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Effect of ICRH on the ion distribution functions evaluation of the ion temperature in the WEST TOKAMAK with ICRF heating

P Huynh, E Lerche, D van Eester, J F Artaud, R Dumont, P Maget, P Manas

► **To cite this version:**

P Huynh, E Lerche, D van Eester, J F Artaud, R Dumont, et al.. Effect of ICRH on the ion distribution functions evaluation of the ion temperature in the WEST TOKAMAK with ICRF heating. 50th EPS Conference on Plasma Physics, Jul 2024, Salamanca, Spain. . cea-04723540

HAL Id: cea-04723540

<https://cea.hal.science/cea-04723540v1>

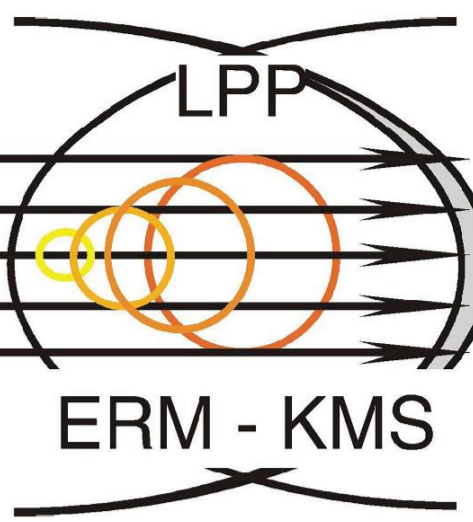
Submitted on 7 Oct 2024

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P. Huynh¹, E. Lerche², D. Van Eester², J.F. Artaud¹, R. Dumont¹, P. Maget¹, P. Manas¹ and WEST team*¹ CEA, IRFM, F-13108 Saint Paul-lez-Durance, France.² Laboratory for Plasma Physics, ERM/KMS, B-1000 Brussels, Belgium.* see <http://west.cea.fr/WESTteam>

West



Introduction & Background

- Ion temperature measurements require sophisticated procedures such as charge-exchange recombination spectroscopy [1] or crystal spectroscopy [2]
- In the absence of such experimental data, the ion temperature estimation is obtained by reverse engineering of the total neutron yield, assuming the ion distributions are Maxwellian [3,4].
- Ion distributions are no more Maxwellian when ICRH external heating is applied.
- Improvement of the procedure is proposed to account for ion Non-Maxwellian distributions by disentangling the thermal and fast components of the bulk ion distributions leading to a better estimate of the 'thermal-only' ion temperature
- The method uses a coupled wave / Fokker-Planck numerical solver and a neutron rate calculator coming from European Transport Simulator / Heating and Current Drive software [5,6] namely Cyrano / StixRedist / Fusreac [7,8] and is applied to the WEST tokamak [9,10]

Effect of ICRH on the ion distribution functions

- Considered discharges are Deuterium plasmas heated by ICRH in flat top phase with Hydrogen minority heating scheme, $n_i/n_e=3-6\%$, RF frequency of antennas $f=55.9\text{MHz}$, coupled power= $3-4\text{MW}$, magnetic field $B_0=3.6\text{T}$

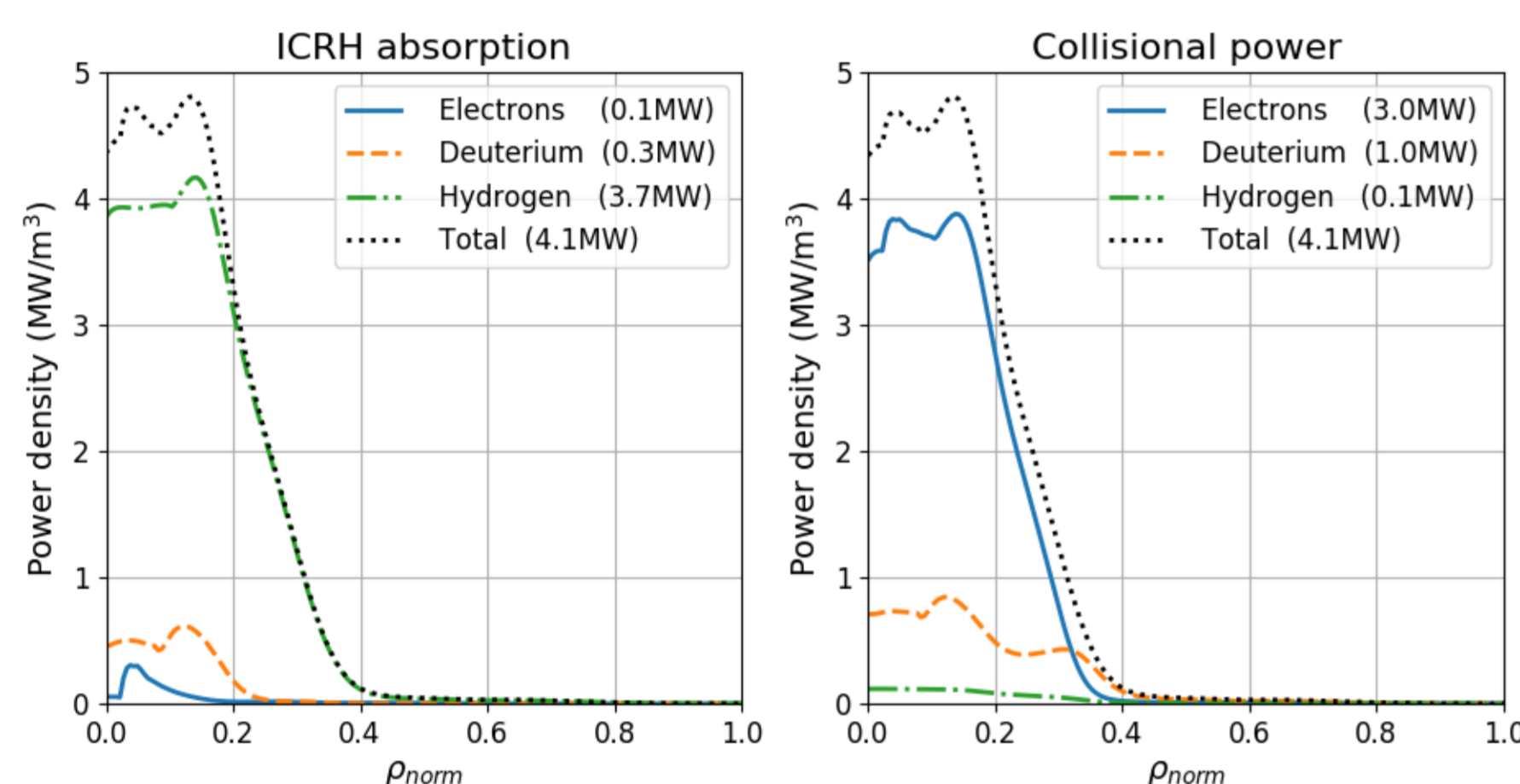


Figure 1: (Left) Direct ICRH power absorption per species and (right) collisional power redistribution for $P_{ICRH}=4.1\text{MW}$ and $n_i/n_e=4.5\%$. The plasma parameters of the WEST pulse #55606 at $t=39.2\text{s}$ were used for the simulation

- H ions absorb most of the power by N=1 direct absorption
- Most of the heating power goes to electron by collisions because of low $E_{crit} \sim 20\text{keV}$ of H ions
- Little power is given to D ions by N=2 direct absorption and collisions
- Average energy density of a given ion population in a magnetic surface is given by the 4th moment of the distribution function (F_i) in velocity space (v) and is related to the (macroscopic) effective ion temperature T_{eff} via the local ion density n_i :

$$\varepsilon = 4\pi \frac{m_i}{2} \int_0^\infty F_i(v) v^4 dv = \frac{3}{2} n_i k_B T_{eff} \quad (1)$$

- In the case of a Maxwellian distribution, T_{eff} represents the actual 'thermal' ion temperature

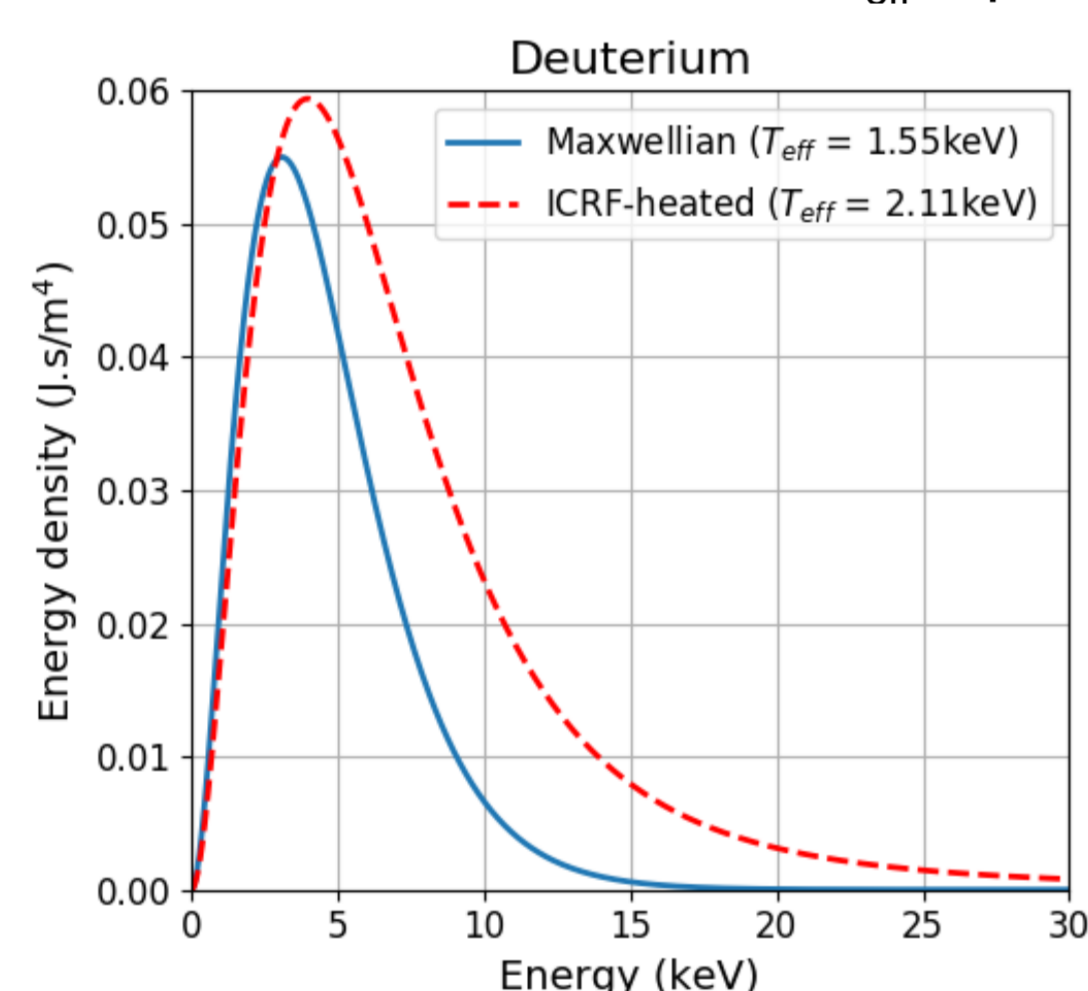


Figure 2: Comparison of the Deuterium energy distributions for the case without ICRH (Maxwellian) and for the ICRF-heated case for pulse #55606 at $\rho_{norm}=0.1$ (0.7MW/m^3). The effective ion temperatures (T_{eff}) are computed by integrating the energy distribution functions as shown in eq.(1).

- RF-acceleration removes particles originally placed in the thermal region and drives them to the supra-thermal energy domain depending on the strength of the local RF acceleration.
- $T_{eff} = T_i = 1.55\text{keV}$ (Maxwellian) and $T_{eff} = 2.11\text{keV}$ (ICRF-heated).

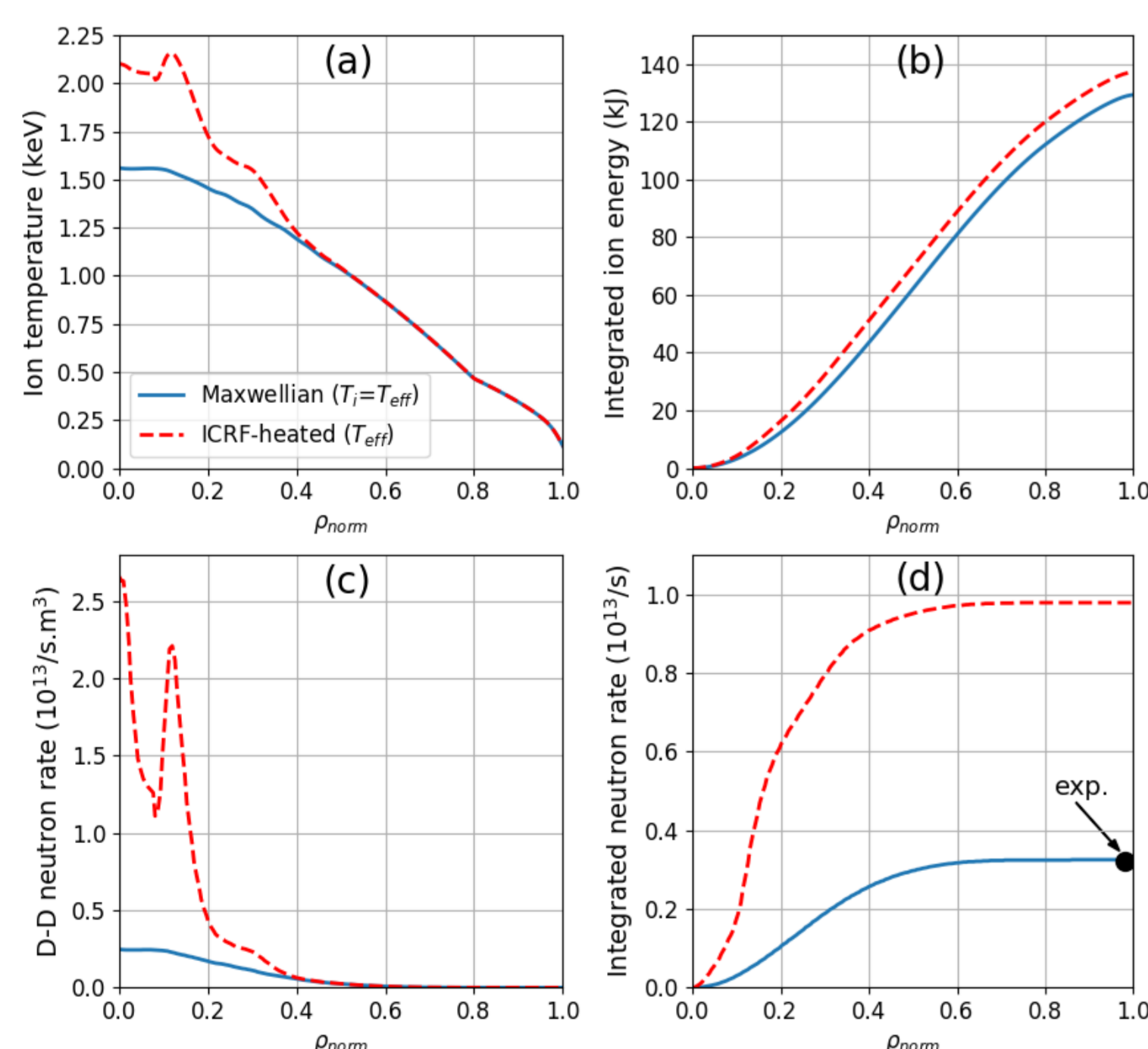


Figure 3: Comparison between two simulations assuming Maxwellian ($P_{ICRH}=0$) and ICRF-heated ($P_{ICRH}=4.1\text{MW}$) Deuterium ion distribution functions computed with the ETS H&CD simulator: (a) Effective D ion temperature, (b) volume integrated average ion energy, (c) D-D neutron rate, (d) integrated neutron rate. The parameters of pulse #55606 at $t=39.2\text{s}$ were used for the simulations. The measured total neutron rate is shown in (d)

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- Small influence of the ICRH acceleration of the D ions on the total ion (Fig. 3b)
- Large impact (factor ~ 3) on the total neutron rate (Fig. 3d) in particular at low ion temperatures due to high sensitivity D-D fusion reaction cross section to the D ion energy [11, 12]. Around 30% change in the central averaged ion energy (T_{eff}) leads to a factor $\sim 5-10$ increase in the local neutron rate.
- The back-calculation of the ion temperature based on the total measured neutron rate for an ICRF-heated case will provide the average energy / effective temperature of the D ions including the supra-thermal contribution to the D-D neutron rate as opposed to the thermal component of the ion distribution, which is the intended definition of T_i .

New T_i evaluation procedure

The process to account for non-Maxwellian ion distribution functions is divided into two steps

- Start from the D ion Maxwellian distribution functions associated with the D ion temperature profile that fit the total measured neutron rate using the regular procedure ([3,4]) without considering ICRH effects. For each magnetic surface, the local thermal ion temperature used as input for the Fokker-Planck calculation is reduced until the calculated effective temperature T_{eff} of the non-Maxwellian ICRF-heated distribution matches the initial (Maxwellian) T_i value

=> Good estimate of the thermal T_i profile but total integrated neutron rate not necessarily match the experimental one, since the expressions for the averaged ion energy (eq.1) and for the neutron rate have different dependencies in velocity space (eq.2)

$$\langle \sigma(V) \rangle = \int d\bar{v}_1 \int d\bar{v}_2 F_{0,1}(\bar{v}_1) F_{0,2}(\bar{v}_2) \sigma(V) V \quad \text{where } V = |\bar{v}_2 - \bar{v}_1| \quad (2)$$

- Adjust the T_i profile in the region where the ICRH absorption is relevant by looping the Fokker-Planck solver *StixRedist* and the neutron calculator *Fusreac* to match the measured neutron rate.

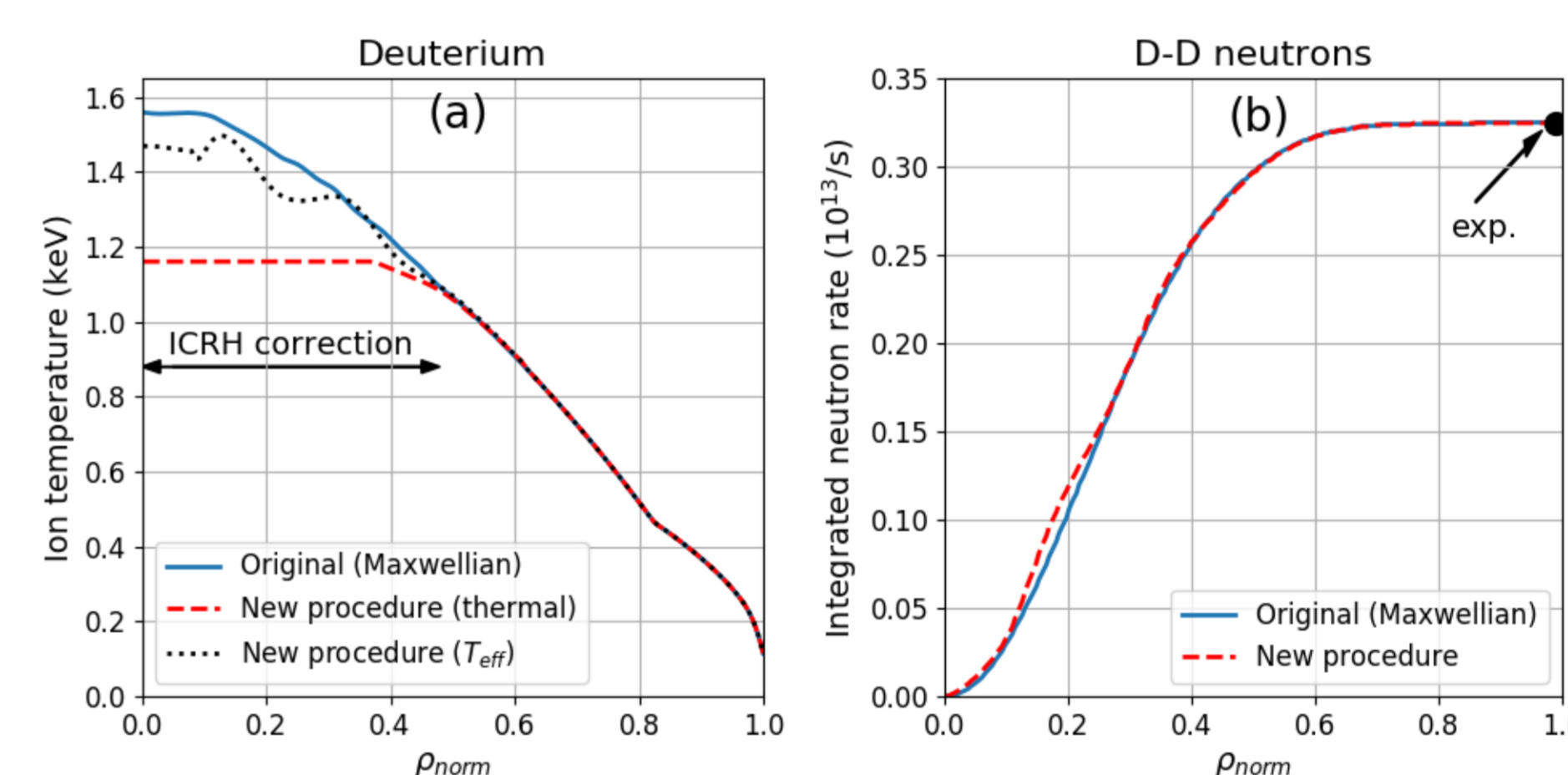


Figure 4: Comparison between the new computed T_i obtained with the method accounting for the ICRF heated distribution functions with the original Maxwellian-based procedure. The dotted curve in (a) represents the average ion temperature (T_{eff}) of the ICRF heated distributions using the thermal T_i profile obtained with the new minimization procedure

- New T_i values is substantially reduced in the region where the ICRF power is deposited because substantial part of the D-D neutrons comes from supra-thermal D ions (Fig. 4a).
- The averaged D ion energies (T_{eff}) obtained with ICRH effects using the T_i profile from the new procedure (dotted curve) are similar to the original non-corrected T_i values in the centre. Not perfect because of the different distribution function integrals needed for the T_{eff} and the neutron rate calculations.
- The total neutron rate matches the experiment one by construction.

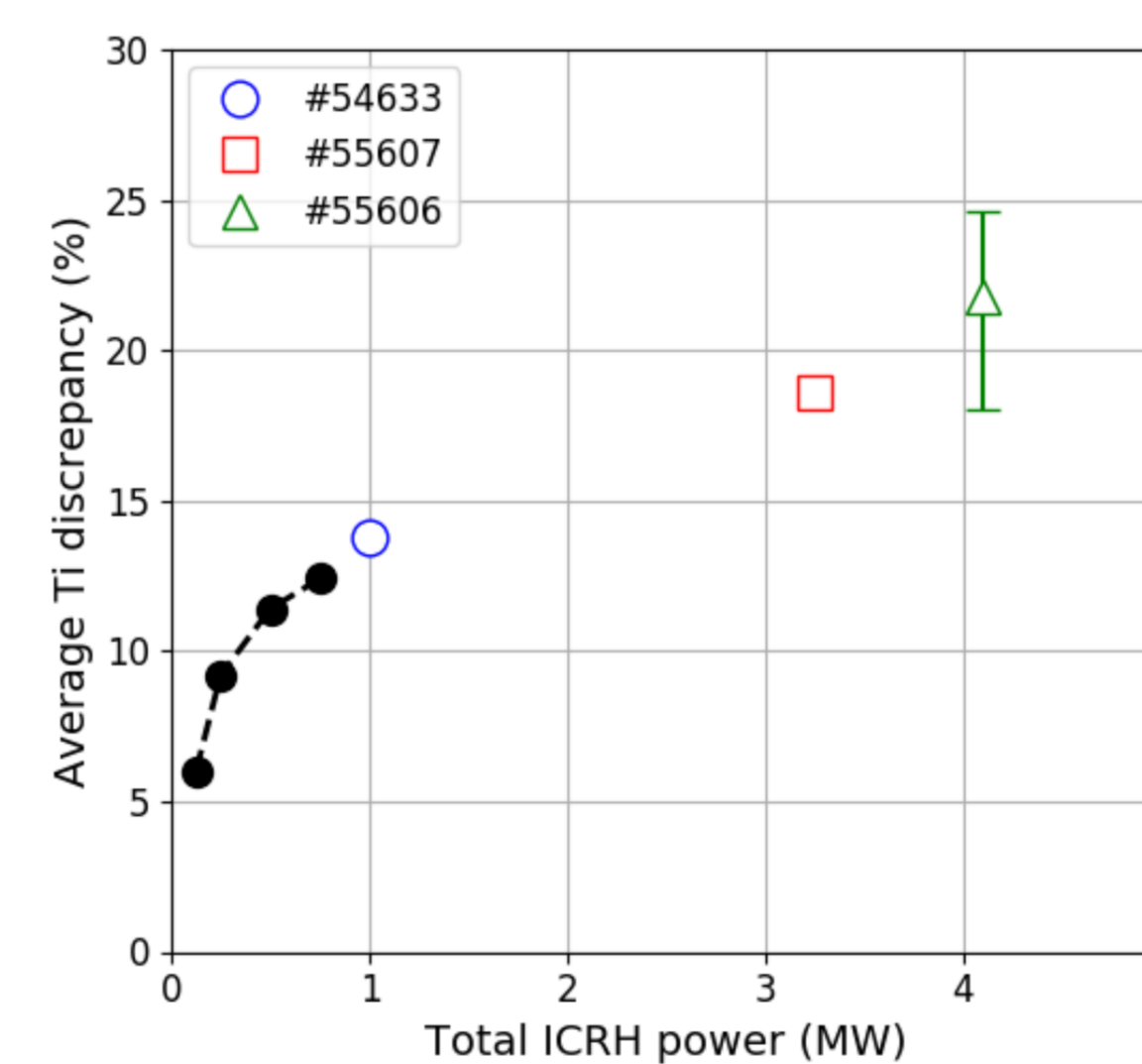


Figure 5: Relative difference between the ICRH corrected T_i estimated with the simulations and the original (Maxwellian-based) T_i as function of ICRF power for 3 different pulses. The T_i values correspond to an average over $\rho_{norm}=[0,0.2]$. The errorbar on the last point represents the extreme values obtained in a sensitivity test, where the H concentration and the plasma density were varied by $\sim 25\%$ from their nominal values.

- ICRF-induced fast ion tails depend on ICRF power, minority concentration and background plasma electron density and temperature. Minority concentration measurement has significant uncertainties.
- A sensitivity study was done by varying the H concentration and plasma electron density by $\sim 25\%$. The errorbars represent the extreme values in the sensitivity scans.
- New T_i values obtained can vary by approximately 15% due to experimental uncertainties.
- For low ICRH power, no exploitable experimental data are available. Additional simulations were done based on pulse #54633 ($P_{ICRH}=1\text{MW}$) with gradually reduced ICRH power represented as dotted symbols. The Maxwellian-based T_i from pulse #54633 is used as reference.
- Zero discrepancy is expected when no ICRH power is applied
- Steep decrease of the T_i discrepancy in the range $P_{ICRH} < 1\text{MW}$ due to the steep D-D reaction cross section in this temperature domain ($T_i < 2\text{keV}$) and a small amount of supra-thermal ions can make a considerable (non-linear) difference to the neutron yield.
- At larger ICRH powers the number of fast ions increases quasi-linearly in the supra-thermal energy range and the T_i corrections become almost linear with power.

Conclusion

- A procedure for improving the ion temperature (T_i) estimate based on the total neutron yield measurement in WEST under the influence of ICRF heating was presented.
- The ion temperature values obtained with the new procedure are lower than the original (Maxwellian-based) ones in the region of ICRF power absorption
- discrepancy between the two methods for computing the ion temperature increases with ICRF power. For $P_{ICRH}=4\text{MW}$ => overestimation by 20-25%. With the full ICRH power capability of WEST (6-7MW), the discrepancy would be considerably higher.
- Improved estimate of the ion temperature can be important for numerical simulations that depend critically on the local ion temperature values and can be useful for cross-calibration of diagnostics.