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

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A Low Plasma Current Approach for ITER’s Q=10 Goal
is Proposed Using High $\beta_p$ Scenario

Main results:

- Self-consistent 1D integrated modeling predicts Q=10 for ITER at $I_p \sim 7-9$ MA
- ITER’s 500 MW fusion power goal, with $Q > 10$, is predicted at $\beta_N > 3.1$
- DIII-D high $\beta_p$ 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 $\beta_p$ scenario

Modeling for high $\beta_p$ version of ITER $Q=10$ scenario

DIII-D experiment supporting the physics basis of ITER high $\beta_p$ 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

[Graph showing ELM energy fluence vs. plasma current ($I_p$)]

- Surface melting
- JET-ASDEX Upgrade-MAST scaling

Pitts, NME 2019
Eich, NME 2017
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  - Challenge from ‘uncontrolled’ ELMs in ITER is expected to increase
  - Divertor heat load increases due to smaller heat flux width
  - Disruption risk increases
- $Q=10$ at low $I_p$ requires higher normalized confinement ($H_{98}$) at high $\beta_N$
- Very high $H_{98}$ obtained in high $\beta_P$ scenario independent of rotation in multiple tokamaks
  - JT-60U, DIII-D and EAST

Possible solution: Reduce plasma current

Sakamoto, NF 2009
Qian, APS 2019
Garofalo, PPCF, 2018
Pitts, NME 2019
Eich, NME 2017
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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 $\beta_p$ scenario
- $Q=\frac{P_{\text{fus}}}{P_{\text{aux}}}$
  - $P_{\text{fus}}$ decreases slower than $P_{\text{aux}}$ does
- $P_{\text{fus}} \sim 500$ predicted at $I_p \sim 8.5-9$ MA

Start point: ITER high $\beta_p$ Q=5 1D sim.

McClenaghan, NF 2020
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 $\beta_p$ scenario
- Q=Fusion Power/Auxiliary Power
  - $P_{\text{fus}}$ decreases slower than $P_{\text{aux}}$ does
- $P_{\text{fus}} \sim 500$ predicted at $I_p \sim 8.5-9$ MA
- Key requirements for ITER high $\beta_p$ Q=10 scenario:
  - $\beta_N \sim 2.8-3.5 @ q_{95} \sim 6-7$
  - $f_{Gw} \sim 1.2-1.3$
  - $H_{98} > 1.5$

Start point: ITER high $\beta_p$ Q=5 1D sim.

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

DIII-D # 81499 @ 3.8 s

- $n_e [10^{19} \text{m}^{-3}]$
- $T_e [\text{keV}]$
- $T_i [\text{keV}]$

EAST # 81481 @ 5.3 s

- High $\beta_p$
- Exp.
- STEP

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

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 $\beta_p$ Solution are Performed Using Iterative Loop

- Using ITER heating and current drive power:
  - Neutral beams $\leq 33$ MW
  - Electron cyclotron $\leq 20$ MW

- Temperature, density and current profiles evolved self-consistently
  - Impurity densities are not evolved
  - Rotation set to zero

- $\beta_N$ feedback control (5% error) + $f_{Oh}$ feedback control (2% error)
  - Aim at low Ohmic current fraction

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

McClenaghan, NF 2020
# Summary of Major Parameters for ITER High $\beta_p$ Q=10 Base Case

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Case</th>
<th>Q=10 Predicted at $I_p \sim 7.5$ MA</th>
<th>Medium $q_{95}$, high $f_{GW}$, high $\beta$</th>
<th>High Confinement, fully non-inductive operation</th>
<th>Relatively low fusion power, triple product</th>
</tr>
</thead>
</table>

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

| $\beta_N$         | 2.81$\pm$0.06  |                                   |                                             |                                               |                                            |                                            |
| $\beta_p$          | 2.27$\pm$0.04  |                                   |                                             |                                               |                                            |                                            |
| $H_{98y2}$         | 1.75$\pm$0.04  |                                   |                                             |                                               |                                            |                                            |
| $P_{fus}$ (MW)     | 294$\pm$27     |                                   |                                             |                                               |                                            |                                            |
| $Q$                | 10.3$\pm$2.5   |                                   |                                             |                                               |                                            |                                            |
| $G_{98}$           | 0.082$\pm$0.005|                                   |                                             |                                               |                                            |                                            |

| $n_iT_i\tau_E$ (10$^{21}$ m$^{-3}$ keV s) | 3.34$\pm$0.22 | 4.91 | Note the high $Z_{eff}$ for realistic impurity seeding divertor solution

**Note**: The prediction of $Q=10$ at $I_p \sim 7.5$ MA is based on medium $q_{95}$, high $f_{GW}$, and high $\beta$. This condition is achieved through high confinement, fully non-inductive operation, with relatively low fusion power, resulting in a triple product.
The Presence of Large Radius ITB Elevates Core Profile at Low Plasma Current

- Prescribed pedestal
  - $n_{e,ped}$: 93% $n_{GW}$
  - $P_{ped}$: ~78% EPED prediction

- ITB foot @ $\rho=0.8$
  - 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 $Z_{\text{eff}}$ will Enhance Q by Increasing $\alpha$ Heating and Reducing Auxiliary Heating at Similar Confinement

- $Q \sim 10$ at $Z_{\text{eff}} \sim 2.5$
- The key of achieving high $Q$ at similar $P_{\text{total}}$ is to replace a part of $P_{\text{aux}}$ by $P_{\alpha}$
- Lower $Z_{\text{eff}}$ enables higher main (fusion) ion densities and higher fusion power
- Impurity species: He (thermal), Ne
Increase $\beta_N$ is An Effective Approach to Enhance Fusion Power

- $\beta_N \sim 2.8$ at $Z_{\text{eff}} \sim 2.5$ gives $P_{\text{fus}} \sim 300\text{ MW}$
- With increasing $\beta_N$:
  - Fusion power increases
  - Fusion gain increases
  - Plasma current increase; $f_{\text{Oh}} \sim 0$
- Most of cases well below $P_{\text{aux}}$ limit (53 MW)
  - Above L-H threshold power (77 MW)
- ITER 500 MW fusion power requires $\beta_N \sim 3.1 - 3.4$
  - $I_P \leq 9\text{ MA}$
- Triple product at baseline level
Recent DIII-D Experiments Address Challenges for ITER High $\beta_p$, Q=10 Scenario

Most challenging parameters in exp.
Recent DIII-D Experiments Address Challenges for ITER High $\beta_p$ Q=10 Scenario

- Previous experiments achieved $H_{98} \geq 1.5$ with $f_{Gw} \sim 1.0$
- At similar $q_{95}$ and $\beta_N$, 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

- $n_{e,\text{ped}}$ is kept below Greenwald limit using pedestal density feedback control
  - $f_{Gw,\text{ped}} < 0.7$
- 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 $f_{\text{GW}}$ Up to 1.4 at $q_{95} \sim 8$

- Stationary phase for $f_{\text{GW}}>1.0$ for 1-2 sec
  - $f_{\text{GW}} \sim 1.3$ is up to $8\times \tau_E$
  - $f_{\text{GW}} > 1.0$ is up to $21\times \tau_E$

- Line-avg density $\geq 7.6\times10^{19}$ m$^{-3}$, ITER-level density
  - Support the modeling

- $H_{98}$ up to 1.4, $\beta_N$ 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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- Self-consistent 1D integrated modeling predicts Q=10 for ITER at $I_p \sim 7-9$ MA
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Merits of ITER high $\beta_p$ 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!