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

by

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with

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1. General Atomics
2. ASIPP
3. SWIP
4. USTC

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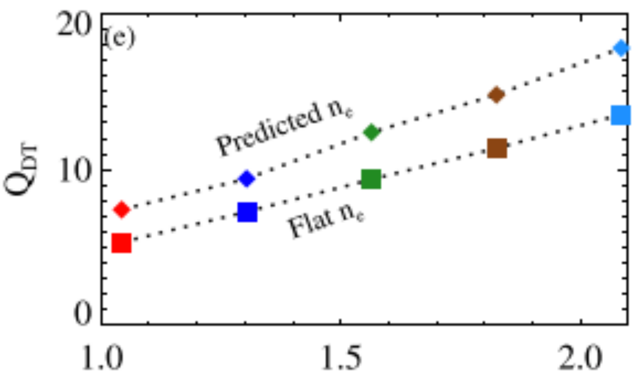
High density operation (f_{gw}~1) is critical for fusion reactor

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

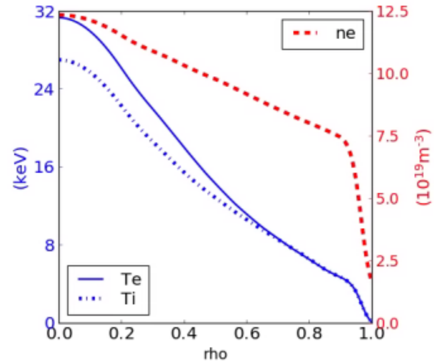
ITER super-H



$f_{gw.ped}\, Z_{eff}$

Solomon et al.,NF 2014

CFETR



li~0.93 f_{gw} ~1.17

Z Deng et al. arXiv 2019

Densities above Greenwald limit have been achieved with core pellet fueling

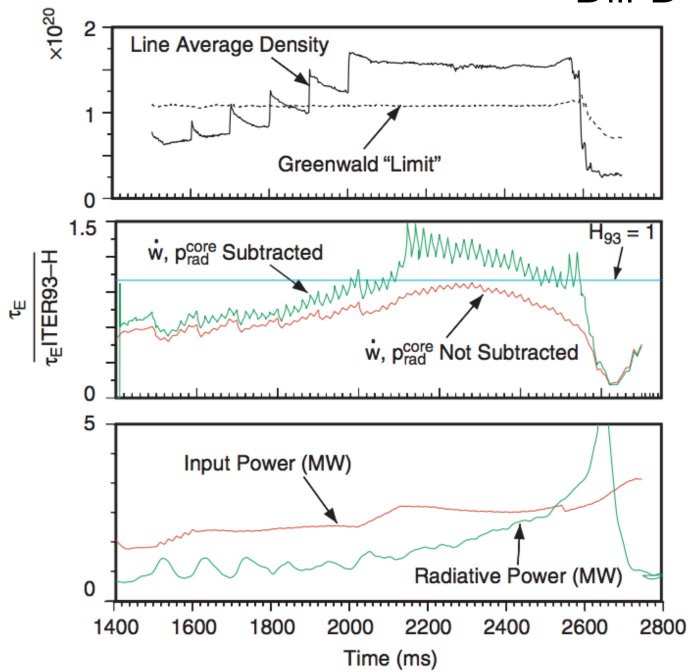
DIII-D

- **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

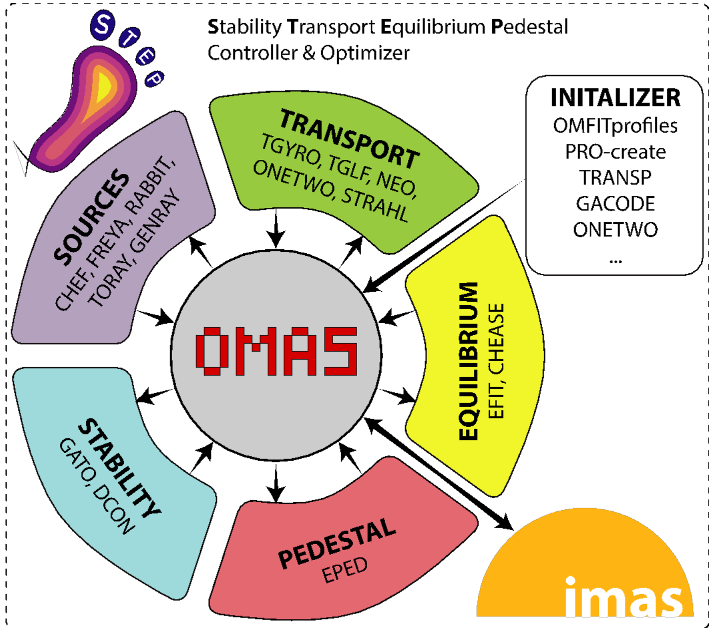
  – pedestal density remains below $n_{e,ped}/n_{gw}<1$
- **Still limited n_e/n_{gw} < 1.5**

  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

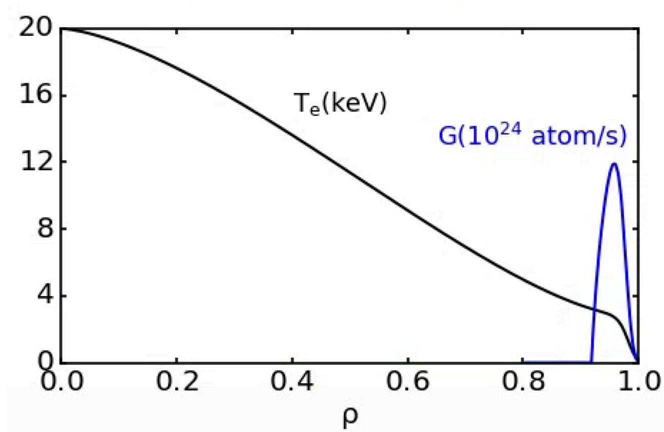
PAM has been developed for STEP transport modeling

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

$$G = C\left(\frac{\langle W\rangle}{W_D}\right)^{2/3}\left(\frac{T_e}{2}\right)^{5/3}\left(\frac{r_p}{0.2}\right)^{4/3} n_{e14}^{1/3}$$

Houlberg et al., C , 1979
Parks et al.,
to be submitted

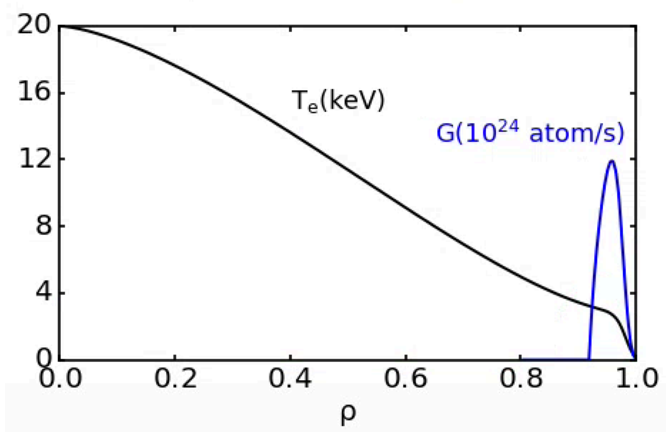
Typical ITER baseline HFS injection v_p=500 m/s, r_p=2.5 mm



GENERAL ATOMICS

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_t dependence of ablation could significantly improve ITER core fueling prospects

- **Recent 2D Eulerian-Lagrangian modeling suggested there is B_t dependence of ablation rate**

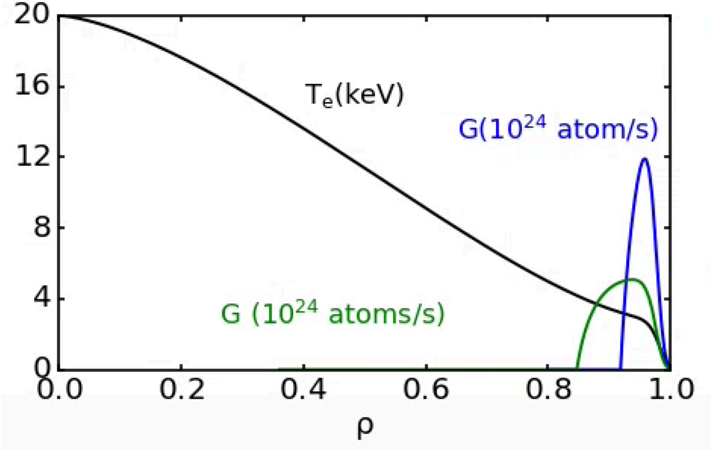
$$G \propto B_t^{-0.872}$$

Bosviel et al., NF 2020

- **Double the depth of ablation of pellet in ITER**

- **Experimental comparisons are ongoing to verify dependence**

No B_t dependence
B_t dependence



GENERAL ATOMICS

Pellet ablation and ∇B drift effect important in determini pellet fueling

- **Local pressure bump combined with ∇B induces a ExB flow which causes pellet mass to drift in R-direction**

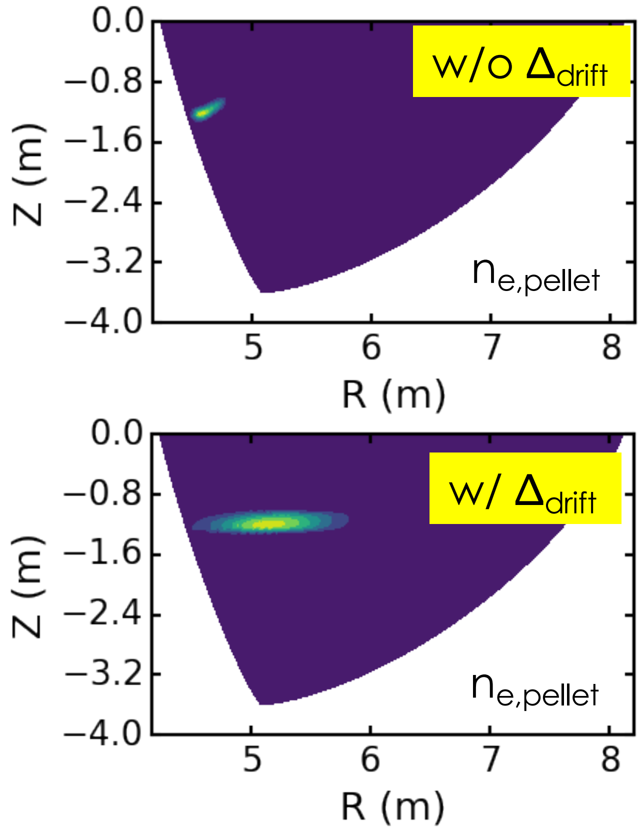
  P. B. Parks et al. PRL 2005

- **Reduced scaling for model used for ITER**

$$\Delta_{drift} \propto \quad Bt^{-0.15} Te0^{-0.13}$$
$$T_{e,ped}^{0.5} r_p^{0.76} q_{95}^{-.15}$$

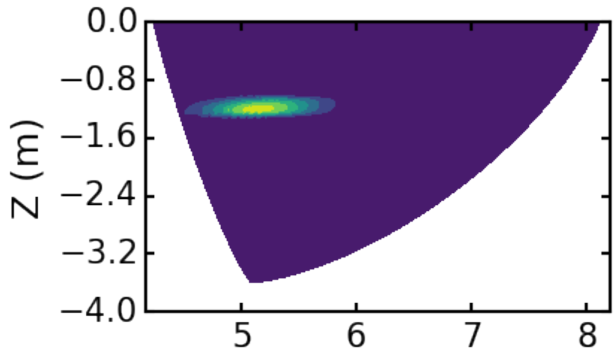
  Baylor et al., NF 2007

- **More complete models to be implemented in PAM**



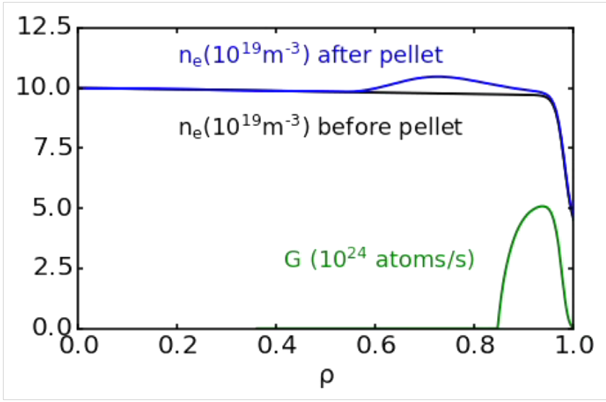
Pellet deposited onto 2D grid (ρ,θ) as Gaussian cloud

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



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

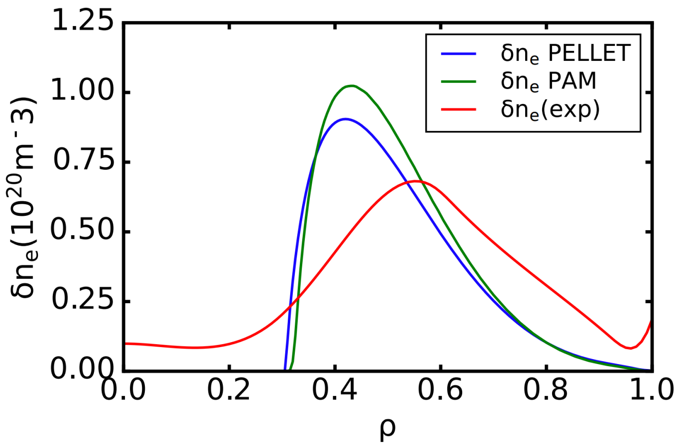
$$S_{n_e}(\rho) = f_{inj}\int n_{pellet}(t,\rho,\theta)dtdl \Big/ \int dl$$



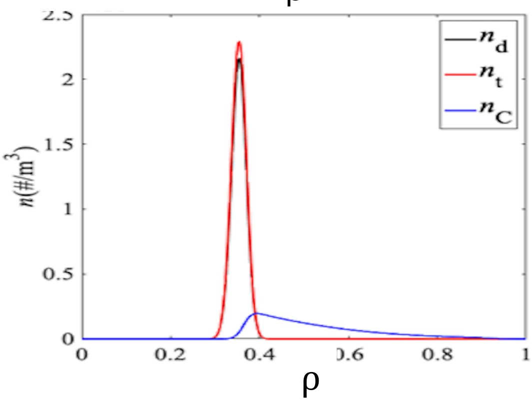
GENERAL ATOMICS

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 ∇B models will improve agreement with experiments



- **PAM predicts 40 μm diamond shell could deliver a payload to ρ=0.3**
  - similar with experiments

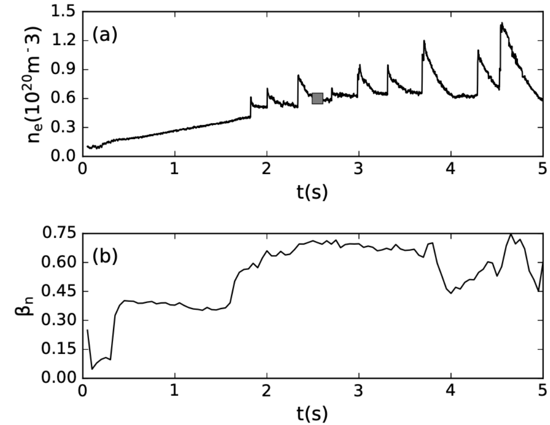


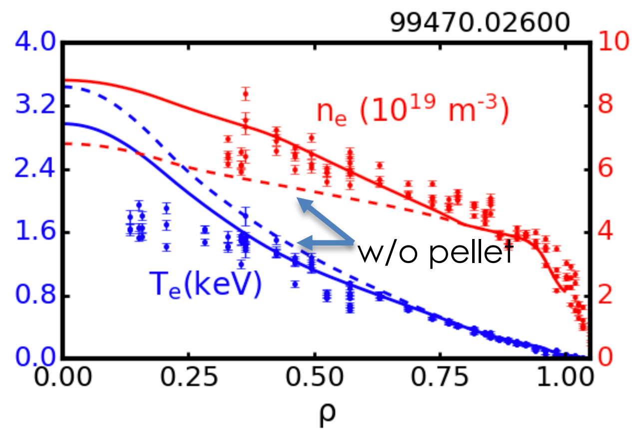
Hollmann et al. PRL 2019

The STEP workflow with pellet fueling has been tested against DIII-D experiments

- Experimental profiles examined after initial transient phase.

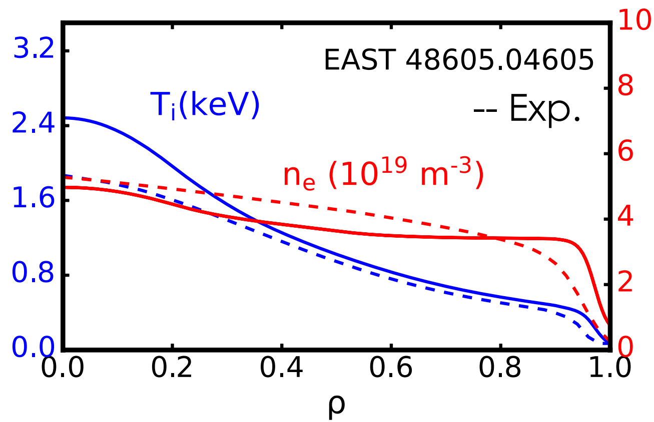
- Adding pellet fueling source to STEP increases density and lowers temperature, consistent with experiments



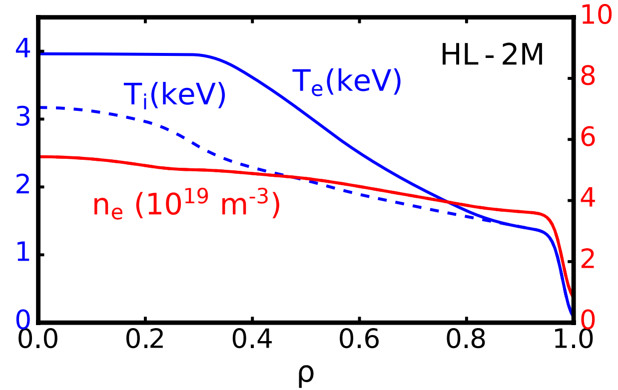


The STEP workflow is also being applied to various other tokamak devices

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

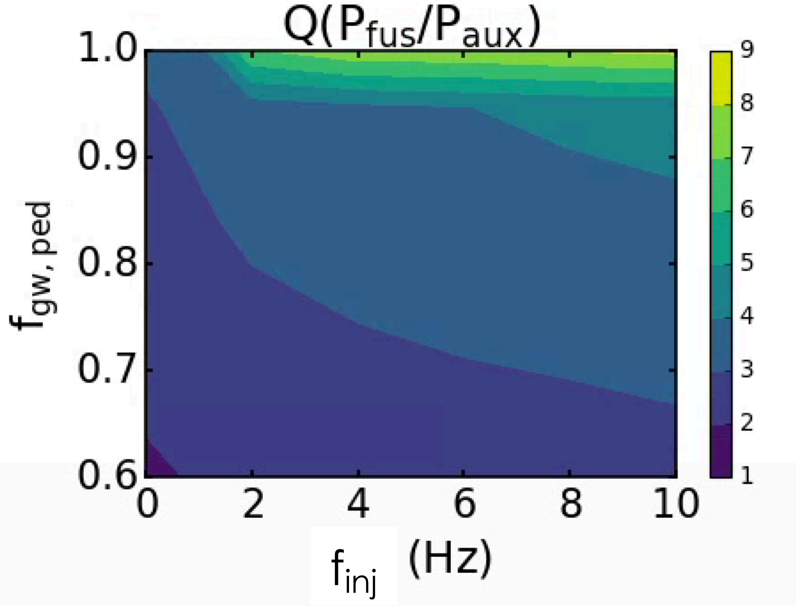


- **STEP has been used to predict an ECH heated H-mode on HL-2M**



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.**

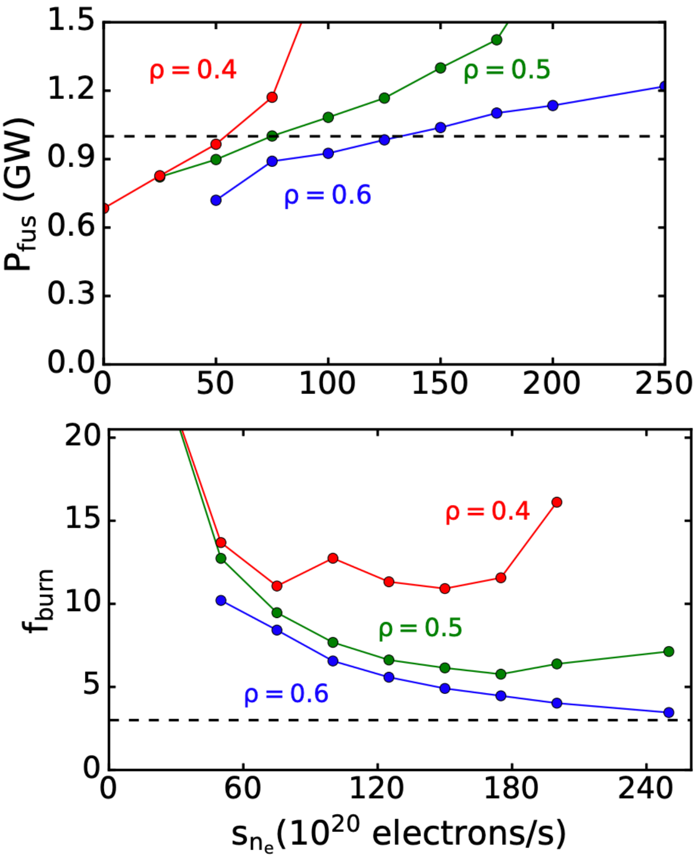


GENERAL ATOMICS

CFETR H-mode scenarios improve dramatically with increased density source

- **Gaussian density source centered at ρ=0.4,0.5, 0.6**
- **Deep core density fueling (ρ<=0.6) likely difficult with conventional pellets**
- **Potential path forward could be shell pellets**

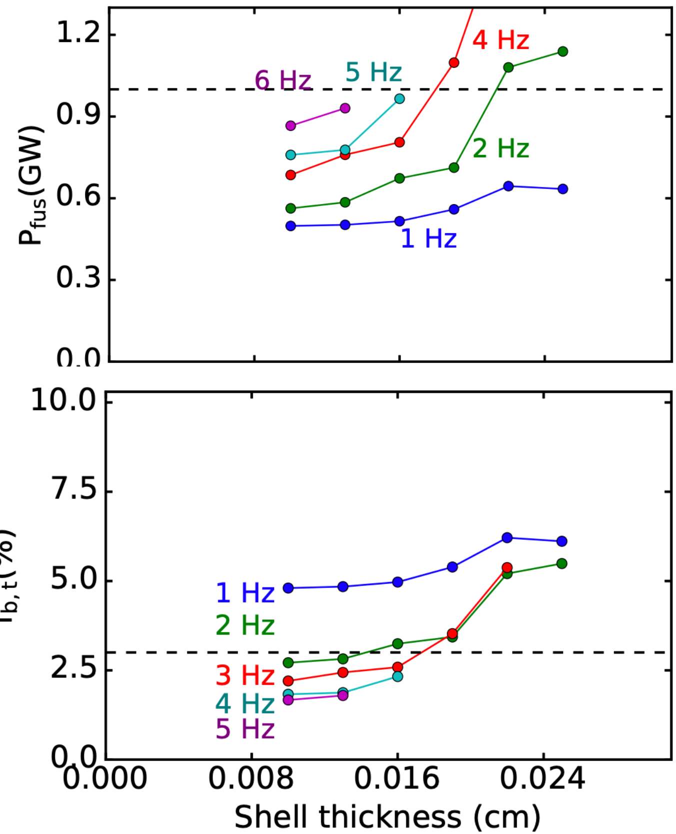
  Hollmann et al PRL 2019



GENERAL ATOMICS

Realistic shell pellet source shows similar improvement in performance

- **LFS injection**
  - v_p= 2000 m/s
  - $r_{p,DT}$ = 3mm
- **Zeff scales with carbon shell impurity concentration**
- **Predicted fusion P_{fus}=1GW and f_{burn}=3% are reached for shell thicknesses above 220 μm and f_p=2-4 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.