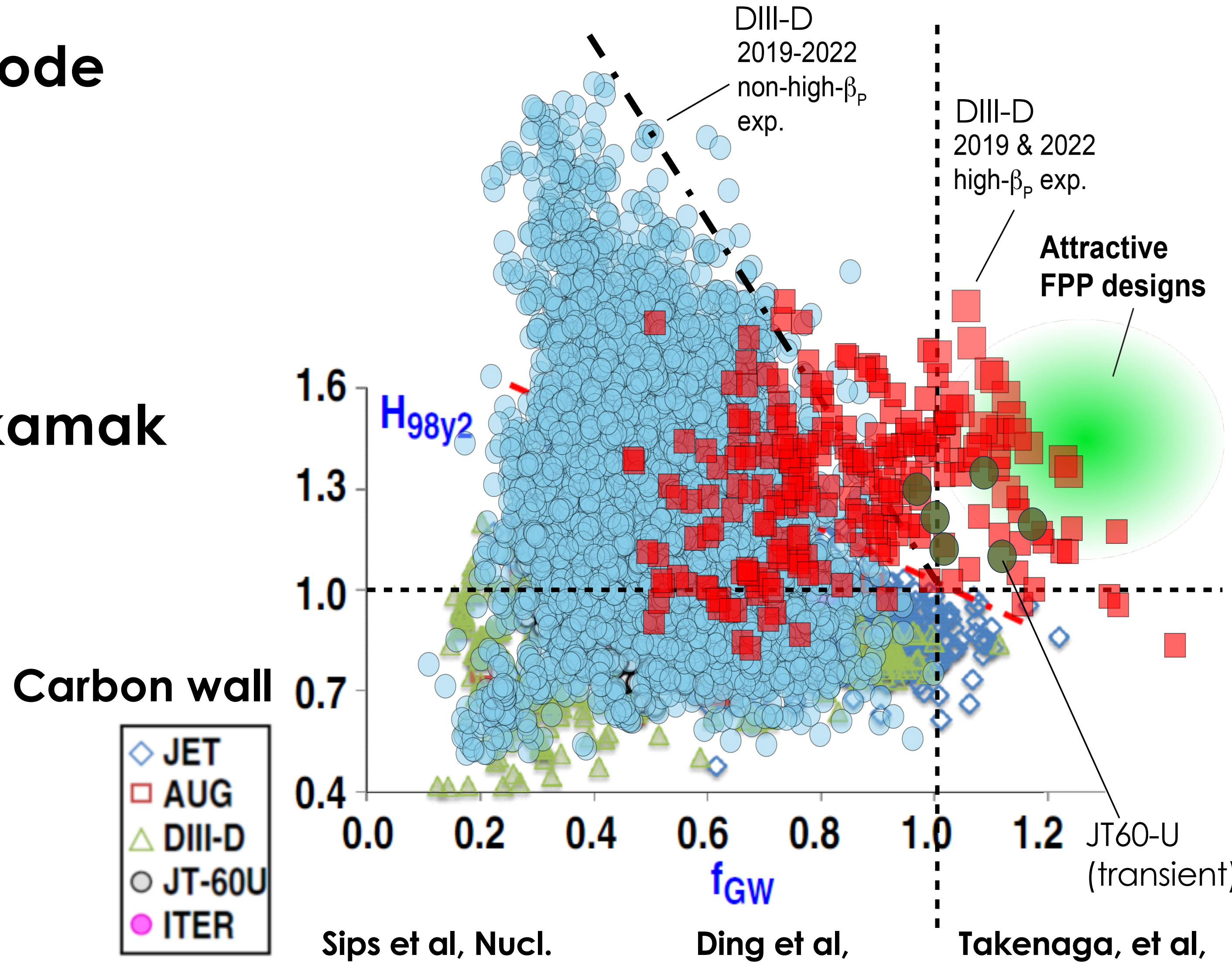

Sips et al, Nucl. Fusion 2018

Ding et al, Nature 2024

Takenaga, et al, Nucl. Fusion 2005

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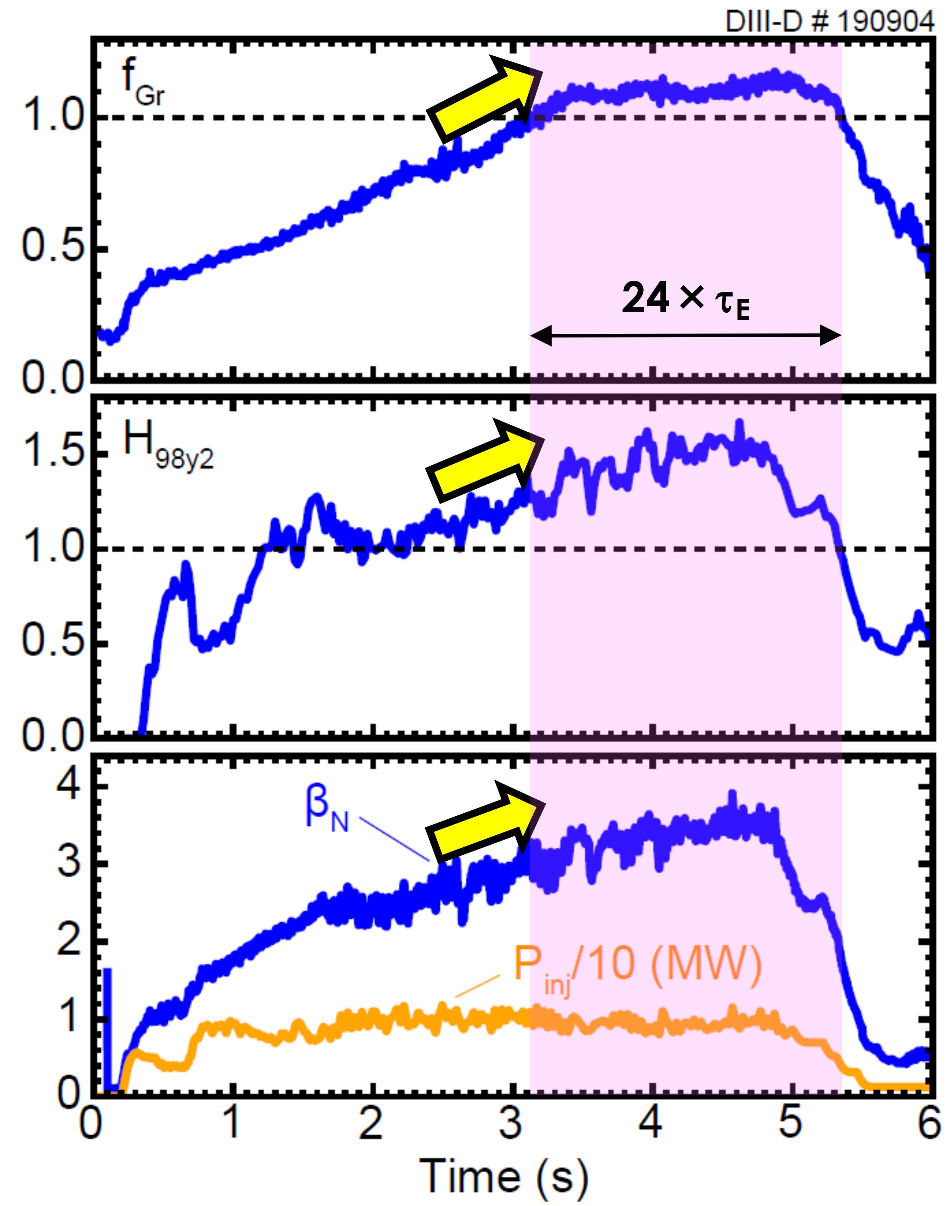
Breakthrough: Stored Energy and Confinement Quality Increase as Density Exceeds the Greenwald Value

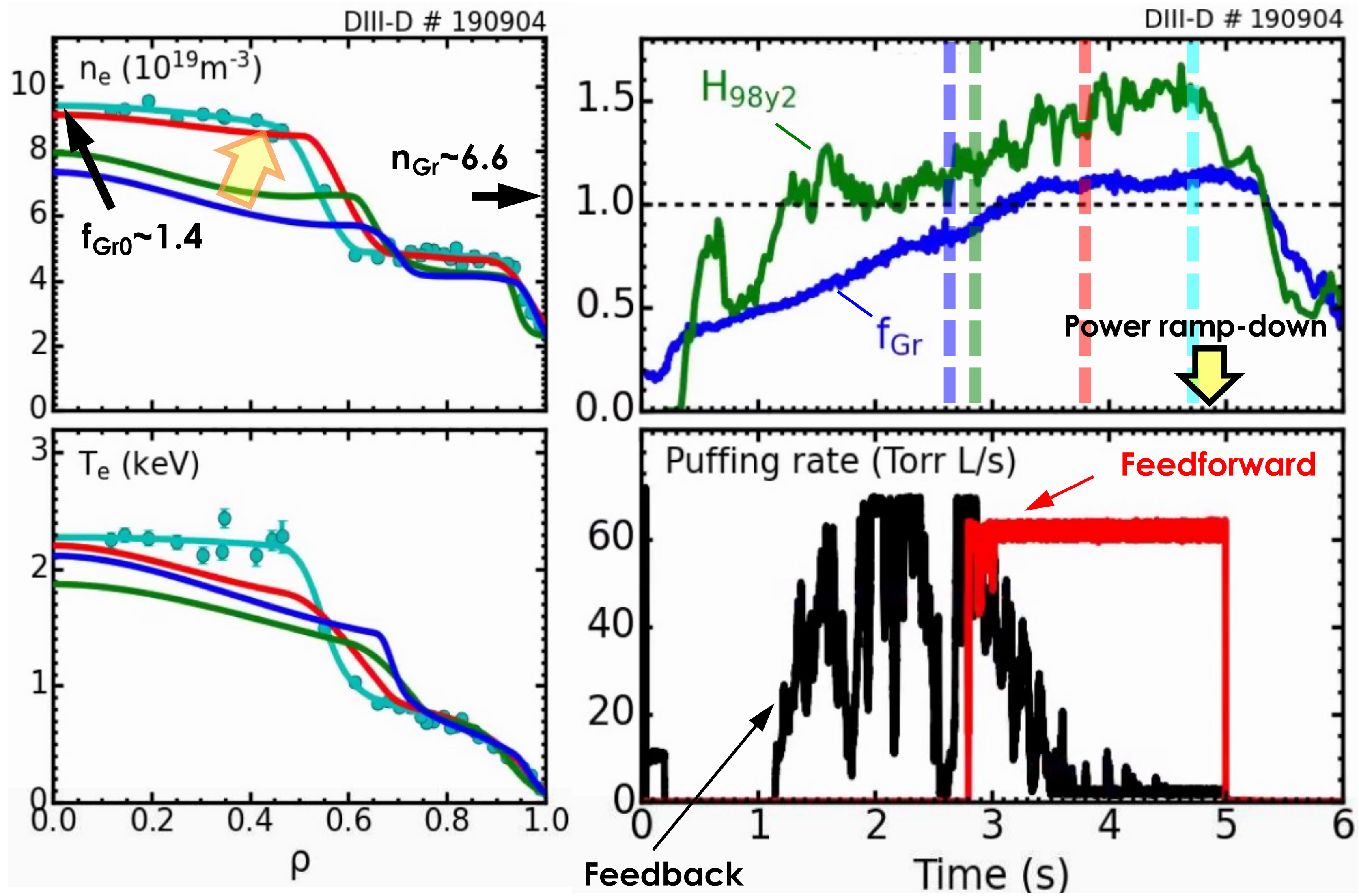
- First time achieve sustained H_{98y2}~1.5 at f_{Gr}>1.1
- β_N>3
- Mixed co-/counter-I_p NBI injection
- T_{i0}/T_{e0}~1.25
- D_2 gas puffing



Ding et al, Nature 2024

Strong Density Internal Transport Barrier (ITB) Develops during Strong D_2 Gas Puffing

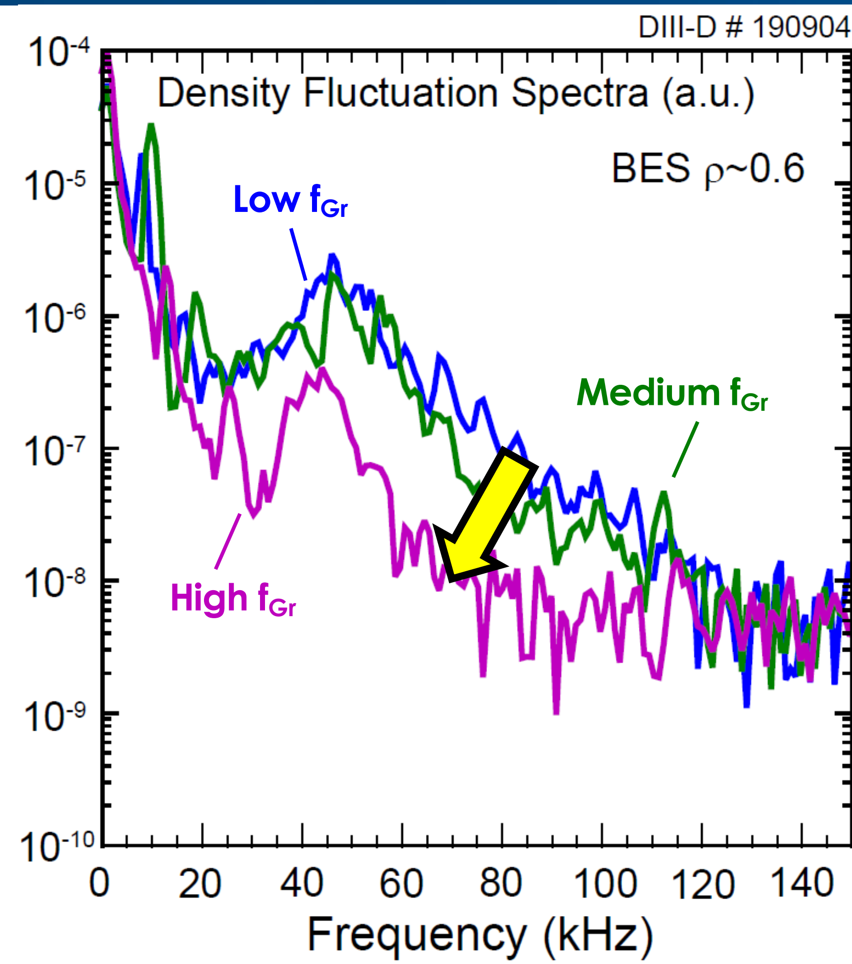
- **Strong density ITB elevates core density, while keeping pedestal density below n_{Gr}**
  - $f_{Gr,ped}$~0.7, $f_{Gr,0}$~1.4
- **Strong temperature ITB develops as well**



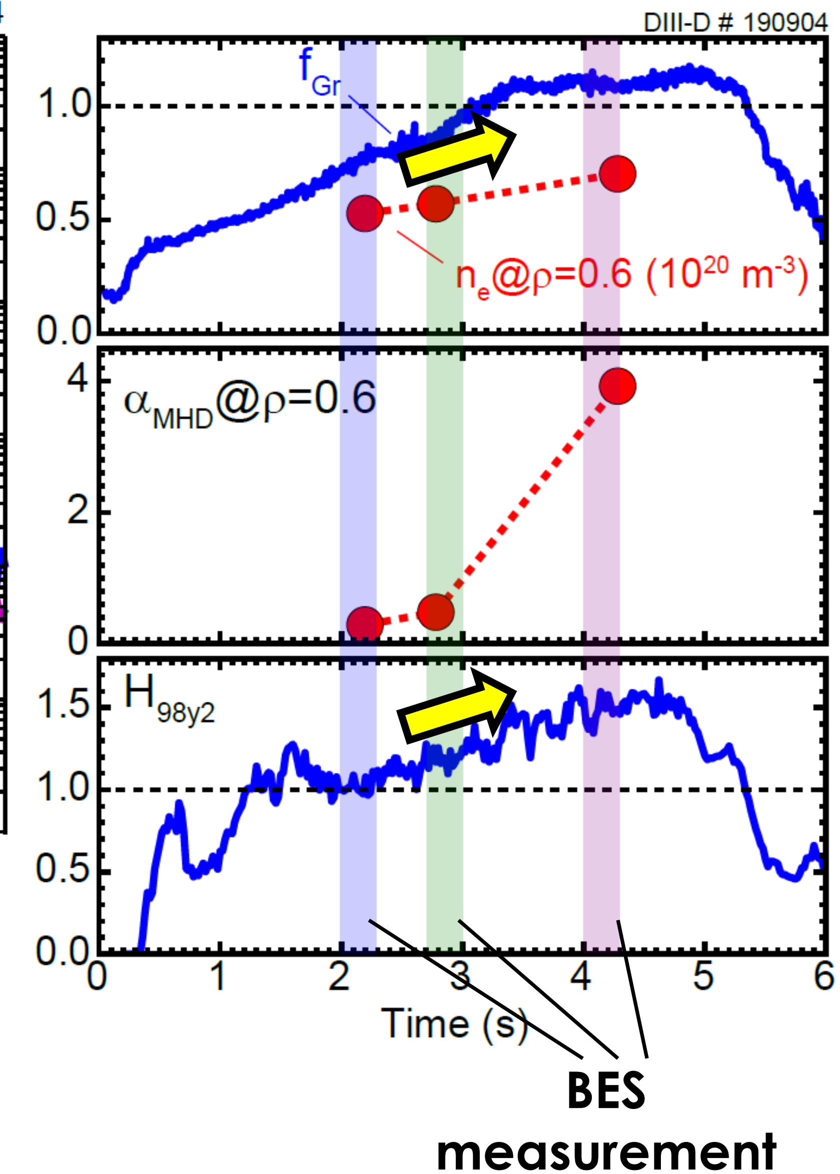
Ding et al, Nature 2024

Weak Turbulence Measured at High Density and High α_{MHD}

- $\alpha_{\mathrm{MHD}} \sim -\dfrac{q^2}{B^2} R \dfrac{\mathrm{d}p}{\mathrm{d}r} \sim \dfrac{\mathrm{d}\beta_{\mathrm{P}}}{\mathrm{d}r}$, **a normalized pressure gradient**
- **Low-k fluctuations measured at mid-radius**
  - 0.1-0.2 cm^{-1}



Ding, Invited Talk, **APS 2023**



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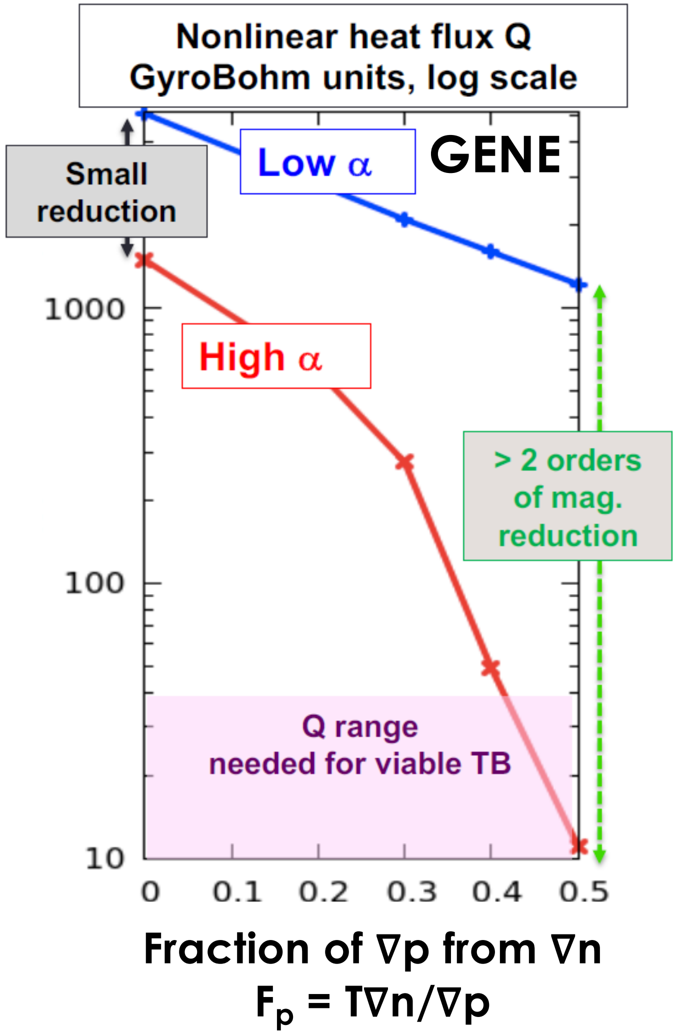
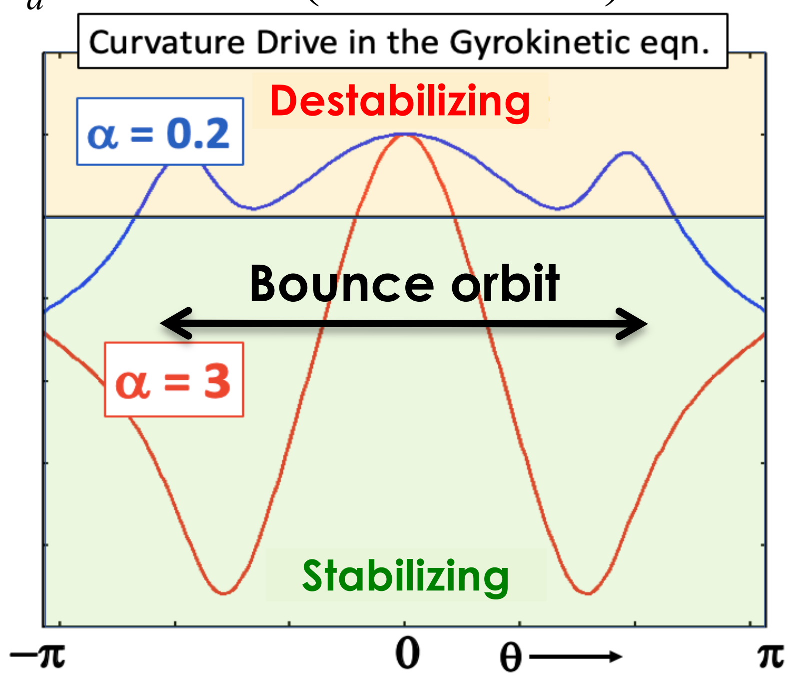
Theory Predicts Enhanced Density Gradient Amplifies Turbulence Suppression by High α_{MHD}



Kotschenreuther et al, NF 2024

- **GENE simulation based on theoretical parameters**
- **As ∇n increases, turbulence transitions from ∇T driven (ITG) to ∇n driven (TEM)**
- **At high α_{MHD}, unstable eigenfunction becomes narrower in poloidal angle (θ)**

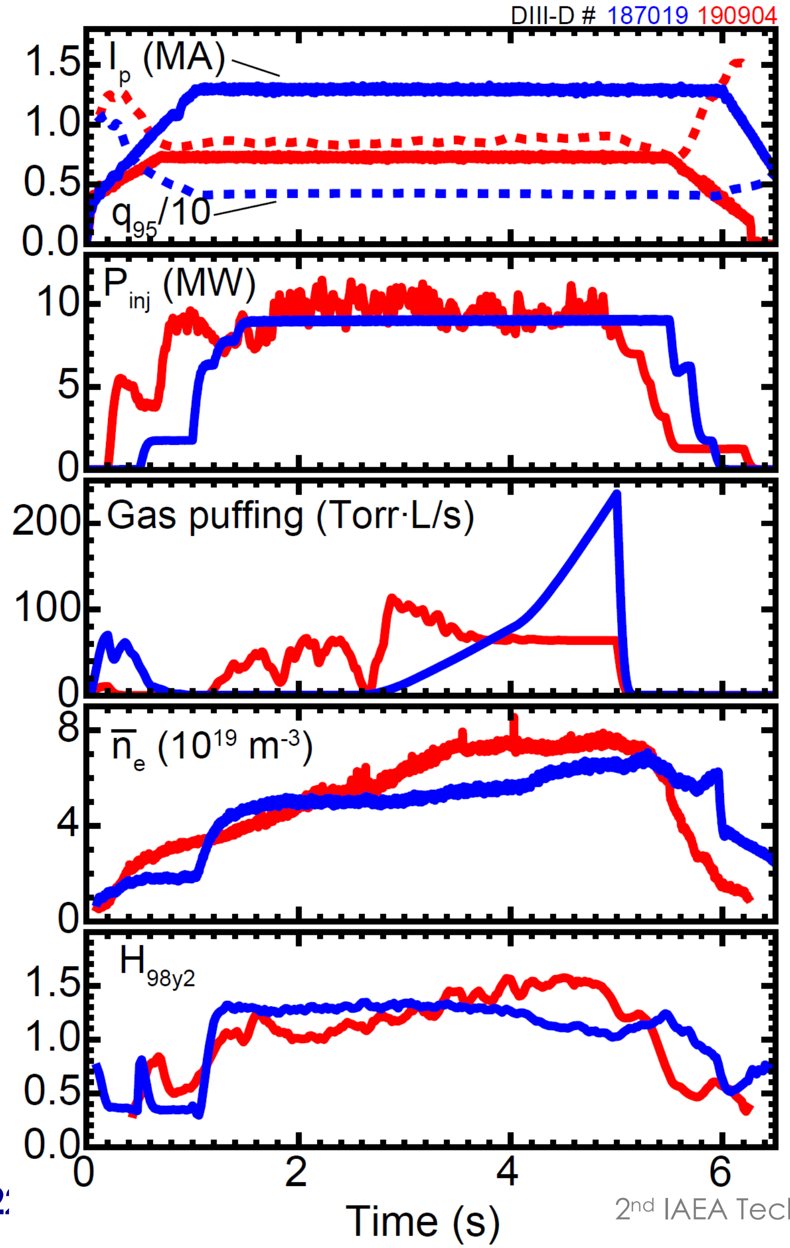
$$\omega_d \sim \cos\theta + (s\theta - \alpha \sin\theta)\sin\theta$$



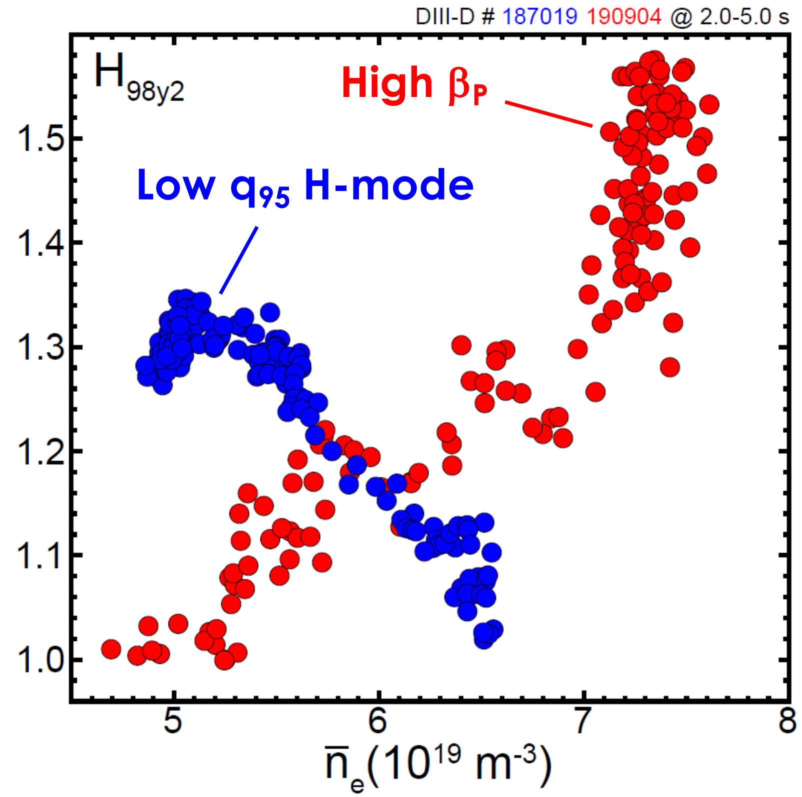
- **Narrow eigenfunction couples poorly to ∇n driven modes**
  - Electrons trapped in large banana orbits
  - Electrons react adiabatically
- **Eventually the turbulence loses free energy drive**

Experiments Confirm High β_P Favorable for Low Turbulence at High Density

Ding, *Invited Talk, APS 2023*



- **High β_P** vs **Low q_{95} H-mode**
  - q_{95}: 8.5 vs 4



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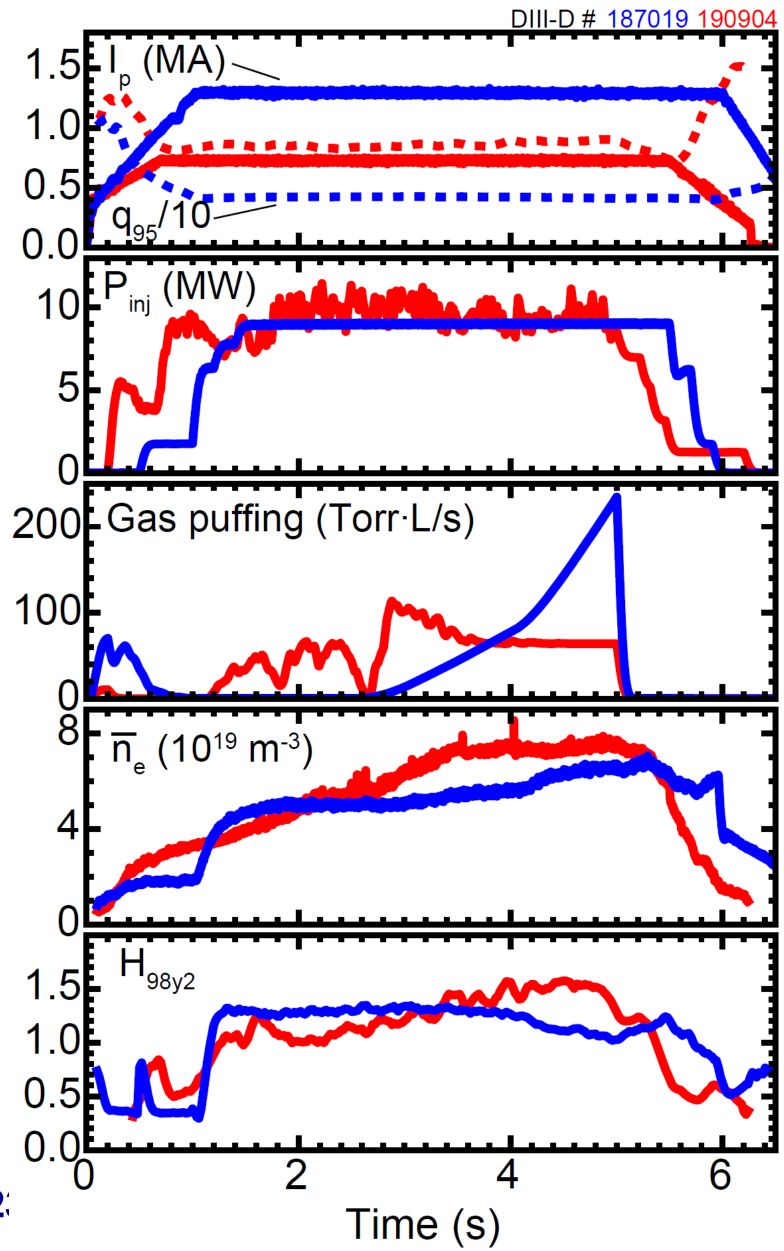
Ding, *Invited Talk, APS 2023*



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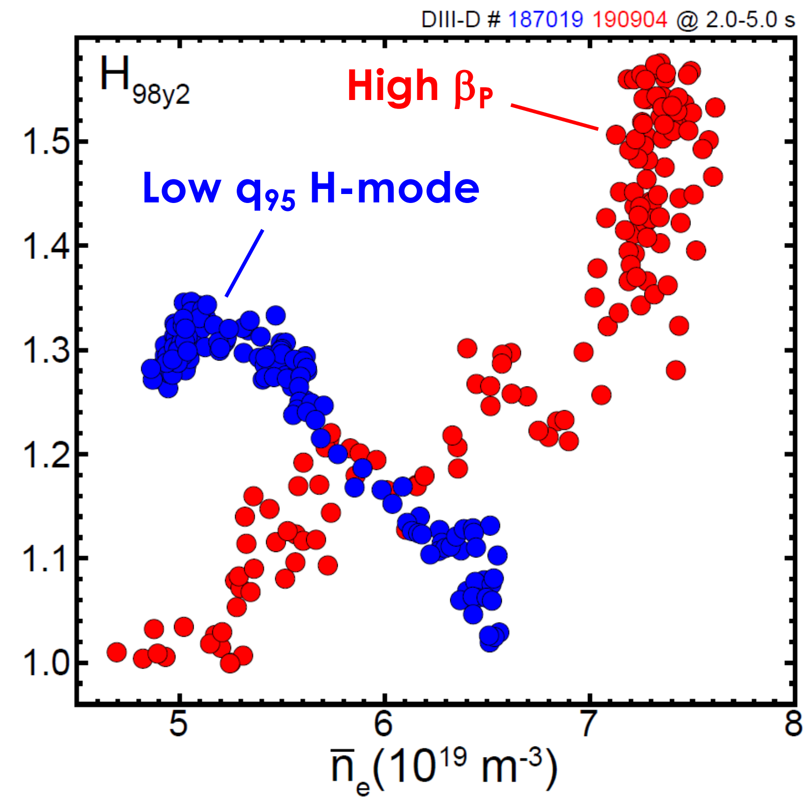
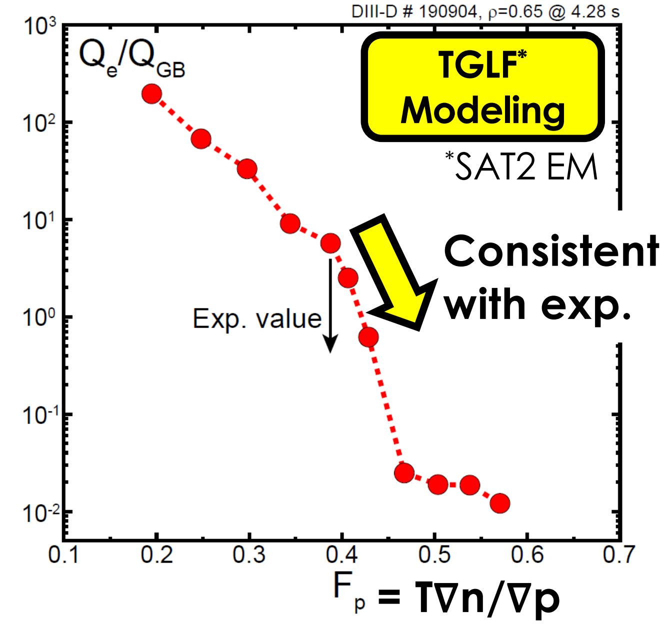
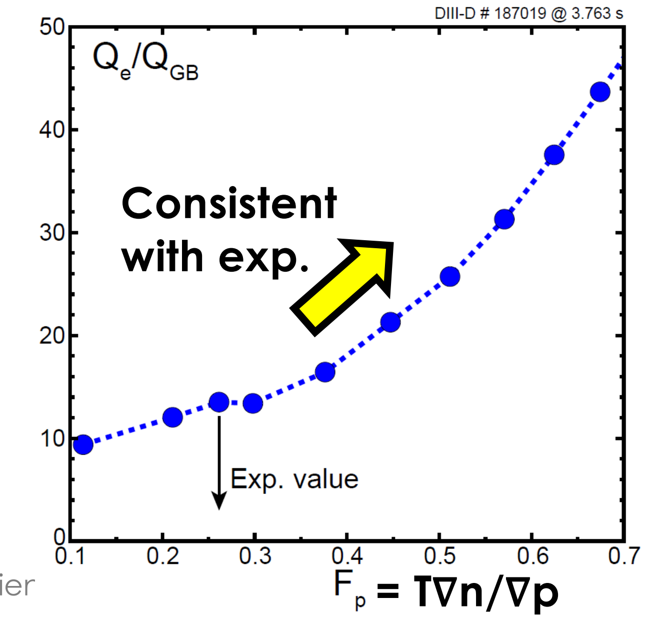


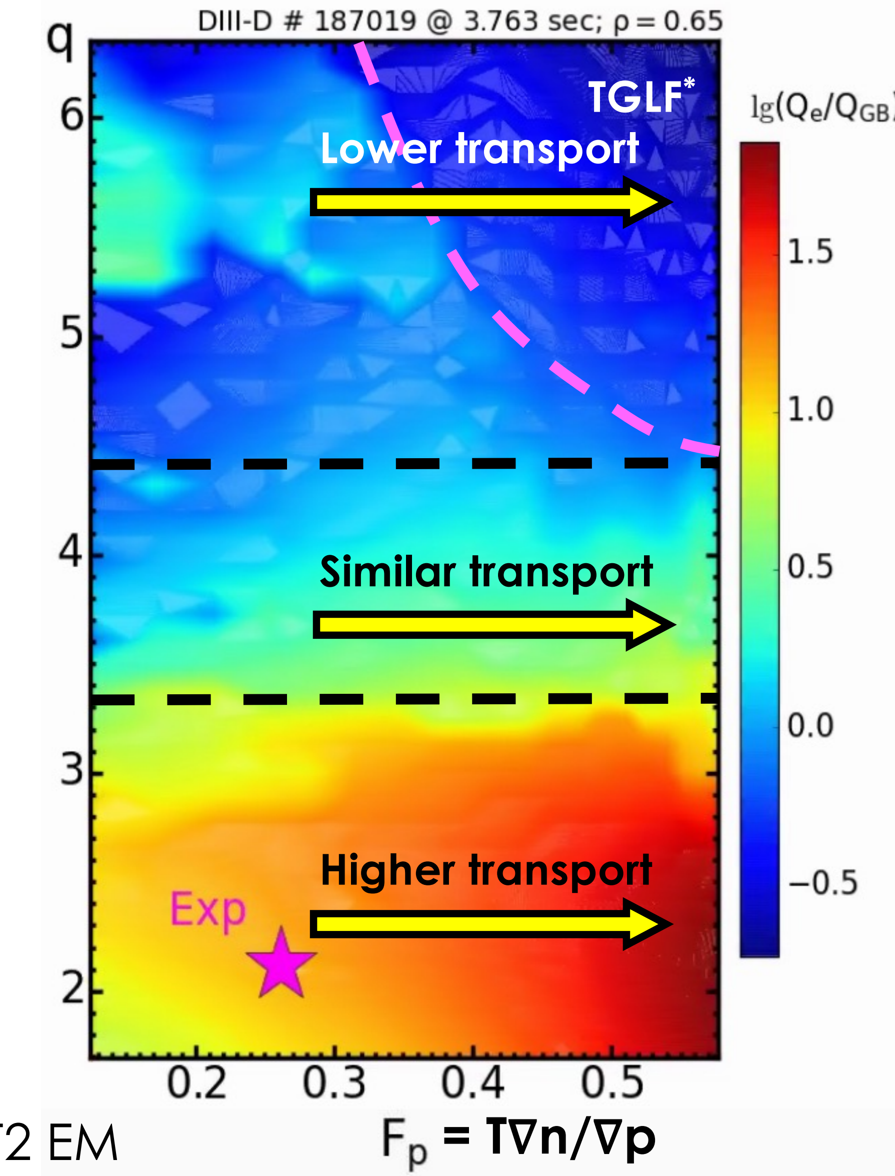
- **TGLF core transport analysis using experimental data**
- **Scan ∇n at constant ∇p to vary F_p**





Dependence of Turbulent Transport on F_p Reverses from Low to High Local q

- **Use low-q experimental data at ρ=0.65**
- **Roughly three regimes**
  - High q: low transport at high F_p
  - Medium q: similar transport at high F_p
  - Low q: high transport at high F_p
- **Stronger α-stabilization effect at high q**
  - α_{MHD}~q^2



Constant ∇T for F_p scan
same magnetic shear

*SAT2 EM

Ding et al, Nature 2024

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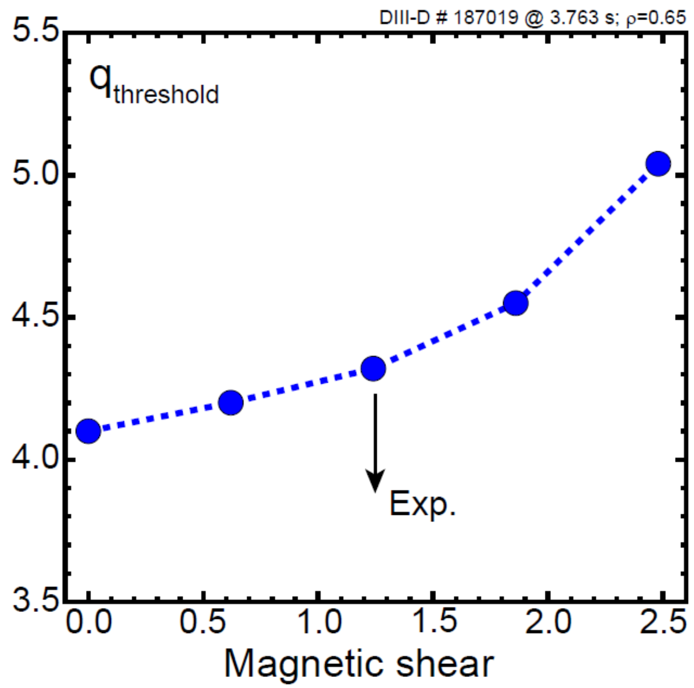
- **Stronger α-stabilization effect at high q**
  - $\alpha_{MHD} \sim q^2$
- **Low magnetic shear lowers q threshold**

Safety factor



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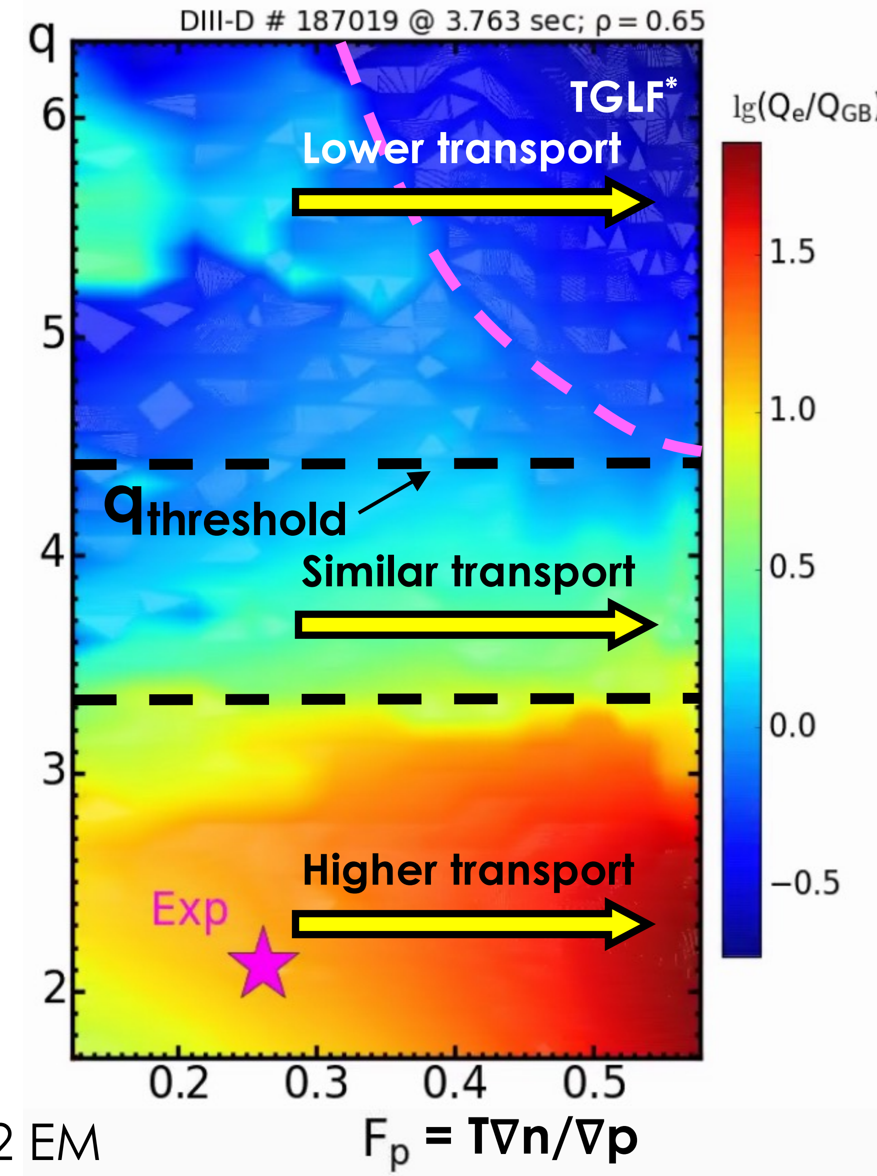

*SAT2 EM

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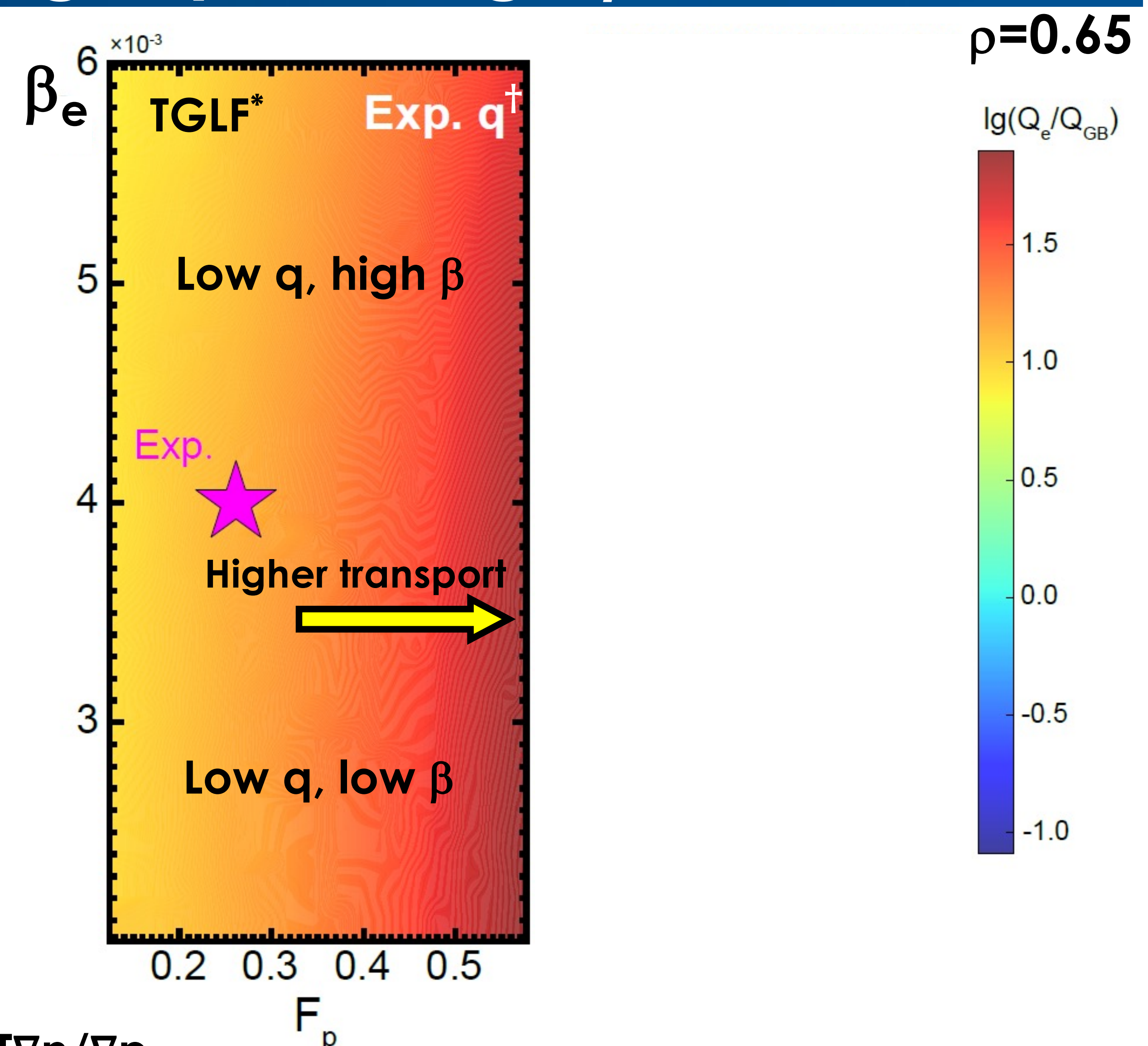
Ding et al, Nature 2024

Reduced Turbulence Transport at High Density Gradient Only Predicted at High q and High β

- **At low-q, transport increases with F_p for all tested β_e**

Ding, *Invited Talk*, APS 2023



*SAT2 EM

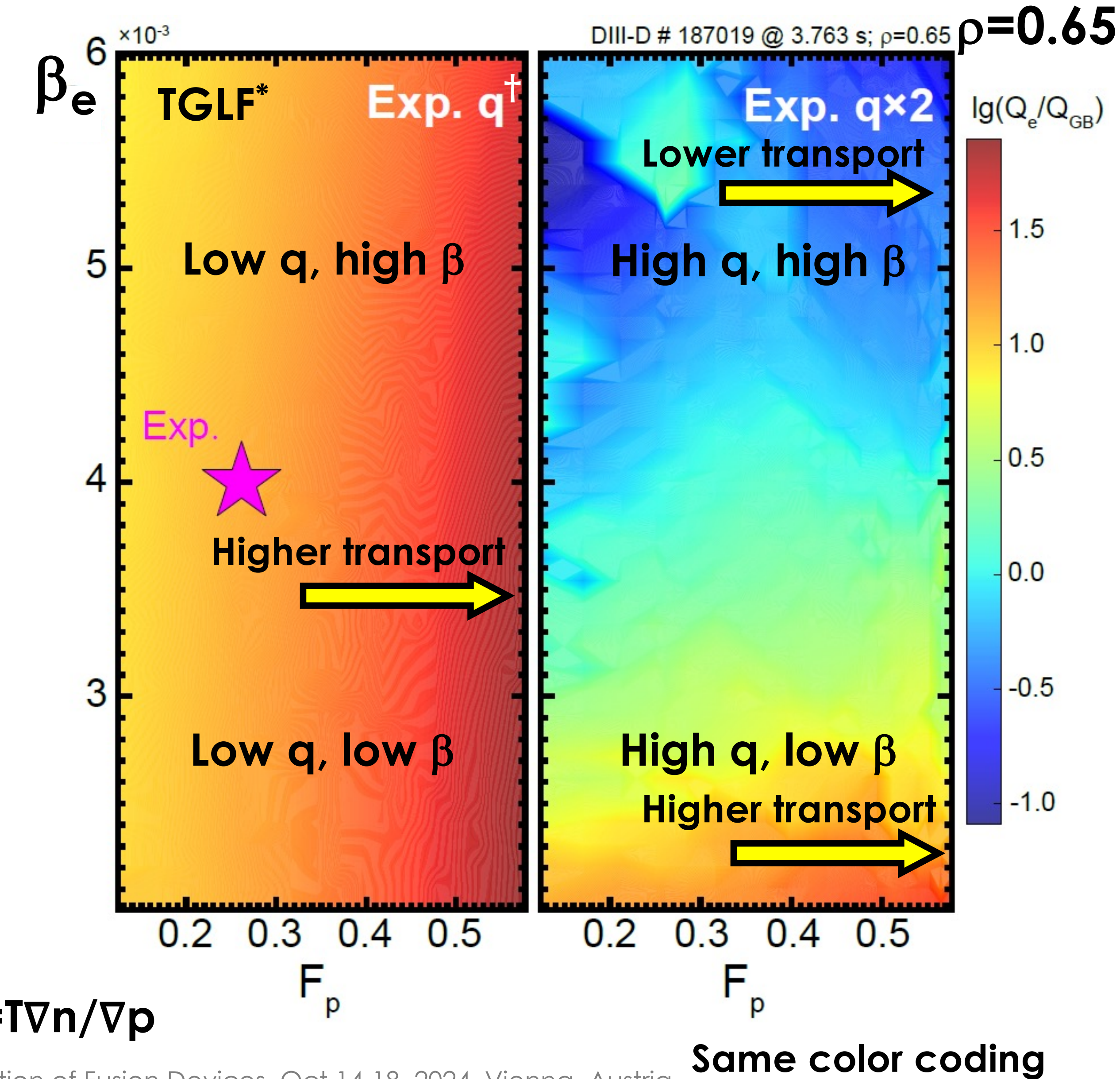
†Local q_{exp}=2.12

$F_p = T\nabla n/\nabla p$

Reduced Turbulence Transport at High Density Gradient Only Predicted at High q and High β

- **At low-q, transport increases with F_p for all tested β_e**
- **At high-q, higher turbulence transport at higher F_p, if β_e is low**

Ding, *Invited Talk*, APS 2023



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$F_p = T\nabla n/\nabla p$

Favorable conditions for accessing <u>low transport at high density</u> (simultaneous f_{Gr}>1 and H_{98y2}>1):

High Local q, high β (→high α_{MHD}) and low magnetic shear

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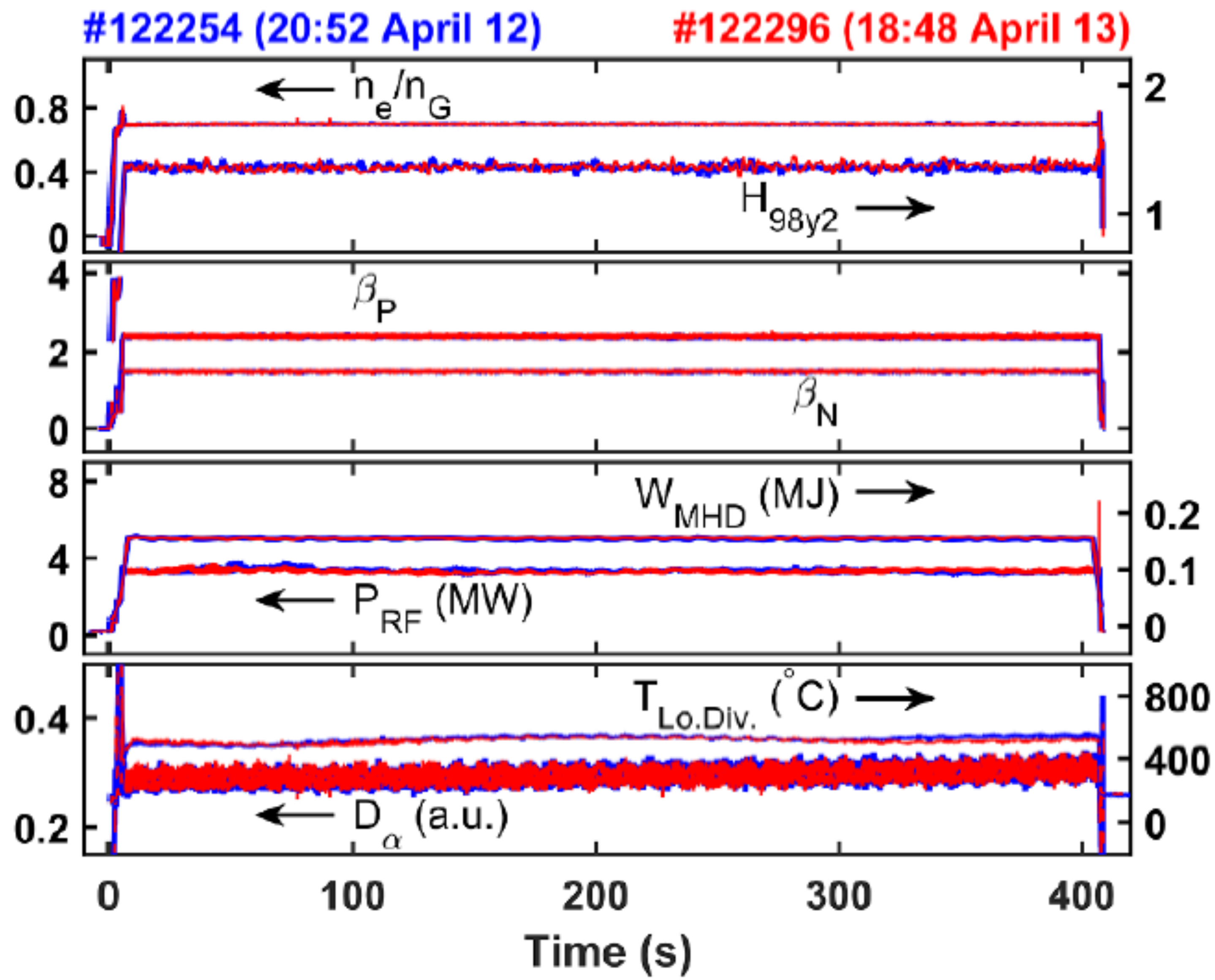
EAST Long-pulse Plasmas Are a Version of High-β_P Scenario

- **EAST achieved for 403 s H-mode with β_P ~2.5 and f_{Gr}~0.7 using only RF power**

Gong et al, Nucl. Fusion 2024



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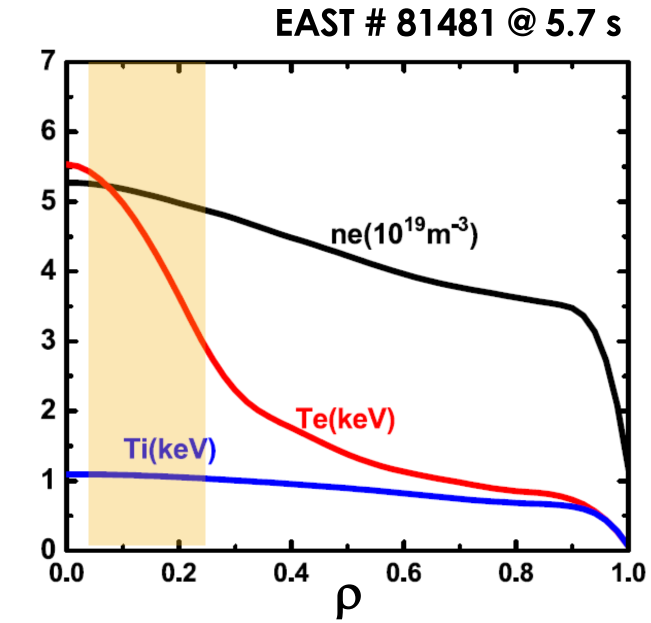
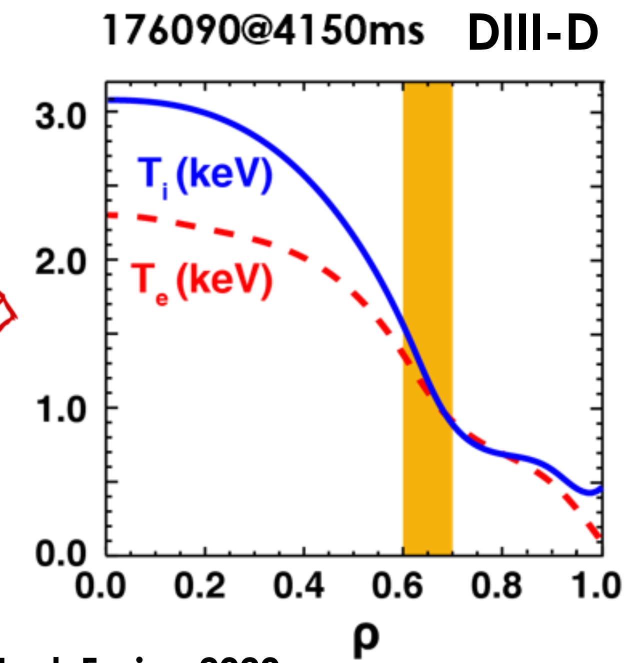
EAST High β_P Plasma Has Comparable β_P to DIII-D Case, but No Large-Radius ITB

- **Scientific challenges:**
  - T_e ITB at small radius
  - $T_i << T_e$ (Long-standing limitation)
- **Important to understand how to increase pressure gradient at mid-radius**
  - Turbulence transport?
  - Not enough power?
    - 3.25 MW in the discharge in this slide
- **Use four different codes to understand/predict how to improve this**



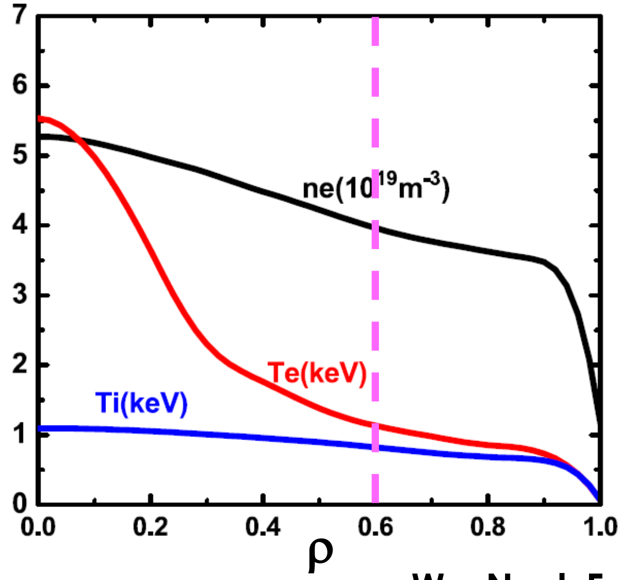
Wu, Nucl. Fusion 2019



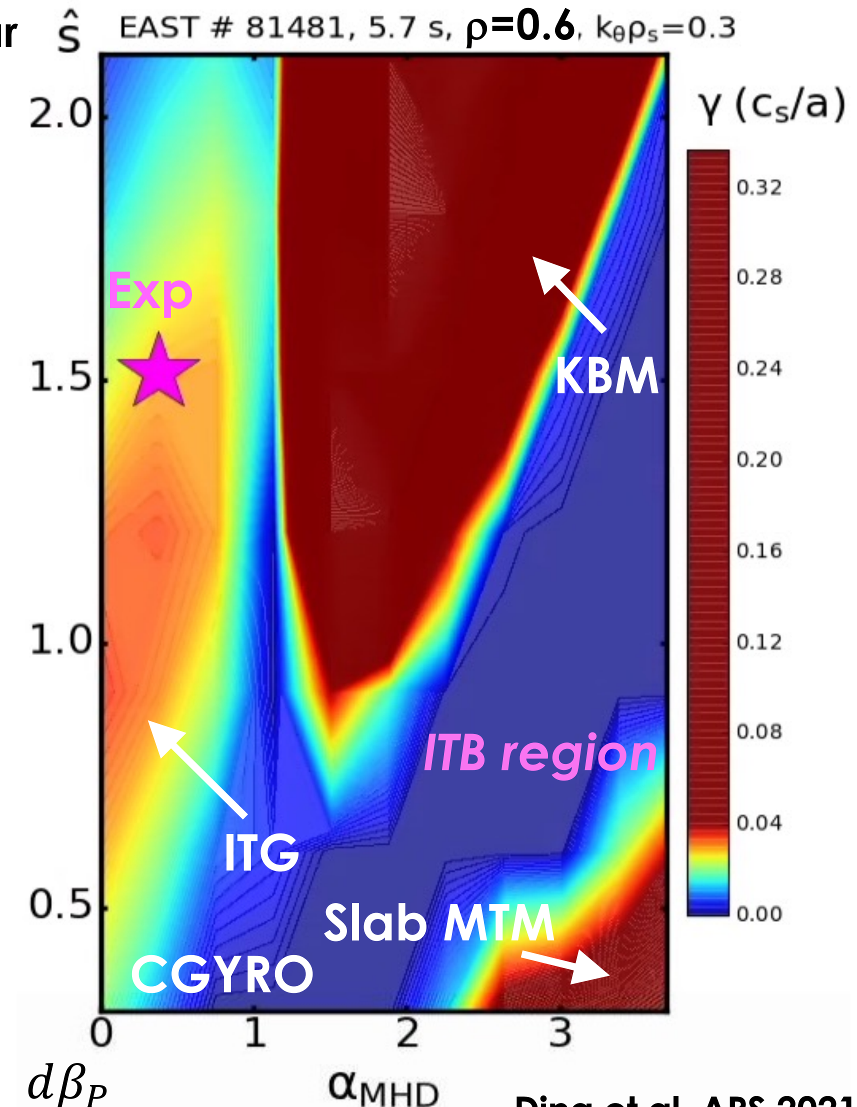
Huang, Nucl. Fusion 2020

	EAST	DIII-D
q_{95}	6.5-11	6-12
β_P	1.95-4.2	1.7-3.5
ρ_{ITB}	0.3	0.6-0.8

Ion Temperature Gradient (ITG) Instability is Dominant at Mid-Radius in EAST Plasma



Wu, Nucl. Fusion 2019



Ding et al, APS 2021

- **Gyrokinetic simulations using CGYRO**
- **Exp. equilibrium 'Trapped' in an ITG mountain**
  - Reduced magnetic shear could avoid ITGs

$$\alpha_{\text{MHD}} \sim -\frac{q^2}{B^2} R \frac{dp}{dr} \sim \frac{d\beta_P}{dr}$$

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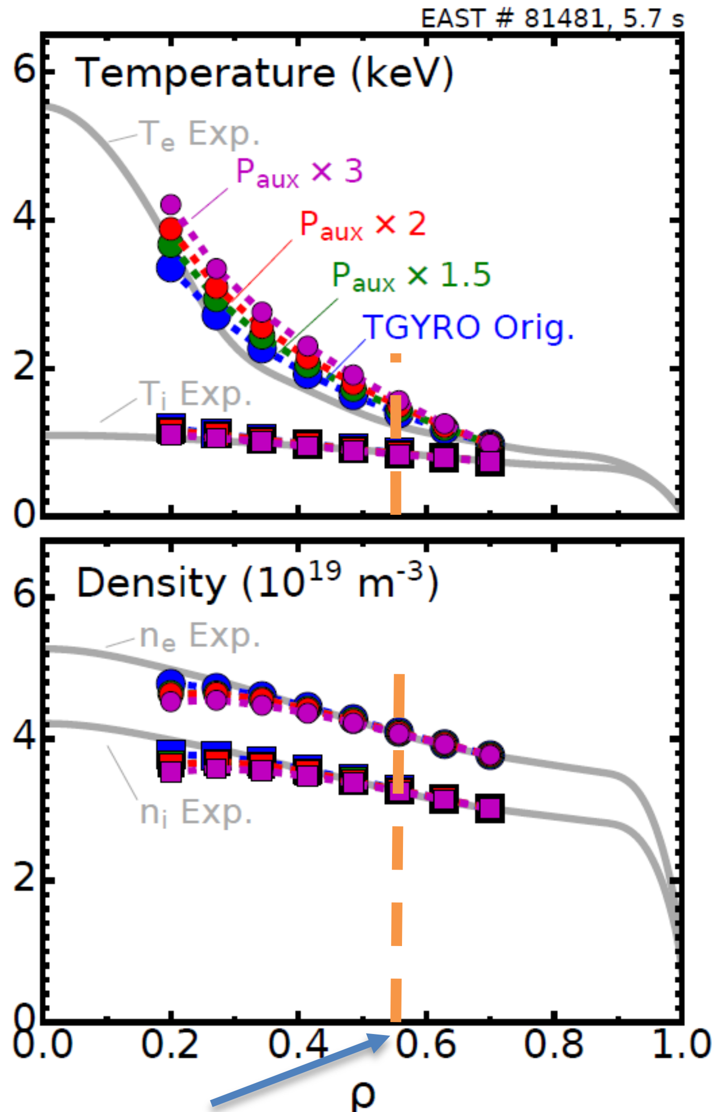
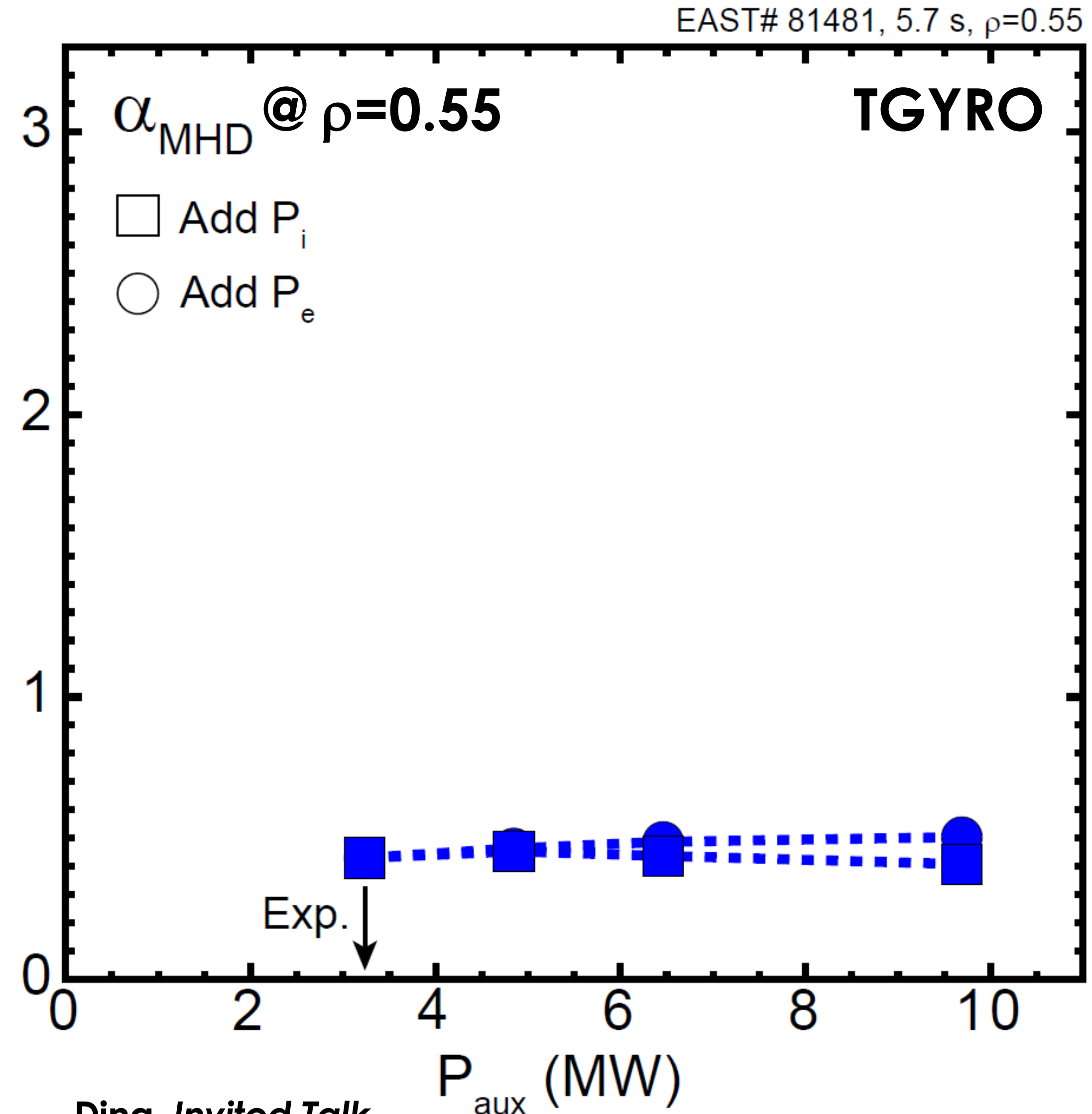
ASIPP

Transport Modeling Suggests Adding Power Alone Cannot Increase Core Pressure Gradient

- **TGYRO+TGLF*** **reproduces experimental profiles**
  - Predict T_e, T_i and n_e
- **Power scan up to 3×**
  - More P_e or P_i



Focus on ρ=0.55

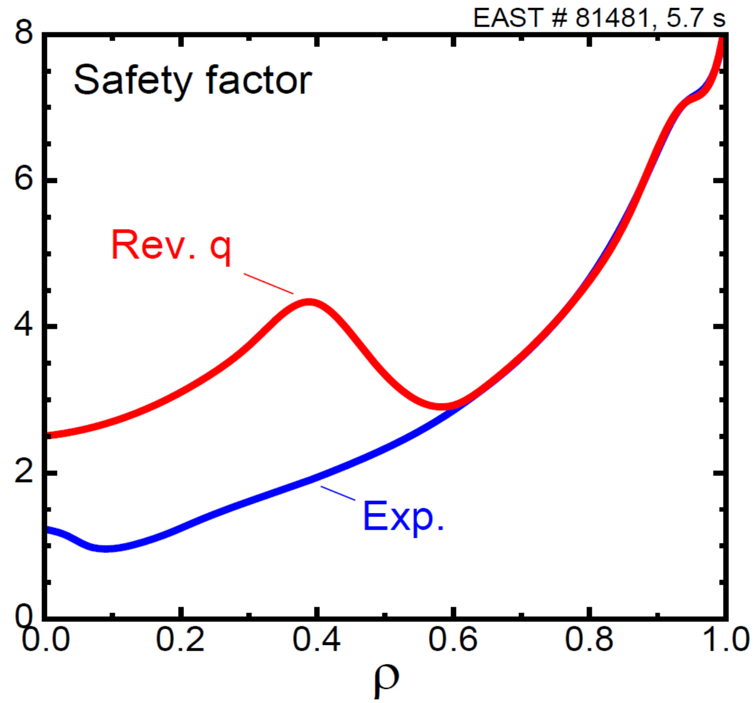


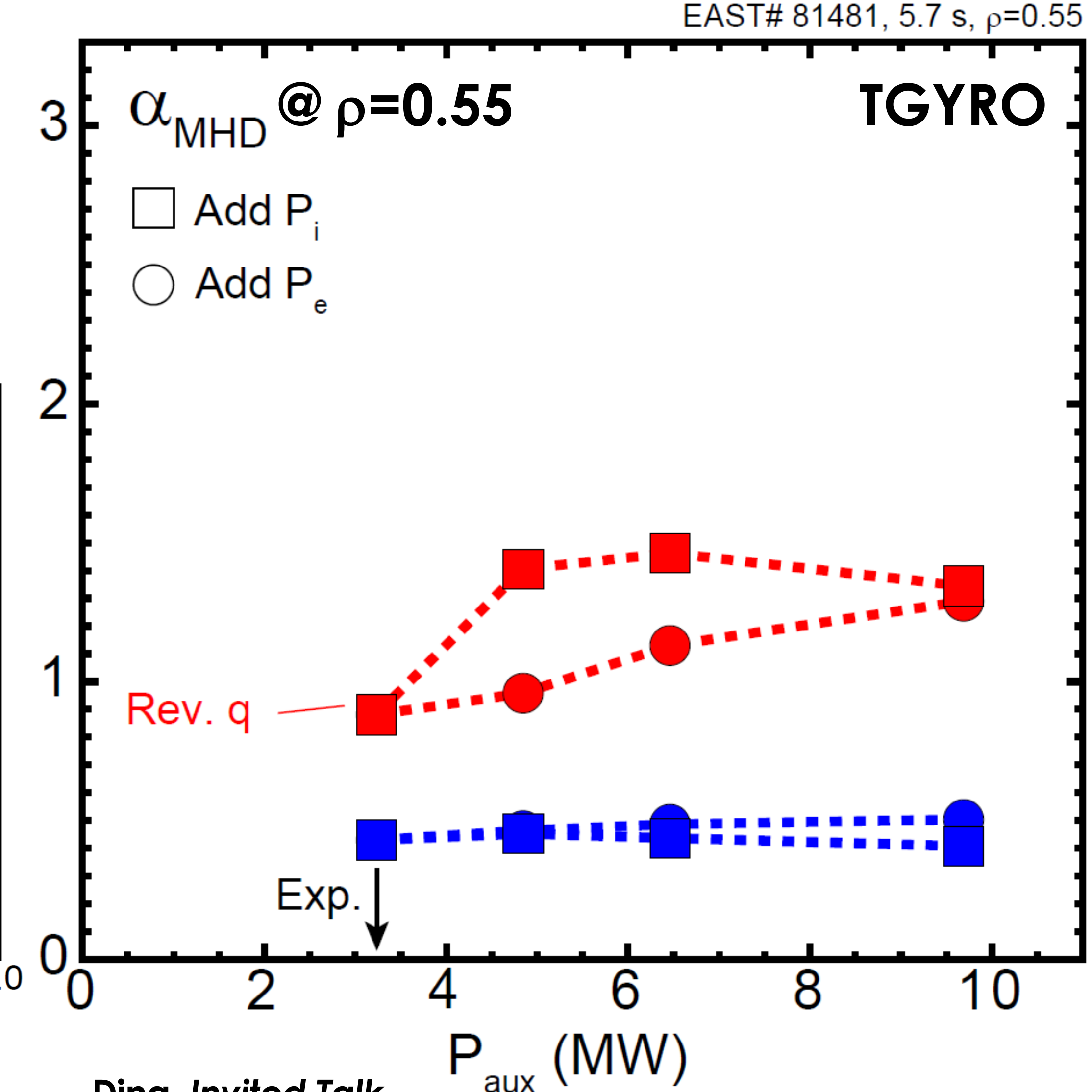
Ding, *Invited Talk*, APS 2023

*: SAT-0 EM

Transport Modeling Suggests Improved Normalized Pressure Gradient at Mid-Radius with Higher q_{min}

- **TGYRO+TGLF* reproduces experimental profiles**
  - Predict T_e, T_i and n_e
- **Power scan up to 3×**
  - More P_e or P_i
- **Reduced magnetic shear at large radius**



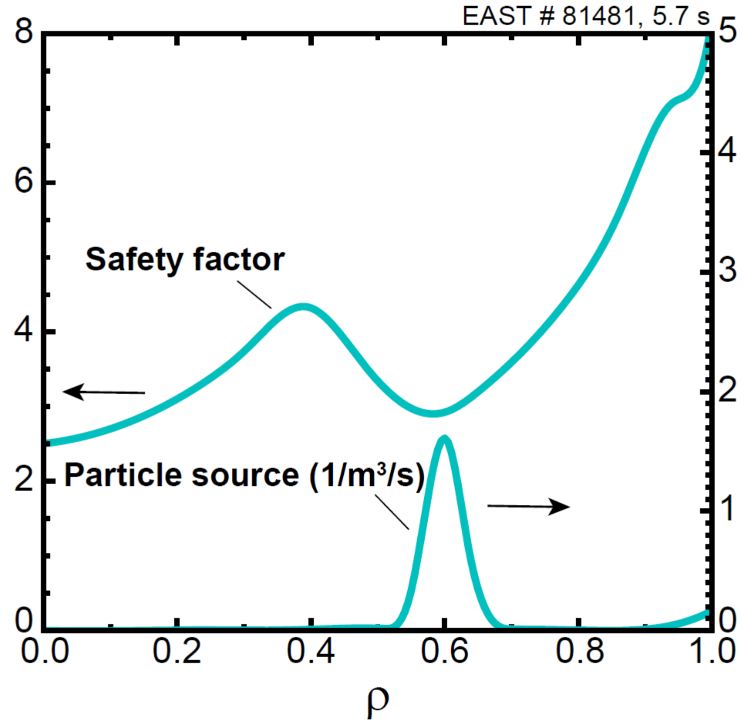


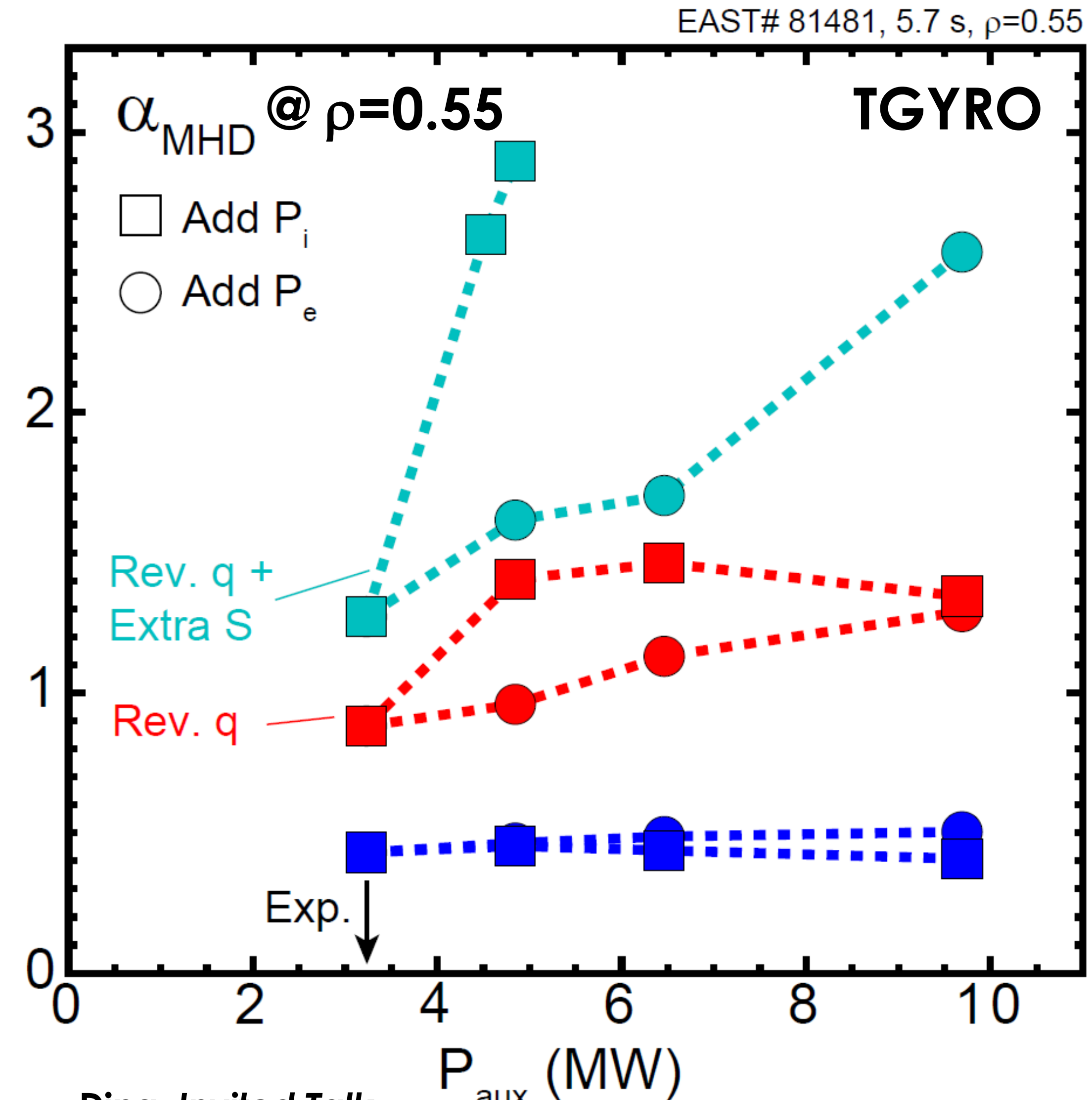
Ding, *Invited Talk*, APS 2023

*: SAT-0 EM

Transport Modeling Suggests Strong α_{MHD} Improvement at Mid-Radius with Combined Actuators

- **TGYRO+TGLF*** **reproduces experimental profiles**
  - Predict T_e, T_i and n_e
- **Power scan up to 3×**
  - More P_e or P_i
- **Reduced magnetic shear at large radius**
- **Add particle source at large radius**





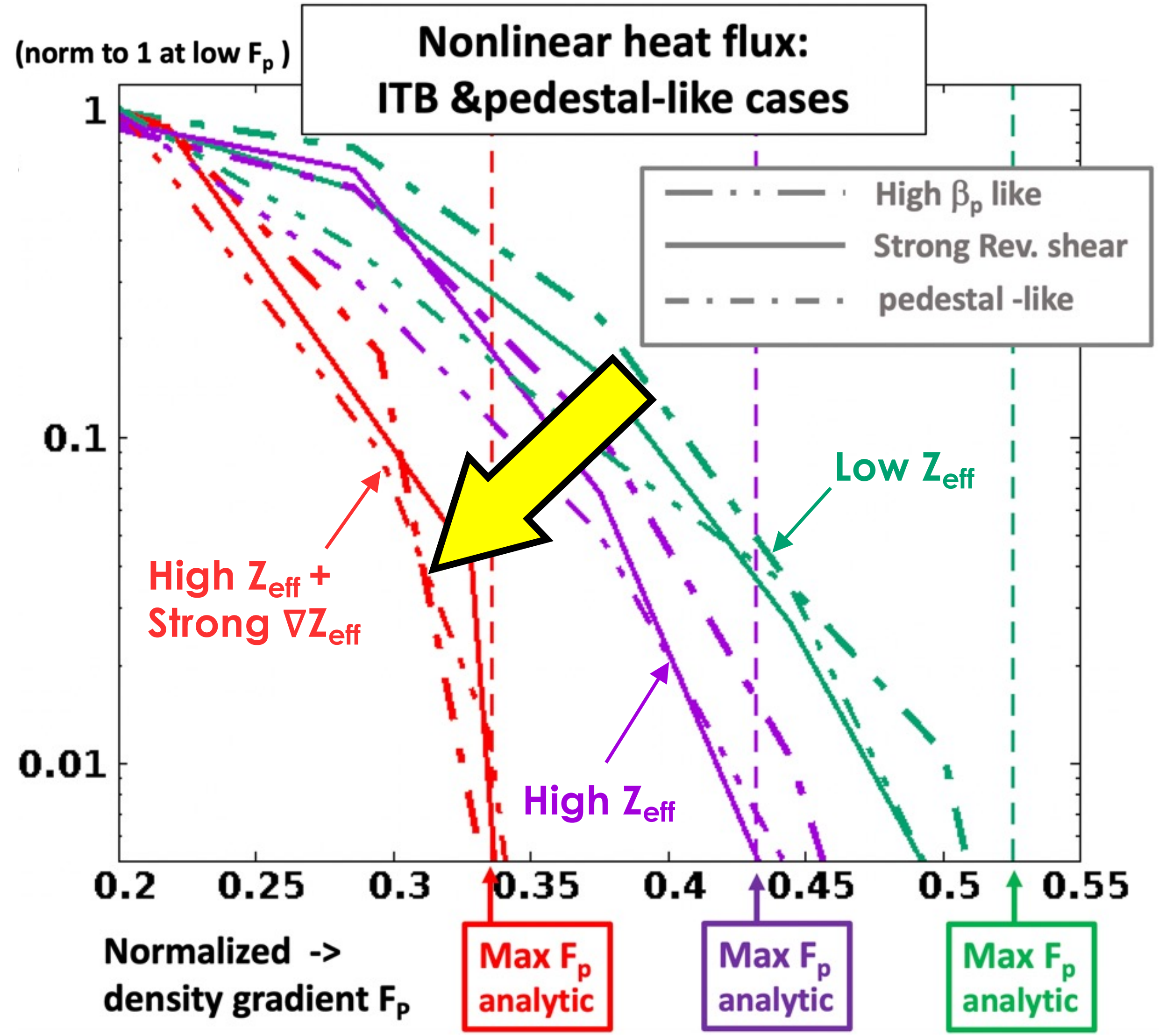
Ding, *Invited Talk*, APS 2023

*: SAT-0 EM

High Density Gradient, High Z_{eff} and High Z_{eff} Gradient Expected to Suppress Turbulent Transport

- GENE nonlinear modeling
- High F_p can suppress turbulent heat flux
- Increase Z_{eff} enhances the suppression effect

- Suggests experimental approach: impurity injection at large radius



Kotschenreuther et al, Nucl. Fusion 2024

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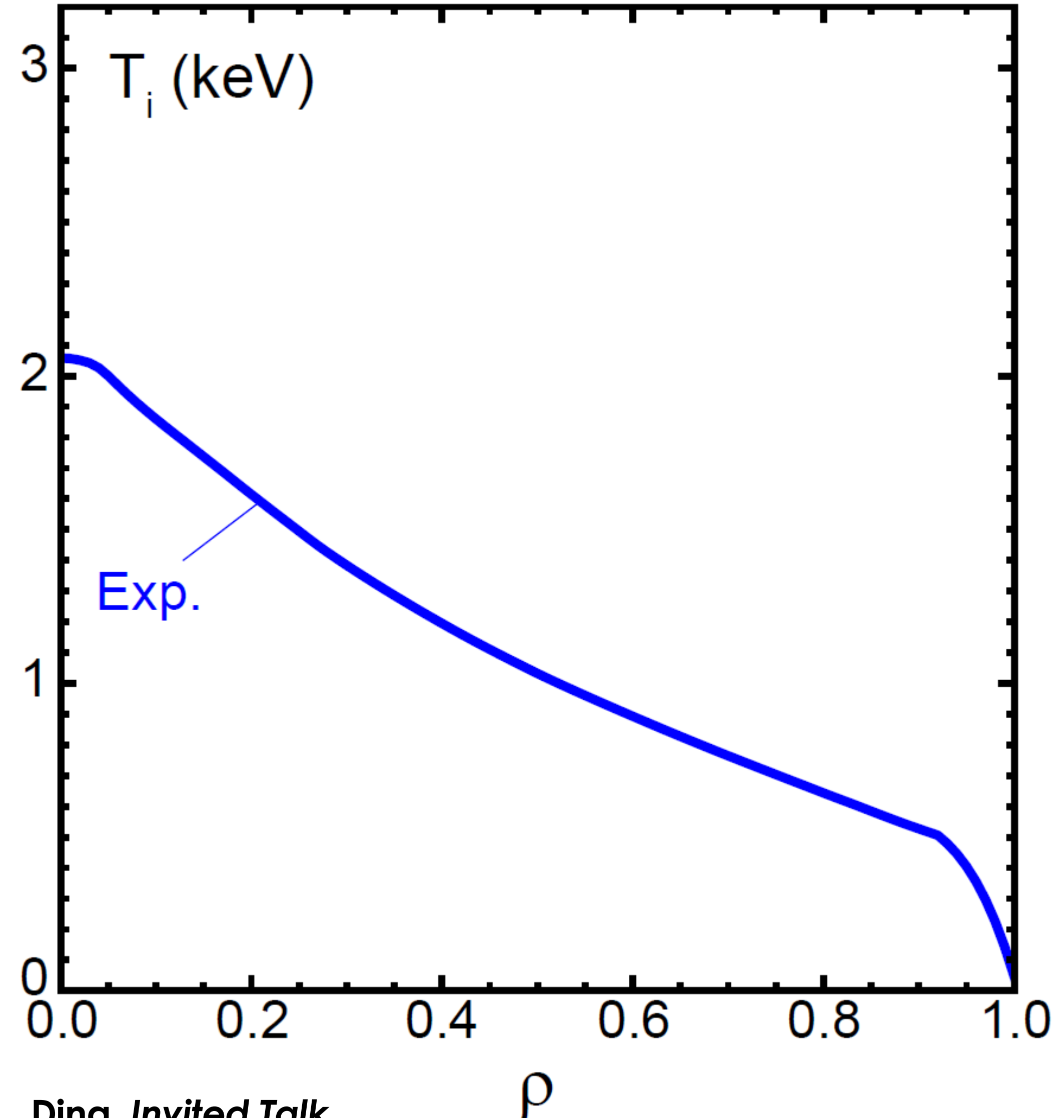
ASIPP

Time-Dependent Modeling Suggests Highest T_i with Combined Actuators

- **FASTRAN+TGLF*, EAST experimental data† as starting point**
  - T, n predictions



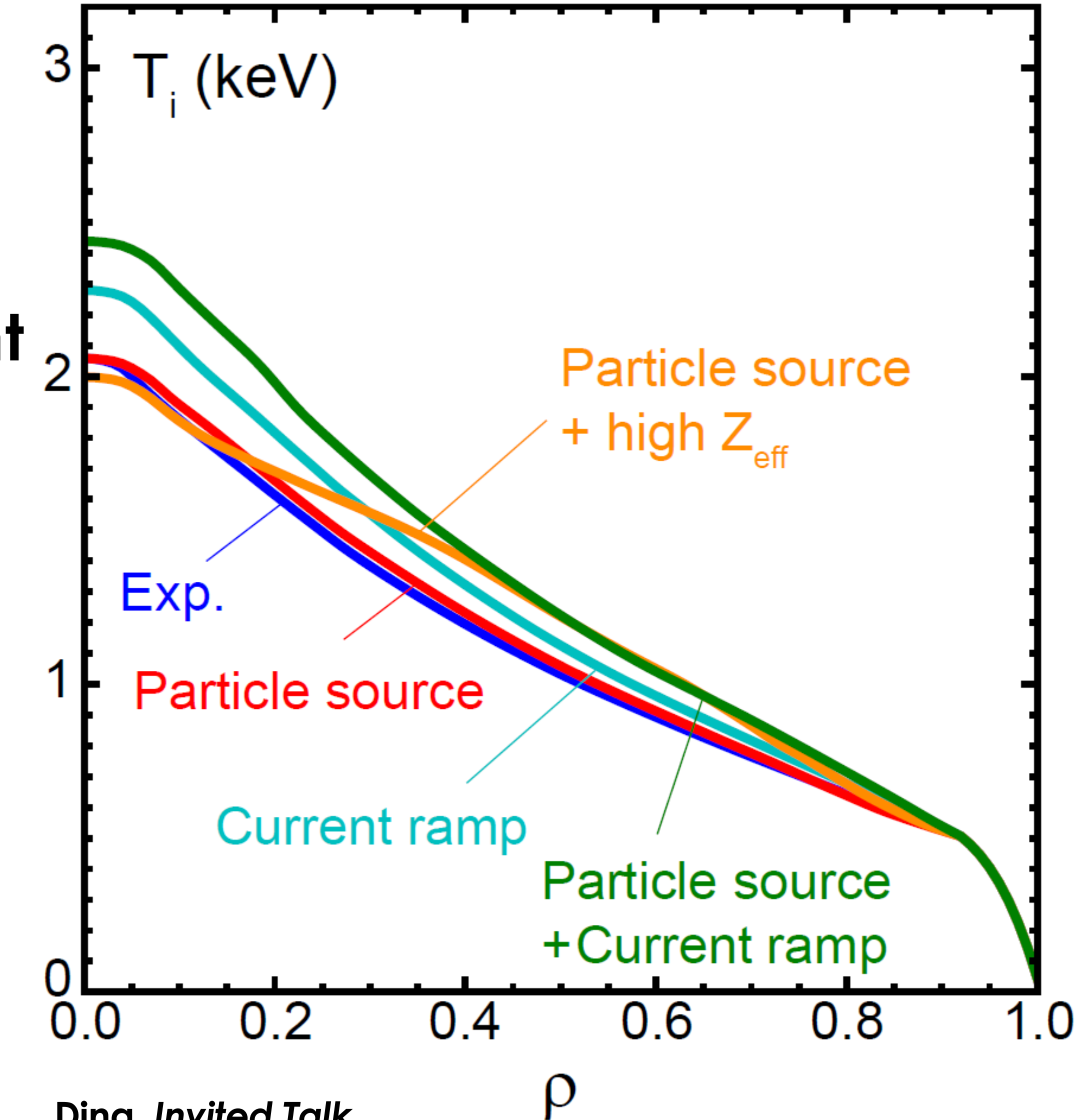
Ding, *Invited Talk*, APS 2023

*SAT2 EM

†B_T=2.5 T, I_p=0.37 MA, P_{NBI}=2.5 MW, P_{RF}=6 MW

Time-Dependent Modeling Suggests Highest T_i with Combined Actuators

- **FASTRAN+TGLF*, EAST experimental data† as starting point**
  - T, n predictions
- **Modeling approaches for better confinement**
  - Particle source: increase density gradient
  - Current ramp: reduce magnetic shear
  - Higher Z_{eff}: mimic impurity injection



Ding, *Invited Talk*, APS 2023

*SAT2 EM
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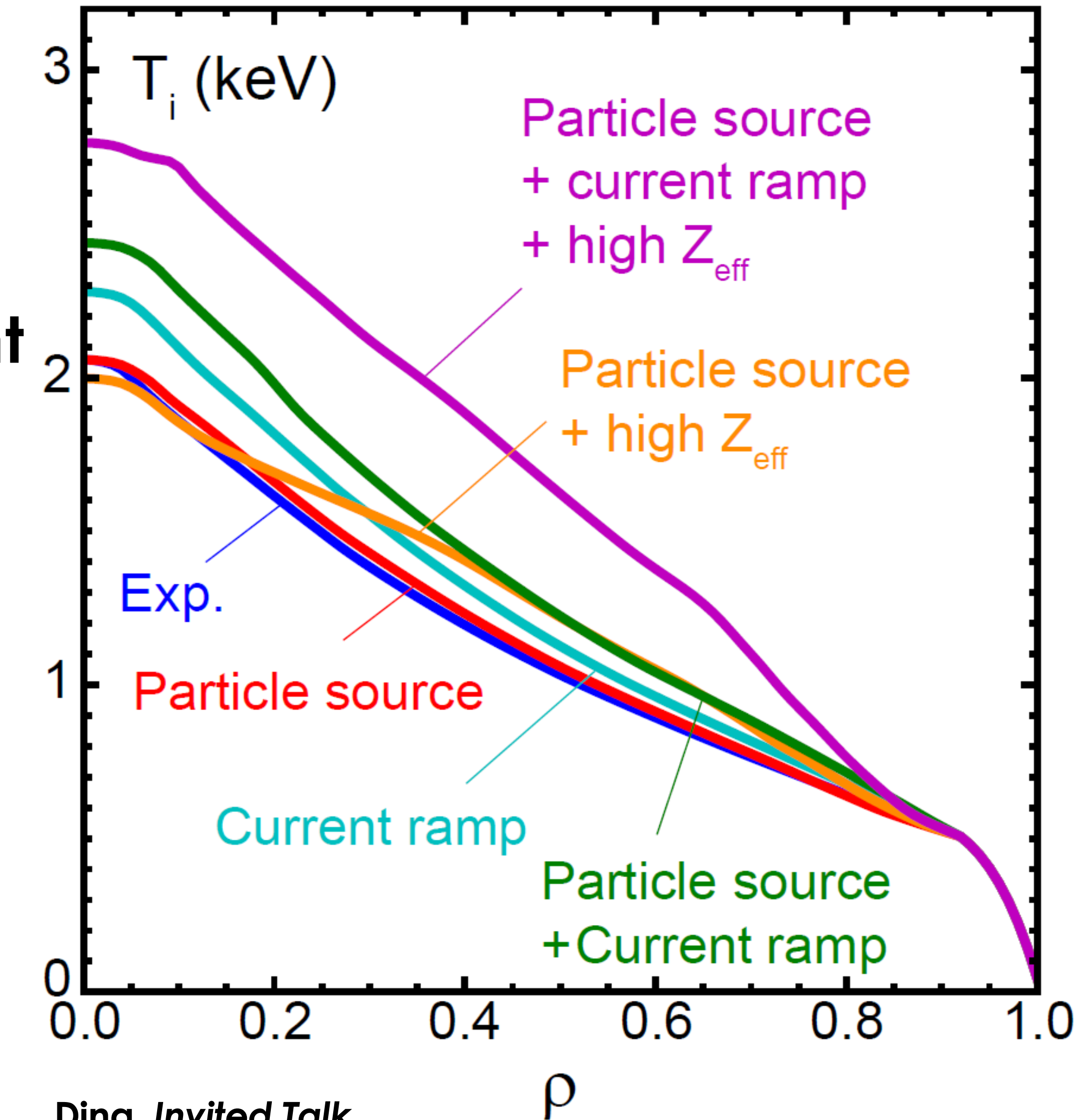
Time-Dependent Modeling Suggests Highest T_i with Combined Actuators

- **FASTRAN+TGLF*, EAST experimental data† as starting point**
  - T, n predictions
- **Modeling approaches for better confinement**
  - Particle source: increase density gradient
  - Current ramp: reduce magnetic shear
  - Higher Z_{eff}: mimic impurity injection
  - **Combinations of the above**

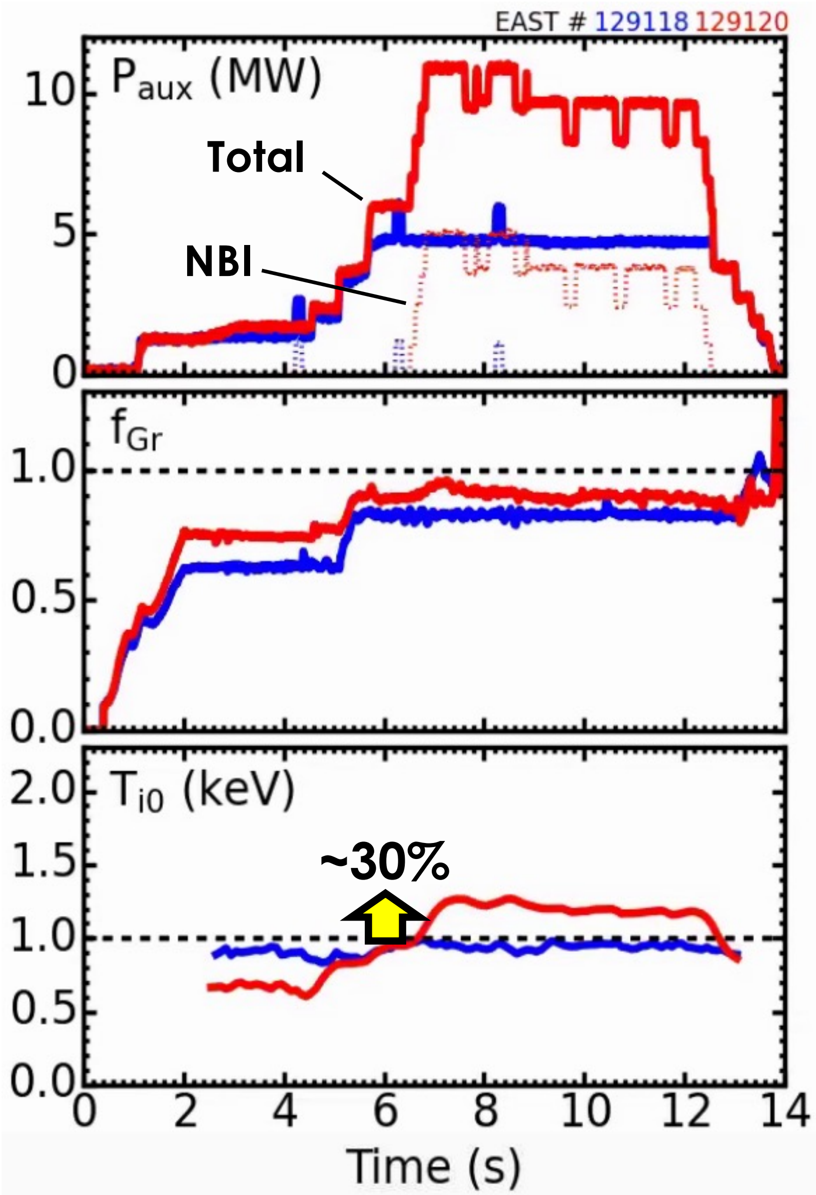


Experiment proposal developed based on the guidance of all modeling results

Ding, *Invited Talk*, APS 2023

*SAT2 EM
†B_T=2.5 T, I_p=0.37 MA, P_{NBI}=2.5 MW, P_{RF}=6 MW

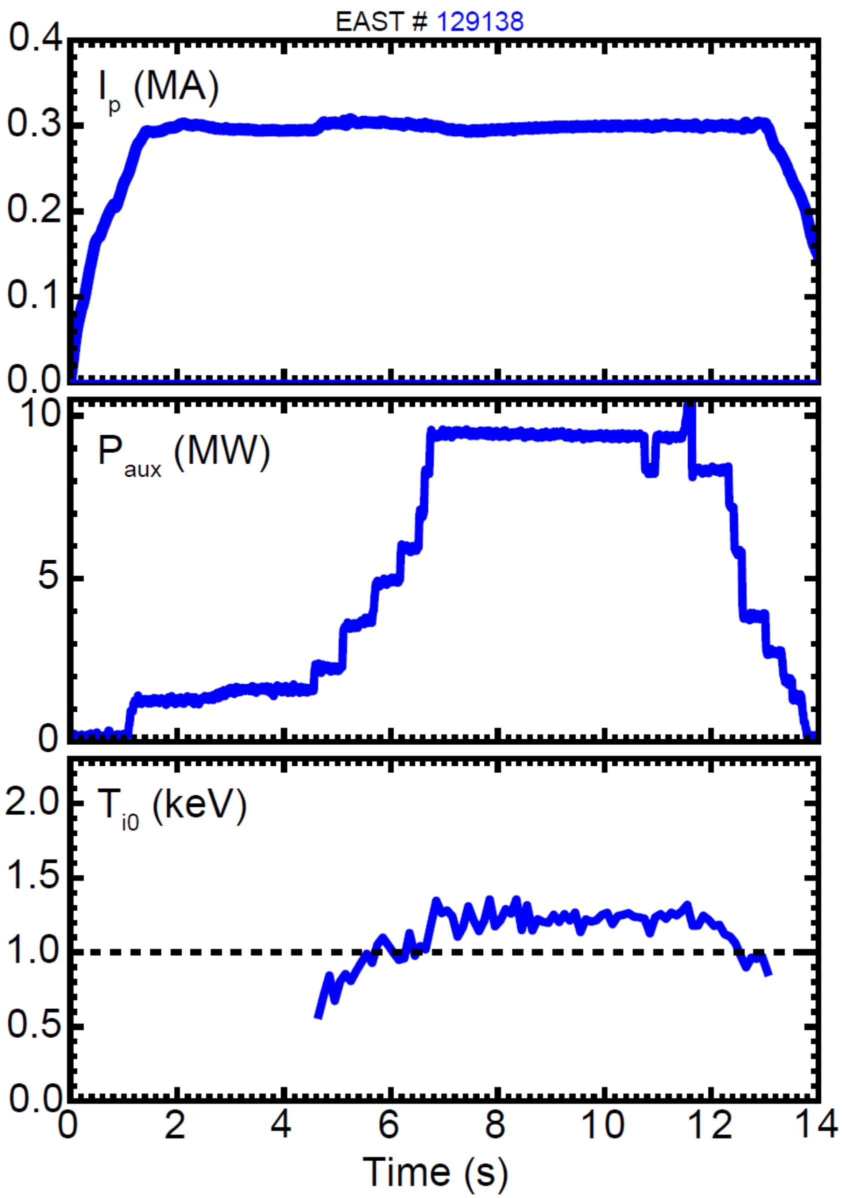
Doubled Input Power Shows Small T_{i0} Increase



- **Power level from 4.8 MW to 10.9 MW**
- **30% increase in T_{i0}**
- **Confirms the previous transport modeling result about limited effect of increasing power alone**
- **Need to incorporate other physics for turbulence suppression**
  - Follows the guidance of transport modeling

Ding, *Invited Talk,* APS 2023

Nearly Doubled T_i Achieved by Combination of 2nd I_p Ramp-Up and Ar Injection at f_{Gr}~0.9



Ding, *Invited Talk,* APS 2023

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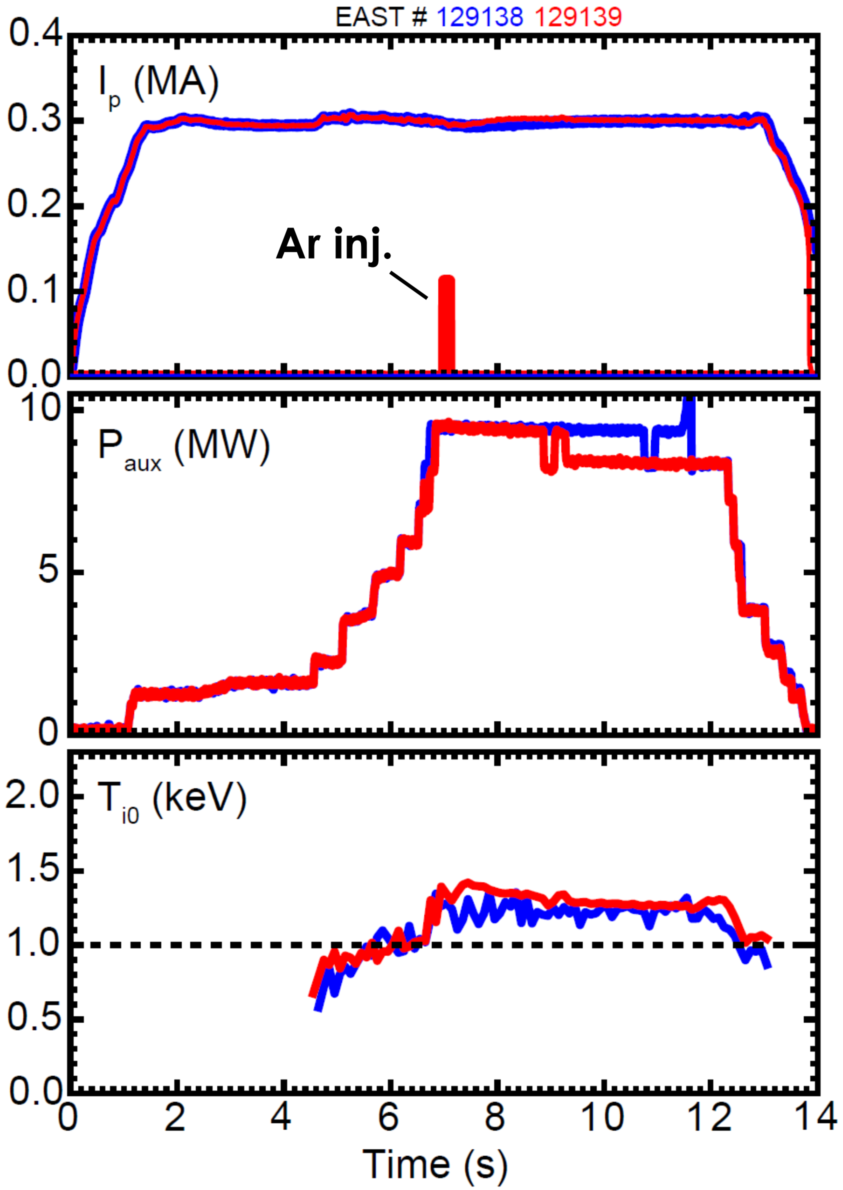

- **Ar injection: small increase of T_i**

Ding, *Invited Talk,* APS 2023

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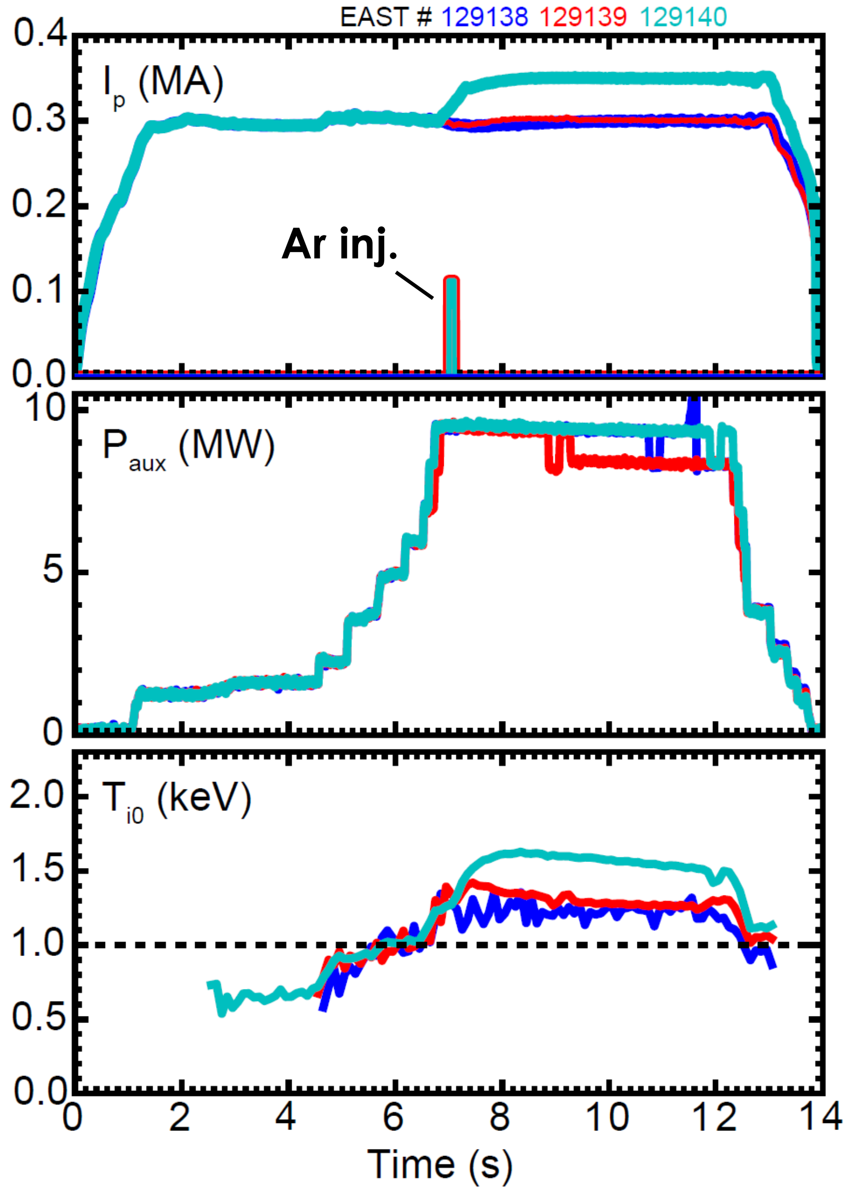
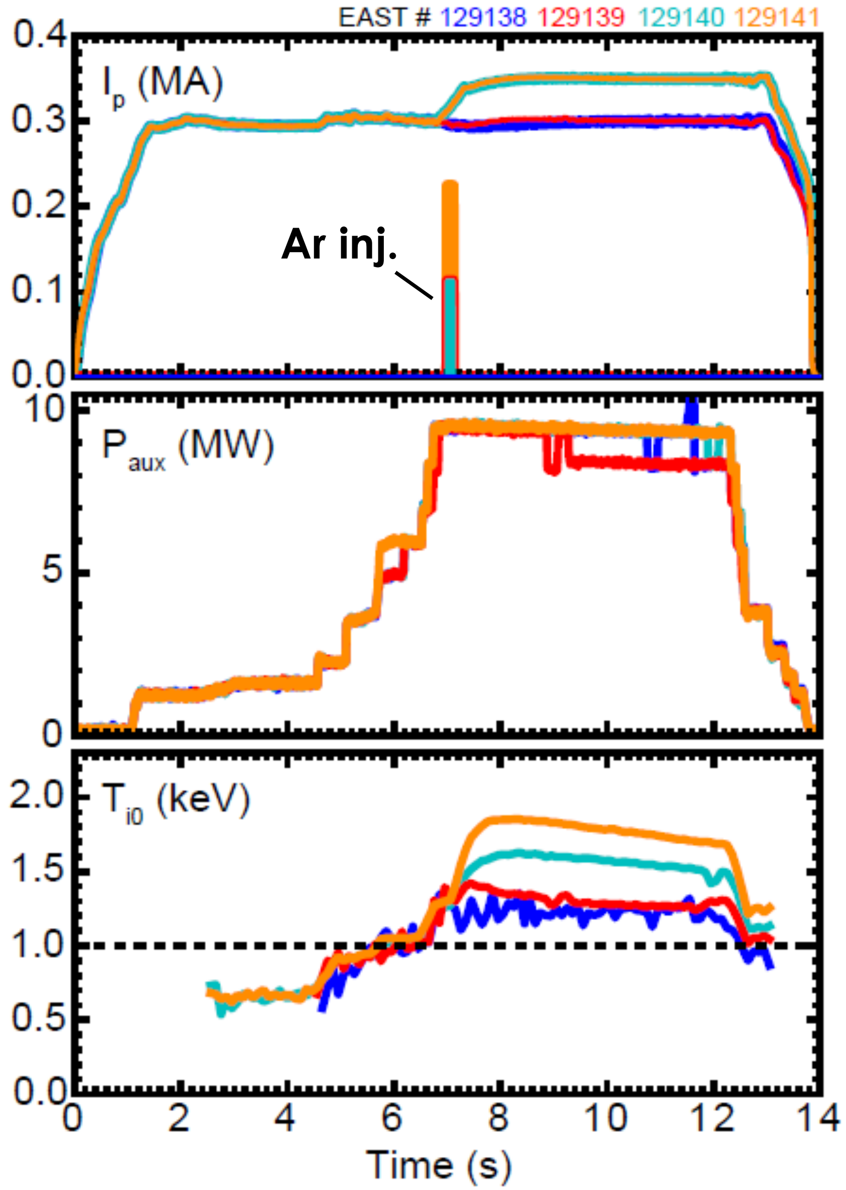


- **Ar injection: small increase of T_i**
- **Add 2nd I_p ramp-up: further improved T_i**

Ding, *Invited Talk,* APS 2023

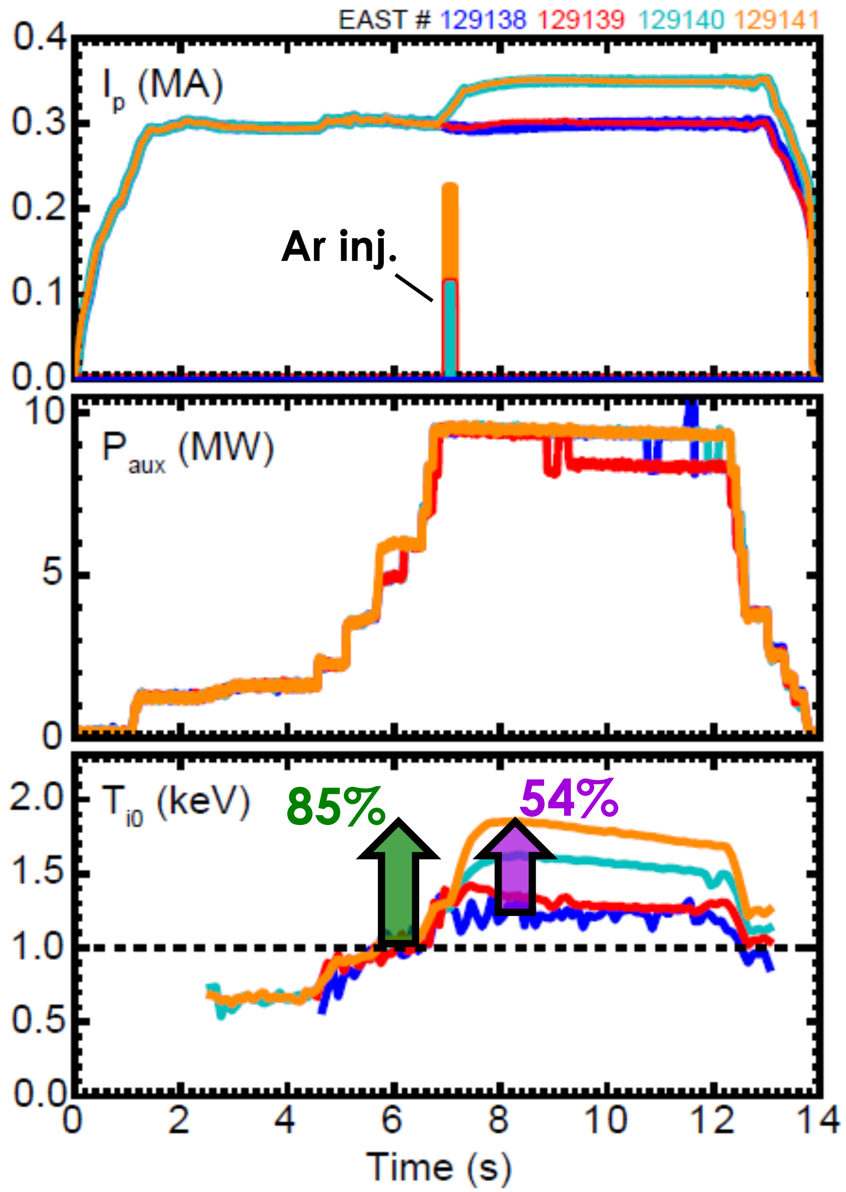
Nearly Doubled T_i Achieved by Combination of 2nd I_p Ramp-Up and Ar Injection at f_{Gr}~0.9



- **Ar injection: small increase of T_i**
- **Add 2nd I_p ramp-up: further improved T_i**
- **Increase Ar amount: highest T_i**
  - Add 2nd Ar injector, total amount doubled

Ding, *Invited Talk,* APS 2023

Nearly Doubled T_i Achieved by Combination of 2nd I_p Ramp-Up and Ar Injection at f_{Gr}~0.9



- **Ar injection: small increase of T_i**
- **Add 2nd I_p ramp-up: further improved T_i**
- **Increase Ar amount: highest T_i**
  - Add 2nd Ar injector, total amount doubled
- **Confirms transport modeling results on the best turbulence suppression by the combined actuators**

Ding, *Invited Talk,* APS 2023

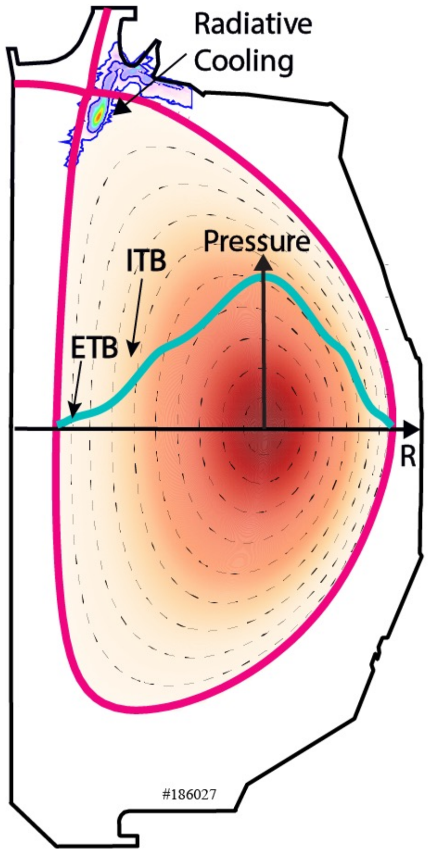
ASIPP

Outline

- On the performance requirements for steady-state fusion pilot plants (FPPs) and for ITER Q=10 P_{fus}=500 MW operation at reduced I_p
- DIII-D high-β_P experiments and transport analysis
- Simulations of EAST high-β_P plasmas and theory-guided expe
- **Core-edge integration in DIII-D high-β_P plasmas**
  - No large ELMs
  - Divertor detachment

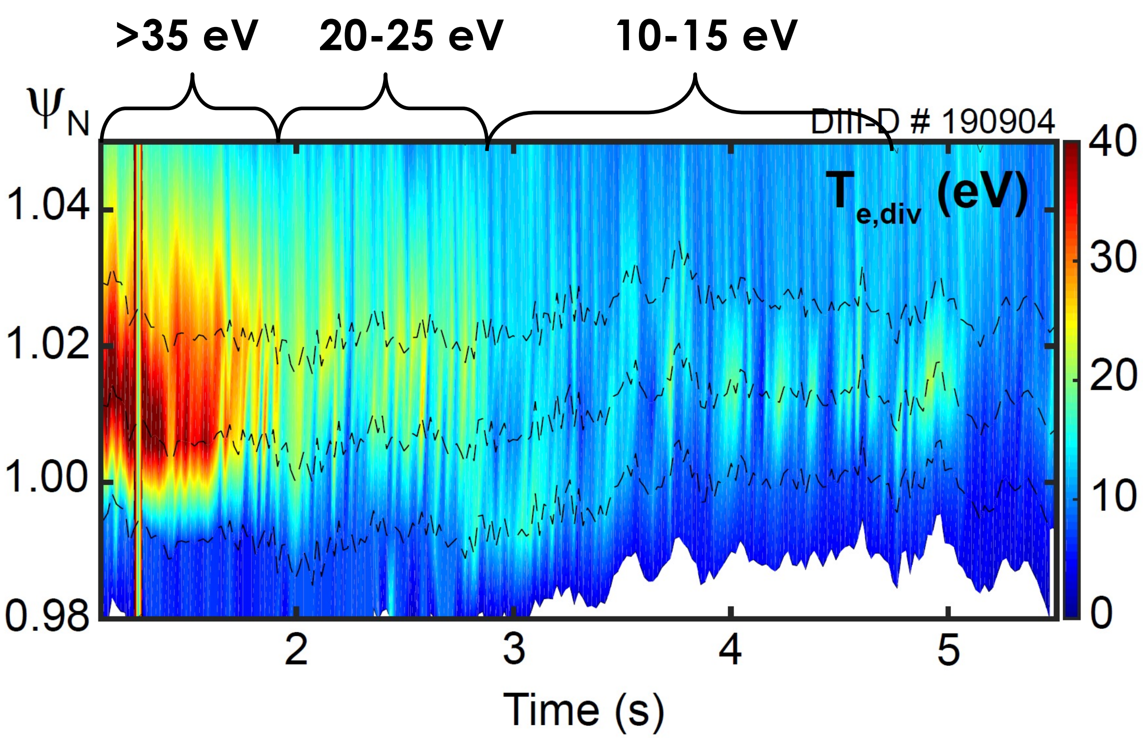
  } + high confinement quality

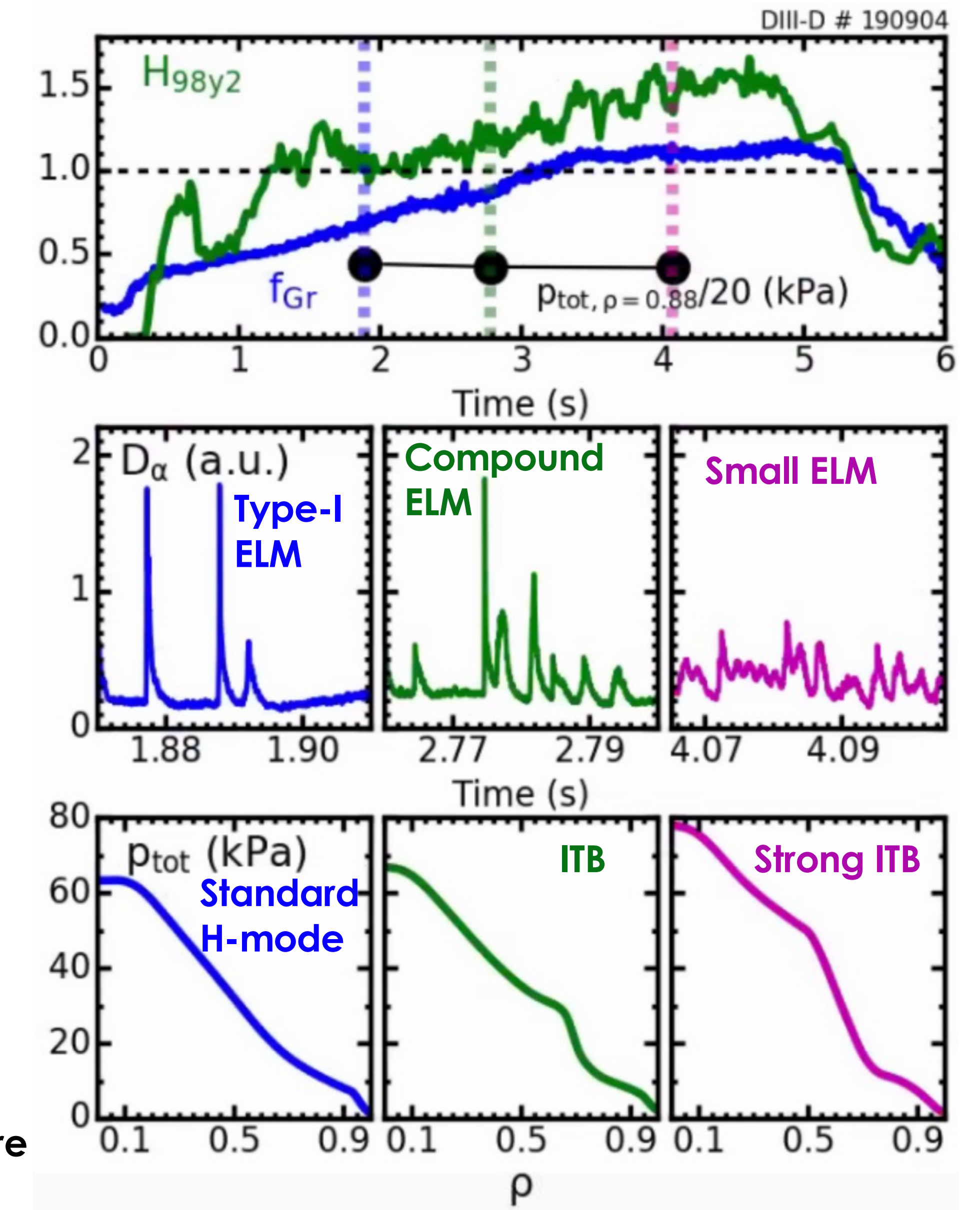
Hot & dense core surrounded by radiative mantle



Small ELMs Observed at High Normalized Density and Confinement

- **Total pedestal pressure remains ~constant**
- **Reduced divertor heat load at higher density with small ELMs**
  - Divertor close to detachment





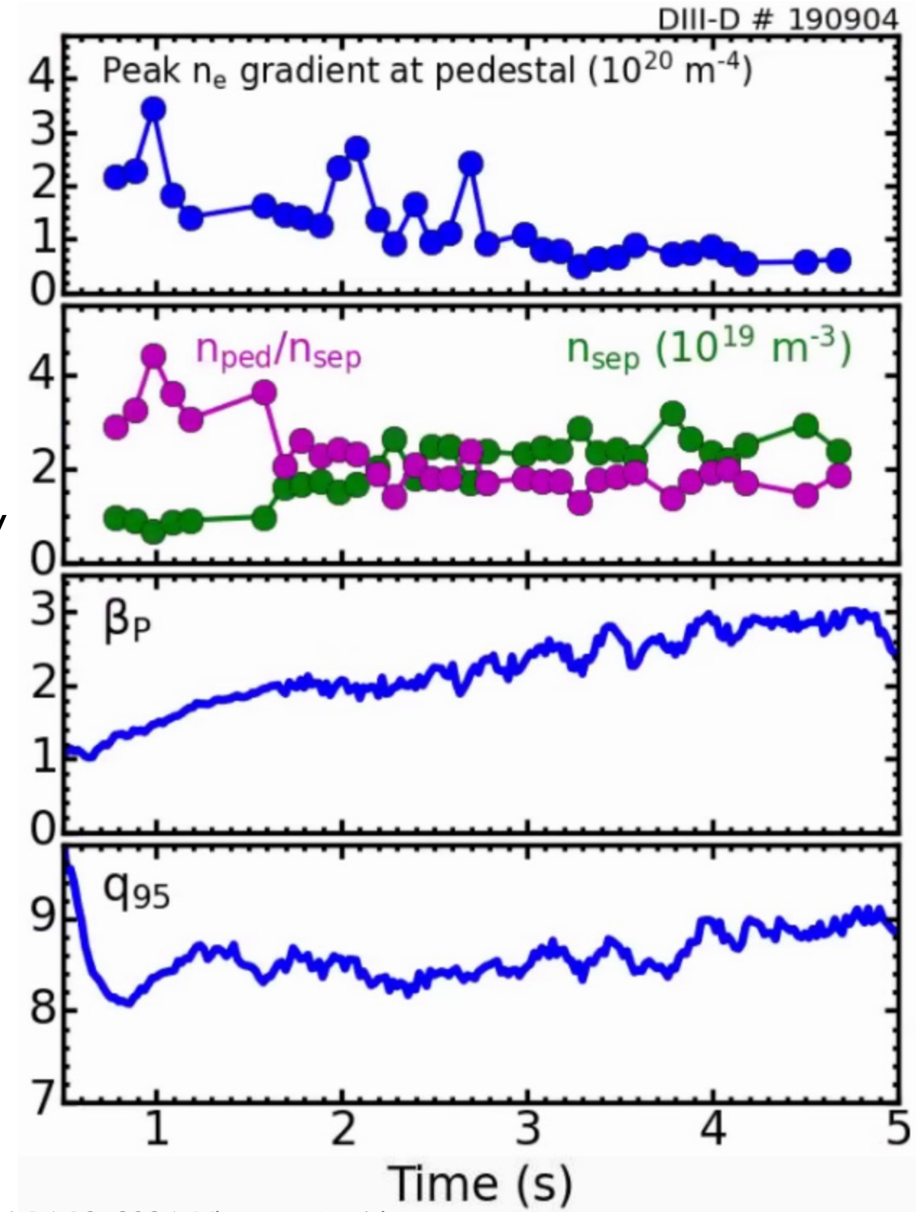
Ding et al, Nature 2024

Discharge Naturally Evolves towards Expected Parameter Domain of Small ELM Regime

Literature points out key parameters related to small ELM regime

Xu, Rev. Mod. Plasma Phys. 2023

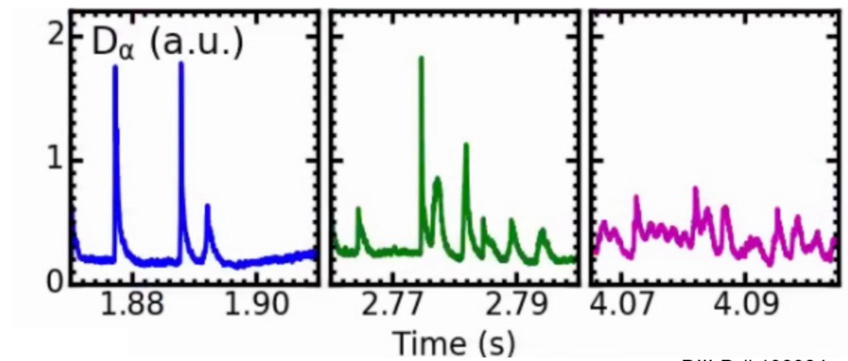
- **Flat pedestal density profile**
  - Reduced peak pedestal n_e gradient at high density
- **High separatrix density**
  - Increased n_{sep} and reduced n_{ped}/n_{sep} at high density
  - May be related with strong gas puffing
- **High β_P**
  - β_P increasing over time
- **High q_{95}**
  - Slightly increasing with β_P

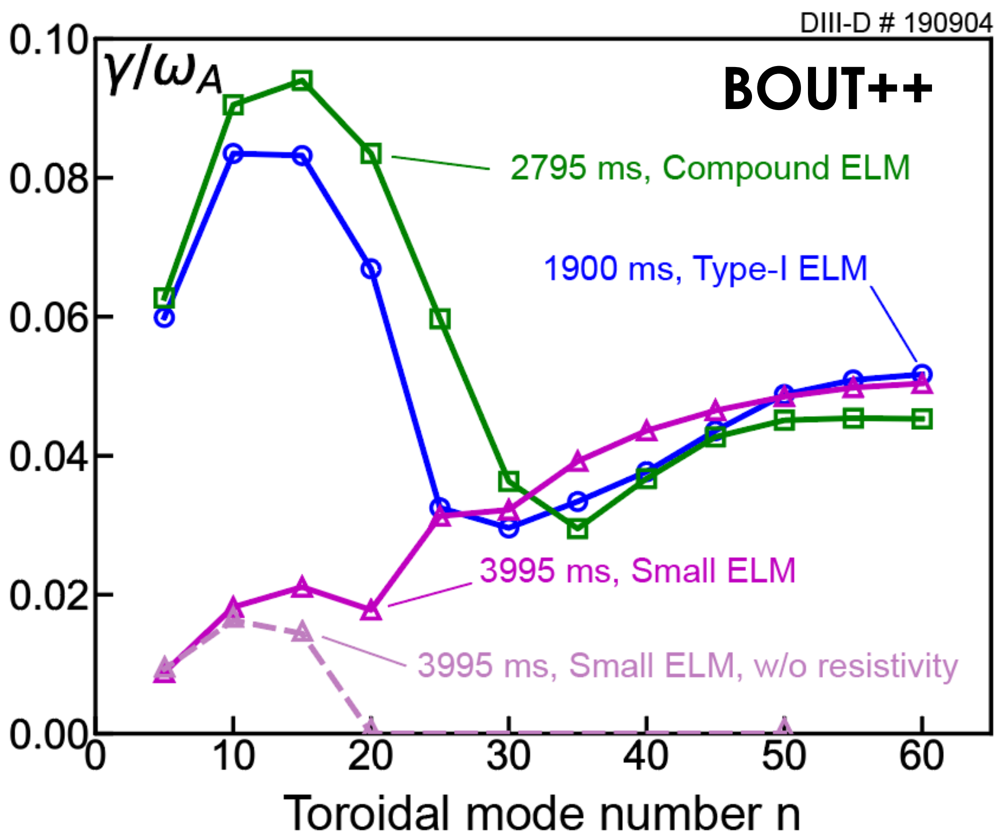


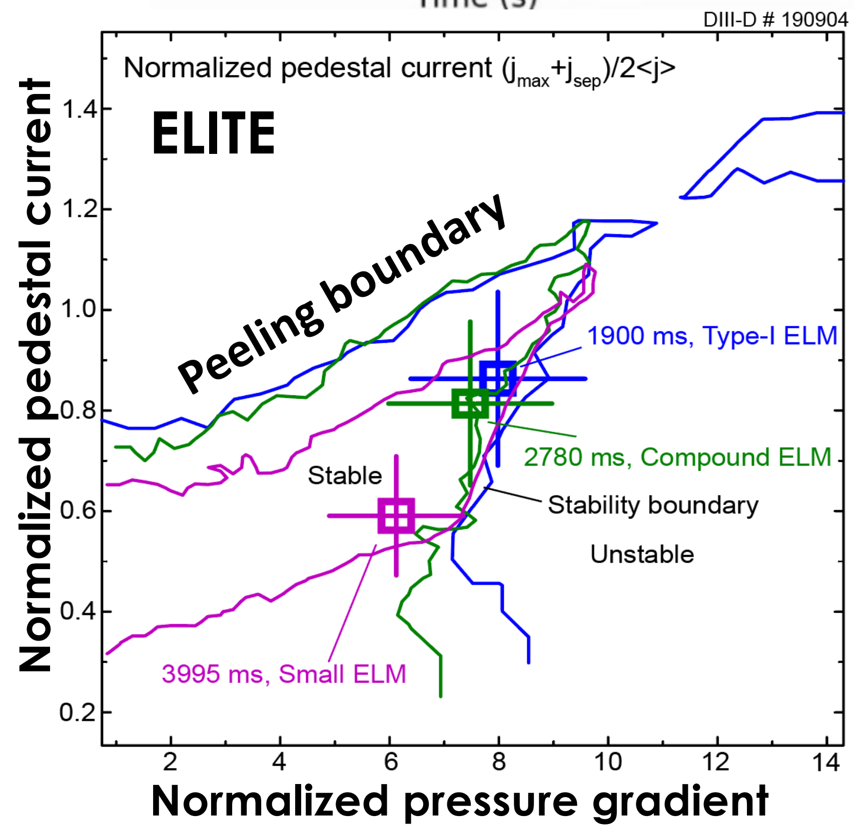
Ding et al, Nature 2024

Low Growth Rate of Low-n Modes and Predominance of High-n Resistive Ballooning Mode near the Separatrix Lead to Small ELMs

- **Low-n (~10) PBM at pedestal peak gradient**
  - BOUT++ agrees with ELITE
  - Small ELM case has lowest growth rate
- **High-n RBM at SOL and near separatrix**



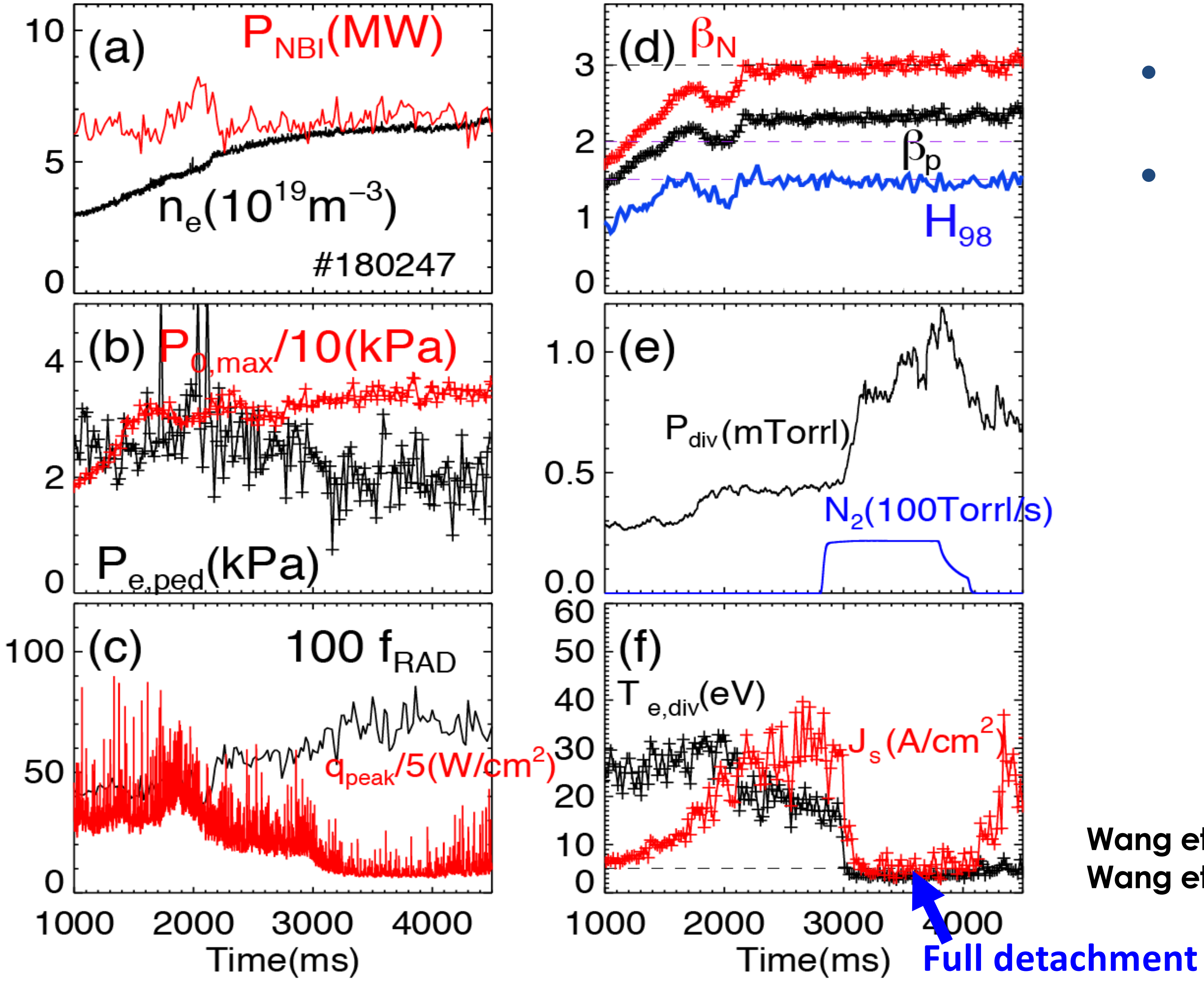




Ding et al, Nature 2024

2nd IAEA Technical Meeting on Long-Pulse Operation of Fusion Devices, Oct 14-18, 2024, Vienna, Austria

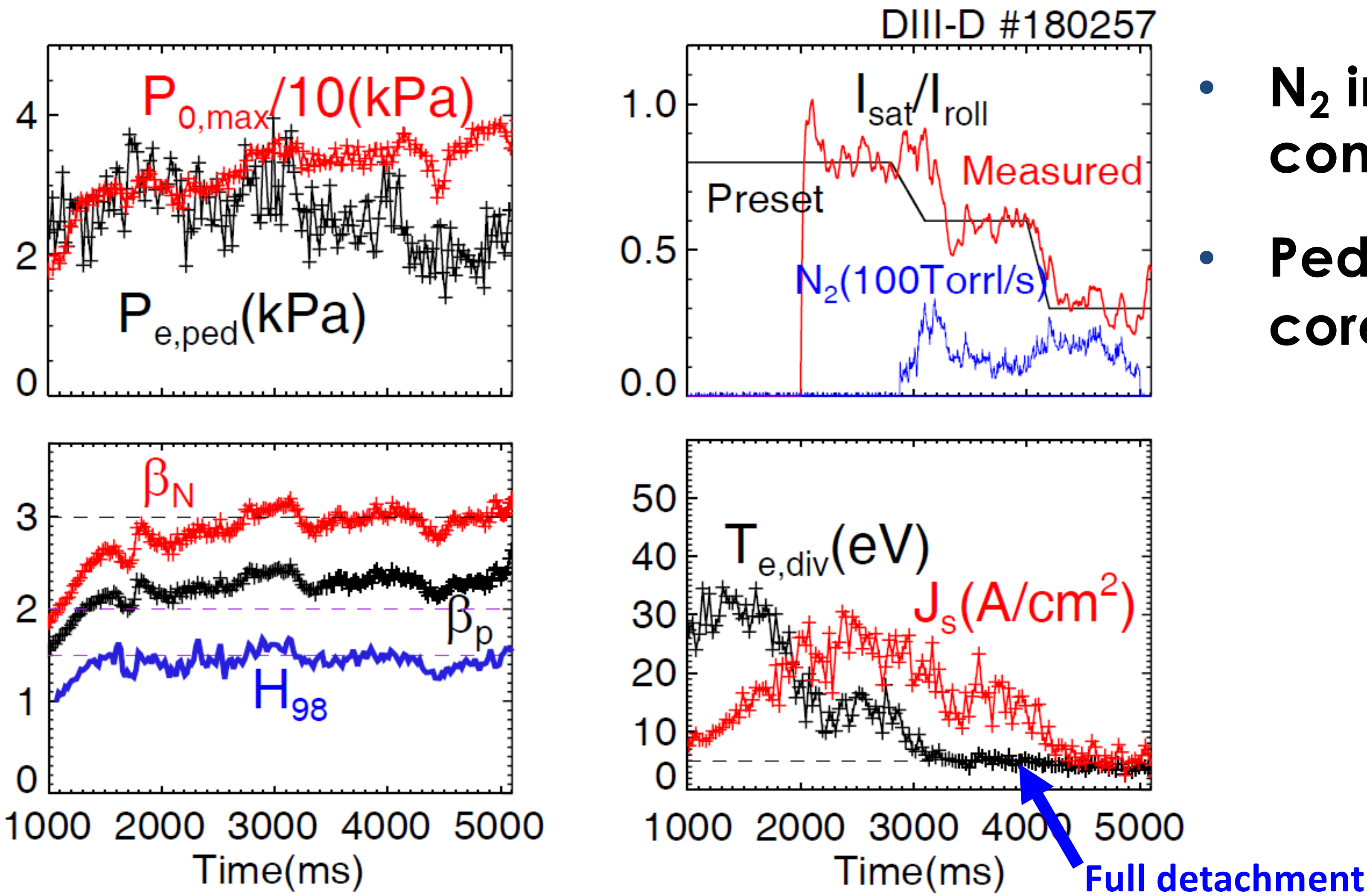
High β_P Plasmas Provided First Demonstrations of Excellent Energy Confinement Quality with Full Divertor Detachment



- N_2 injection in feedforward
- Pedestal height degrades, while core pressure is maintained

Wang et al, Nat. Commun. 2021
Wang et al, Phys. Plasmas 2021

High β_P Plasmas Provided First Demonstrations of Excellent Energy Confinement Quality with Full Divertor Detachment

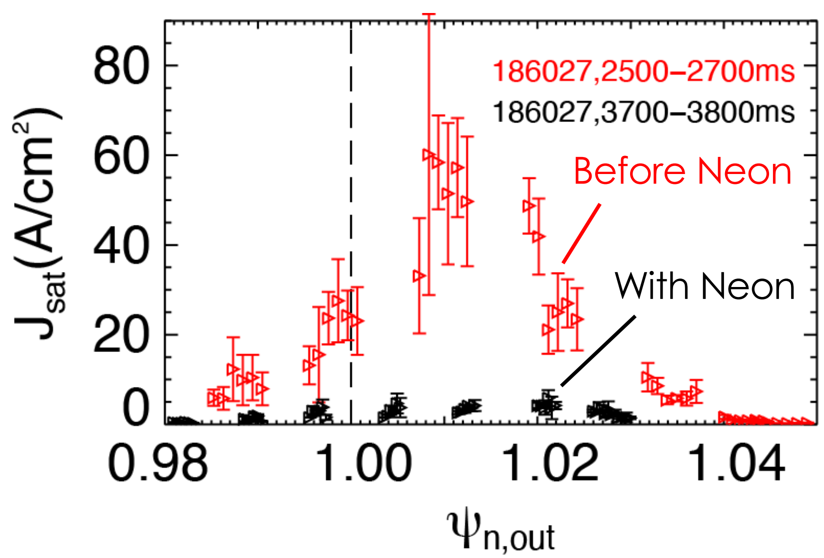


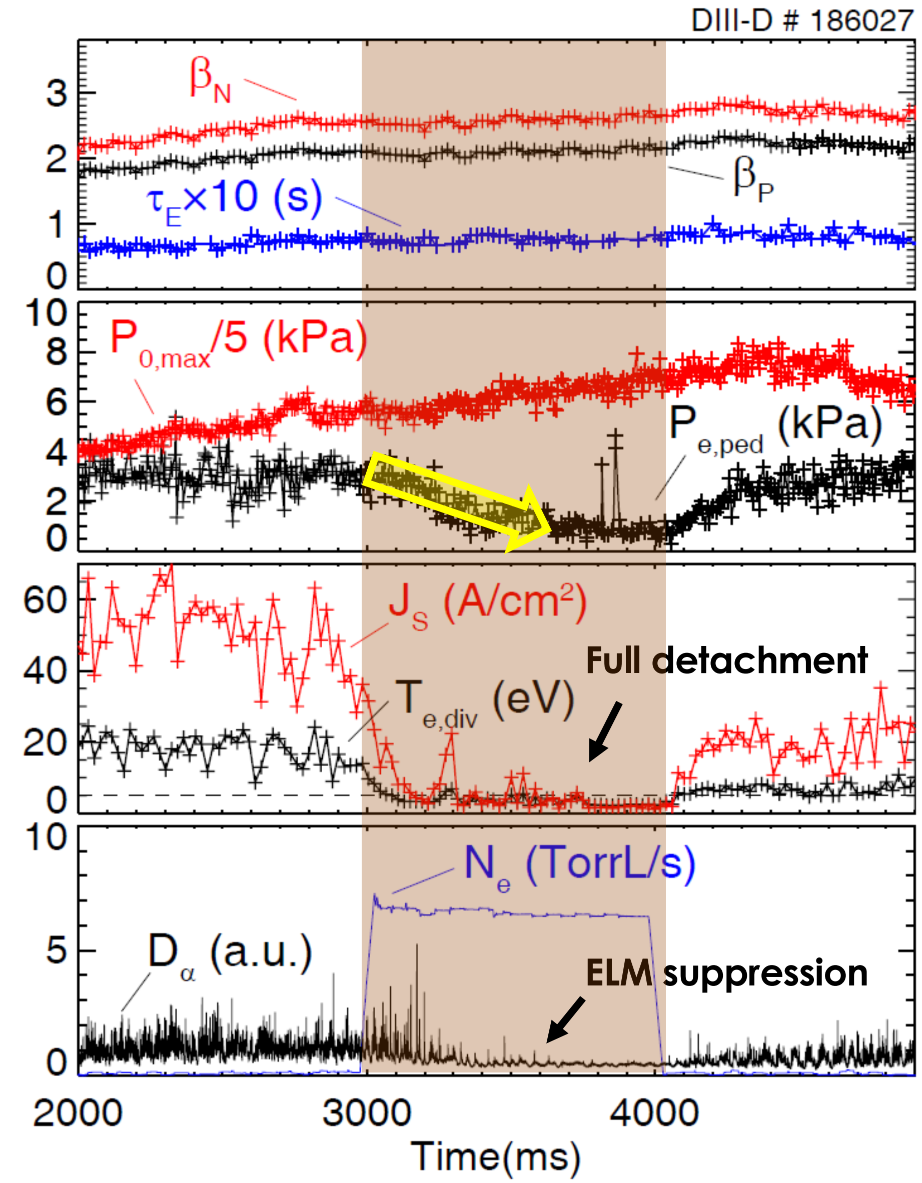
- N_2 injection under feedback control
- Pedestal height degrades, while core pressure is maintained

Wang et al, Nat. Commun. 2021
Wang et al, Phys. Plasmas 2021

High β ITB Core + Full Divertor Detachment + ELM Suppression in ITER-Similar Shape Achieved on DIII-D

- Neon injection for divertor detachment
- Steady ELM suppression
- Core performance maintained





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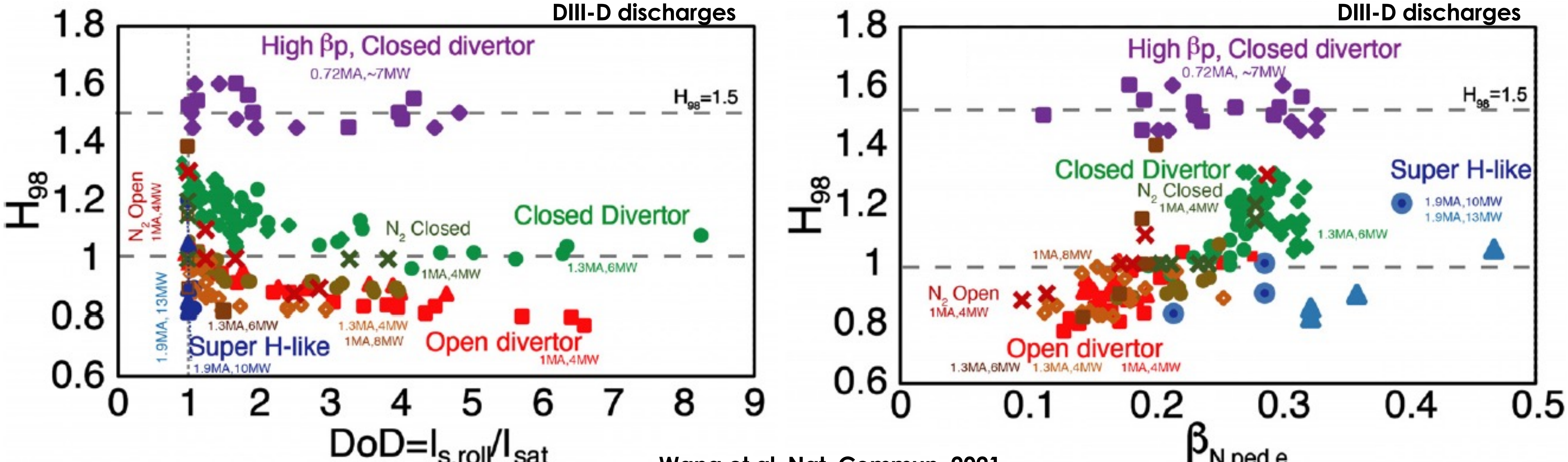
Wu et al, Nucl. Fusion 2024

High β_P Plasmas Exhibit Core-Edge Integration Advantages Compared to Other H-Mode Scenarios

- **High H_{98y2} with high Degree of Detachment (DoD) and low pedestal height**

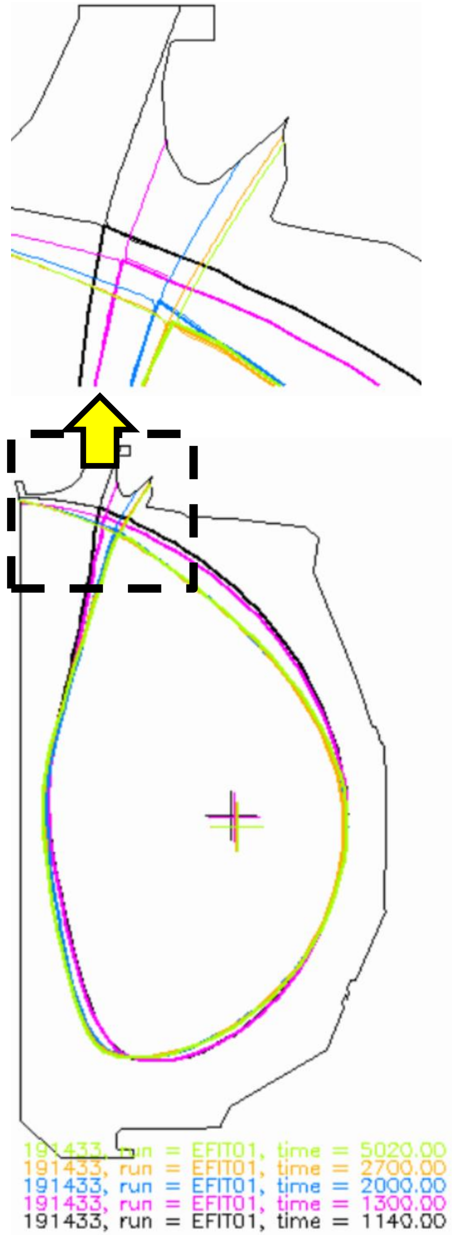


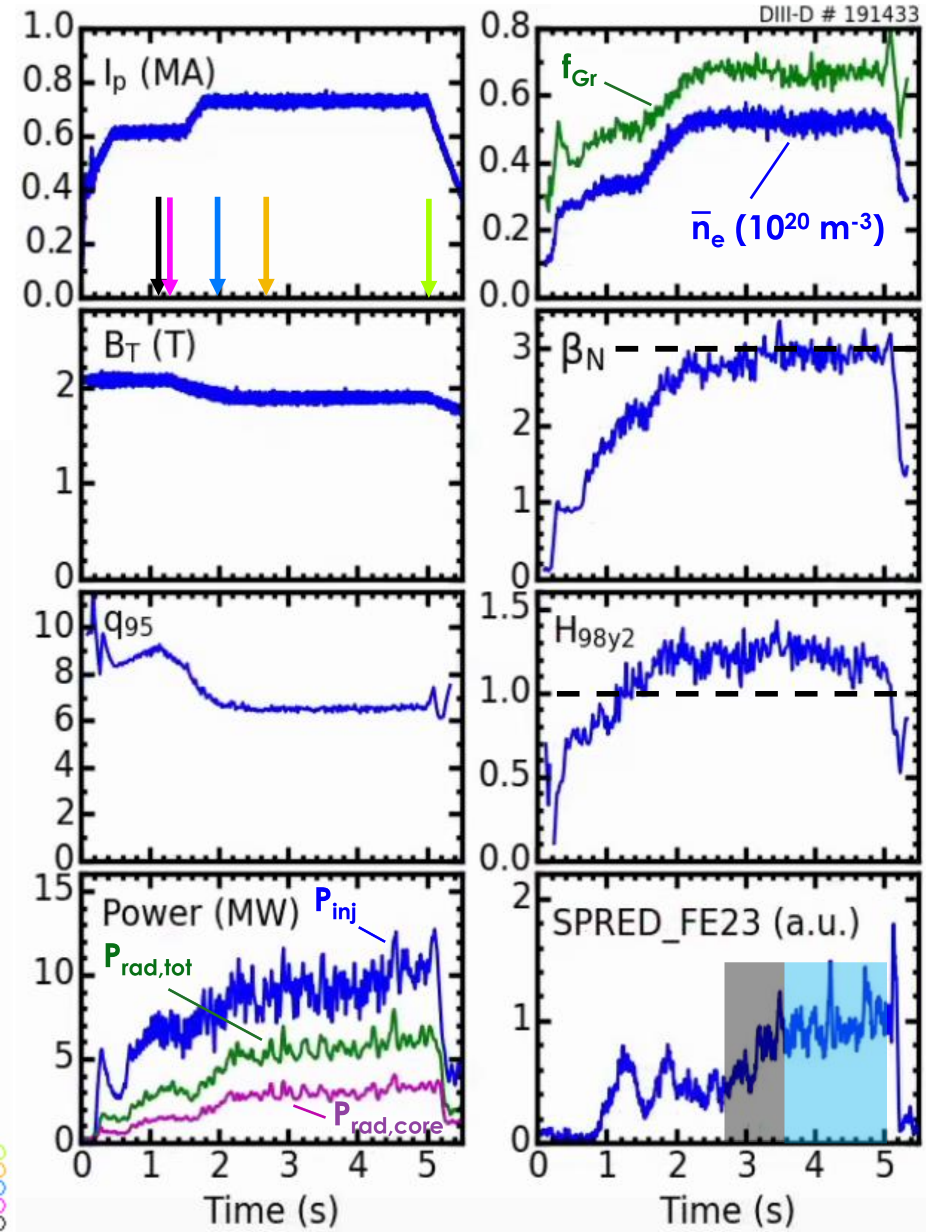
Wang et al, Nat. Commun. 2021

Make up for pedestal degradation and maintain global performance by breaking core stiffness and developing large-radius ITB

On DIII-D, High β_P Is Only Scenario Not Affected by Operation with Strike Point on Tungsten Divertor Ring

- **Well-controlled strike point at tungsten ring from 2.7 s to 5 s**
- **High-Z emission first increases, then stays constant**
- **No ECH**





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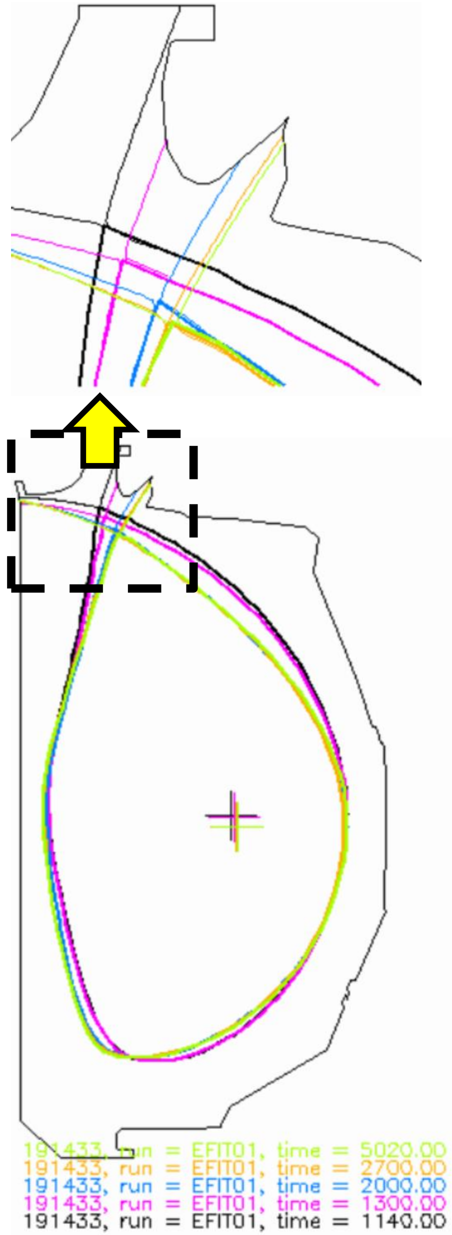

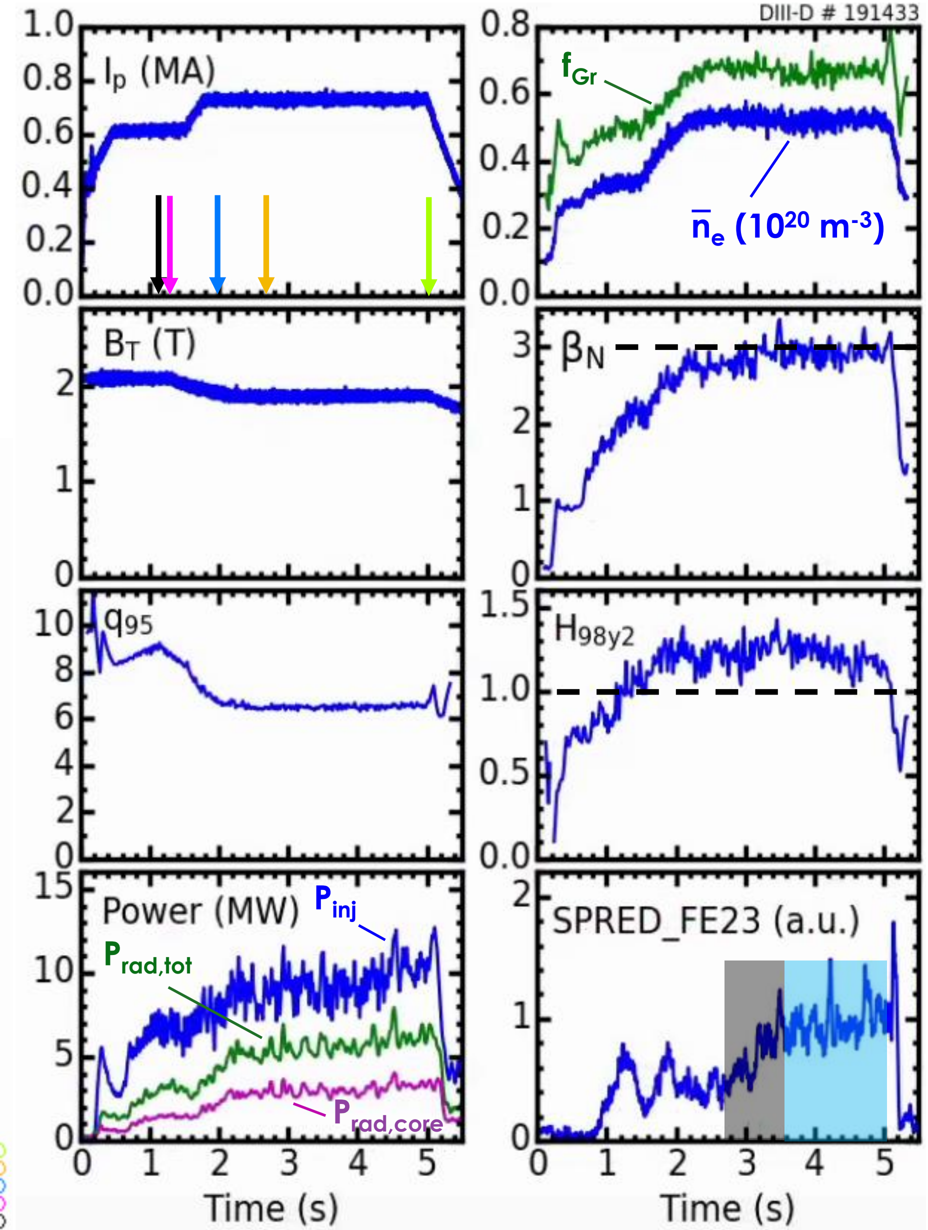

- **Strike point moves onto W surface when core state well developed**
- **Can we access the same core state if the strike point is on W from the onset?**

Density ←→ Confinement Synergy Is Extremely Favorable towards a Core-edge Integration Solution

- **High density reduces the temperature at divertor and wall**
  - Experiment close to full detachment even without impurity seeding
- **High density strengthens ITB & reduces edge pedestal → smaller ELM risk**
  - ELM damage ~ Peak ELM fluence ~ Pedestal pressure **[Eich et al, NME 2017]**

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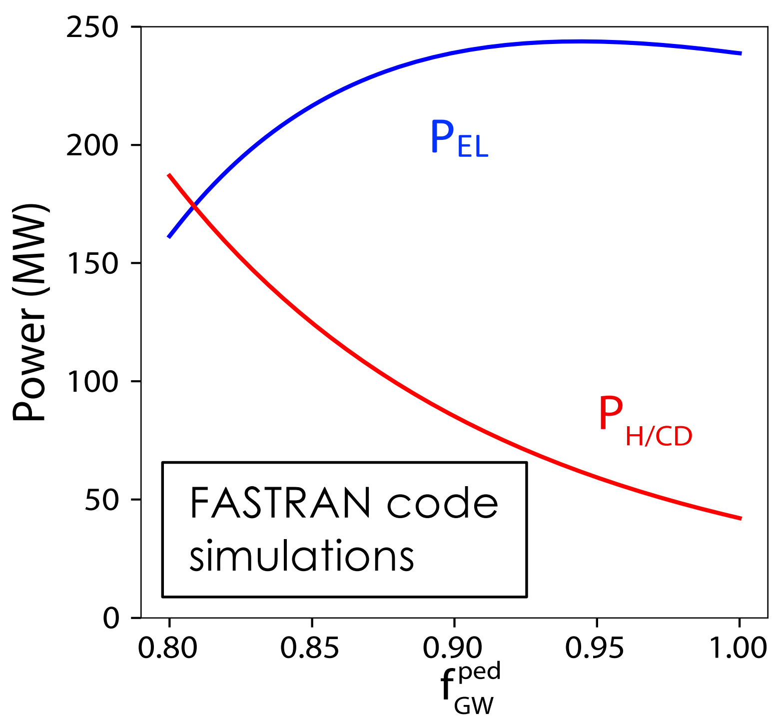
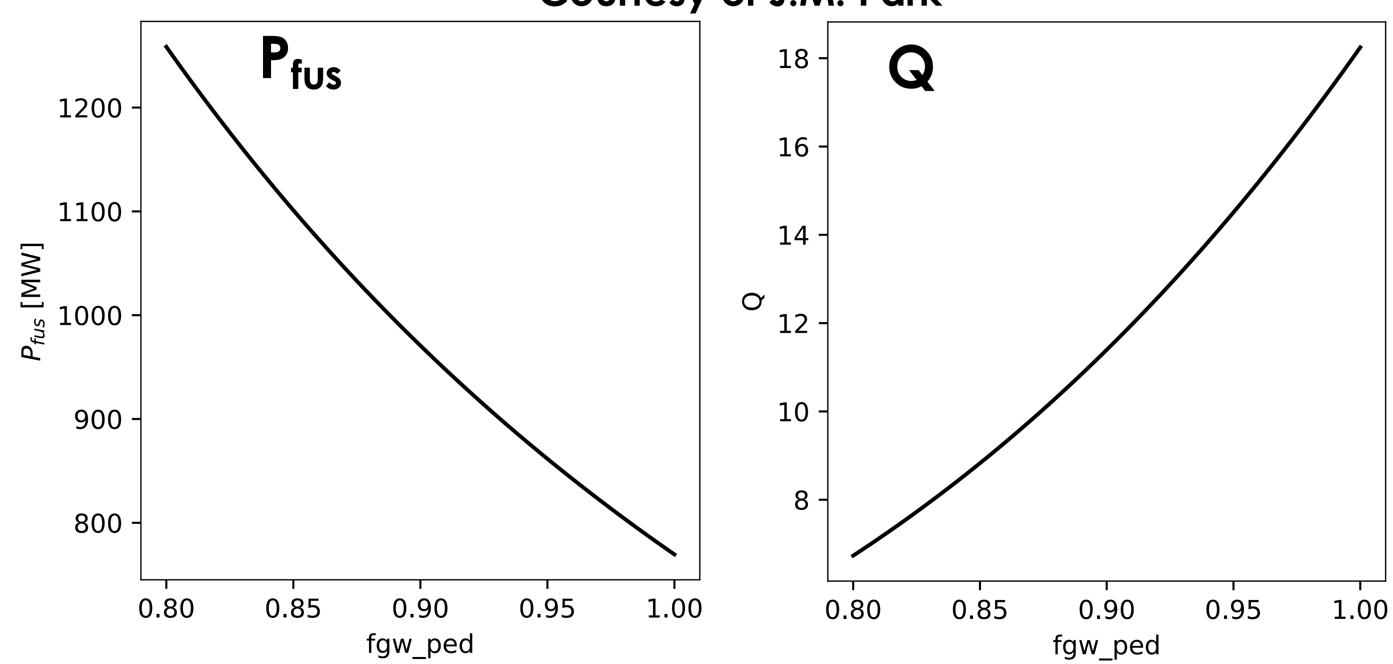
  - ELM damage ~ Peak ELM fluence ~ Pedestal pressure **[Eich et al, NME 2017]**
- **Higher density Greenwald fraction can REDUCE external CD power, for fixed β_N target**
  - Higher f_{Gr} → lower I_P, lower P_{fus}, and much lower auxiliary power are required to maintain ~constant electric power output

Buttery et al, NF 2021, "The advanced tokamak path to a compact net electric fusion pilot plant"



Courtesy of J.M. Park



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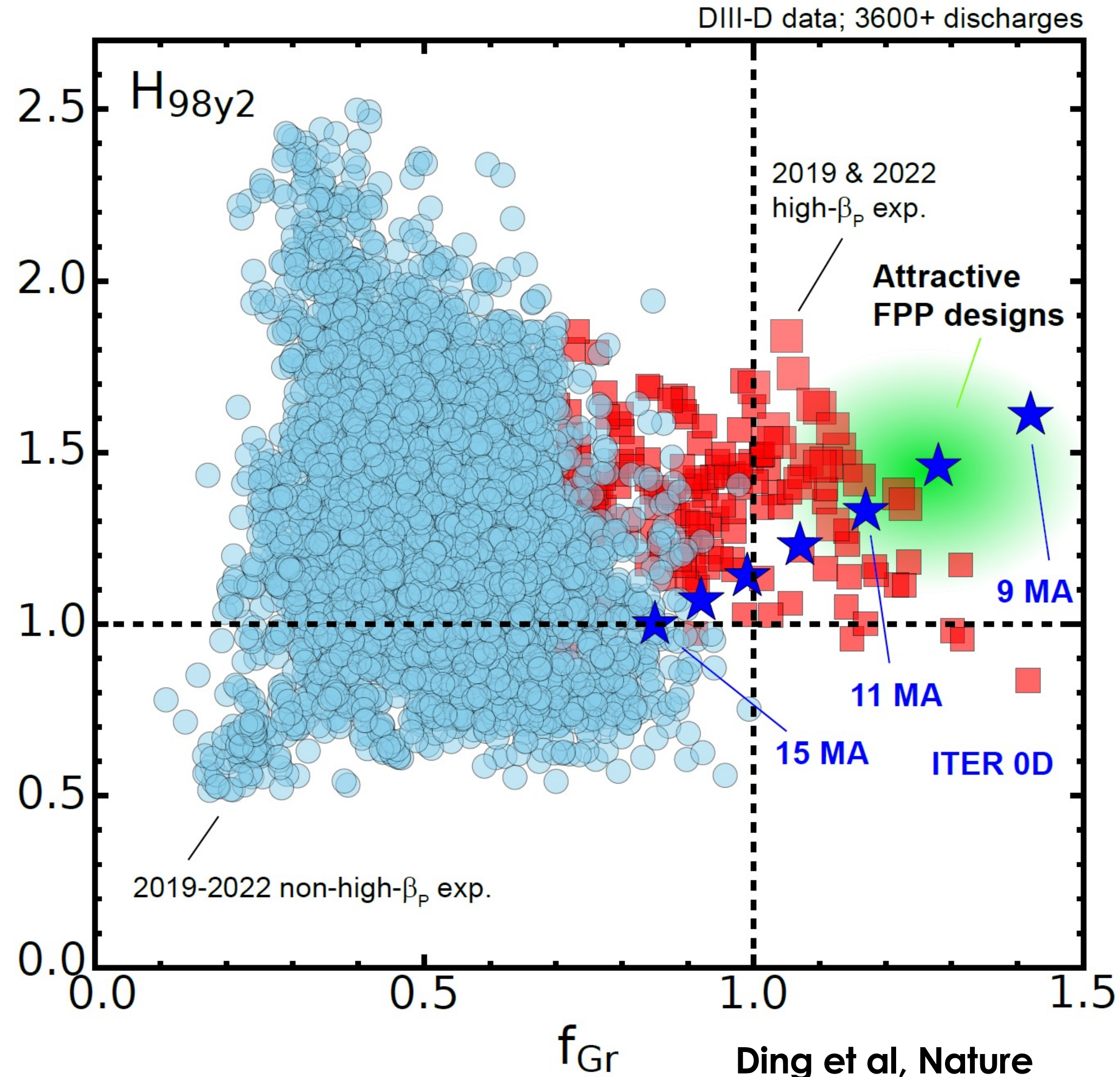
Coordinated Breakthroughs on DIII-D and EAST Overcome Long-standing Performance Limit, Show Path to High Confinement at High Density

Key physics: α-stabilization of turbulence, amplified by high density gradients

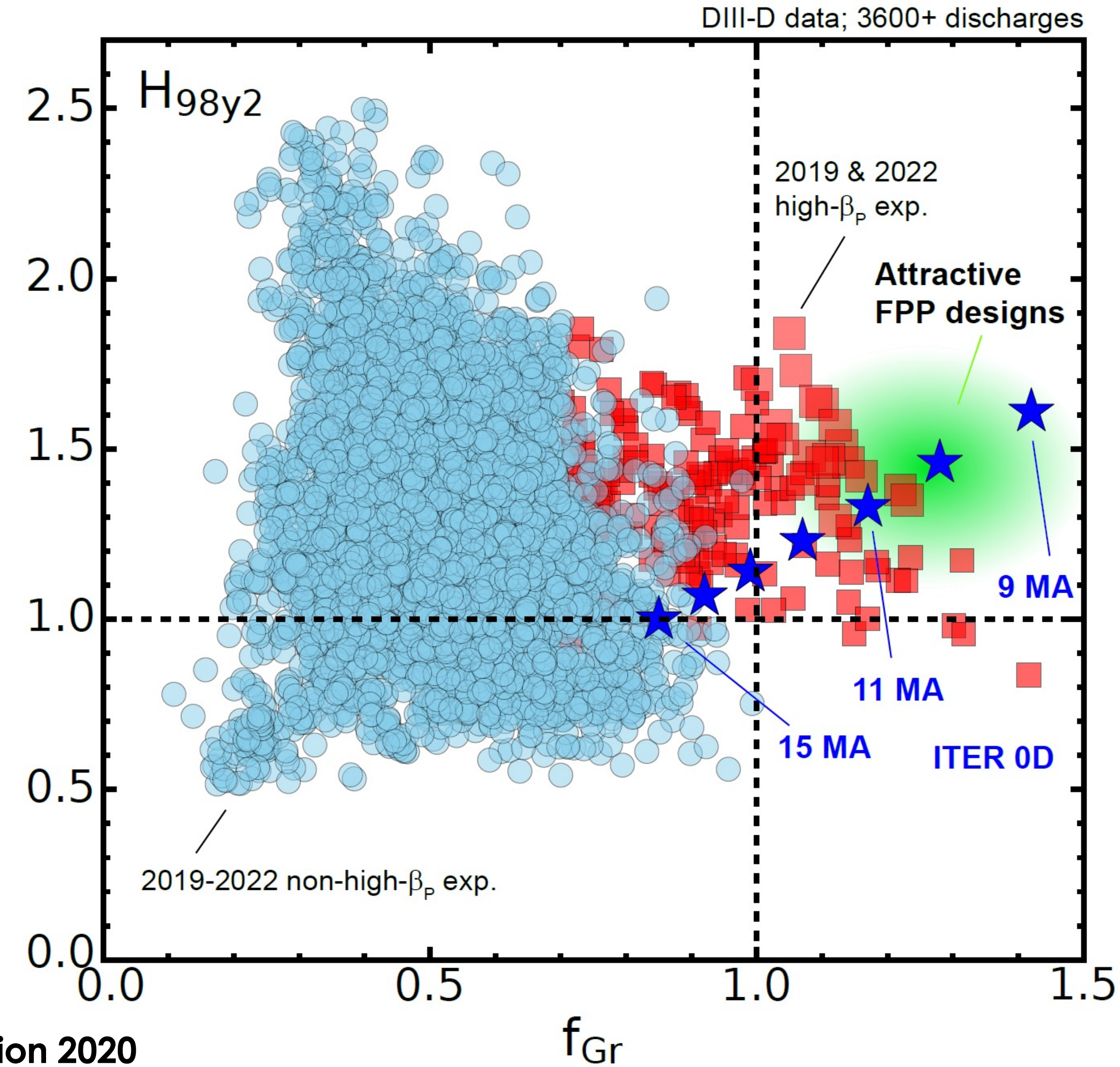


Ding et al, Nature 2024

Coordinated Breakthroughs on DIII-D and EAST Overcome Long-standing Performance Limit, Show Path to High Confinement at High Density

Key physics: α-stabilization of turbulence, amplified by high density gradients

- **Only path to sustained operation with $f_{Gr} > 1$ and $H_{98y2} > 1$** — Ding et al, Nature 2024
- **Only path to sustained operation with detached divertor and $H_{98y2} > 1$** — Wang et al, Nat. Comm. 2021
- **Only path for long-pulse H-mode on tungsten divertor (EAST, KSTAR) and high performance with strike point on tungsten ring (DIII-D)** — Gong et al, Nucl. Fusion 2024; Kim H-S et al, this meeting
- **Only path achieving SS Q=5 & low-I_P Q=10 using day-1 H&CD in theory-based predictions for ITER** — McClenaghan et al, Nucl. Fusion 2020; Ding et al, IAEA FEC 2021



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ASIPP

Outstanding Challenges

- **What determines the radius of ITB?**
- **Impurity transport (W inward, helium outward)**
- **RWM stabilization at low rotation**
- **Impact of collisionality**
- **Scenario access compatible with reactor constraints**