Validation of Pellet Ablation Models and Investigation of Density Fueling Needs on ITER and CFETR

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High density operation ($f_{gw}$~1) is critical for fusion reactor

- Self-consistent (TGLF+NEO,EPED) simulations important for accurately predicting next generation device confinement
- Predicted increased $Q = P_{fus}/P_{aux}$ with increased density.

**ITER super-H**

$Q_{DR}$ vs $f_{gw\,ped} Z_{eff}$

**CFETR**

$li \sim 0.93$, $f_{gw} \sim 1.17$

Z Deng et al., arXiv 2019

Solomon et al., NF 2014
Densities above Greenwald limit have been achieved with core pellet fueling

- Due to $n_e$ peaking from core pellet fueling
- Greenwald limit likely due to pedestal, edge effect.

Greenwald PPCF 2002  
Eich et al. NF 2018

- pedestal density remains below $n_{e,ped}/n_{gw} < 1$

Still limited $n_e/n_{gw} < 1.5$

Mahdavi et al. EPS 1997
OMFIT STEP module provides useful tool for integrated modeling for steady-state transport

- Self-consistent modeling loop iterates between kinetic evolution (TGYRO) current evolution (ONETWO), and magnetic equilibrium solver (EFIT)

- $T_i$, $T_e$, $n_e$, $q$, and $T_i$, $T_e$ pedestal are evolved

- Pellet Ablation Module (PAM) has been incorporated in STEP

Meneghini et al. 2020
PAM has been developed for STEP transport modeling

- Pellet ablation (G) rate based on PELLET formulation for homogeneous DT mixtures

\[ G = C \left( \frac{\langle W \rangle}{W_D} \right)^{2/3} \left( \frac{T_e}{2} \right)^{5/3} \left( \frac{r_p}{0.2} \right)^{4/3} n_e^{1/3} \left( e^{-14} \right) \]

Typical ITER baseline HFS injection \( v_p = 500 \text{ m/s}, r_p = 2.5 \text{ mm} \)

Houlberg et al., C, 1979
Parks et al., to be submitted
PAM has been developed for STEP transport modeling

- Arbitrary injection angles
- General geometry
- Supports multiple layered pellets
  - Shell pellets
- Modular to easily add new models
  - $B_t$ dependence of pellet ablation
B\textsubscript{t} dependence of ablation could significantly improve ITER core fueling prospects

- Recent 2D Eulerian-Lagrangian modeling suggested there is B\textsubscript{t} dependence of ablation rate
  
  \[ G \propto B_{t}^{-0.872} \]
  
  *Bosviel et al., NF 2020*

- Double the depth of ablation of pellet in ITER

- Experimental comparisons are ongoing to verify dependence
Pellet ablation and $\nabla B$ drift effect important in determining pellet fueling

- Local pressure bump combined with $\nabla B$ induces an $\nabla \times B$ flow which causes pellet mass to drift in $R$-direction
  
  *P. B. Parks et al. PRL 2005*

- Reduced scaling for model used for ITER
  
  $\Delta_{\text{drift}} \propto Bt^{-0.15}Te0^{-0.13} T_{e,\text{ped}}^{0.5} r_p^{0.76} q_{95}^{-0.15}$

  *Baylor et al., NF 2007*

- More complete models to be implemented in PAM
Pellet deposited onto 2D grid \((\rho, \theta)\) as Gaussian cloud

\[
n_{\text{pellet}}(t, \rho, \theta) = G(t) \exp \left( - \frac{(R - R_p - \Delta_{\text{drift}})^2}{R_c^2} \right. \\
\left. - \frac{(Z - Z_p)^2}{Z_c^2} \right)
\]

- Cloud integrated for steady-state particle source for STEP modeling

\[
S_{n_e}(\rho) = \int_{\text{inj}} \int n_{\text{pellet}}(t, \rho, \theta) dt \, dl / \int dl
\]

\[
S_{n_e}(\rho) = \frac{n_e(10^{19} \text{m}^{-3}) \text{after pellet}}{n_e(10^{19} \text{m}^{-3}) \text{before pellet}}
\]

\[
G(10^{24} \text{ atoms/s})
\]
PAM has been used to predict traditional and shell pellets

- PAM shows good agreement with PELLET and reasonable agreement with DIII-D experiments.
  - Incorporation of $\nabla B$ models will improve agreement with experiments

- PAM predicts 40 µm diamond shell could deliver a payload to $\rho=0.3$
  - Similar with experiments

Hollmann et al. PRL 2019
The STEP workflow with pellet fueling has been tested against DIII-D experiments.

- Experimental profiles examined after initial transient phase.

- Adding pellet fueling source to STEP increases density and lowers temperature, consistent with experiments.
The STEP workflow is also being applied to various other tokamak devices.

- **STEP prediction of EAST H-mode discharge with** $P_{nbi}=5$ **MW finds reasonable agreement with the experiment.**

- **STEP has been used to predict an ECH heated H-mode on HL-2M**
ITER advanced inductive scenario predicts near Q=10 with strong pellet fueling

- 12 MA advanced inductive hybrid scenario
- Q=9 predicted with $f_{gw,ped}=1$ and max pellet fueling.
CFETR H-mode scenarios improve dramatically with increased density source

- Gaussian density source centered at $\rho = 0.4, 0.5, 0.6$

- Deep core density fueling ($\rho \leq 0.6$) likely difficult with conventional pellets

- Potential path forward could be shell pellets

Hollmann et al PRL 2019
Realistic shell pellet source shows similar improvement in performance

- **LFS injection**
  - $v_p = 2000 \text{ m/s}$
  - $r_{p,DT} = 3\text{ mm}$

- **Zeff scales with carbon shell impurity concentration**

- **Predicted fusion**
  - $P_{fus} = 1\text{ GW}$ and $f_{\text{burn}} = 3\%$
  - are reached for shell thicknesses above 220 $\mu\text{m}$ and $f_p = 2-4 \text{ Hz}$,
Pellet fueling is critical for ITER and reactors

- Pellet Ablation Module (PAM) has been developed and tested for pellet fueling transport studies

- Integrated modeling with STEP predicts improved fusion performance with pellet fueling in both ITER and CFETR

- CFETR H-mode scenario requires significant central fueling for peaked density
  - Shell pellets are potential way forward.