Simulations of temperatures in FIRE plasmas using the GLF23 model in the TRANSP code

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The GLF23 prediction model, incorporated in the TRANSP plasma analysis code, is used to predict temperatures for burning plasmas in the proposed FIRE tokamak. Flat electron density profiles with various central values are assumed. Scaling of the fusion power P_{dt} and gain Q_{dt} with density and pedestal temperature are given. Classification: MO (Reactor Physics and Design)

1. Introduction

Nest-step tokamaks for burning plasma experiments are being proposed. In order for these experiments to provide clear results for alpha heating studies and for reliable extrapolations to fusion power reactors, the dt fusion power P_{dt} and fusion gain $Q_{dt} = P_{dt} / P_{aux}$ should be large. One of the proposed next-step tokamaks is FIRE [1] with a goal of achieving $Q_{dt} = 10$ for durations of about 20 s.

There are many uncertainties in extrapolating present tokamak experiments to those envisioned in FIRE. One of the theory-based predictive models, GLF23 [2], is promising since it has been successful in simulating T_e and T_i in present plasmas. This model has been incorporated into the TRANSP plasma analysis code [3], which has strong capabilities for simulating the heat depositions in present experiments.

The goal of this paper is apply the TRANSP-GLF23 code to simulate T_e, T_i, and Q_{dt} in FIRE. Peaked electron density profiles have been proposed for FIRE since they are often associated with high energy confinement in present experiments, but there is uncertainty of whether they can be created in the high n_e and temperature plasmas required for high Q_{dt}. To be conservative about the technological difficulties in generating peaked density profiles, very broad n_e profiles, similar to those envisioned for the ITER-FEAT tokamak [4], are assumed.

Other studies have used the GLF23 model to predict temperatures in FIRE, using either the BALDUR [5], ONE-TWO [6], or TSC [7] codes. The TRANSP code [3] uses a number of difference techniques, such as Monte Carlo techniques [8] to calculate the fusion alpha heating, and the SPRUCE full-wave, reduced order code [9] to calculate the ICRH heating. The results of this study are more optimistic than those studies in that the height of the pedestal temperature needed for $Q_{dt} \geq 10$ is lower, around 2 keV.

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2. FIRE Plasmas.

FIRE [1] is designed to have normal-conducting magnets, and a double-null divertor geometry. The normal heating scheme is ICRH at a frequency of 100 MHz to resonate with small concentrations of He^3 and large concentrations of T on axis. The heating power P_{RF} is assumed to start high (20 MW) early in the discharge to provoke the L to H-mode transition, and then lowered to 11.5 MW as the alpha heating increases, to keep $P_\alpha + P_{ext}$ roughly constant. The assumed evolution of the heating powers are shown in Fig. 1. The ICRH heating and alpha parameters for a similar FIRE H-mode plasma are discussed in Ref. 10. Plasma parameters for a FIRE AT plasma are discussed in Ref. 11.

The toroidal field is assumed to be 10 [T], and the plasma current I_p is ramped to a flattop value of 7.7 [MA] for 20 [s], as shown in Fig. 2. The area-integrated bootstrap current calculated from neoclassical theory [12] for one of the simulations is also shown in the Fig. The q_{MHD} profile at several times is shown in Fig. 3, plotted against the toroidal flux variable, $x \equiv \sqrt{\text{normalized toroidal flux}}$, which is roughly equal to r/a. The relatively rapid ramp-up of I_p and T_e have the result of keeping $q_{MHD} \geq$ 1.0 for most of the discharge

The central plasma densities are assumed to ramp-up as shown in Fig. 4. Plasma profiles in the flattop are shown in Fig. 5. The Z_{eff} profile is assumed to be about 1.36. Accumulation of the alpha ash is modeled, as described in Ref. 10, assuming a recycling coefficient of 20 %. The discharge duration is too short for the ash concentration to reach steady state, or to significantly reduce P_{dt}.

3. Temperature predictions

The TRANSP plasma analysis code is used to analyze plasmas with either measured or assumed plasma profiles. TRANSP is a fixed-boundary code, so the FIRE plasma boundary is specified by assuming time evolutions of the major and minor radii, elongation, triangularity, and vertical displacement of the boundaries. The MHD equilibria are calculated in TRANSP by solving the Grad-Shafranov equation. The heat and particle fluxes are calculated from the continuity equations. The fusion alpha particles and beam ions are treated using Monte Carlo methods [8] to model their source rates, neoclassical orbits, and slowing-down rates.

An example of the evolutions of the central T_e and T_i for one of the plasmas are shown in Fig. 6. The GLF23 prediction starts at 5 s. At that time, the central temperatures drop from their guessed values, then rise again with the start of the ICRH at 6 [s]. They continue to rise until about 27 [s], when the density starts to ramp down.

The predictions start from an assumed boundary temperature, nominally at the top of the H-mode pedestal. Here, this boundary is assumed to occur at $x = 0.95$. The evolution of the assumed pedestal temperature is shown in Fig. 6. Note that it is not held fixed in time. A scan was done with the pedestal temperature held at 5.3 keV, with the density scaled. Results for the T_i at the time of peak value is shown in Fig. 7. During this scan the Greenwald ratio $f_{GW} = \bar{n}_e/\bar{n}_{Greenwald}$ varied from 0.29 to 0.66. The resulting peak values for P_{dt} and β_n are plotted in Fig. 8. Since the auxiliary heating power at that time is $P_{RF} + P_{Oh} =$ 11.5 + 1.0 [MW], the Q_{dt} is greater than 10 for $\bar{n}_e/\bar{n}_{Greenwald} \geq$ 0.29.

Lastly, we hold $\bar{n}_e/\bar{n}_{Greenwald}$ fixed at 0.66 and scan the pedestal temperature down to 2.4 [keV]. The resulting profiles for T_i at the peak are shown in Fig. 9. The values for T_e are shown in Fig. 10. The values for P_{dt} and β_n are plotted in Fig. 11. Thus a pedestal temperature of about 2 [keV] appears sufficient to achieve $Q_{dt} \geq$ 10. Results are given in Table 1.

4. Summary and Discussion

This paper reports results for self-consistent transport simulations of plasmas for FIRE using the GLF23 model incorporated into the TRANSP analysis code. For the relatively flat density profiles and heating assumed, the plasmas achieve $Q_{dt} \geq$ 10 for $\bar{n}_e/\bar{n}_{Greenwald} = 0.66$ with pedestal temperatures as low as 2 [keV].

5. Acknowledgments

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TRANSP run ID	$\bar{n}_e/\bar{n}_{Greenwald}$	β_n	T_{ped}	P_{dt}	P_α	$\tau_E(0.95)$	$\tau_{98,y}(0.95)$
units			[keV]	[MW]	[MW]	[s]	[s]
50000G07	0.29	1.30	5.3	82	16.2	0.89	0.68
50000G09	0.44	1.90	5.3	175	34.2	0.81	0.56
50000G10	0.58	2.50	5.3	293	58.0	0.73	0.47
50000G13	0.66	2.80	5.3	366	72.0	0.67	0.42
50000G14	0.66	2.46	4.3	285	56.0	0.71	0.50
50000G15	0.66	1.75	2.3	152	30.0	0.83	0.74
50000G17	0.66	0.95	1.4	35	7.0	0.90	1.20

Table 1. *Summary of plasma parameters at a steady state time (26.5 s).*

References

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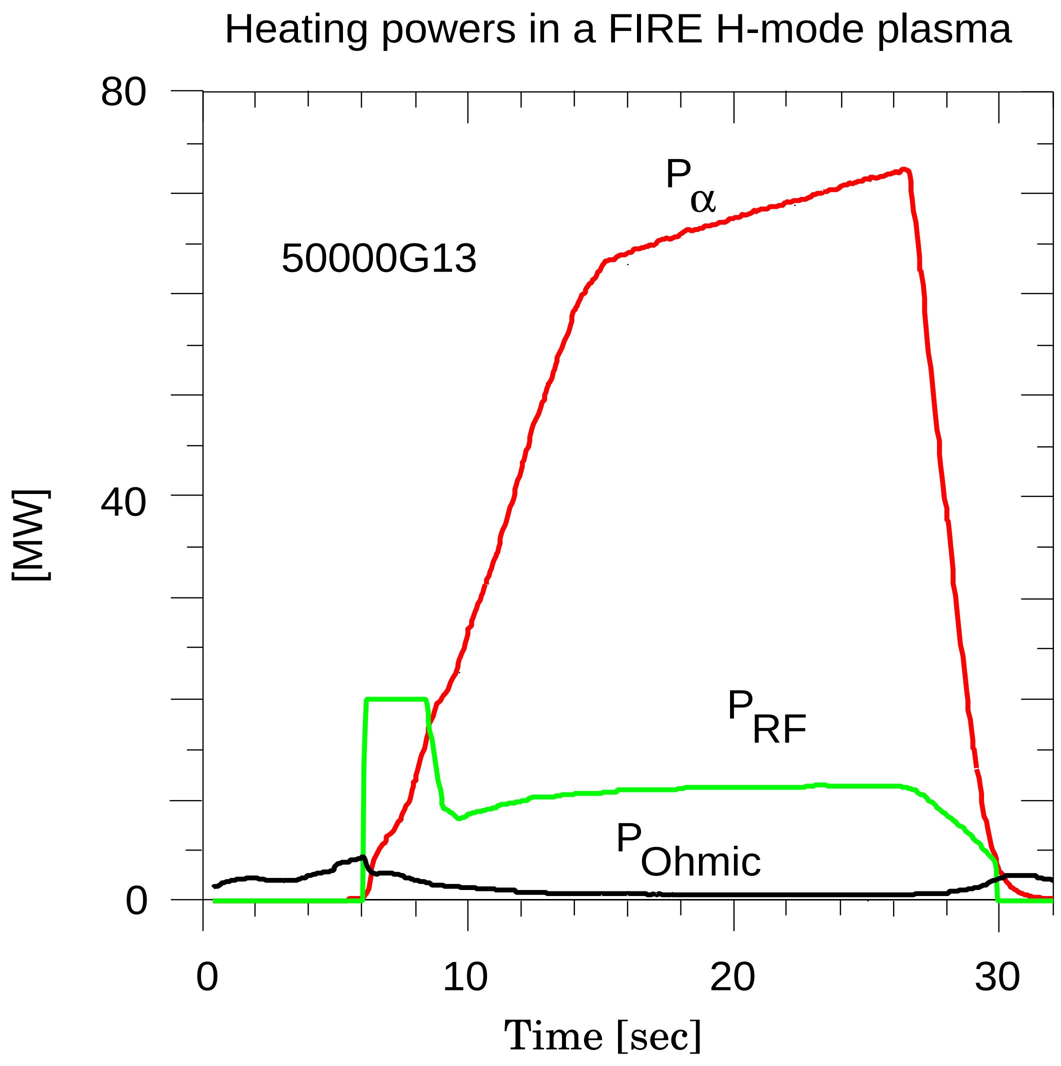

Figure 1. Evolution of the heating powers in a FIRE plasma.

Figure Captions

Fig. 1 - Evolution of the heating powers in a FIRE plasma.
Fig. 2 - Evolution of the assumed total current and computed I_{boot} in a FIRE plasma.
Fig. 3 - Profile of q_{MHD} for one of the FIRE plasmas.
Fig. 4 - Evolution of the assumed central density in a FIRE plasma.
Fig. 5 - Density profiles at a flattop time.
Fig. 6 - Evolution of central and pedestal temperatures for one of the FIRE plasmas.
Fig. 7 - Scaling of T_i with Greenwald fraction.
Fig. 8 - Scaling of dt fusion power with Greenwald fraction in FIRE plasma with $T_{ped} = 5.3$ KeV.
Fig. 9 - Scaling of with the pedestal Temperature.
Fig.10 - Scaling of T_e with the pedestal Temperature.
Fig.11 - Scaling of dt fusion power with T_{ped}.

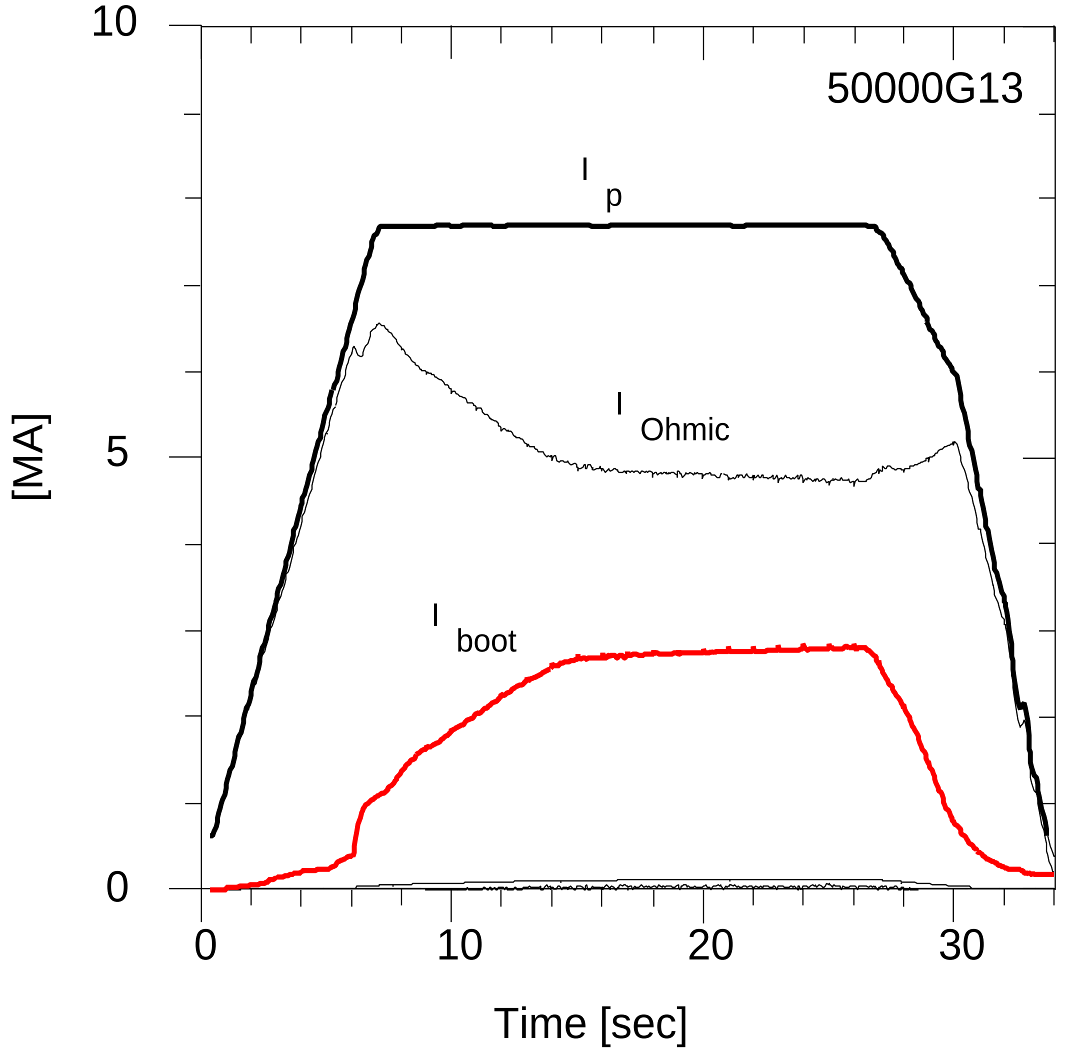

Figure 2. Evolution of the assumed total current and computed I_{boot} in a FIRE plasma.

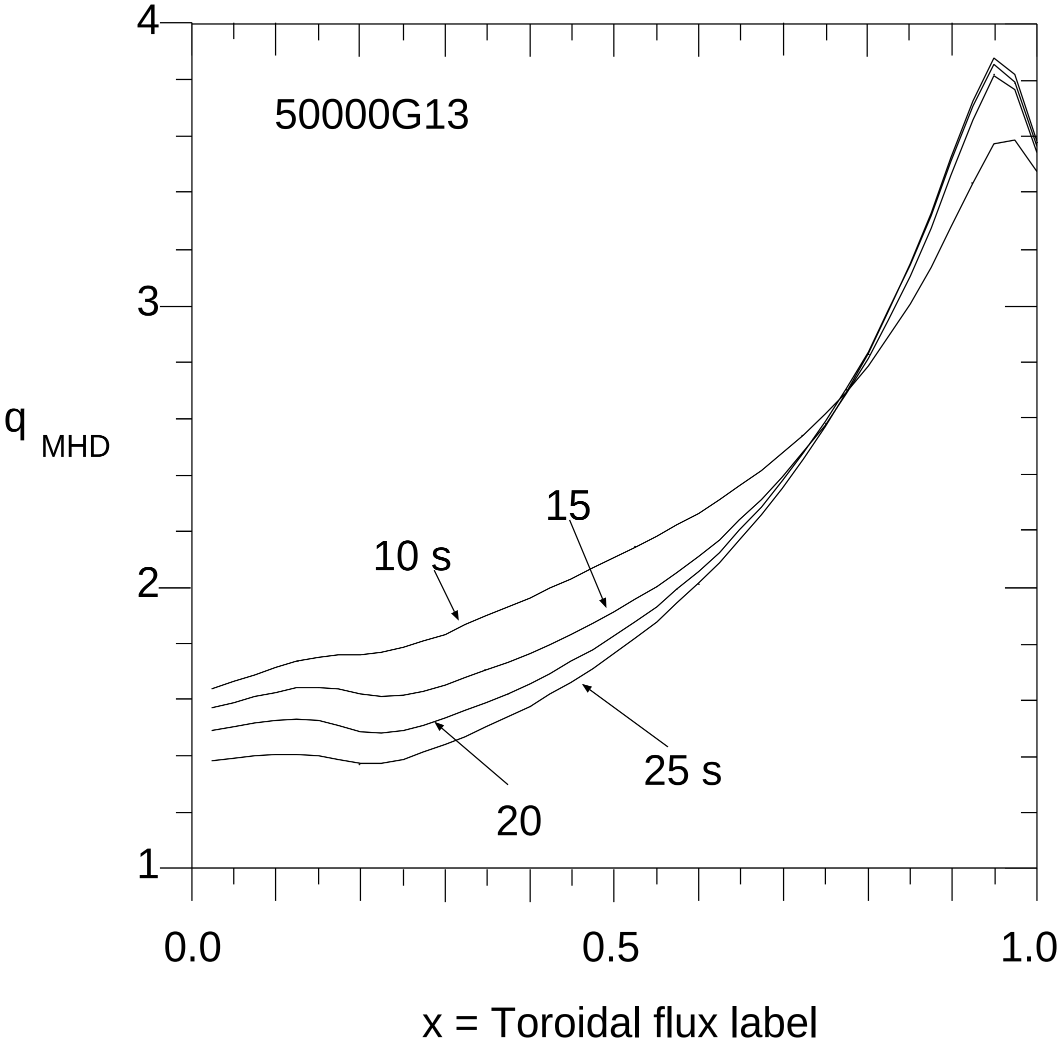

Figure 3. Profile of q_{MHD} for one of the FIRE plasmas.

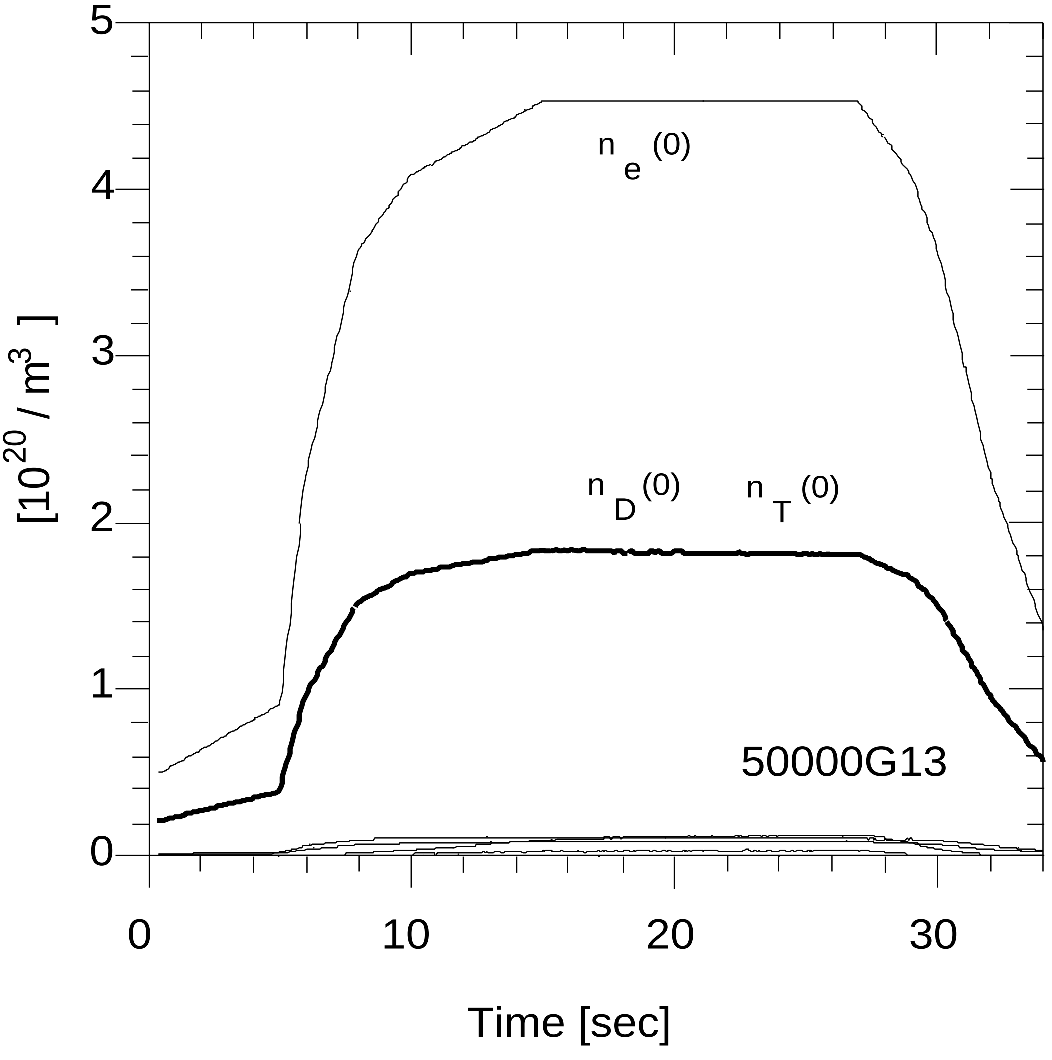

Figure 4. Evolution of the assumed central density in a FIRE plasma.

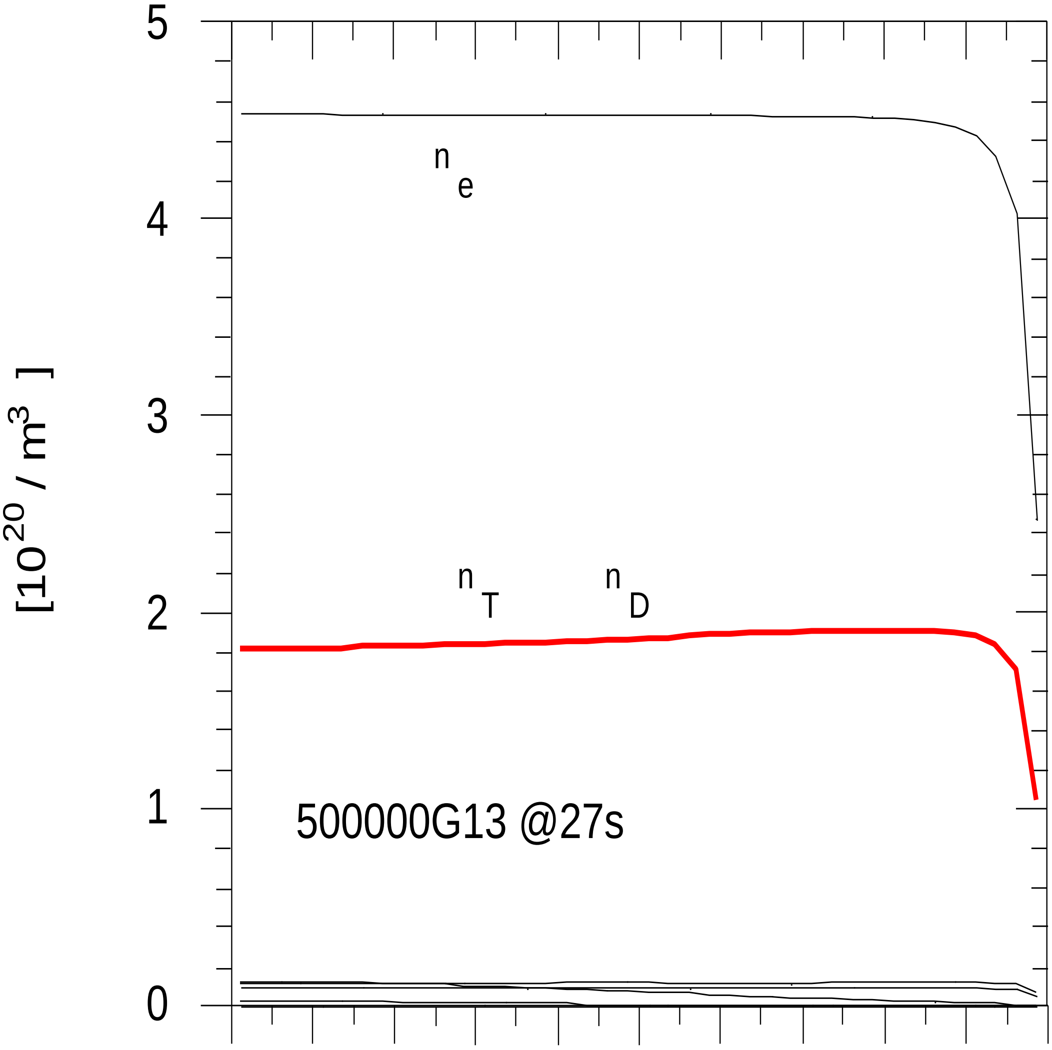

Figure 5. Density profiles at a flattop time.

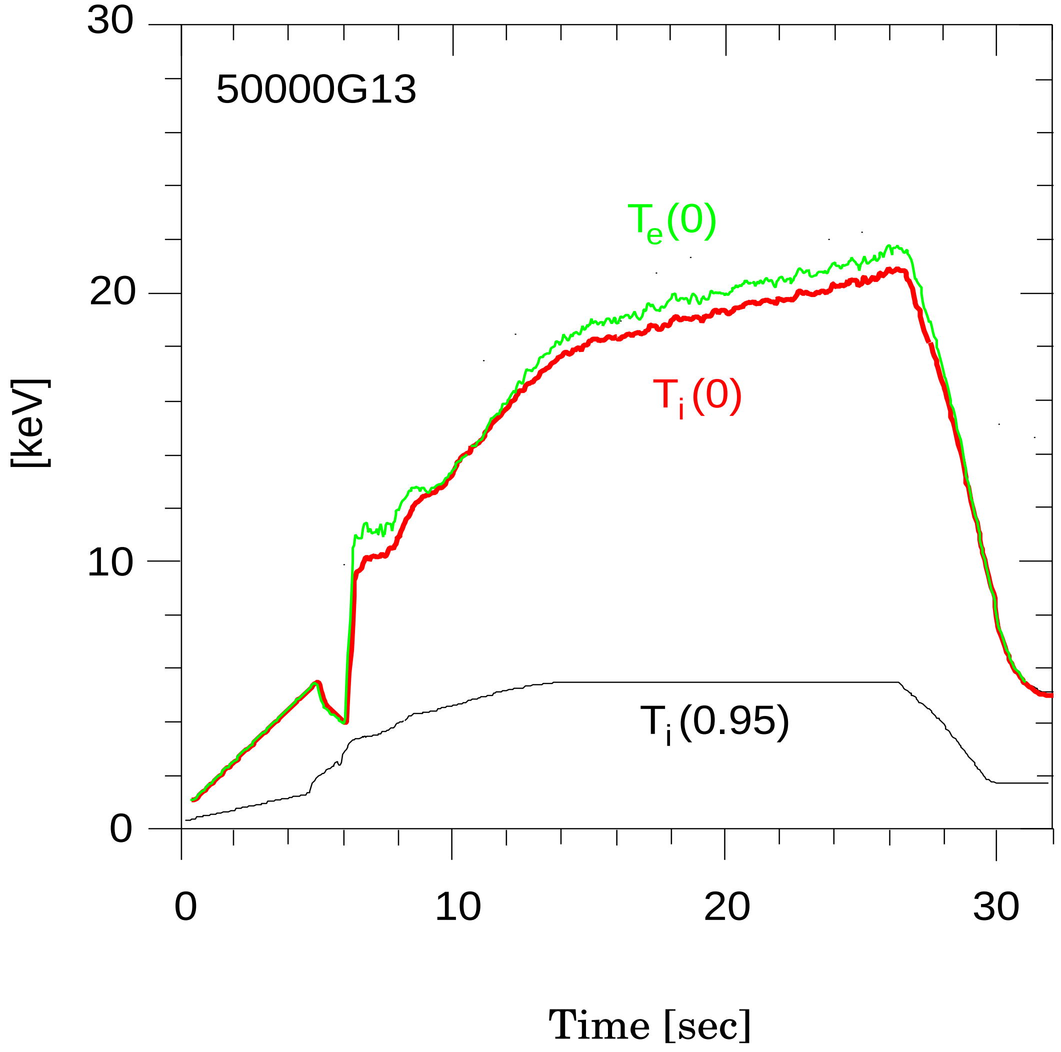

Figure 6. Evolution of central and pedestal temperatures for one of the FIRE plasmas.

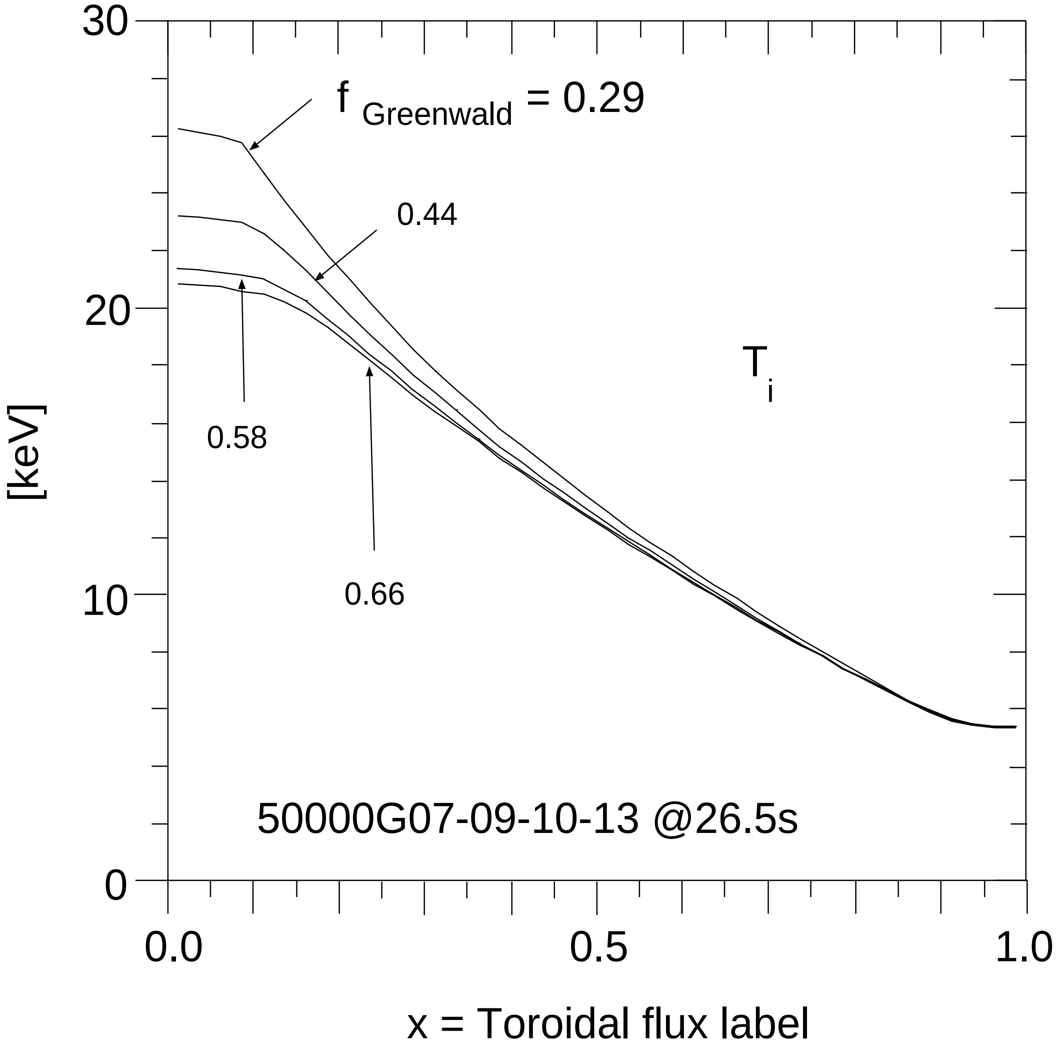

Figure 7. Scaling of T_i with Greenwald fraction.

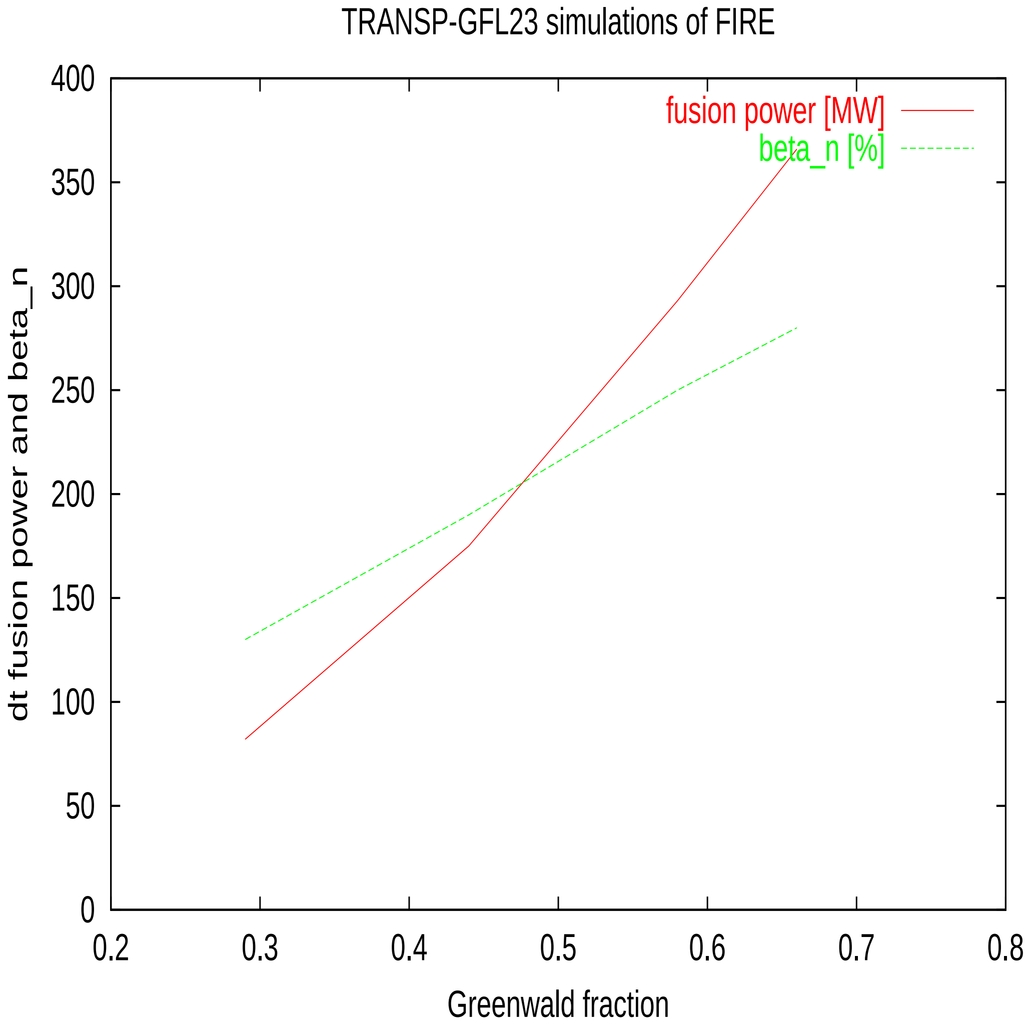

Figure 8. Scaling of dt fusion power with Greenwald fraction in FIRE plasma with $T_{ped} = 5.3$ KeV.

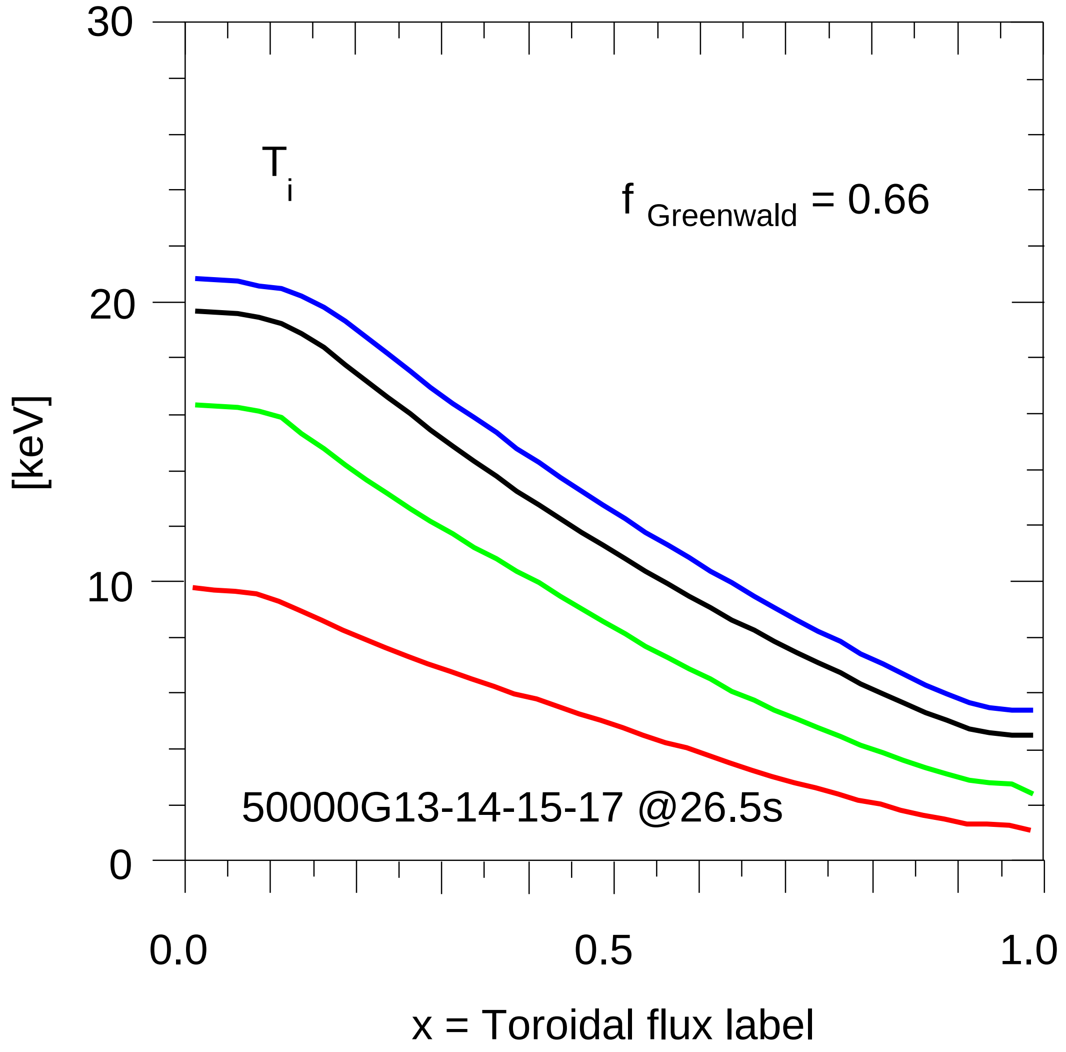

Figure 9. Scaling of with the pedestal Temperature.

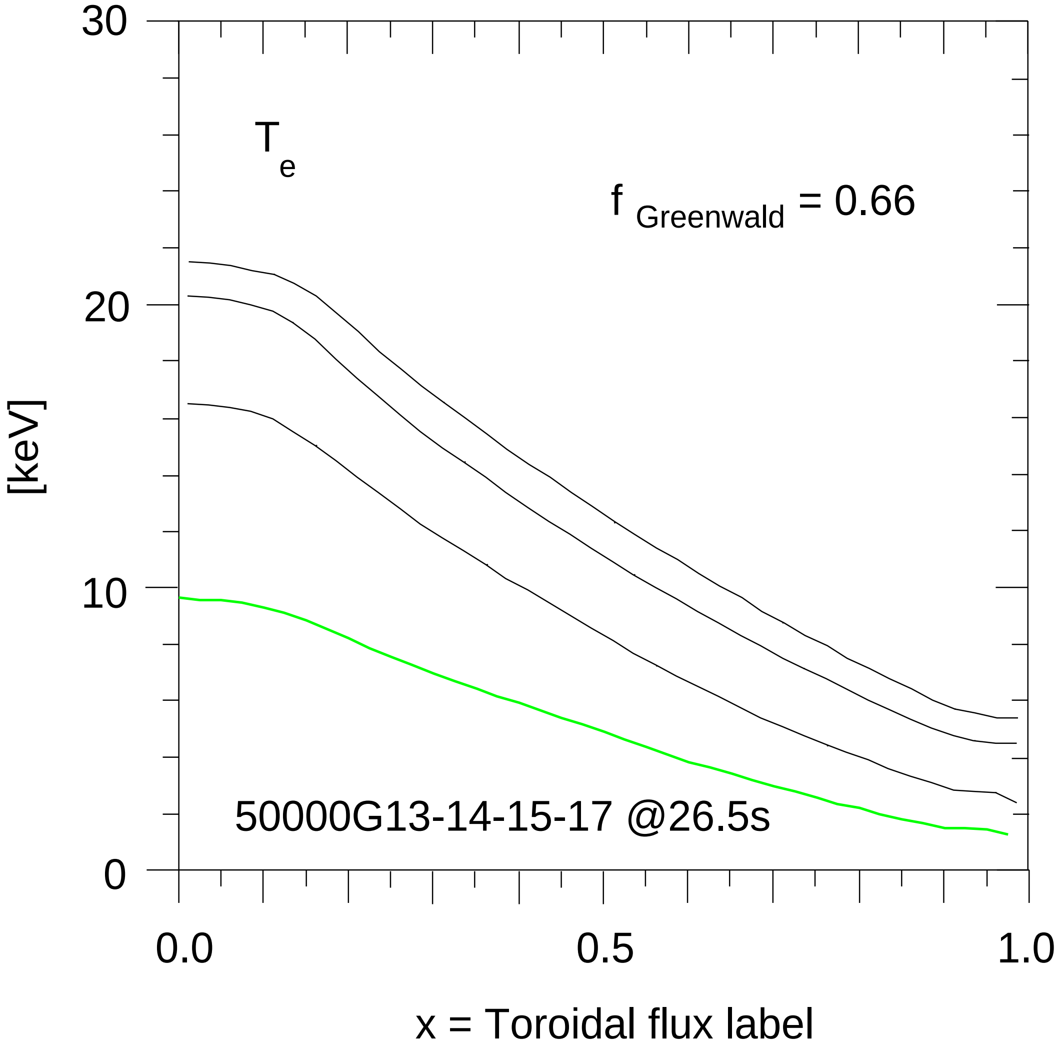

Figure 10. Scaling of T_e with the pedestal Temperature.

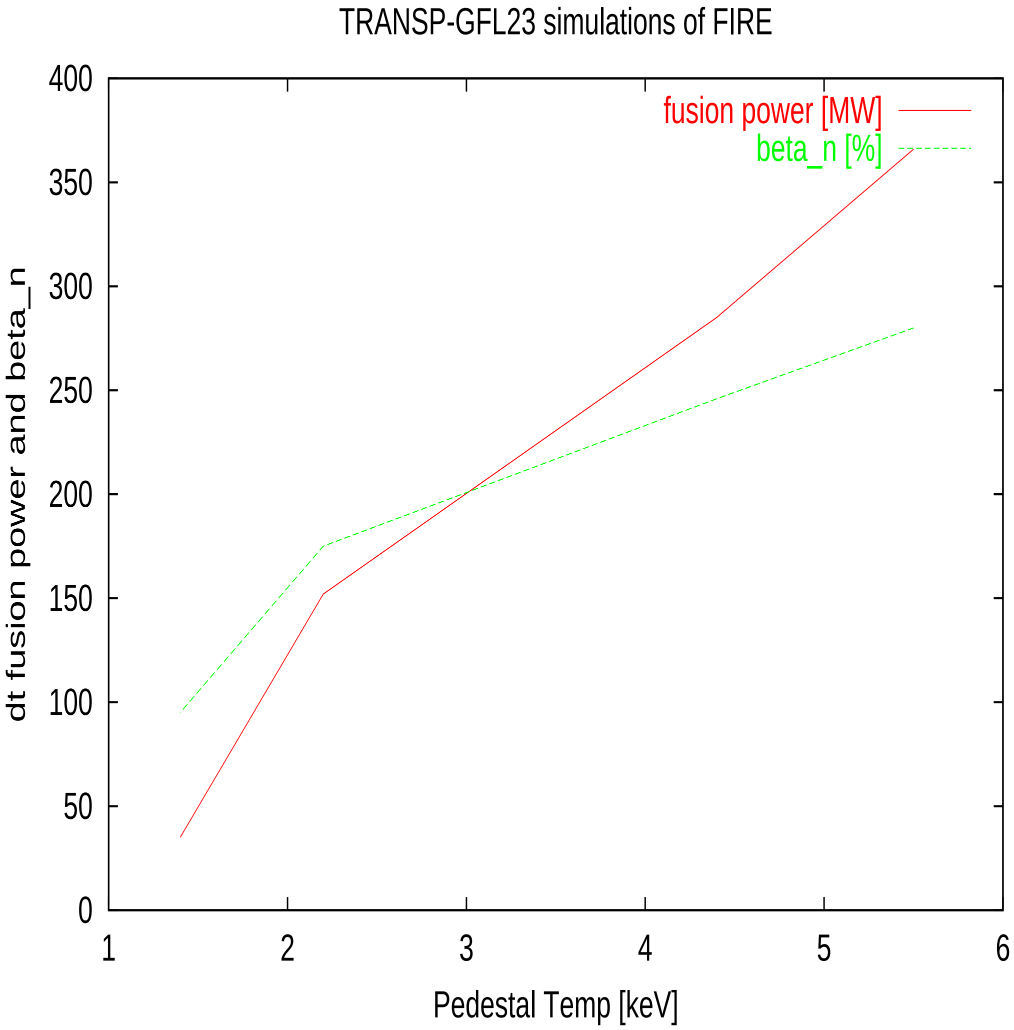

Figure 11. Scaling of dt fusion power with T_{ped}.