# Predictive Transport Modeling of FIRE

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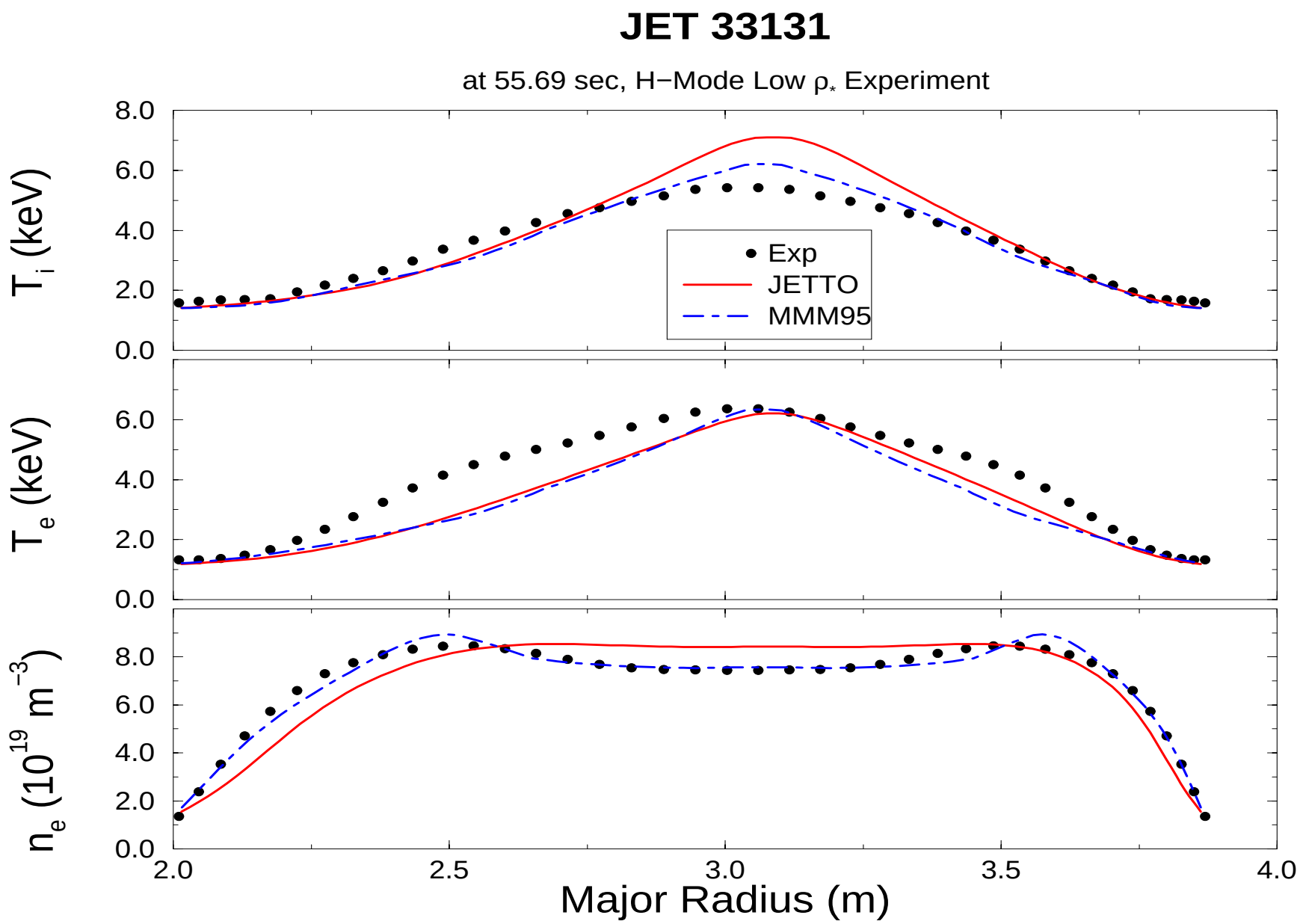
# Predictive Transport Simulations of FIRE

## BALDUR simulations carried out for the FIRE design

- **using Multi-Mode Model (MMM95) and Mixed-Bohm/gyro-Bohm (JETTO) transport models**
  - **MMM95 predicts confinement scaling in systematic scans over power, current, density, $\rho_*$, $\nu_*$, $\beta$, isotope**
  - **MMM95 and JETTO models match experimental data from DIII-D, JET, and TFTR equally well**
  - **Need separate model for pedestal height at the edge of H-mode plasmas (scans of pedestal height used in FIRE simulations)**
- **These time-dependent simulations include sawtooth oscillations, current ramp, $< n_e >$, $P_{\rm aux}(t)$, $P_\alpha(t)$**
  - **Hydrogenic and impurity density profiles are predicted as well as temperature and current profiles**

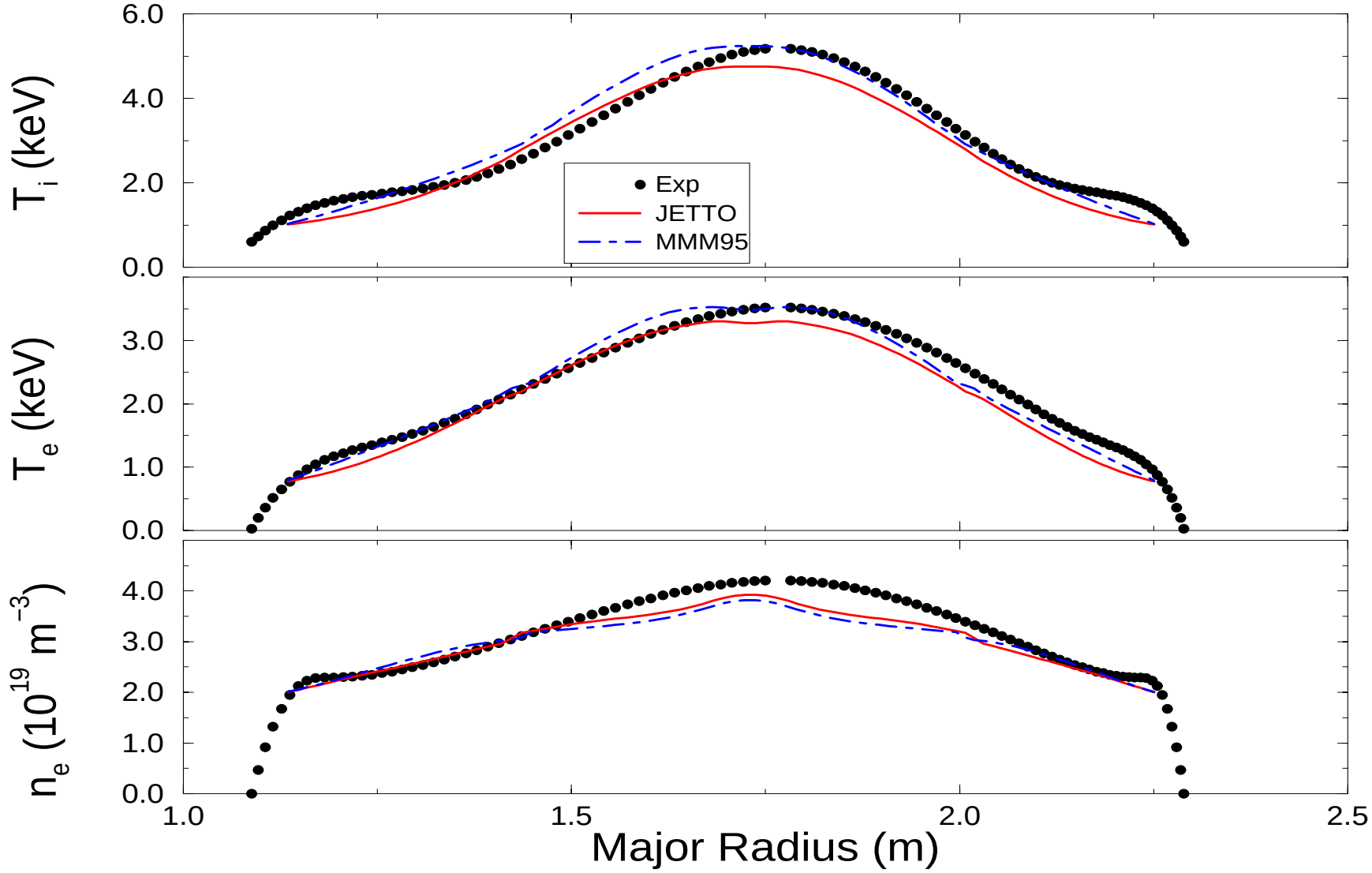
# Different Transport Models Compared at Lehigh University

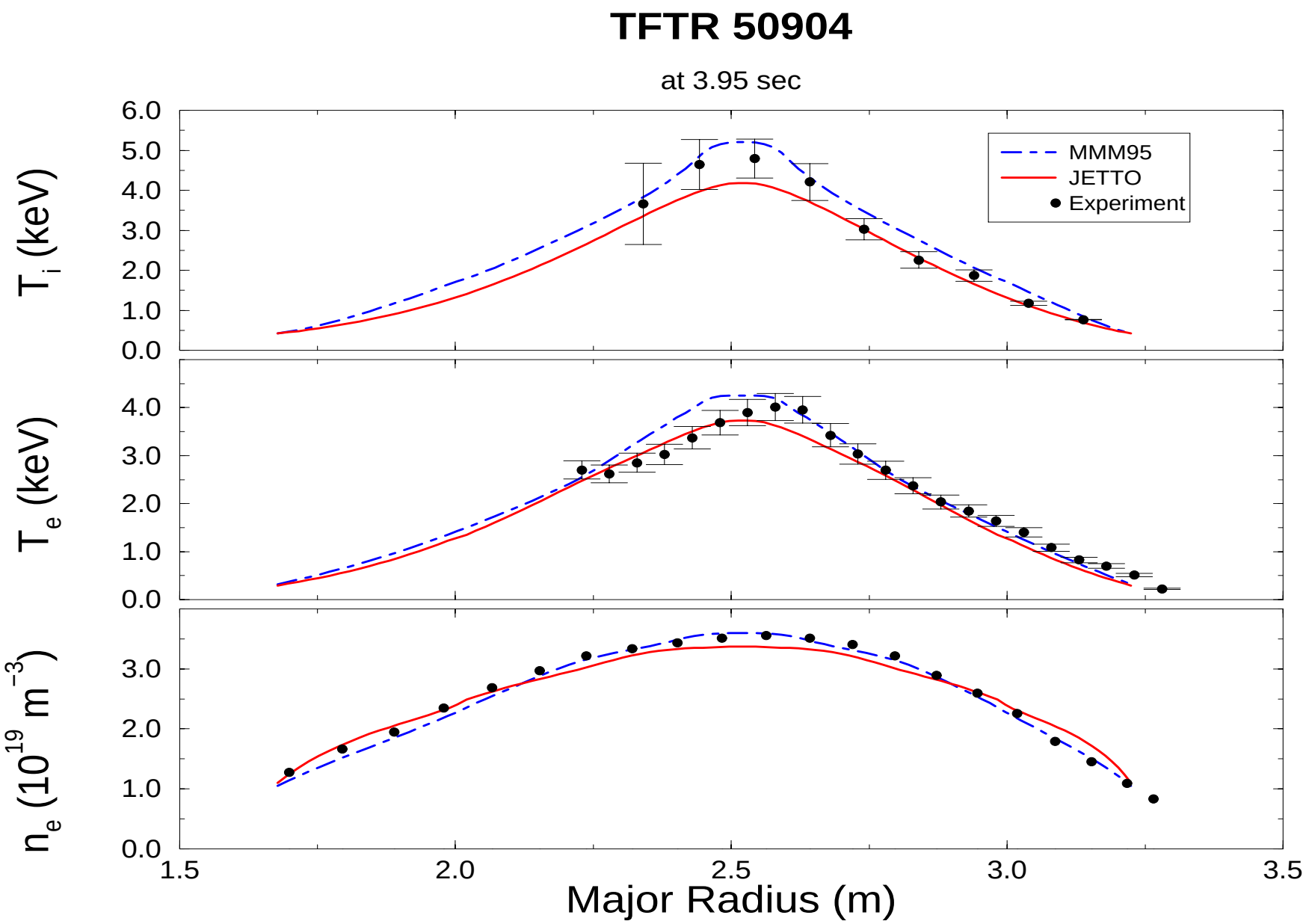
- **Multi-Mode transport model (Lehigh)**
  - **Combination of theory-based transport models (Weiland, resistive and kinetic ballooning, and neoclassical)**
  - **Particle as well as thermal transport**
  - **Follows gyro-Bohm scaling** $(\chi \propto \rho_s^2 c_s/R)$
  - **Flow shear stabilization**
- **Mixed-Bohm/gyro-Bohm (JETTO) model developed at JET**
  - **Empirical non-local model with a combination of Bohm** $(\chi \propto \rho_s c_s)$ **and gyro-Bohm scaling** $(\chi \propto \rho_s^2 c_s/R)$
- **Both model match data within 15% relative rms deviations for DIII-D, JET, and TFTR simulations**


JET 33131
at 55.69 sec, H−Mode Low ρ* Experiment
T_i (keV)
T_e (keV)
n_e (10^19 m^−3)
Exp
JETTO
MMM95
8.0
6.0
4.0
2.0
0.0
2.0
2.5
3.0
3.5
4.0
Major Radius (m)

# DIII−D 81321

at 3.9 sec, H−Mode Low $n_e$ Experiment




TFTR 50904
at 3.95 sec
MMM95
JETTO
Experiment
$T_i$ (keV)
$T_e$ (keV)
$n_e$ ($10^{19}$ $m^{-3}$)
Major Radius (m)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1.5
2.0
2.5
3.0
3.5

# Baseline Simulation of FIRE

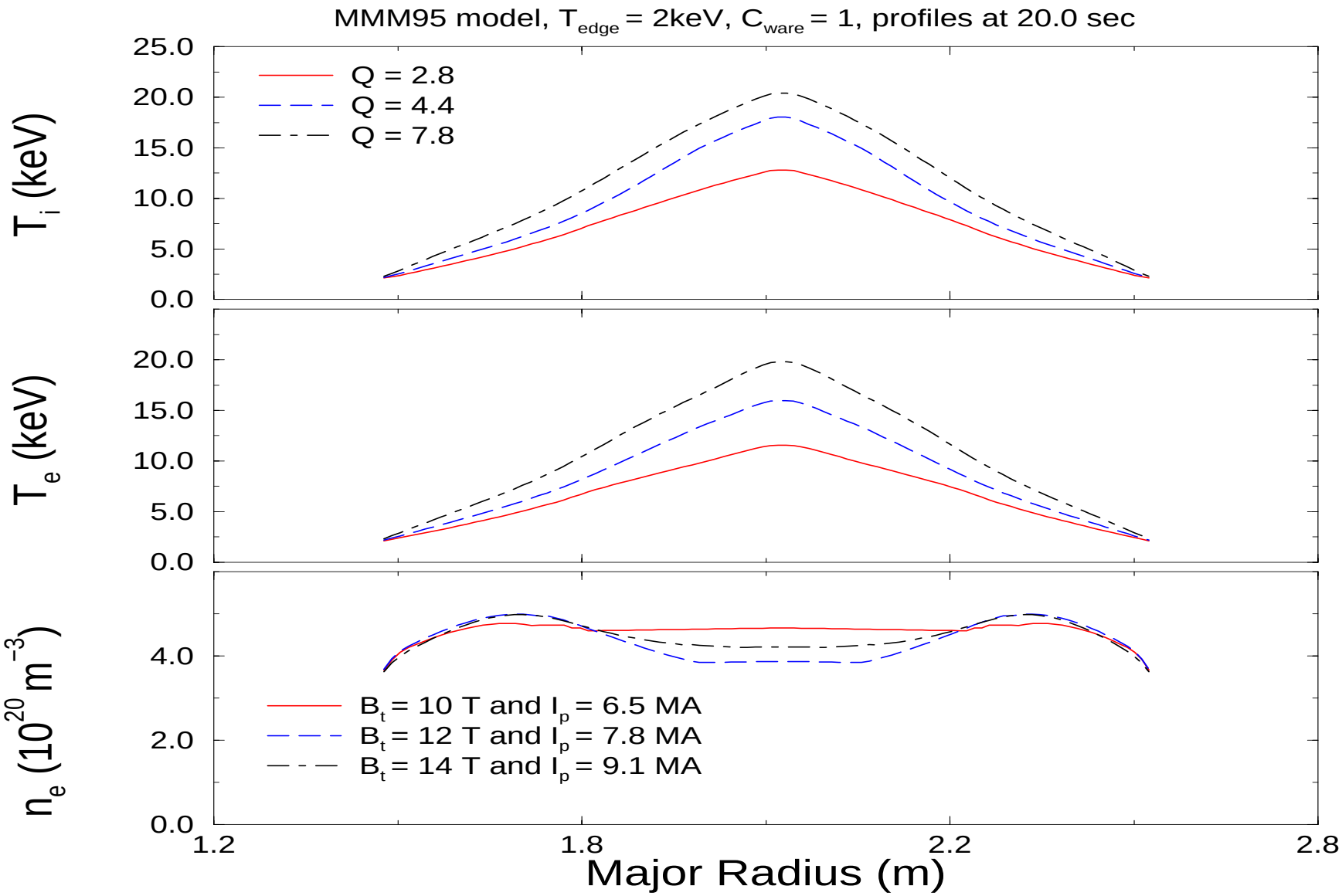
| | |
|---|---|
| $R$ | 2.0 m |
| $a$ | 0.525 m |
| $\kappa$ | 1.8 |
| $\delta$ | 0.4 |
| $B_T$ | 10.0 tesla |
| $I_p$ | ramped up to 6.5 MA at 6 sec. |
| $\langle n_{e20} \rangle$ | ramped up to 4.5 at 10 sec |
| $\langle Z_{\mathrm{eff}} \rangle$ | 1.2 from Carbon and Helium |
| $P_{\mathrm{aux}}$ | 30 MW from 4 to 7.5 sec |
| | 22 MW from 7.5 to 20 sec |
| | applied entirely to ions |
| $T_{\mathrm{edge}}$ | 2 keV |
| model | MMM95 transport model |

# Increasing Plasma Current Has the Biggest Effect on Performance

| $I_P$ (MA) | $B_T$ (tesla) | $T_{i0}$ keV | $\tau_E$ | $H$ | $P_\alpha$ (MW) | $Q_{\text{fusion}}$ |
|---|---|---|---|---|---|---|
| 6.5 | 10 | 12.8 | 0.52 | 1.75 | 12.3 | 2.8 |
| 7.8 | 12 | 18.0 | 0.53 | 1.63 | 19.4 | 4.4 |
| 9.1 | 14 | 20.4 | 0.50 | 1.53 | 34.2 | 7.8 |

- **Multi-Mode MMM95 model**
- $T_{\text{edge}} = 2$ **keV**
- **30 MW auxiliary power decreased to 22 MW after 7.5 sec**
- $\langle Z_{\text{eff}} \rangle \approx 1.2$ **(Carbon and Helium)**
- $\langle n_{e20} \rangle$ **increases to 4.5 at end of simulation**
- $H \equiv \tau_E / \tau_E^{\text{Goldston}}$
- $Q_{\text{fusion}} \equiv 5P_\alpha / P_{\text{aux}}$ **where** $P_{\text{aux}} = 22$ **(MW)**

# FIRE : Current Scan



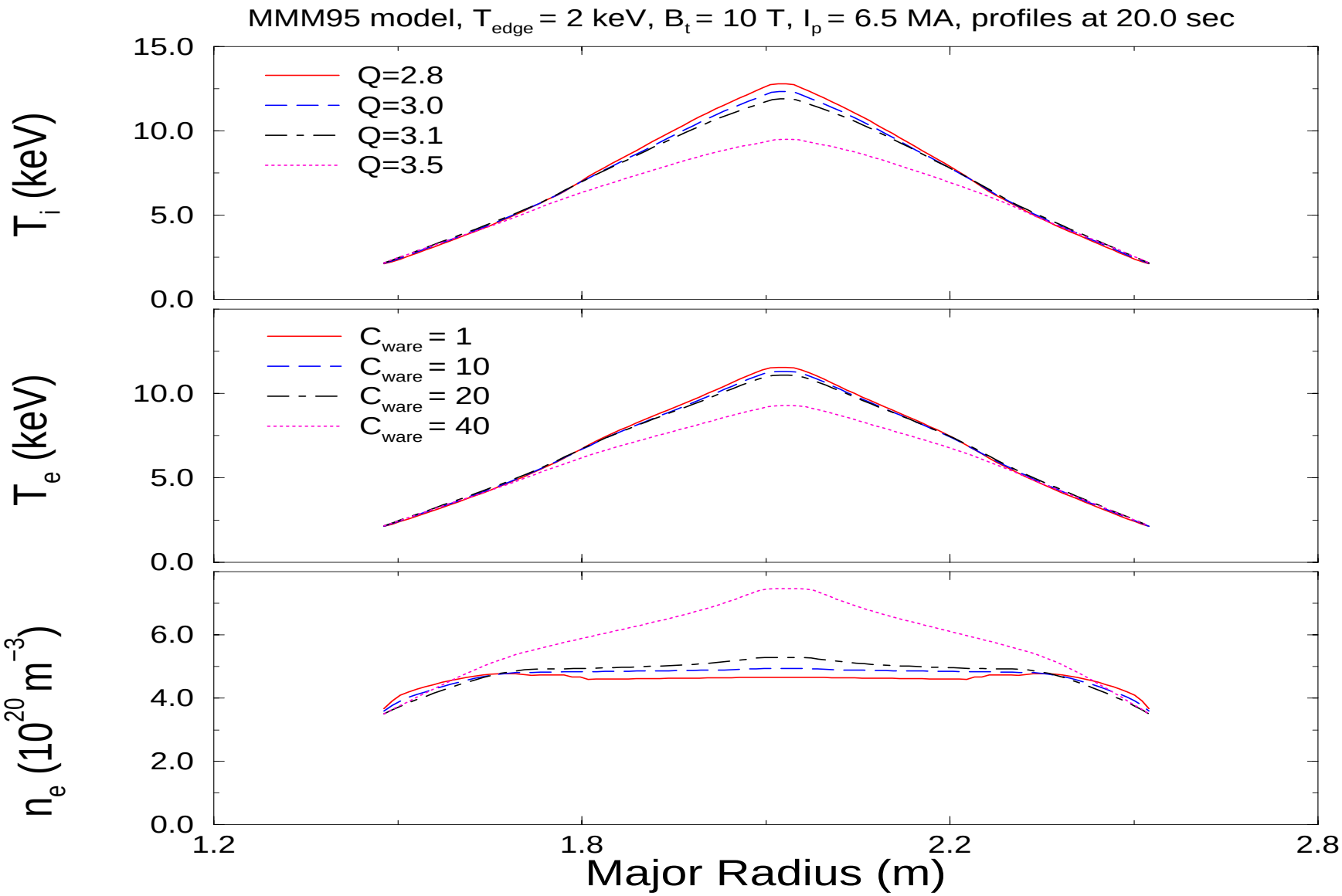
# Peaking the Density Profile Has a Modest Effect on Performance

**Enhanced Ware pinch used to increase density peaking.**
$C_{\text{Ware}} \equiv$ **Ware pinch multiplier used to peak the density profile**
**Pellets would need to be used in more realistic simulations.**

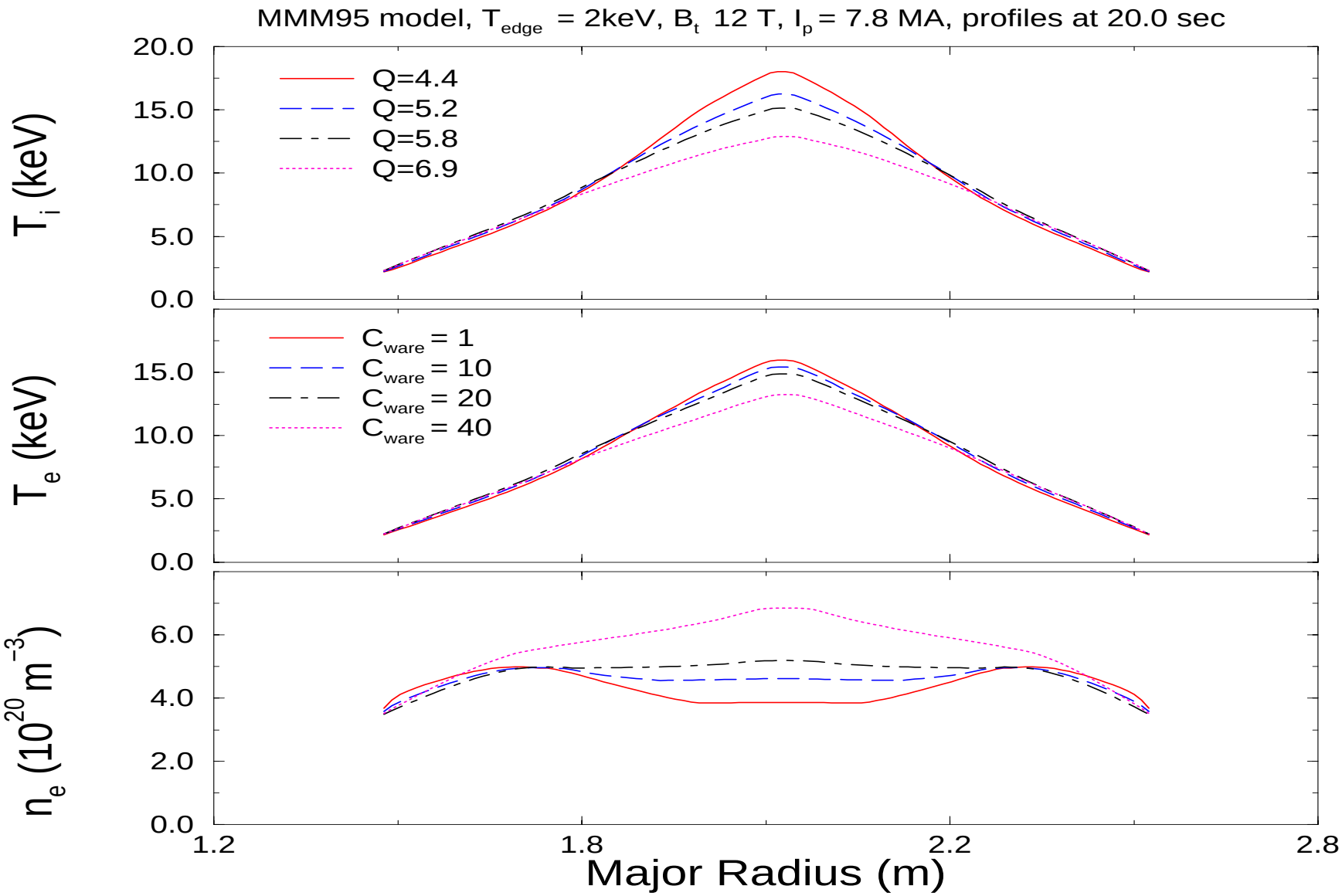
| $I_P$ (MA) | $B_T$ (tesla) | $C_{\text{Ware}}$ | $n_{e20}(0)$ | $\tau_E$ | $H$ | $P_\alpha$ (MW) | $Q_{\text{fusion}}$ |
|---|---|---|---|---|---|---|---|
| 6.5 | 10 | 1 | 4.7 | 0.52 | 1.75 | 12.3 | 2.8 |
| 6.5 | 10 | 10 | 4.9 | 0.53 | 1.82 | 12.9 | 2.9 |
| 6.5 | 10 | 20 | 5.3 | 0.53 | 1.83 | 13.6 | 3.1 |
| 6.5 | 10 | 40 | 7.5 | 0.56 | 1.95 | 15.2 | 3.5 |
| 7.8 | 12 | 1 | 3.9 | 0.53 | 1.63 | 19.4 | 4.4 |
| 7.8 | 12 | 10 | 4.4 | 0.52 | 1.66 | 22.8 | 5.2 |
| 7.8 | 12 | 20 | 5.2 | 0.50 | 1.68 | 25.4 | 5.8 |
| 7.8 | 12 | 40 | 6.9 | 0.51 | 1.75 | 30.5 | 6.9 |
| 9.1 | 14 | 1 | 4.2 | 0.50 | 1.53 | 34.2 | 7.8 |
| 9.1 | 14 | 10 | 4.8 | 0.48 | 1.54 | 39.6 | 9.0 |
| 9.1 | 14 | 20 | 5.3 | 0.47 | 1.55 | 43.6 | 9.9 |
| 9.1 | 14 | 40 | 6.3 | 0.46 | 1.59 | 50.9 | 11.6 |

**MMM95 model,** $T_{\text{edge}} = 2$ **keV,** $P_{\text{aux}} = 22$ **(MW) and** $\langle n_{e20} \rangle = 4.5$ **at 20 sec.**

# FIRE : Pinch Scan

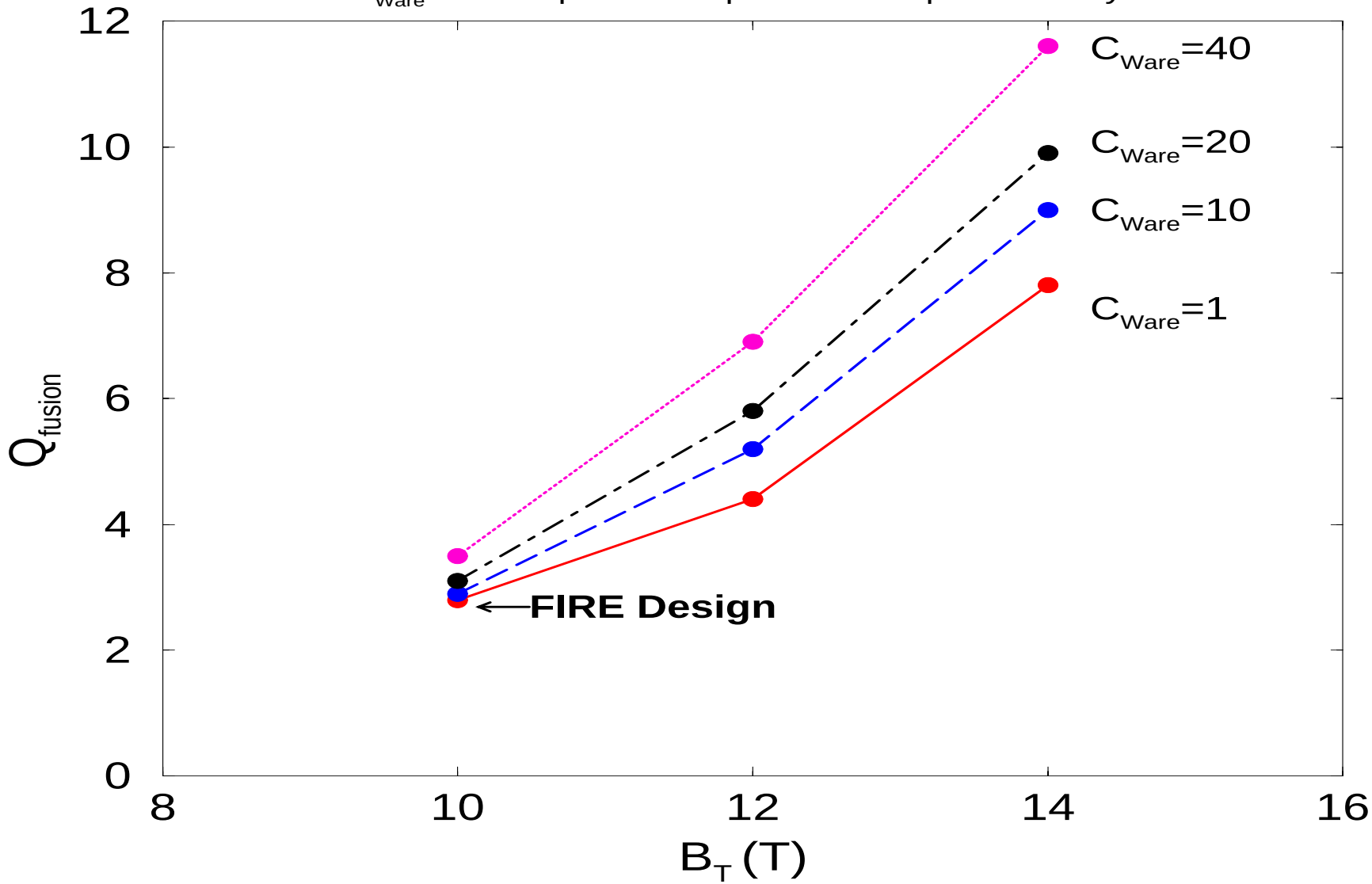


# FIRE : Pinch Scan



# FIRE Fusion Q vs Toroidal Field

$C_{Ware}$ = Ware pinch multiplier used to peak density



# Increasing Edge Temperature Improves Performance

$T_e(\text{edge}) = T_i(\text{edge})$ **are the temperatures at the top of the H-mode pedestal, which are used as boundary conditions for these simulations.**

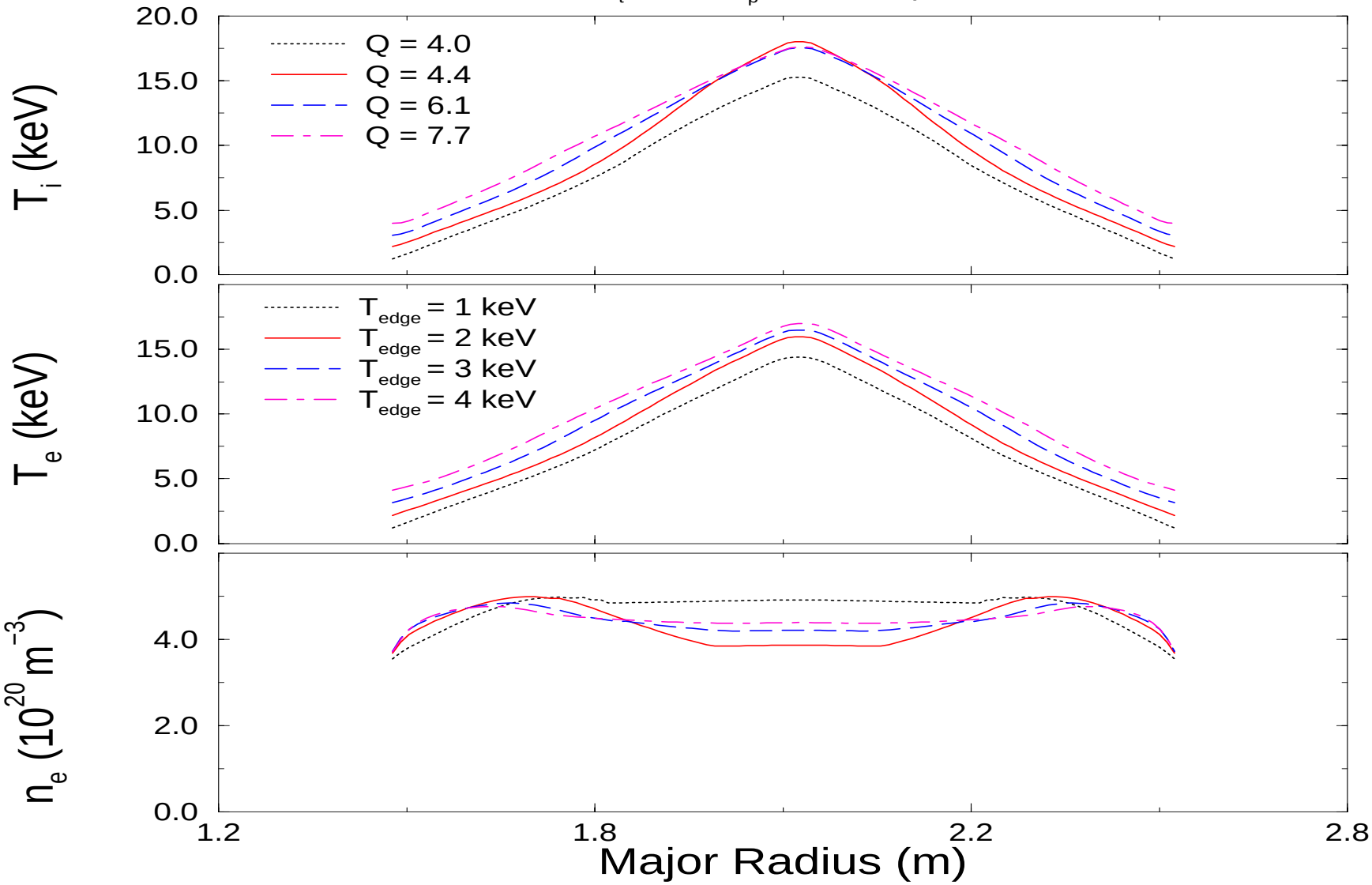
| $I_P$ (MA) | $B_T$ (tesla) | $T(\text{edge})$ (keV) | $n_{e20}(0)$ | $\tau_E$ | $H$ | $P_\alpha$ (MW) | $Q_{\text{fusion}}$ |
|---|---|---|---|---|---|---|---|
| 7.8 | 12 | 1.0 | 4.9 | 0.48 | 1.46 | 17.6 | 4.0 |
| 7.8 | 12 | 2.0 | 3.9 | 0.53 | 1.63 | 19.4 | 4.4 |
| 7.8 | 12 | 3.0 | 4.2 | 0.50 | 1.66 | 26.7 | 6.1 |
| 7.8 | 12 | 4.0 | 4.4 | 0.53 | 1.87 | 33.7 | 7.7 |

**MMM95 model,** $Z_{\text{eff}} = 1.2$**,** $P_{\text{aux}} = 22$ **(MW) and** $\langle n_{e20} \rangle = 4.5$ **at 20 sec.**

- **Stiff models generally yield better confinement with higher edge temperature.**
- **It is not known what the boundary conditions will be in FIRE.**

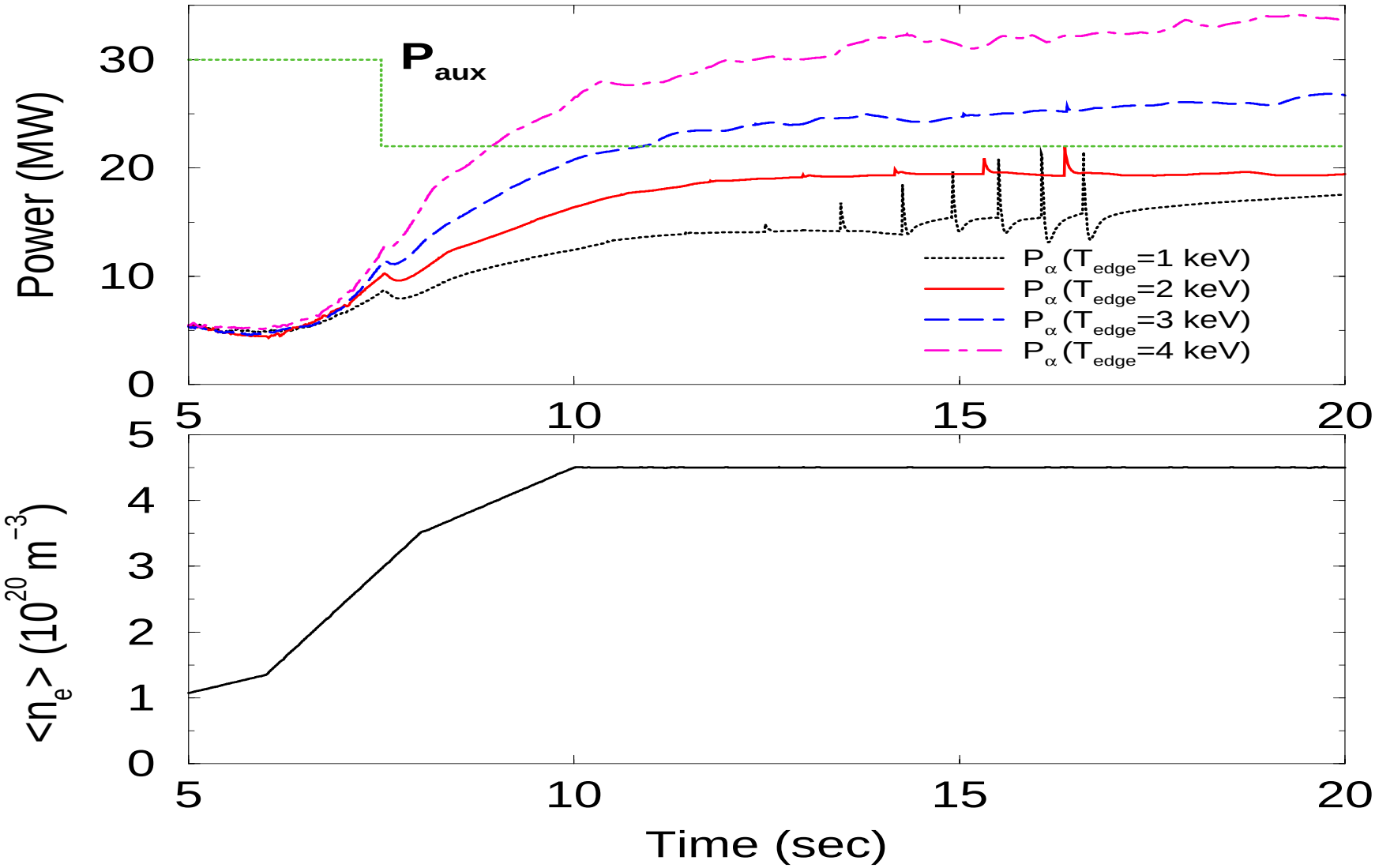
# FIRE : $T_{edge}$ Scan

MMM95 model, $B_t$ = 12 T, $I_p$ = 7.8 MA, profiles at 20.0 sec



# FIRE Alpha Power and Density vs Time

$I_p$=7.8 MA, $B_t$=12 tesla, $C_{Ware}$=1, MMM95



# Mixed-Bohm/gyro-Bohm (JETTO) Model Predicts Lower Performance Than MMM95 Model

| $I_P$ (MA) | $B_T$ (tesla) | Model | $n_{e20}(0)$ | $\tau_E$ | $H$ | $P_\alpha$ (MW) | $Q_{\text{fusion}}$ |
|---|---|---|---|---|---|---|---|
| 6.5 | 10 | MMM95 | 4.7 | 0.52 | 1.75 | 12.3 | 2.8 |
| 6.5 | 10 | JETTO | 4.7 | 0.47 | 1.62 | 13.2 | 3.0 |
| 7.8 | 12 | MMM95 | 3.9 | 0.53 | 1.63 | 19.4 | 4.4 |
| 7.8 | 12 | JETTO | 4.7 | 0.46 | 1.38 | 16.0 | 3.6 |
| 9.1 | 14 | MMM95 | 4.2 | 0.50 | 1.53 | 34.2 | 7.8 |
| 9.1 | 14 | JETTO | 4.7 | 0.45 | 1.20 | 18.4 | 4.2 |

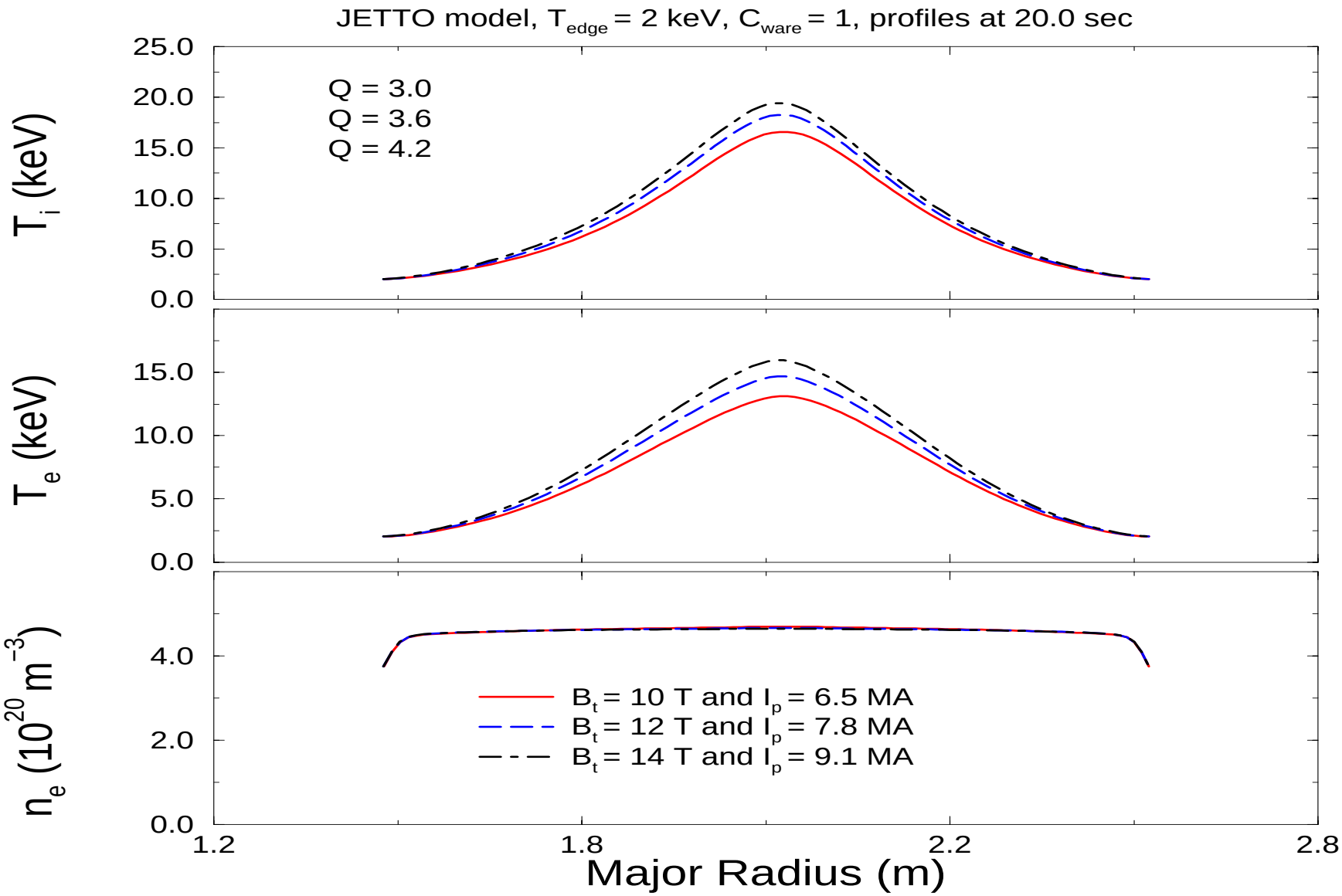
$T_{\text{edge}} = 2$ **keV,** $Z_{\text{eff}} = 1.2$**,** $P_{\text{aux}} = 22$ **(MW) and** $\langle n_{e20} \rangle = 4.5$ **at 20 sec.**

**Lack of significant improvement of performance with increased magnetic field and current using the JETTO model**

**May be caused by the fact that the JETTO model has predominantly Bohm scaling** ($\chi \propto \rho_s c_s \propto B^{-1/3}$)

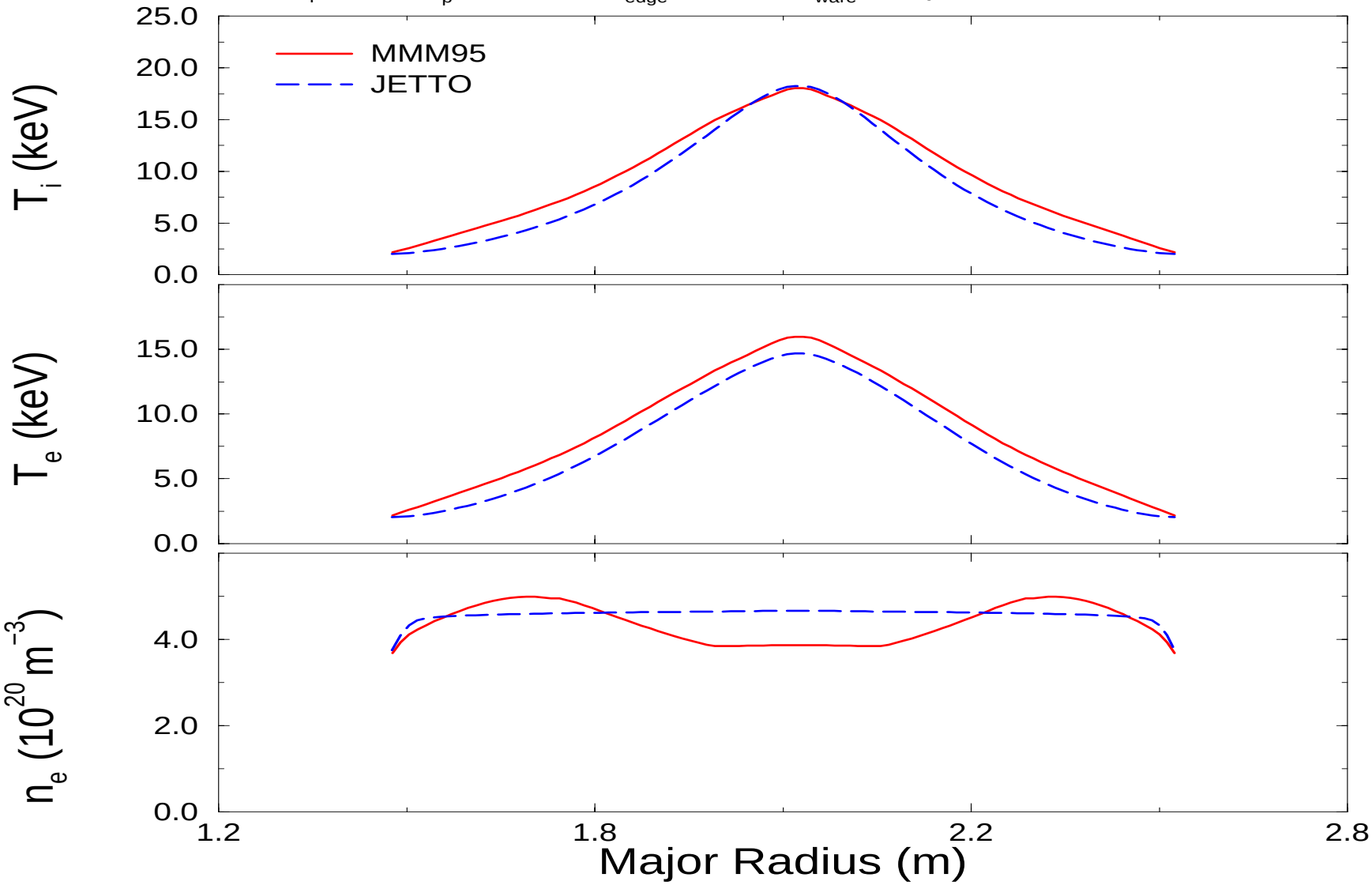
**while the MMM95 model has gyro-Bohm scaling** ($\chi \propto \rho_s^2 c_s / R \propto B^{-1}$) **at constant** $\beta$ **and collisionality.**

# FIRE : Current Scan – Mixed Bohm/gyro–Bohm



# FIRE : MMM95 vs JETTO model

$B_T$ = 12 T, $I_p$ = 7.8 MA, $T_{edge}$ = 2keV, $C_{ware}$ = 1, profiles at 20.0 sec



# Examination of $Z_{\text{eff}}$ Dependence

| $I_P$ (MA) | $B_T$ (tesla) | $Z_{\text{eff}}$ | $n_{e20}(0)$ | $\tau_E$ | $H$ | $P_\alpha$ (MW) | $Q_{\text{fusion}}$ |
|---|---|---|---|---|---|---|---|
| 6.5 | 10 | 1.2 | 4.7 | 0.52 | 1.75 | 12.3 | 2.8 |
| 6.5 | 10 | 1.6 | 4.8 | 0.53 | 1.76 | 10.2 | 2.3 |
| 7.8 | 12 | 1.2 | 3.9 | 0.53 | 1.63 | 19.4 | 4.4 |
| 7.8 | 12 | 1.6 | 4.2 | 0.55 | 1.63 | 16.1 | 3.8 |
| 9.1 | 14 | 1.2 | 4.2 | 0.50 | 1.53 | 34.2 | 7.8 |
| 9.1 | 14 | 1.6 | 4.2 | 0.52 | 1.50 | 27.1 | 6.2 |

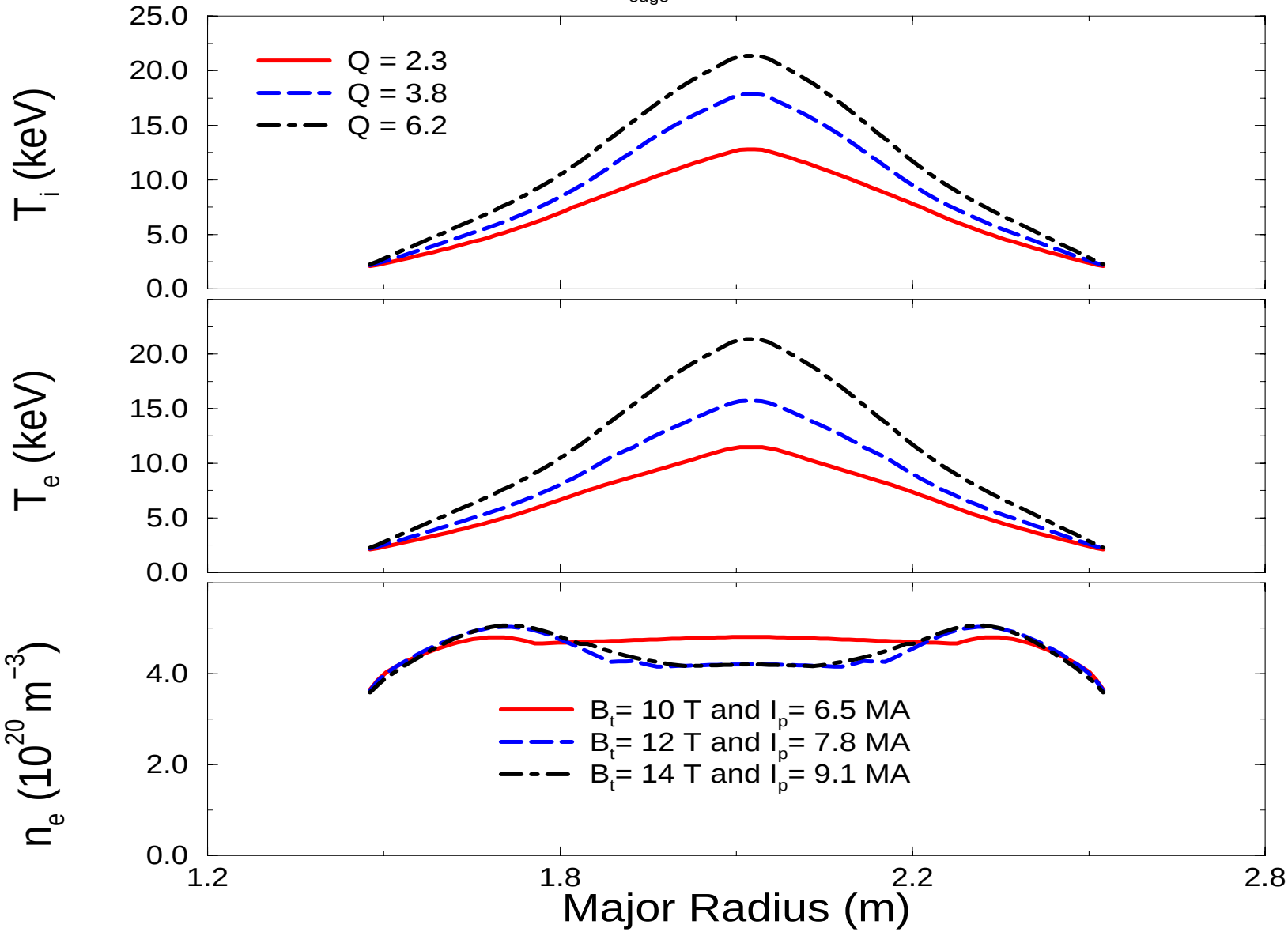
$T_{\text{edge}} = 2$ **keV, Transport Model = MMM95** $P_{\text{aux}} = 22$ **(MW) and** $\langle n_{e20} \rangle = 4.5$ **at 20 sec.**

**Increase of $Z_{\text{eff}}$ achieved by increasing carbon component**

**Slight degradation of performance with increased $Z_{\text{eff}}$**

# FIRE : Current Scan -- $Z_{eff}$ = 1.6

MMM95 model, $T_{edge}$= 2 keV, profiles at 20.0 sec



# Conclusions

- **Fusion $Q \approx 3$ for the baseline FIRE simulation**
  - **Using MMM95 model,** $I_p = 6.5$ **MA,** $B_T = 10$ **tesla**
    $T_{\text{edge}} = 2$ **keV,** $\langle n_{e20} \rangle = 4.5$**,** $\langle Z_{\text{eff}} \rangle = 1.2$**,** $P_{\text{aux}} = 22$ **MW**
- **Fusion $Q$ improves with higher current and field**
  $Q \approx 4.4$ **when** $I_p = 7.8$ **MA,** $B_T = 12$ **tesla**
- **Peaking density profile produces some improvement**
- **Fusion $Q$ increases with increasing edge temperature**
  $Q \approx 7.7$ **when** $I_p = 7.8$ **MA and** $T_{\text{edge}} = 4$**keV**
- **Mixed Bohm/gyro-Bohm (JETTO) transport model produces more pessimistic results than MMM95**
  $Q \approx 3.6$ **when** $I_p = 7.8$ **MA and** $T_{\text{edge}} = 2$ **keV**