A Low Plasma Current (~ 8 MA) Approach for ITER's Q=10 Goal

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EX/1-TH/1-3

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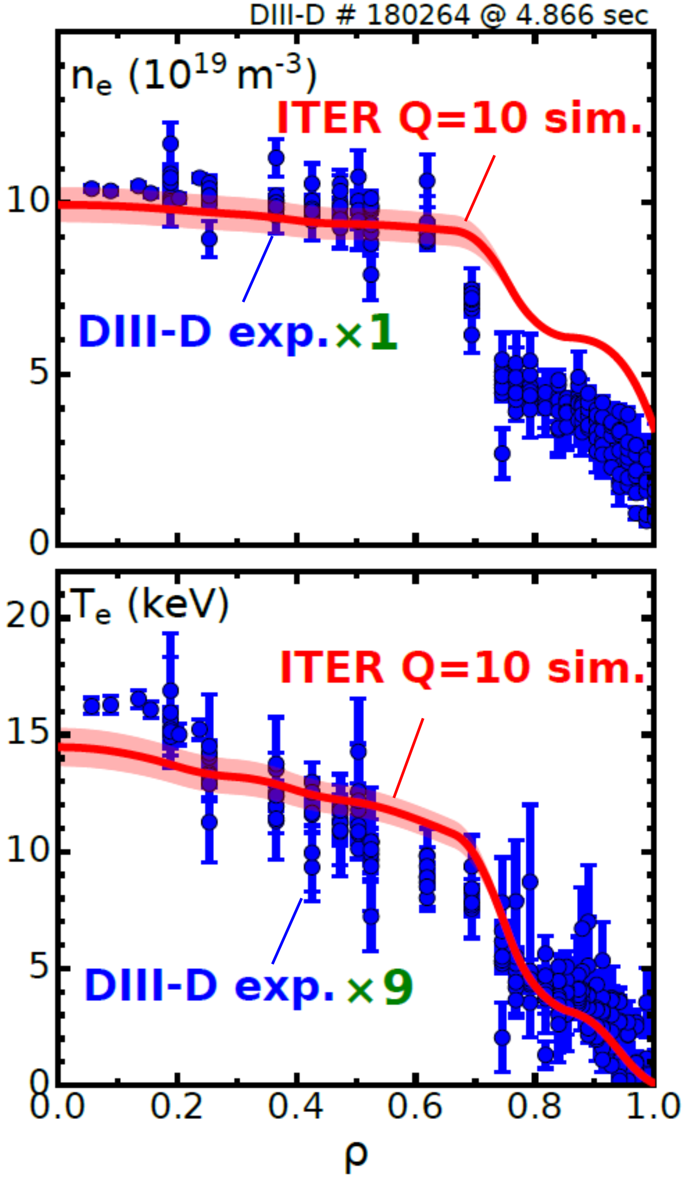
A Low Plasma Current Approach for ITER's Q=10 Goal is Proposed Using High β_P Scenario

Main results:

- **Self-consistent 1D integrated modeling predicts Q=10 for ITER at I_p~7-9 MA**
- **ITER's 500 MW fusion power goal, with Q>10, is predicted at β_N>3.1**
- **DIII-D high β_P experiments support the physics basis of ITB formation predicted in the ITER simulations**



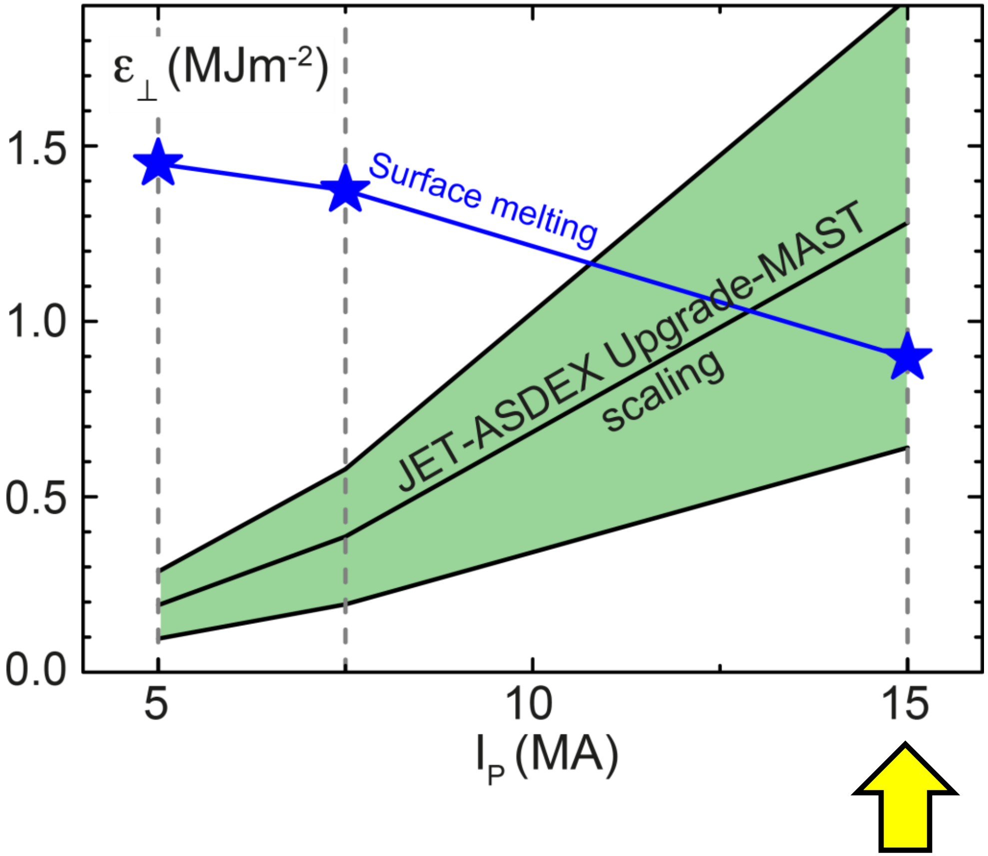
Outline

- Challenge of ITER baseline approach for Q=10 at high I_p and a possible low I_p solution using high β_P scenario
- Modeling for high β_P version of ITER Q=10 scenario
- DIII-D experiment supporting the physics basis of ITER high β_P scenario
- Summary

ITER Baseline Scenario Faces Several Challenges due to High Plasma Current

- **With increasing I_p**
  - **Challenge from 'uncontrolled' ELMs in ITER is expected to increase**
  - **Divertor heat load increases due to smaller heat flux width**
  - **Disruption risk increases**

ELM energy fluence



ITER Baseline

Pitts, NME 2019
Eich, NME 2017

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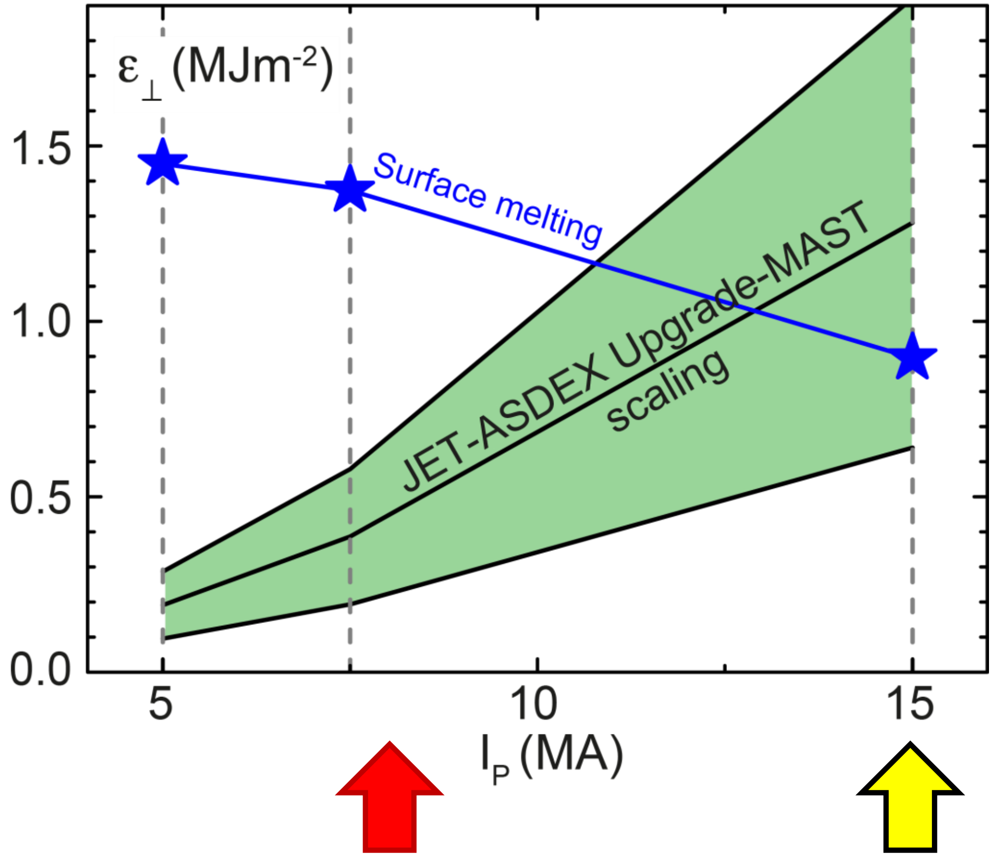
  - **Disruption risk increases**
- **Q=10 at low I_p requires higher normalized confinement (H_{98}) at high β_N**
- **Very high H_{98} obtained in high β_P scenario independent of rotation in multiple tokamaks**
  - JT-60U, DIII-D and EAST

ELM energy fluence



Possible solution:
Reduce plasma current

ITER Baseline

Sakamoto, NF 2009
Qian, APS 2019
Garofalo, PPCF, 2018

Pitts, NME 2019
Eich, NME 2017

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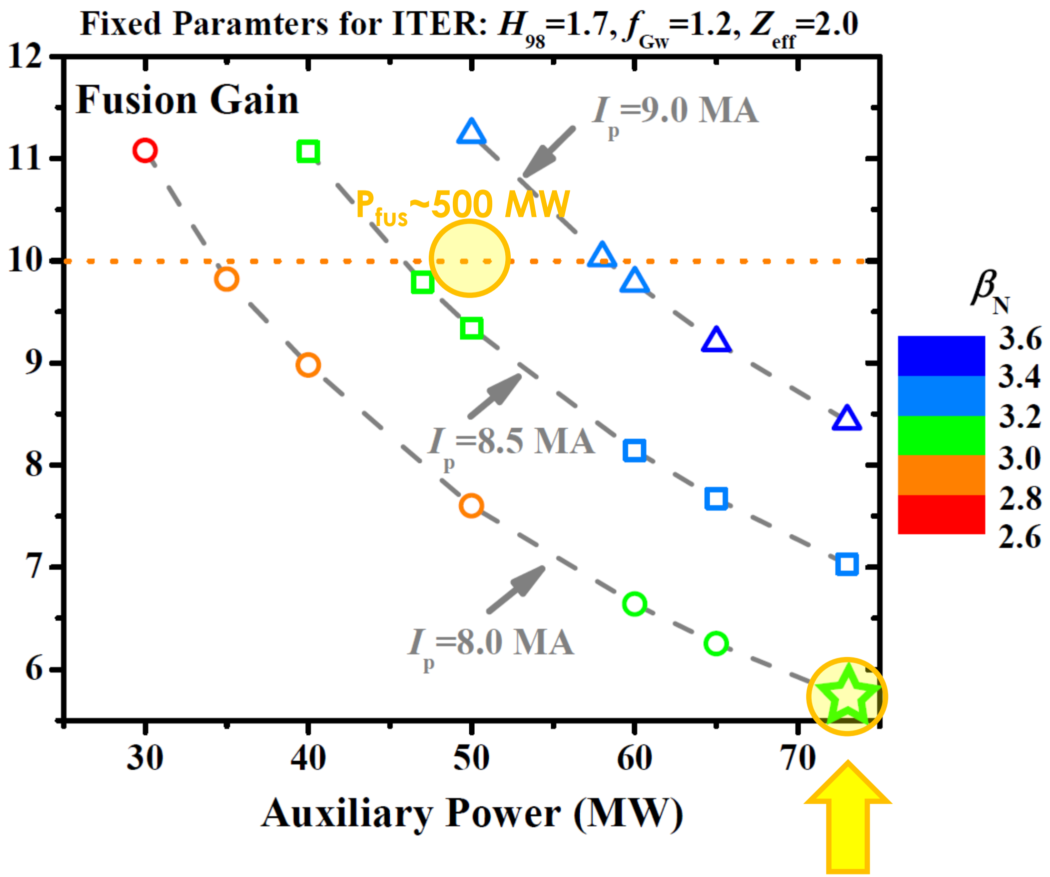
Modeling for high β_P version of ITER Q=10 scenario

DIII-D experiment that supports the physics basis of ITER high β_P scenario

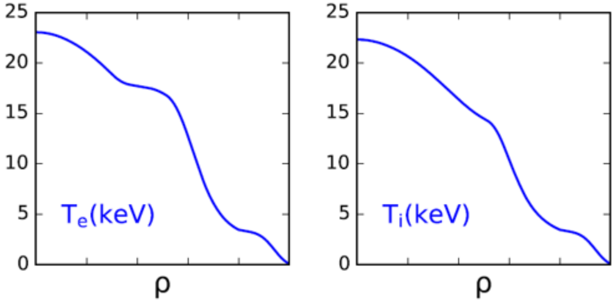
Summary

ITER Q=10 is Predicted by Reducing Auxiliary Power at Low Plasma Current

- **0D modeling provides insight into the possible path towards ITER Q=10 using high β_P scenario**
- **Q=Fusion Power/Auxiliary Power**
  - P_{fus} decreases slower than P_{aux} does
- **P_{fus}~500 predicted at I_p~8.5-9 MA**



Start point: ITER high β_P Q=5 1D sim.



McClenaghan, NF 2020

ITER Q=10 is Predicted by Reducing Auxiliary Power at Low Plasma Current

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- **Q=Fusion Power/Auxiliary Power**
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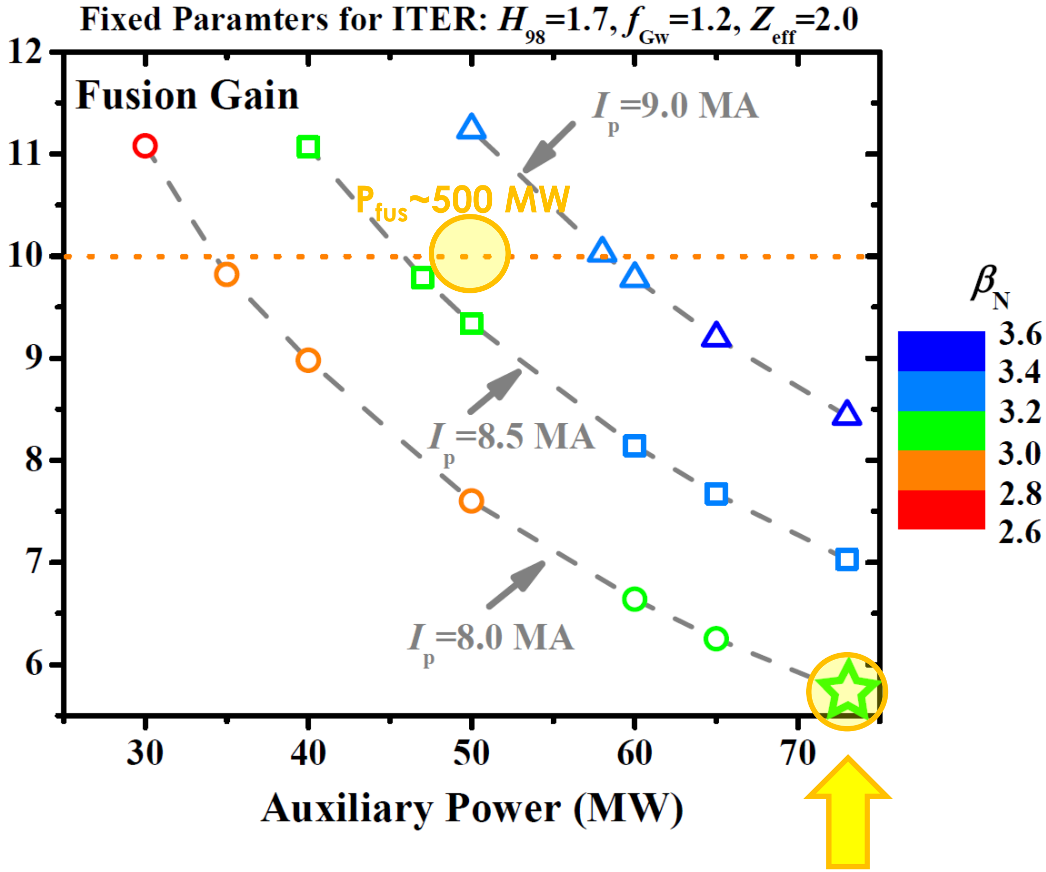
- **P_{fus}~500 predicted at I_p~8.5-9 MA**
- **Key requirements for ITER high β_P Q=10 scenario:**
  - β_N~2.8-3.5 @ q_{95}~6-7
  - f_{Gw}~1.2-1.3
  - H_{98}>1.5

Main challenges!



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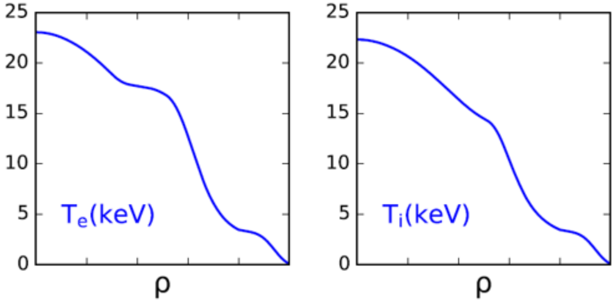
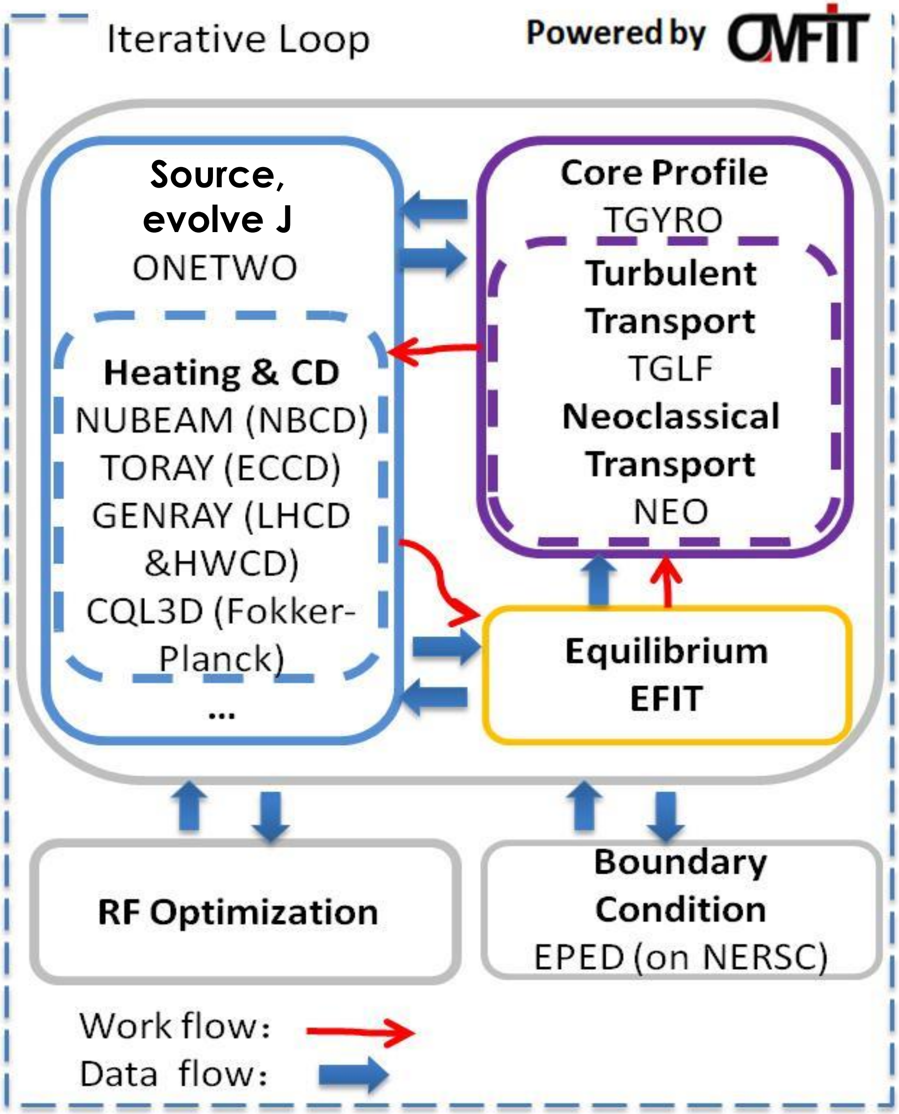


McClenaghan, NF 2020

OMFIT Provides Capability of Self-Consistent Prediction of Tokamak Stability Transport Equilibrium and Pedestal (STEP)

- **Workflow 'STEP' in OMFIT**
  - Core profile prediction
  - Heating source, current profile calculation
  - Equilibrium reconstruction



Iterative Loop

Powered by

Source, evolve J
ONETWO

Heating & CD
NUBEAM (NBCD)
TORAY (ECCD)
GENRAY (LHCD &HWCD)
CQL3D (Fokker-Planck)
...

Core Profile
TGYRO
Turbulent Transport
TGLF
Neoclassical Transport
NEO

Equilibrium
EFIT

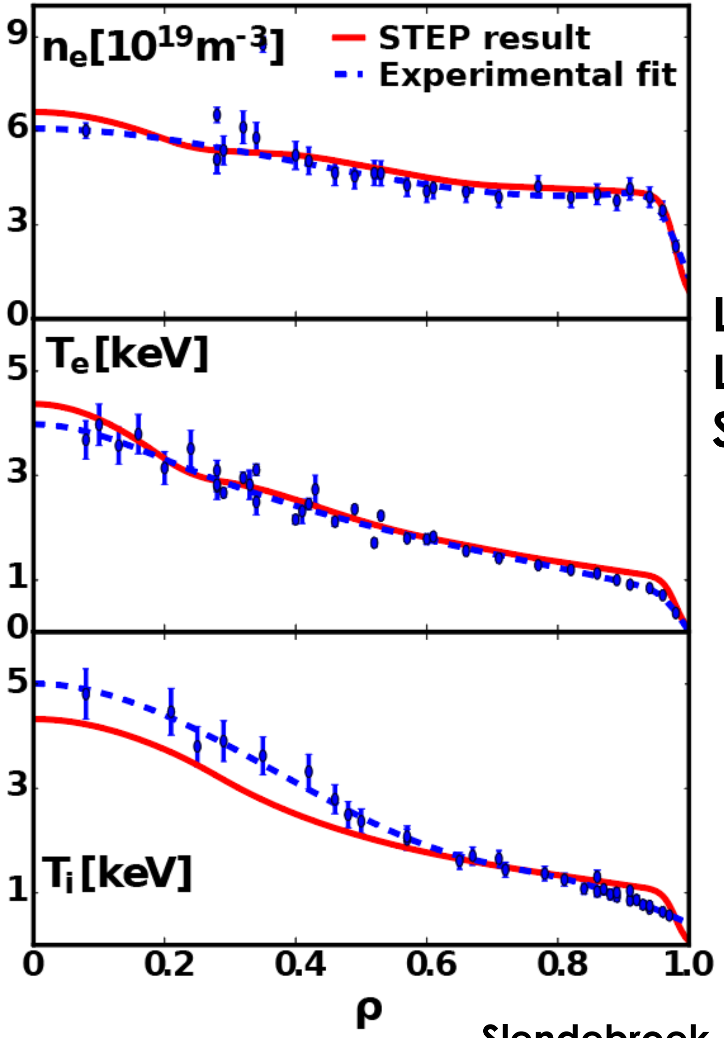
RF Optimization

Boundary Condition
EPED (on NERSC)

Work flow: →
Data flow: ➡

STEP Module has been Successfully Validated on Reproducing DIII-D and EAST Experimental Data

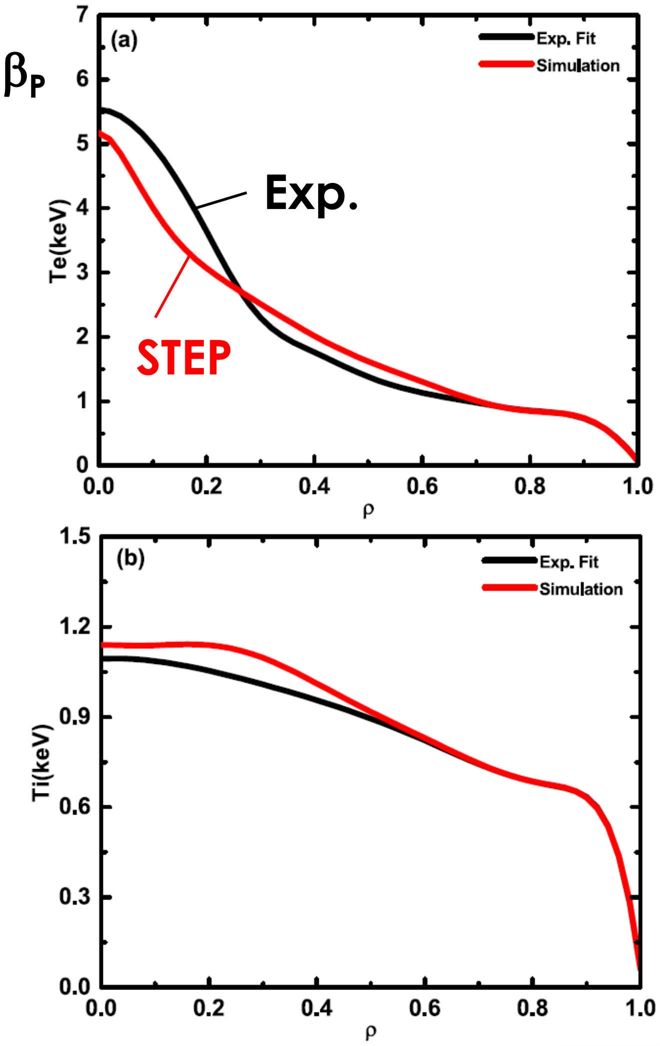
DIII-D # 81499 @ 3.8 s



Lower single null
Low q_{95}
Standard H-mode

EAST # 81481 @ 5.3 s

High β_P



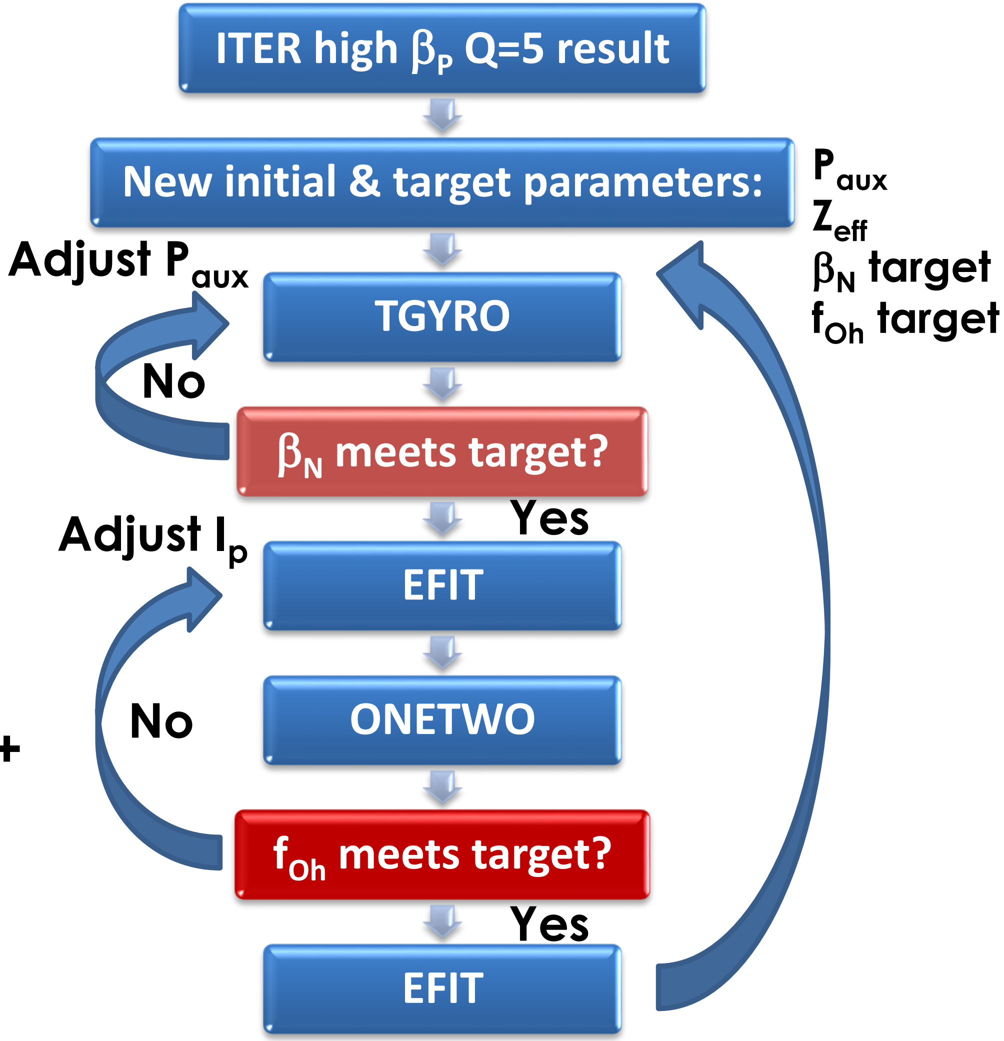
Slendebroek, to be submitted to PoP
McClenaghan, this conference, poster, May 14, 2021

Wu, NF 2019

1D Integrated Simulations Aimed for ITER Q=10 High β_P Solution are Performed Using Iterative Loop

- **Using ITER heating and current drive power:**
  - Neutral beams ≤ 33 MW
  - Electron cyclotron ≤ 20 MW
- **Temperature, density and current profiles evolved self-consistently**
  - Impurity densities are not evolved
  - Rotation set to zero
- **β_N feedback control (5% error) + f_{Oh} feedback control (2% error)**
  - Aim at low Ohmic current fraction

McClenaghan, NF 2020



ITER high β_P Q=5 result

New initial & target parameters:

P_{aux}
Z_{eff}
β_N target
f_{Oh} target

Adjust P_{aux}

TGYRO

No

β_N meets target?

Yes

Adjust I_p

EFIT

ONETWO

No

f_{Oh} meets target?

Yes

EFIT

Will lower P_{aux} give higher Q as 0D predicted?

Summary of Major Parameters for ITER High β_P Q=10 Base Case

I_p (MA)	q_{95}	n_e (10^{19} m^{-3})	f_{Gw}	Z_{eff}	f_{NI} (%)
7.5±0.15	**7.74**±0.18	**8.6**±0.35	**1.46**±0.06	**2.48**±0.04	**98.9**±0.8

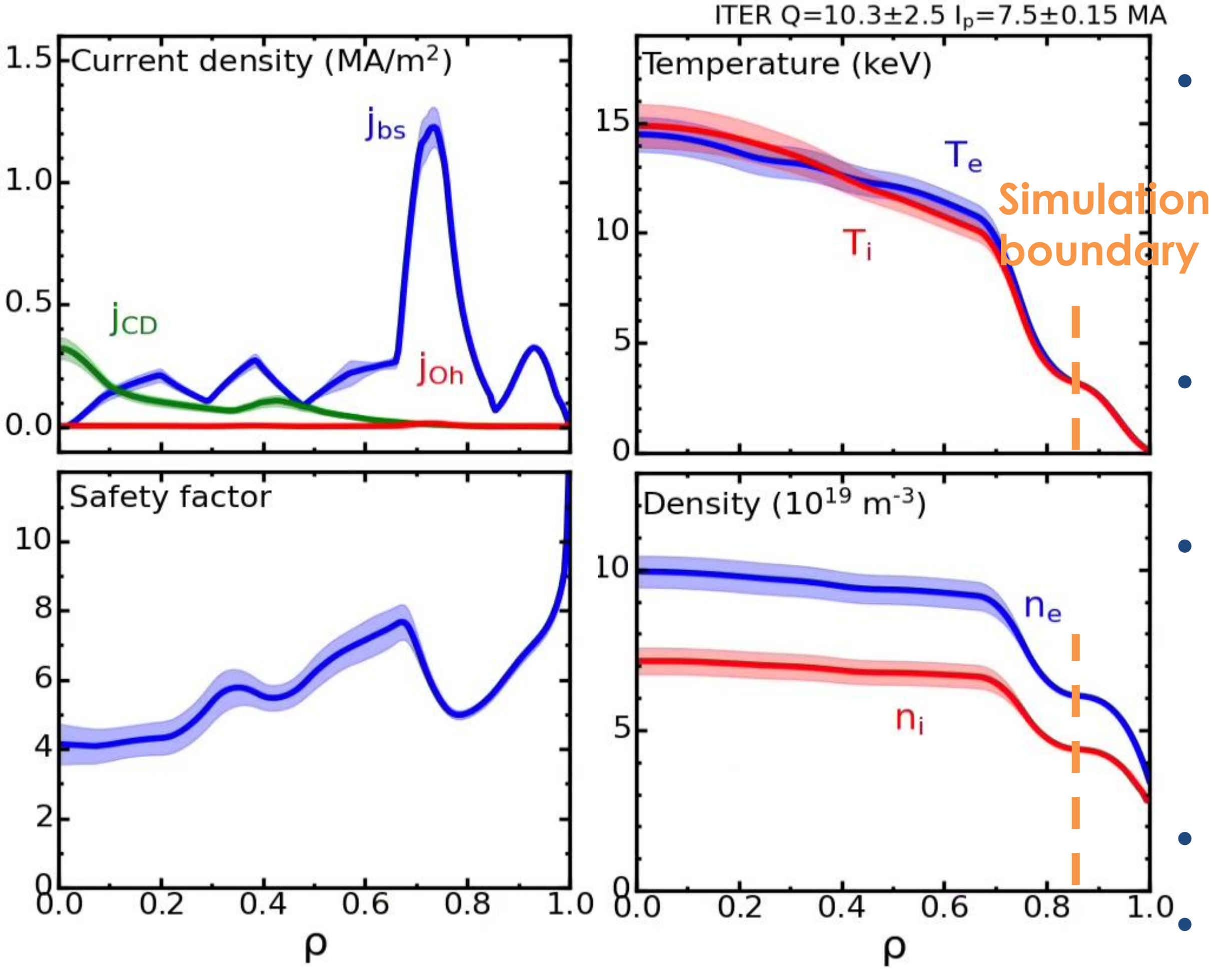
β_N	β_p	H_{98y2}	P_{fus} (MW)	Q	G_{98}
2.81±0.06	**2.27**±0.04	**1.75**±0.04	**294**±27	**10.3**±2.5	**0.082**±0.005

$n_i T_i \tau_E$ (10^{21} m^{-3} keV s)	$n_i T_i \tau_E$ - 15 MA (10^{21} m^{-3} keV s)
3.34±0.22	**4.91**

- **Q=10 is predicted at I_p ~ 7.5 MA**
- **Medium q_{95}, high f_{GW}, high β**
- **High confinement, fully non-inductive operation**
- **Relatively low fusion power, triple product**

Note the high Z_{eff} for realistic impurity seeding divertor solution

The Presence of Large Radius ITB Elevates Core Profile at Low Plasma Current

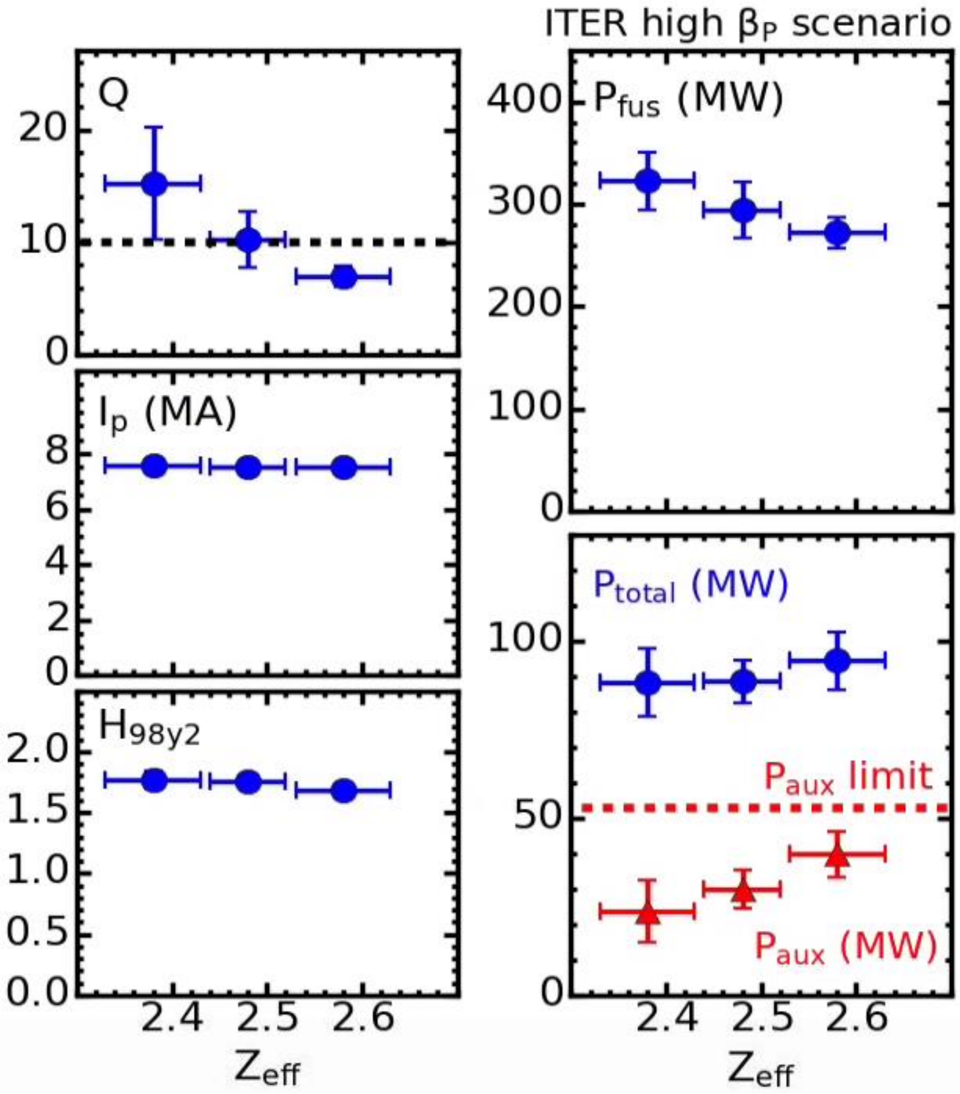


McClenaghan, NF 2020

- **Prescribed pedestal**
  - $n_{e,ped}$: 93% n_{Gw}
  - P_{ped}: ~78% EPED prediction
- **ITB foot @ ρ=0.8**
  - All n, T channel
- **Negative Off-Axis magnetic Shear at large radius (NOAS)**
  - Not NCS
- **q_{min}>2.5**
- **$\beta_N \sim l_i \times 6$**
  - Above n=1 no wall limit
  - Well below n=1 ideal wall limit

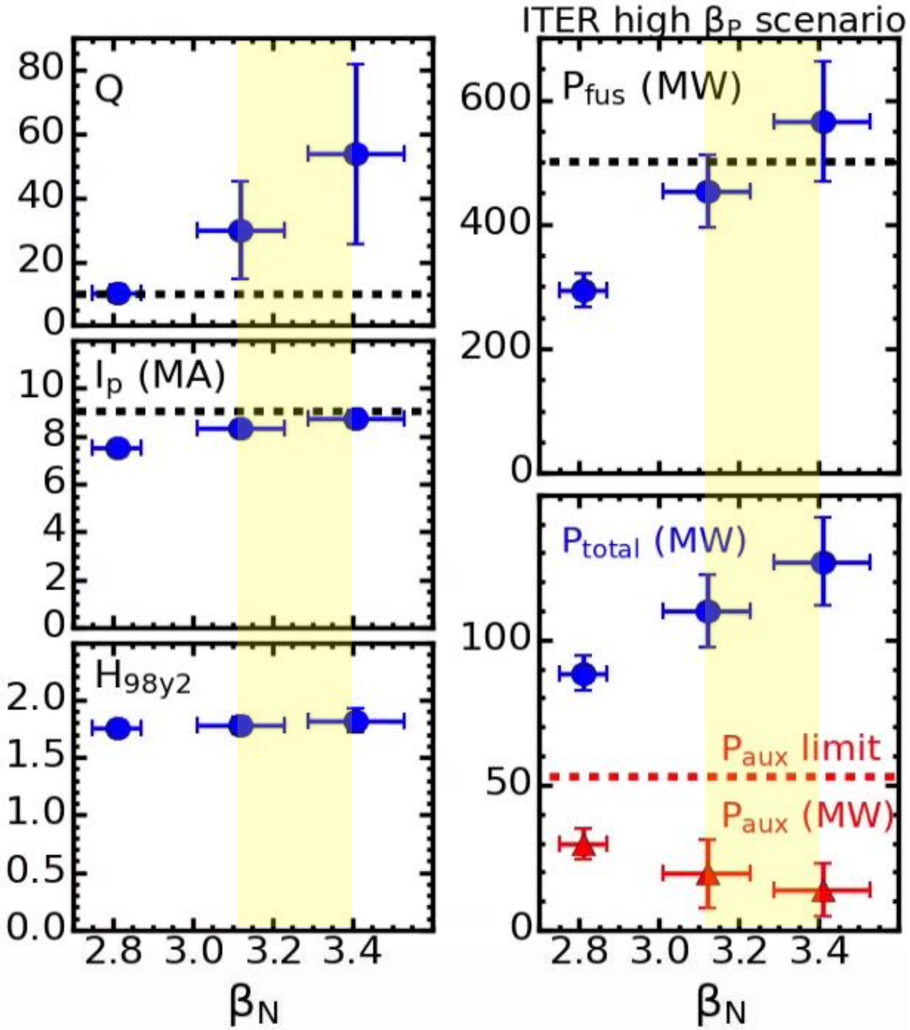
Lower Z_{eff} will Enhance Q by Increasing α Heating and Reducing Auxiliary Heating at Similar Confinement

- **Q~10 at Z_{eff}~2.5**
- **The key of achieving high Q at similar P_{total} is to replace a part of P_{aux} by P_α**
- **Lower Z_{eff} enables higher main (fusion) ion densities and higher fusion power**
- **Impurity species: He (thermal), Ne**

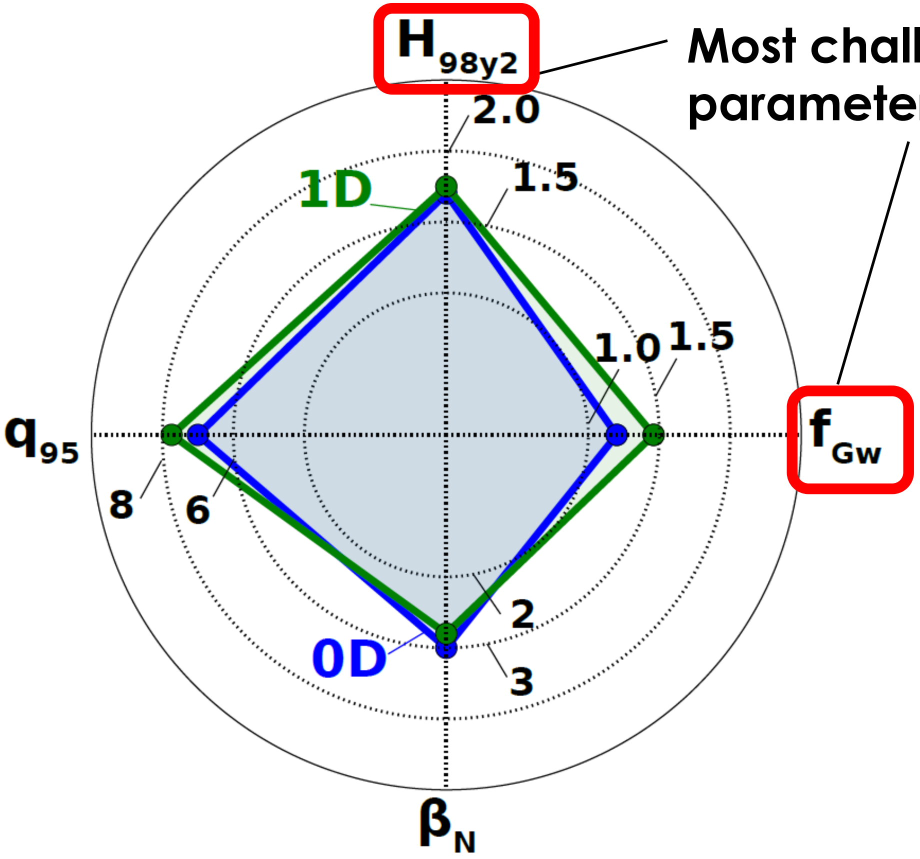


Increase β_N is An Effective Approach to Enhance Fusion Power

- **β_N~2.8 at Z_{eff}~2.5 gives P_{fus}~300 MW**
- **With increasing β_N:**
  - Fusion power increases
  - Fusion gain increases
  - Plasma current increase; f_{Oh}~0
- **Most of cases well below P_{aux} limit (53 MW)**
  - Above L-H threshold power (77 MW)
- **ITER 500 MW fusion power requires β_N~3.1-3.4**
  - $I_p \leq 9$ MA
- **Triple product at baseline level**



Recent DIII-D Experiments Address Challenges for ITER High β_P Q=10 Scenario



Most challenging parameters in exp.

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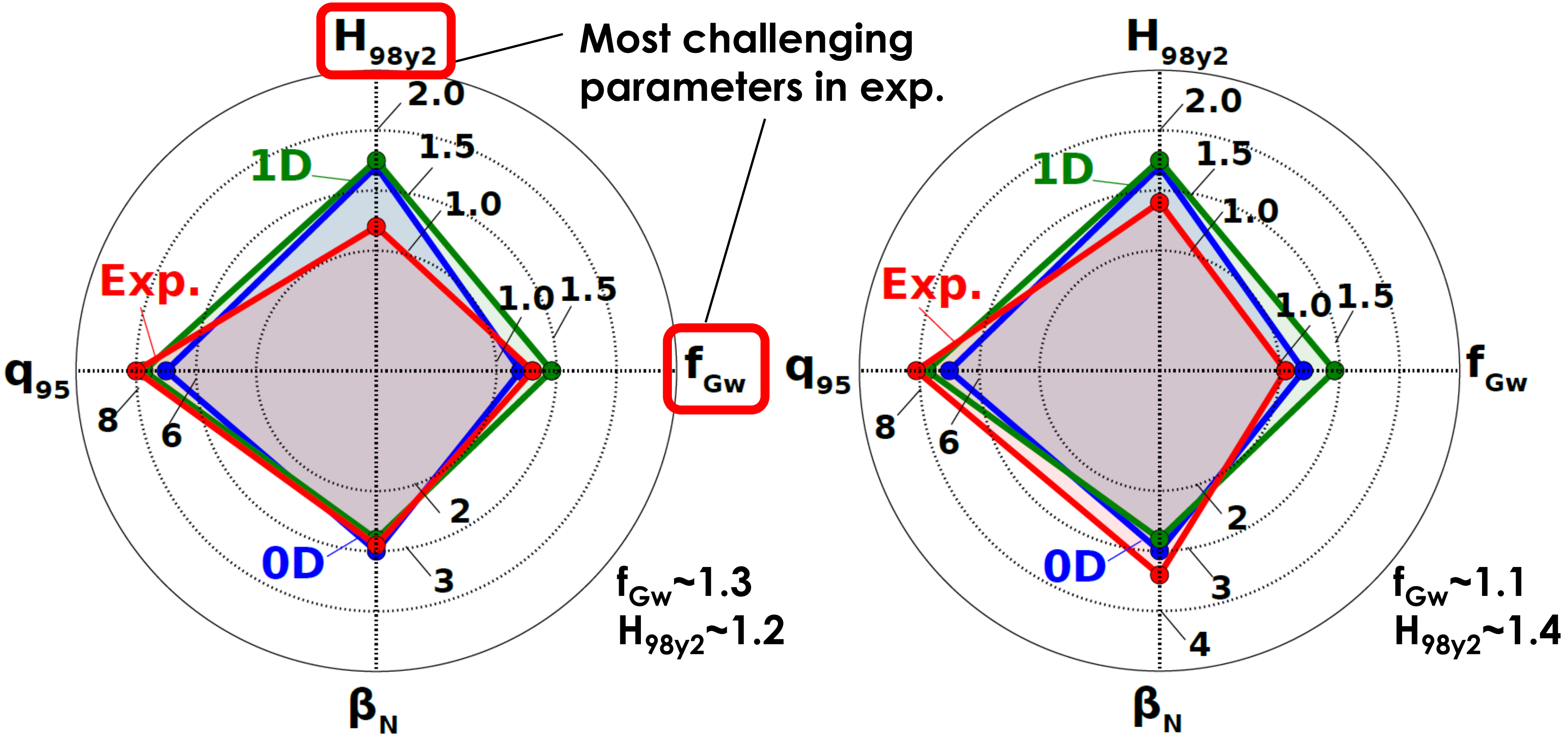

Most challenging parameters in exp.

f_{Gw}~1.3
H_{98y2}~1.2

f_{Gw}~1.1
H_{98y2}~1.4

- **Previous experiments achieved $H_{98}\geq1.5$ with f_{Gw}~1.0**
- **At similar q_{95} and β_N, two combinations of high density (>n_{Gw}) and high confinement (H_{98y2}>1) parameters are achieved simultaneously**

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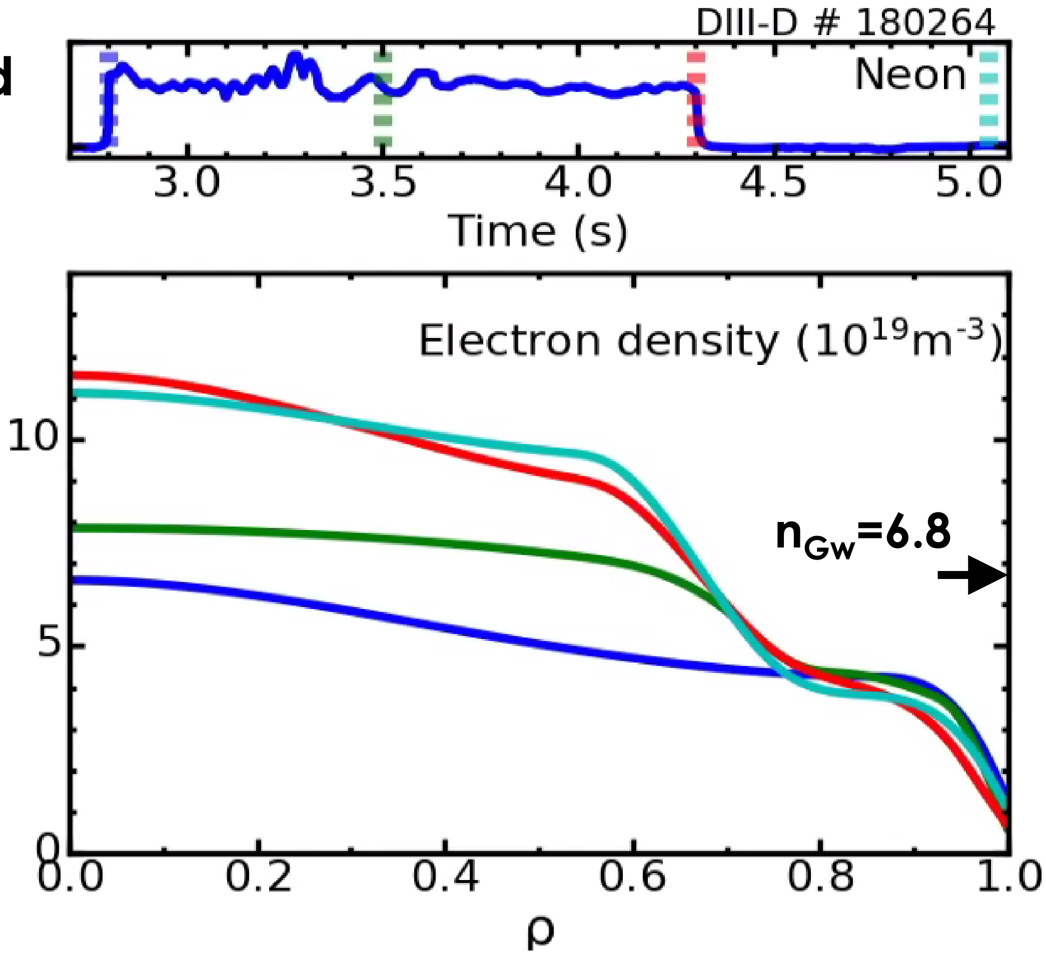
Summary

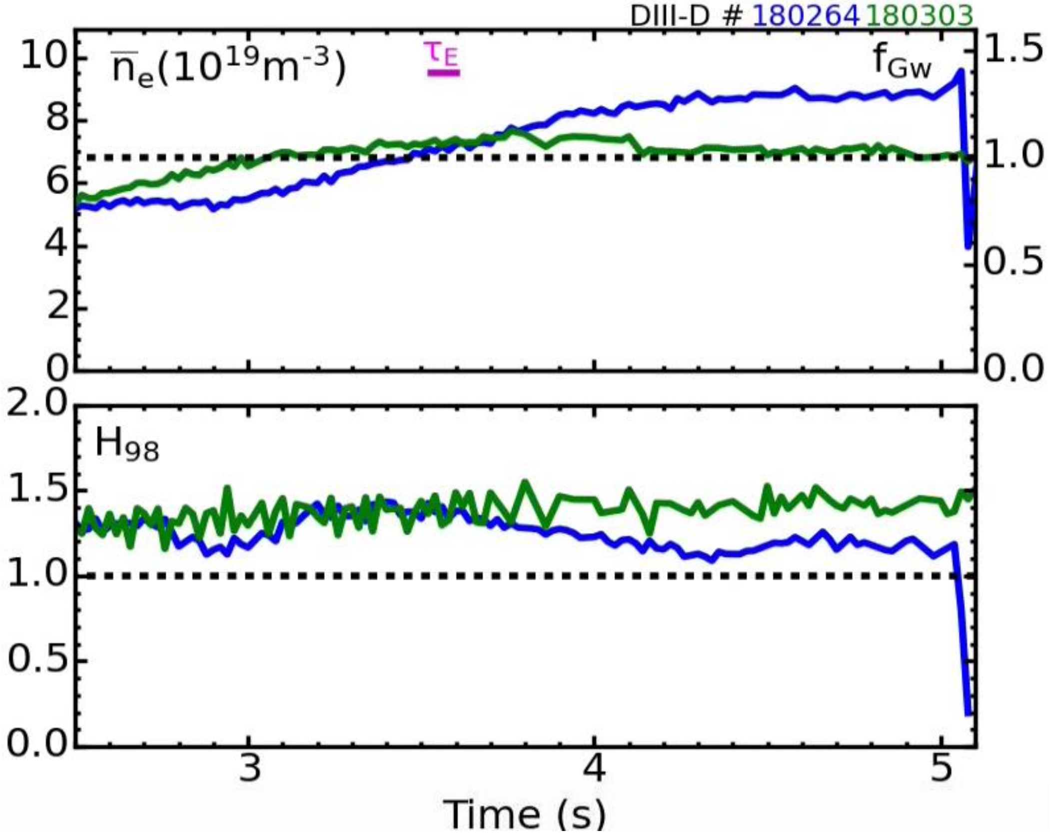
Developing Density ITB is An Effective Approach to Achieve Line-avg Density Above Greenwald Limit

- **$n_{e,ped}$ is kept below Greenwald limit using pedestal density feedback control**
  - $f_{Gw,ped}<0.7$
- **Neon injection triggers large radius density ITB**
- **ITB sustains when neon injection is turned off**
- **Achieve reactor-level absolute density and f_{Gw} up to 1.4**



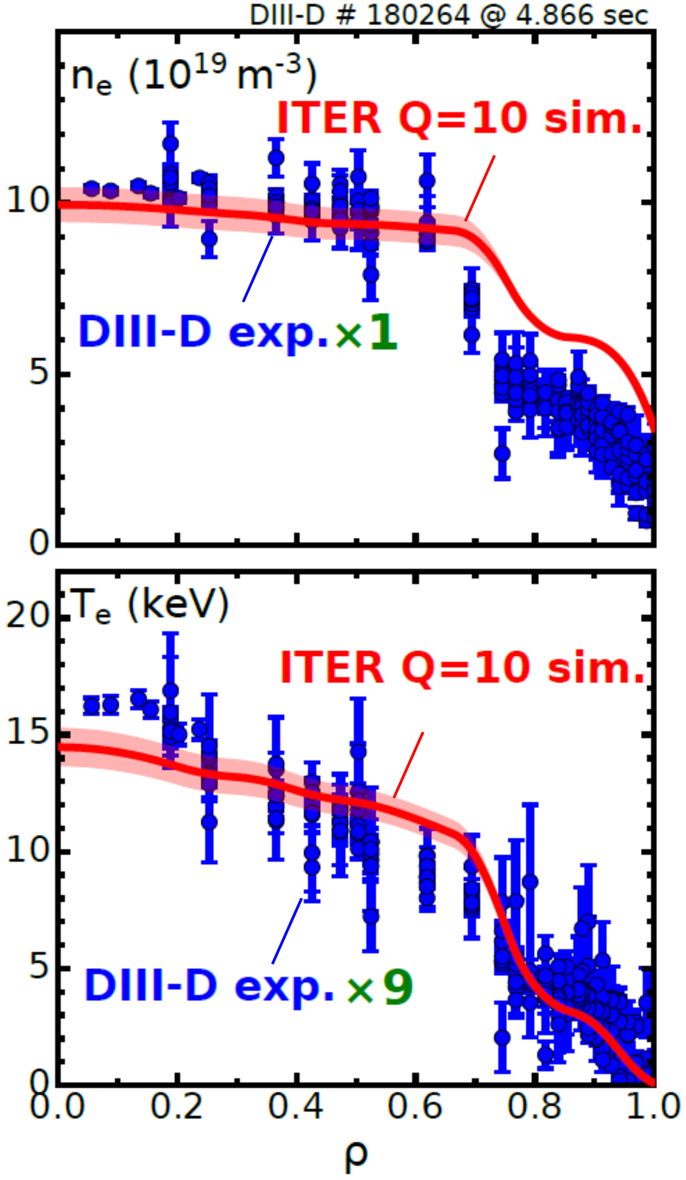
Experiments Demonstrate the Compatibility of High Confinement Core and Reactor Level Density with f_{Gw} Up to 1.4 at q_{95}~8

- **Stationary phase for f_{Gw}>1.0 for 1-2 sec**
  - f_{Gw}~1.3 is up to 8×τ_E
  - f_{Gw}>1.0 is up to 21×τ_E
- **Line-avg density ≥ 7.6×10^{19} m^{-3}, ITER-level density**
  - Support the modeling
- **H_{98} up to 1.4, β_N up to 3.5**



Demonstration of the Feasibility of Developing Large Radius ITB in Future Reactor Condition

- **DIII-D experiment confirms the density ITB in ITER modeling is achievable at similar q_{95}**
  - Same absolute value in the core
  - Similar shape with large radius ITB
- **Electron temperature profile in experiment also has similar shape with ITB compared to ITER simulation**
  - Much lower value due to different I_p, B_T, power, etc.
  - Different collisionality does not seem to affect ITB formation



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- DIII-D high β_P experiments support the physics basis of ITB formation predicted in the ITER simulations

Merits of ITER high β_P scenario

Low disruption risk

Low transient heat load

High confinement at low rotation

Low inductive current fraction

High q_{min}, no ST, 2/1, etc.

Excellent core compatibility with divertor detachment

L. Wang, et al., this conference, Oral talk, Friday, May 14, 2021

Thank you !