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Measurement and analyses of the mean effective ion charge in the centre of tokamak discharges*

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There are two different definitions for specifying the mean effective ion charge $Z_{\rm eff}$ in plasmas: a) from the Spizer electrical resistivity of the plasma and b) from bremsstrahlung radiation losses of the plasma. In this paper $Z_{\rm eff}$ in the centre of tokamak ohmic discharges has been determined from information on sawtooth-relaxations of the steady state plasma, based on the analysis for the power balance of the plasma electrons in the plasma centre during the period of recovery after the sawtooth crashes. This method is found to supply reliable results for tokamak parameters. While its application requires some efforts in data analysis, it can provide a reliable determination of $Z_{\rm eff}$, independent of the information from bremsstrahlung radiation losses of the plasma.

Keywords: mean effective ion charge, sawtooth relaxation, power balance of plasma electrons
PACC: 5225D, 5225V, 5270D

1. Introduction

The mean effective ion charge $Z_{\rm eff}$ in the centre of tokamak discharges is an important quantity. It should ideally be as small as possible to minimize both fuel dilution and radiation losses. It also is an important parameter in the detailed description of the plasma performance in tokamak ohmic discharges. This is often derived from bremsstrahlung radiation losses of the plasma, particularly the $Z_{\rm eff}$ measurement in the visible region is to ensure that the intensity is measured in spectral region free from strong impurity line radiation. This is often a difficult requirement to meet. $Z_{\rm eff}$ may also be obtained from information on the electrical plasma resistivity.[1] For the mentioned two kinds of methods the measurement error is very big, and the results received also are different. Here the procedure is applied in considering the relaxation of the central plasma region of tokamak discharges immediately after sawtooth crashes.[2] Phenomenologically, relatively peaked radial profiles of the plasma temperature (or density) are suddenly flattened and then recover slowly again to the state before the crash, successively followed by the next sawtooth cycle, as shown in Fig.1. The crash is due to an instability and is associated with the existence of a $q = 1$ surface in the centre,[3,4] and it is difficult in explaining sawtooth crash behaviour, so power balance must be applied.

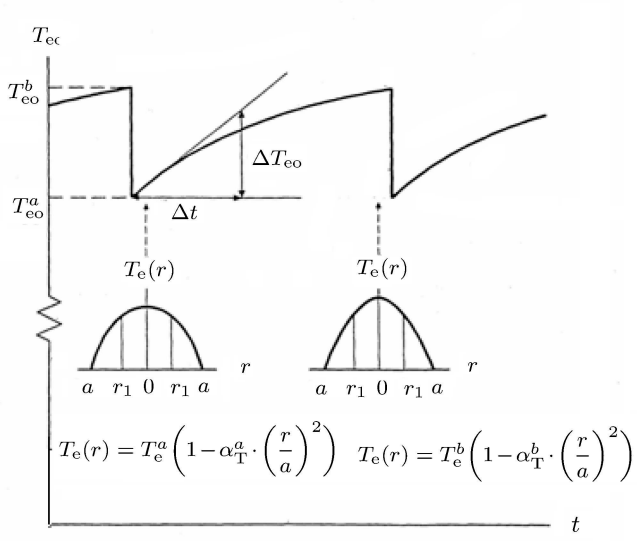


Fig.1. $T_{\rm e}$ performance during sawtooth period.

2. Power balance of the plasma electrons in the centre

Applying the continuity equation and the equation of motion, we then obtain an equation for the transport of internal energy, or the power balance of equation. The power balances of the plasma electrons

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in the centre for the initial period of plasma recovery after the sawtooth collapse[3] (assuming an isotropic velocity distribution function of the electrons) is

$$\frac{\partial}{\partial t}\Big(\frac{3}{2}n_{\rm e}\cdot kT_{\rm e}\Big)+{\rm div}\Big(\frac{3}{2}n_{\rm e}\cdot kT_{\rm e}\cdot\boldsymbol{\upsilon}\Big)+(n_{\rm e}\cdot kT_{\rm e})\cdot{\rm div}\boldsymbol{\upsilon}+{\rm div}\boldsymbol{q}_{\rm e}=P_{\Omega}^{\rm el}+P_{\rm ei}+P_{\rm rad},\qquad(1)$$

where the vector $\boldsymbol{\upsilon}$ is the velocity of electrons and the vector $\boldsymbol{q}_{\rm e}$ is the flux density of heat carried by electrons, k is Boltzmann's constant.

The equation of continuity ($\partial n_{\rm e}/\partial t+{\rm div}(n_{\rm e}\cdot\boldsymbol{\upsilon})=0$) can again be used to obtain

$$\frac{\partial}{\partial t}\Big(\frac{3}{2}n_{\rm e}\cdot kT_{\rm e}\Big)+{\rm div}\Big(\frac{3}{2}n_{\rm e}\cdot kT_{\rm e}\cdot\boldsymbol{\upsilon}\Big)=\frac{3}{2}\cdot n_{\rm e}\frac{{\rm d}kT_{\rm e}}{{\rm d}t}.$$

If we define the anomalous heat transported power density of the plasma electrons by

$$P_{\rm cd}=(n_{\rm e}kT_{\rm e}){\rm div}\boldsymbol{\upsilon}+{\rm div}\boldsymbol{q}_{\rm e},$$

then Eq.(1) can be represented as

$$\frac{3}{2}\cdot n_{\rm e}\frac{{\rm d}(kT_{\rm e})}{{\rm d}t}+P_{\rm cd}=P_{\Omega}+P_{\rm ei}+P_{\rm rad},\qquad(1a)$$

where the heat transport terms of the electrons on the left-hand side $(3n_{\rm e}/2)\cdot[{\rm d}(kT_{\rm e})/{\rm d}t]$ is change rate of plasma interior electron energy density in the plasma centre, $P_{\rm cd}=(n_{\rm e}kT_{\rm e})\,{\rm div}\boldsymbol{\upsilon}+{\rm div}\boldsymbol{q}_{\rm e}$ is anomalous heat transported power density of the plasma electrons, where $P_{\rm conv}=(n_{\rm e}\cdot kT_{\rm e})\cdot{\rm div}\boldsymbol{\upsilon}$ is convectively transported power density, $P_{\rm cond}={\rm div}\boldsymbol{q}_{\rm e}$ is conductively transported power density and the heating terms appearing on the right-hand side of Eq.(1a), P_{Ω} is ohmic power density deposition to electrons, $P_{\rm ei}$ is power density transfer from the electrons to the ions, $P_{\rm rad}$ is power density losses of the electrons by radiation.

3. Achievement of $Z_{\rm eff}$

We now replace the individual terms of Eq.(1a) with the following approximate forms and absolute units (m.k.s. units).

3.1. Change rate of plasma interior electron energy density in the plasma centre

$$\frac{3}{2}n_{\rm e}\frac{d(kT_{\rm e})}{{\rm d}t}\underset{r\to0}{\longrightarrow}2.4\times10^{-19}n_{\rm eo}T_{\rm eo}\frac{\Delta T_{\rm eo}/T_{\rm eo}}{\Delta t},\qquad(2)$$

where $T_{\rm eo}$ is electron temperature in the plasma centre derived from ECE (electron cyclotron emission receiver), $(\Delta T_{\rm eo}/\Delta t)$ is the change of magnitude electron temperature during sawtooth period Δt. $n_{\rm eo}$ is electron density in the plasma centre derived from the five channels laser interferometer, it determines the line-integrated density

$$\bar{n}_{\rm e}=\frac{\int_{-a}^{a}n_{\rm e}(r)\cdot{\rm d}r}{2a}\quad(a\text{ is plasma radius})$$

through the experimentally determined relation

$$n_{\rm e}(r)=n_{\rm eo}\Big(1-\Big(\frac{r}{a}\Big)^{\gamma}\Big),$$

where γ is electron density profile peaking factor.[5]

3.2. Anomalous transported power density

$$P_{\rm cd}=(n_{\rm e}kT_{\rm e})\,{\rm div}\boldsymbol{\upsilon}+{\rm div}\boldsymbol{q}_{\rm e}=P_{\rm conv}+P_{\rm cond}.\qquad(3)$$

3.2.1. Convectively transported power density

$$P_{\rm conv}=(n_{\rm e}\cdot kT_{\rm e})\cdot{\rm div}\boldsymbol{\upsilon}=(n_{\rm e}kT_{\rm e})\cdot\Big(\frac{\upsilon_r}{r}+\frac{\partial\upsilon_r}{r}\Big).\qquad(3a)$$

Applying the continuity equation again:

$$-\frac{\partial n_{\rm e}}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}(r\cdot n_{\rm e}\cdot\upsilon_r),\qquad(3b)$$

we get

$$P_{\rm conv}=-kT_{\rm e}\Big(\frac{\partial n_{\rm e}}{\partial t}+\upsilon_r\cdot\frac{\partial n_{\rm e}}{\partial r}\Big),$$

and

$$r\cdot n_{\rm e}\cdot\upsilon_r=-\frac{r^2}{2}\cdot\frac{\partial n_{\rm e}}{\partial t}+\int\frac{r}{2}\cdot\frac{\partial^2}{\partial t\partial r}\cdot{\rm d}r\,.\qquad(3c)$$

Approximating the radial profiles of $n_{\rm e}$ and $T_{\rm e}$ about the plasma centre after the sawtooth crash by

$$n_{\rm e}\approx n_{\rm eo}\cdot\Big(1-\Big(\frac{r}{a}\Big)^2\Big)^{\alpha_{\rm n}^a}\to n_{\rm eo}\cdot\Big(1-\alpha_{\rm n}^a\Big(\frac{r}{a}\Big)^2\Big),$$

$$T_{\rm e}\approx T_{\rm eo}\cdot\Big(1-\Big(\frac{r}{a}\Big)^2\Big)^{\alpha_{\rm T}^a}\to T_{\rm eo}\cdot\Big(1-\alpha_{\rm T}^a\Big(\frac{r}{2}\Big)^2\Big),$$

where $\alpha_{\rm n}^a$ is $n_{\rm e}$ profile factor after the sawtooth crash and $\alpha_{\rm T}^a$ is $T_{\rm e}$ profile factor after the sawtooth crash, and making use of Eq.(3b) we have

$$v_r \cdot \frac{\partial n_{\rm e}}{\partial r} \approx \frac{\alpha_{\rm n}^a}{1-\alpha_{\rm n}^a (r/a)^2}\Big[\frac{\partial n_{\rm eo}}{\partial t}\Big(\frac{r}{a}\Big)^2 + \frac{3}{2}\Big(\alpha_{\rm n}^a \cdot \frac{\partial n_{\rm eo}}{\partial t} + n_{\rm eo}\cdot\frac{\partial \alpha_{\rm n}^a}{\partial t}\Big)\cdot(\frac{r}{a})^4\Big],$$

i.e.

$$P_{\rm conv} \cong -kT_{\rm eo}\cdot\Big(1-\alpha_{\rm T}^a\cdot\Big(\frac{r}{a}\Big)^2\Big)\Big[\frac{\partial n_{\rm eo}}{\partial t} - n_{\rm eo}\cdot\frac{\partial \alpha_{\rm n}^a}{\partial t}\cdot\Big(\frac{r}{a}\Big)^2 + (\cdots)\cdot\Big(\frac{r}{a}\Big)^4\cdots\Big].$$

For the central plasma region

$$P_{\rm conv} \underset{r\to 0}{\longrightarrow} kT_{\rm eo}\cdot\frac{\partial n_{\rm eo}}{\partial t} \to 1.6\times 10^{-19}\cdot T_{\rm eo}\cdot n_{\rm eo}\cdot\frac{\Delta n_{\rm eo}/n_{\rm eo}}{\Delta t}\,. \tag{3d}$$

3.2.2. Conductively transported power density

$$P_{\rm cond} = {\rm div}\boldsymbol{q}_{\rm e} \to ({\rm div}\boldsymbol{q}_{\rm e})_r = \frac{(\boldsymbol{q}_{\rm e})_r}{r} + \frac{\partial}{\partial r}(\boldsymbol{q}_{\rm e})_r.$$

Substituting the following radial part of the electron heat flux density into the above equation:

$$(q_{\rm e})_r = -\chi_\perp^e\cdot\frac{\partial(kT_{\rm e})}{\partial r} = -n_{\rm e}\cdot\chi_{\rm e}\cdot\frac{\partial(kT_{\rm e})}{\partial r},$$

where $\chi_\perp^e$, $\chi_{\rm e}$ are the perpendicular electron heat diffusivity and the general electron heat diffusivity respectively, we obtain

$$P_{\rm cond} = -\frac{n_{\rm e}\cdot\chi_{\rm e}}{r}\frac{\partial(kT_{\rm e})}{\partial r} - \frac{\partial(n_{\rm e}\cdot\chi_{\rm e})}{\partial r}\cdot\frac{\partial(kT_{\rm e})}{\partial r} - n_{\rm e}\cdot\chi_{\rm e}\cdot\frac{\partial^2(kT_e)}{\partial r^2},$$

and with the radial profile approximation after the sawtooth crash

$$n_{\rm e} \to n_{\rm eo}\cdot\Big(1-\alpha_{\rm n}^a\cdot\Big(\frac{r}{a}\Big)^2\Big),$$

$$T_{\rm e} \to T_{\rm eo}\cdot\Big(1-\alpha_{\rm T}^a\cdot\Big(\frac{r}{a}\Big)^2\Big),$$

where $\alpha_{\rm T}^a$ and $\alpha_{\rm T}^b$ are the relevant T_e profile factor after and before sawtooth crash respectively. Diagnostics for $T_{\rm e}$ profiles with high time- and space-resolution (such as ECE-diagnostics) may allow the derivation of this quantity directly from experimental data. Sufficiently reliable results proved to be achievable also in the following way.

Approximating the $T_{\rm e}$ profiles about the plasma centre before the crash:

$$T_{\rm e}^b(r) \approx T_{\rm eo}^b\Big(1-\alpha_{\rm T}^b\cdot\Big(\frac{r}{a}\Big)^2\Big),$$

after the crash:

$$T_{\rm e}^a(r) \approx T_{\rm eo}^a\Big(1-\alpha_{\rm T}^a\cdot\Big(\frac{r}{a}\Big)^2\Big),$$

defining the inversing radius $r_{\rm s}$ by

$$T_{\rm e}^b(r) \approx T_{\rm eo}^b\Big(1-\alpha_{\rm T}^b\cdot\Big(\frac{r_s}{a}\Big)^2\Big)$$

$$\approx T_{\rm eo}^a\Big(1-\alpha_{\rm T}^a\cdot\Big(\frac{r_s}{a}\Big)^2\Big) \approx T_{\rm e}^a(r_{\rm s})$$

and introducing time averaged values of central electron temperature $T_{\rm eo}^{\rm av} \approx (T_{\rm eo}^a + T_{\rm eo}^b)/2$ and profile factor $\alpha_{\rm T}^{\rm av} \approx (\alpha_{\rm T}^a + \alpha_{\rm T}^b)/2$, we get the approximate representation after little rearrangements

$$\alpha_{\rm T}^a \approx \alpha_{\rm T}^{\rm av} - \frac{1}{2}\Big[\Big(\frac{a}{\tau_{\rm s}}\Big)^2 - \alpha_{\rm T}^{\rm av}\Big]\cdot\Big(\frac{T_{\rm eo}^b - T_{\rm eo}^a}{T_{\rm eo}^{\rm av}}\Big).$$

(information on $\alpha_{\rm T}^{\rm av}$ may be gained with the help of a profile fitting program attached to the computerized ECE-data- conversion into the $T_{\rm e}(r)$ representation, which allows for averaging about several sawtooth periods).

We obtain

$$P_{\rm cond} \to 4\cdot n_{\rm eo}\cdot\chi_{\rm eo}\cdot(kT_{eo)}\cdot\frac{\alpha_{\rm T}^a}{a^2}\Big[1+2(b-\alpha_{\rm n}^a)\cdot(\frac{r}{a})^2 + (\cdots)\cdot\Big(\frac{r}{a}\Big)^4\cdots\Big].$$

For the central plasma in absolute units

$$P_{\rm cond} \underset{r\to 0}{\longrightarrow} 6.4\times 10^{-19}\cdot\frac{n_{\rm eo}\cdot\chi_{\rm eo}\cdot T_{\rm eo}\cdot\alpha_{\rm T}^a}{a^2}\,, \tag{3e}$$

where (assuming $q = 1$ in plasma centre after sawtooth crash)

$$\chi_{\rm eo} = 1.61\times 10^{22}\cdot\frac{{\rm B_{To}}}{n_{\rm eo}\cdot T_{\rm eo}\cdot {\rm A}^{1/2}}\,,^{[6]} \tag{3f}$$

and

$$\alpha_{\rm T}^a \approx -\frac{1}{2}\Big[\Big(\frac{\alpha}{\tau_s}\Big)^2 - \alpha_{\rm T}^{\rm av}\Big]\cdot\Big(\frac{T_{\rm eo}^b - T_{\rm eo}^a}{T_{\rm eo}^{\rm av}}\Big), \tag{3g}$$

where τ_s is sawtooth inversion radius, $\alpha_{\rm T}^{\rm av}$ is time-averaged $T_{\rm e}$ profile factor.

3.3. Ohmic power density deposition to the electron

$$P_\Omega = \frac{l_\circ^2}{\sigma_{\parallel}} = 1.4\times 10^8 \frac{Z_{\rm eff} B_{\rm To}^2 \ln\Lambda}{R_0^2 T_{\rm eo}^{3/2}}, \tag{4}$$

$$\sigma_{\parallel} = 1.81 \frac{T_{\rm e}^{3/2}}{Z_{\rm eff}\cdot \ln\Lambda}, \tag{4a}$$

$$\Lambda = 1.55\times 10^{13} T_{\rm e}^{3/2}/Z^2 n_{\rm e}^{1/2}, \tag{4b}$$

$$j_\circ = \frac{2\cdot B_{\rm p}(r\to 0)}{\mu_{\rm o}\cdot(r\to 0)} = \frac{2\cdot B_{\rm T}(r\to 0)}{\mu_{\rm o}\cdot R_{\rm o}\cdot q(r\to 0)},$$

$$q(r) = \frac{r}{R}\cdot\frac{B_{\rm T}}{B_{\rm p}} \underset{r\to 0}{\longrightarrow} 1 \quad \text{(after sawtooth crash)}.$$

3.4. Power density transfer from the electrons to the ions

$$P_{\rm ei} = \sum_\nu \frac{(3/2)\cdot n_{\rm e}\cdot k(T_{\rm e}-T_{\rm i})}{\tau_\nu^{\rm eq}},$$

where the equipartition time for the ion species ν (density $n_{\rm i}^\nu$) is

$$\tau_\nu^{\rm eq} = 3.14\times 10^{14} \frac{A_\nu\cdot T_{\rm e}^{3/2}}{Z_\nu^2\cdot n_{\rm i}^\nu\cdot(\ln\Lambda)_\nu}.$$

The power density transfer from electrons to plasma ions is approximated by

$$P_{\rm ei} = 7.65\times 10^{-34}\frac{n_{e.}^2}{T_{\rm eo}^{1/2}}\Big(\frac{T_{\rm eo}-T_{\rm io}}{T_{\rm eo}}\Big)\cdot\ln\Lambda. \tag{5a}$$

Due to scatter in the experimentally obtained electron and ion temperatures the error margins of directly derived $((T_{\rm eo}–T_{\rm io})/T_{\rm eo})$-values are usually intolerable for reliable evaluations of the power density transfer from plasma electrons to ions (Eq.(5a)). On the other hand, compilations of extensive experimental data from former HL-2A discharges suggest that most of the widely scattering $((T_{\rm eo}–T_{\rm io})/T_{\rm eo})_{\rm exp}$ results are confined to about the bounds:[7]

$$[1+n_{\rm eo}(\times 10^{-19}{\rm m}^3)]^{-1} \le \frac{T_{\rm eo}-T_{\rm io}}{T_{\rm eo}} \le [1+(n_{\rm eo}(\times 10^{-19}{\rm m}^3))^2]^{-1}. \tag{5c}$$

3.5. Power density losses of the electrons by radiation

$$P_{\rm rad} = P_{\rm ff} + P_{\rm fb} + P_{\rm bb} + \cdots, \tag{6}$$

where $P_{\rm ff}$ is (free-free)-bremsstrahlung radiation losses, $P_{\rm fb}$ is (free-bound)-recombination radiation losses, $P_{\rm bb}$ is (bound-bound)-line radiation losses.

Information on $P_{\rm rad}$ may be derived experimentally from the bolometric measurements, but completely general statements on the plasma radiation losses are hard to make themselves analytical, except for the contribution

$$P_{\rm ff} \underset{(r\to 0)}{\longrightarrow} 1.71\times 10^{-38} n_{\rm eo}^2({\rm m}^{-3}) \cdot T_{\rm eo}^{1/2}({\rm meV})\cdot\sum_\nu\Big(\frac{Z_\nu^2 n_{\rm io}^\nu}{n_{\rm eo}}\Big). \tag{6a}$$

For $T_{\rm eo}$ values of the HL-2A tokamak, this is a small quantity compared with $P_{\rm ei}$:

$$\frac{P_{\rm ff}}{P_{\rm ei}} \underset{r\to 0}{\longrightarrow} 2.2\times 10^{-5}\cdot\frac{T_{\rm eo}}{\ln\Lambda}\cdot\Big(\frac{T_{\rm eo}-T_{\rm io}}{T_{\rm eo}}\Big)^{-1}\frac{\sum_\nu\Big(\frac{Z_\nu^2\cdot n_{\rm io}^\nu}{n_{\rm eo}}\Big)}{\sum_\nu\Big(\frac{Z_\nu^2\cdot n_{\rm io}^\nu}{n_{\rm eo}\cdot A_\nu}\Big)} \approx 10^{-5}\cdot T_{\rm eo} \ll 1 \tag{6b}$$

(for representative values: $\ln\Lambda\approx 17$; $(T_{\rm eo}-T_{\rm io})\approx 0.25T_{\rm eo}$; $A\approx 2$).

In discharges with high levels of impurities, the power losses by recombination plus line radiation may exceed the bremsstrahlung contribution by orders of magnitude and the $P_{\rm rad}$contribution must definitively be taken into account in Eq.(1a). For simplicity, we will neglect $P_{\rm rad}$ in the following for tokamak discharges of interest.

3.6. Summary

Replacing the individual terms of Eq.(1a) with the mentioning approximate forms and summarizing the results of Eqs.(2)–(6), we obtain from Eq.(1a) after few transformations:

$$Z_{\rm eff} = 1.7\times 10^{-23}\Big(\frac{R_{\rm o}}{B_{\rm To}}\Big)^2 n_{\rm eo}T_{\rm eo}\Big[\frac{T_{\rm eo}^{3/2}}{\ln\Lambda}\Big\{\Big(\frac{\Delta T_{\rm eo}/T_{\rm eo}}{\Delta t}-\frac{2}{3}\frac{\Delta n_{\rm eo}/n_{\rm eo}}{\Delta t}\Big)+2.7\cdot\frac{\chi_{\rm eo}\alpha_{\rm T}^a}{a^2}\Big\}+3.2\times 10^{-15} n_{\rm eo}\frac{T_{\rm eo}-T_{\rm io}}{T_{\rm eo}}, \tag{7}$$

where

$$\Lambda = 1.55 \times 10^{13} \cdot \frac{T_{\rm eo}^{3/2}}{Z^2 \cdot n_{\rm eo}^{1/2}}, \quad \chi_{\rm eo} = 1.61 \times 10^{22} \cdot \frac{B_{\rm To}}{n_{\rm eo} \cdot T_{\rm eo} \cdot A^{1/2}} \Big(\frac{m^2}{\rm s}\Big),$$

$$\alpha_{\rm T}^{\rm low} = \alpha_{\rm T}^{\rm av} - \frac{1}{2}\Big[\Big(\frac{a}{\tau_{\rm i}}\Big)^2 - \alpha_{\rm T}^{\rm av}\Big] \cdot \Big(\frac{T_{\rm eo}^{top} - T_{\rm eo}^{\rm low}}{T_{\rm eo}^{\rm av}}\Big).$$

Examples of $Z_{\rm eff}$ results derived with the discussed method from several HL-2A- discharges are presented in Table 1 and compared with corresponding values $(Z^*) = \sum_\nu (\frac{Z_\nu^2 \cdot n_{\rm io}^\nu}{n_{\rm eo}})$ from bremsstrahlung measurements[8] and $Z_{\rm eff}^{\rm PS}$ from computer simulations of the plasma performance.[9] Discharges with high levels of impurities have been selected on purpose for these comparisons and the residual dependences of the results on Z and A occurring by the terms $\ln\Lambda$ and $\chi_{\rm eo}$ were considered iteratively.

Table 1. Examples of experimental $Z_{\rm eff}$ results.

No.	Gas	$B_{\rm T}$/T	$I_{\rm P}$/kA	$n_{\rm eo}/10^{19}{\rm m}^{-3}$	$T_{\rm eo}$/eV	$\frac{\Delta T_{\rm eo}/T_{\rm eo}}{\Delta t}/{\rm s}^{-1}$	$\frac{\Delta n_{\rm eo}/n_{\rm eo}}{\Delta t}/{\rm s}^{-1}$	a/m	$\frac{T_{e0}-T_{i0}}{T_{e0}}$	$Z_{\rm eff}$	Z^*	$Z_{\rm eff}^{\rm PS}$
3852	H_2	1.9	220	1.7	990	17.2	4.8	0.4	0.31	3.2	3.3	2.6
3654	H_2	2.0	250	1.6	925	23.4	6.2	0.4	0.34	3.6	3.4	3.0

4. Conclusion

Achievement of $Z_{\rm eff}$ in the centre of ohmic tokamak discharges from sawtooth-relaxation of the plasma is considered. This method is found to be simple and fast during performance of the steady state discharges and to supply trustworthy results for tokamak parameters.

These quantities derived from bremsstrahlung radiation losses of the plasma in the visible region and impurities radiation losses of the plasma by multichannel spectrum and from information on the plasma electrical resistivity have very big measurement error, and the results received are also different. Replacing old methods with the above-mentioned method can provide a kind of valid and dependable tool for the tokamak research.

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