Contribution of Quantitative Spectroscopy to Fusion Plasma Research

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Role of Impurities in fusion plasmas

Fusion reactors require simultaneously:

- **High temperature plasma** and
- Protection of PFCs

⇒ Control of impurity radiation

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**Core plasma**

- $T \sim 10^4$ eV
- $n \sim 10^{20}$ m$^{-3}$

**Peripheral Plasma**

- $T \sim 10^{-1}$ eV
- $n \sim 10^{20}$ m$^{-3}$

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**Core plasma**

- Impurity radiation **suppressed**
- ⇒ Low impurity concentration

**Peripheral plasma**

- Impurity radiation **enhanced**
- ⇒ External impurity seeding

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Tungsten (W) target in ITER

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Divertor
Impurity control: needs to understand radiation properties

\[ \text{Cooling rate (W/m}^3) \]

Peripheral (divertor) plasma

Core plasma

\begin{align*}
\text{Assumption:} & \quad \frac{C \text{ density}}{e \text{ density}} = 1\% \\
\text{W density} & \quad \frac{e \text{ density}}{=0.01\%}\end{align*}

\[ \text{T_e (eV)} \]

\[ \begin{array}{c}
10^{-33} \\
10^{-34} \\
10^{-35} \\
10^{-36} \\
10^{-37} \\
10^0 \\
10^1 \\
10^2 \\
10^3 \\
10^4 \\
\end{array} \]

\text{W: useless in divertor and harmful in core} \\
\Rightarrow \text{Only demerit. Particularly W core density needs to be suppressed}

\text{C: useful in divertor and not harmful in core} \\
\Rightarrow \text{Significant merit as a radiator in divertor plasmas}
Various W atomic data needed for W density / radiation measurement

**W charge state distribution**
<= Ioniz/recomb. rates

**Ioniz. equilibrium model**

\[ \frac{nW_{q^+}}{nW} \]
(Fractional abundance of \( W^{q^+} \))

\[ nW \]
(total \( W \) density)

\[ \frac{nW_{q^+}}{W^{q^+} \text{ density}} \]

**Cooling rate**

\[ P_w \]
\( W^{q^+} \) (q:all) CR models

**Line identification**
<= spectral data

**Photon Emission Coefficient**
<= excitation rate. A coef. Energy

**W^{q^+} Collisional-Radiative model**
Plasma rotation and central heating effective in avoiding W accumulation

Plasma rotation and central heating effective in avoiding W accumulation.

\[ \Delta P^{BOL} = P_{\text{before}} - P_{\text{after}} \]

Radiation collapse

JT-60U Neutral Beam

Plasma rotation and central heating effective in avoiding W accumulation

Various W atomic data needed for W density / radiation measurement

W charge state distribution <= Ioniz/recomb. rates

Ioniz. Equilibrium model

Line identification <= spectral data

Photon Emission Coefficient <= excitation rate, $A_{\text{cof}}$, Energy

$\sum nW_{q^+}$

Fractional abundance of $W_{q^+}$

Cooling rate

(W radiation)

$P_w$

$W_{q^+}$ (q:all) CR models

2x deviation

4x deviation

$2 \times$ deviation

$4 \times$ deviation

$10^{-30}$

$10^{-31}$

$10^{-32}$

Cooling rate (W m$^{-3}$)

$10^2$

$10^3$

$10^4$

$I_{q^+}$

$T_e$ (eV)

$(W_{q^+} \text{ density})$

$W_{q^+}$ Collisional-Radiative model

*T Puetterich et al NF 50 (2010) 025012

**T Nakano et al JNM 415 (2010) S327
Evaluation of ioniz./recomb. Rate: Direct comparison btw Exp. and Cal.

Measurement

\[
\frac{I_{W^{45+}}(6.2 \text{ nm})}{I_{W^{44+}}(6.1 \text{ nm})} = \frac{4s^2S_{1/2} - 4p^2P_{3/2}}{4s4s^1S_0 - 4s4p^1P_1}
\]

Excitation rate

\[
\frac{C_{e}^{45+}(4s,4p)}{C_{e}^{44+}(4s,4p)} = \frac{nW^{45+}(4s)}{nW^{44+}(4s)} \frac{n_e}{n_e}
\]

Similar excitation energy (199 eV and 204 eV) ⇒ Similar temperature dependence of \( C_e \)

\[
\sim 0.44
\]

\[
\frac{S_{44+ \rightarrow 45+}^{44+ \rightarrow 45+}}{(\text{ioniz. rate})} \frac{(\text{recomb. rate})}{45+ \rightarrow 44+}
\]

Calculation

Independent of \( T_e \) ⇒ Enables direct comparison
Calculated ioniz./recomb. rate agrees with measured $W^{45+}/W^{44+}$

Exp:
$$n_{W}^{45+} / n_{W}^{44+} = [I^{45+} / I^{44+}] / 0.44$$

Cal:
$$n_{W}^{45+} / n_{W}^{44+} = S^{44+} / \alpha^{45+}$$

FAC and ADAS agree with JT-60U experimental data within 30%

⇒ Accuracy of $S^{44+}$ to $\alpha^{45+}$ evaluated

***http://open.adas.ac.uk
**W⁴⁴⁺ ioniz. & W⁴⁵⁺ recomb. rates should be evaluated around 4 keV.**

Large uncertainty may be acceptable at low and high \( T_e \). Efforts on data evaluation should depend on importance of the data.
Impurity control: needs to understand radiation properties

Peripheral (divertor) plasma

Core plasma

Cooling rate (W/m$^3$)

10$^{-37}$
10$^{-36}$
10$^{-35}$
10$^{-34}$
10$^{-33}$

Te (eV)

10$^0$
10$^1$
10$^2$
10$^3$
10$^4$

C: efficient radiator at low $T_e$

W: huge radiator at high $T_e$

Assumption:

C density / e density = 1%

W density / e density = 0.01%

W: useless in divertor and harmful in core
⇒ Only demerit. Particularly W core density needs to be suppressed

C: useful in divertor and not harmful in core
⇒ Significant merit as a radiator in divertor plasmas
JT-60U tokamak

- Plasma current: < 2.5 MA
- Toroidal Magnetic field: < 4.1 T
- Discharge duration: < 65 s
- Heating (Neutral Beam) < 25 MW
  (Waves) < 8 MW
At low gas puffing (low density):
CIV peak between inner strike point and X point

\[ \text{C IV (3s}^2\text{S}_{1/2} - \text{3p}^2\text{P}_{3/2}) \]

\[ I_P = 1.5 \text{ MA} \]
\[ B_T = 3.6 \text{ T} \]
\[ P_{\text{NB}} = 15 \text{ MW} \]
At middle density:
Two C IV peaks near X point

\[ I_P = 1.5 \text{ MA} \]
\[ B_T = 3.6 \text{ T} \]
\[ P_{NB} = 15 \text{ MW} \]
During high radiation:
Peak at X point

High density

VUV

C IV ($3s^2S_{1/2} - 3p^2P_{3/2}$)

Intensity ($10^{17}$ ph/sr m$^2$/s)

Viewing chord (ch)

C IV ($3s^2S_{1/2} - 3p^2P_{3/2}$)

Intensity ($10^{17}$ ph/sr m$^2$/s)

Viewing chord (ch)

$\bar{n}_e$

$D_2$ Puff

Extrapolation

$C_{IV}$ ($3s^2S_{1/2} - 3p^2P_{3/2}$)

Ext

$D_2$ Puff

High density

$P_{NB} = 15$ MW

$I_p = 1.5$ MA

$B_T = 3.6$ T

Intensity ($10^{17}$ ph/sr m$^2$/s)

$C_{IV}$ ($3s^2S_{1/2} - 3p^2P_{3/2}$)
C IV and C III lines observed in VUV and visible range

VUV spectrum

Visible spectrum
C IV(C$^{3+}$): $n < 5$ : Ionizing component
$n \geq 5$ : Recombining component

Term Energy (eV)
3s
3p
3d
4d
6
7
9

Recomb.
Ioniz.

Volume recombination of C$^{4+}$ is observed for the first time
**C III (C^{2+}):** Ionization component dominates

Population of C II (C^{2+})

No recombination of C^{3+} is observed for unlike C^{4+}
C\textsuperscript{3+} is the biggest radiator.

C\textsuperscript{3+} is produced by ionization of C\textsuperscript{2+} and recombination of C\textsuperscript{4+}.

⇒ Recombination converts inefficient radiator, C\textsuperscript{4+} into efficient radiator, C\textsuperscript{3+}. Recombination of Ne\textsuperscript{8+} was observed in Ne seeded plasmas.
Which line of C IV contributes the most to the total radiation?

Collisional-Radiative model => Photon Emission Coefficient
x photon energy
=> Radiative power Coefficient (2s-2p,.., & total )

The 2s-2p line contributes 95% to the total radiative power coefficient
⇒ The most responsible line for radiation
What yields the uncertainty of 2s-2p PEC?

At low density, PEC \( \sim \) Collisional excitation rate from 2s to 2p, \( C_e(2s, 2p) \)

\[ \Rightarrow \text{Uncertainty of } C_e(2s, 2p) \sim \text{equal to that of the Photon Emission coef.} \]

\[ \sim \text{equal to that of the total radiative power coef.} \]
Summary

- W concentration and radiation increased with increasing plasma rotation in the direction opposite to the plasma current. But particularly processed data such as cooling rate suffer from uncertainty propagation.

⇒ Experimental evaluation of calculated data

- $W^{45+}$ recombination rate / $W^{44+}$ ionization rate: quantitative agreement

W data needs: evaluated ioniz. & recomb. rates
evaluated (equilibrium-averaged) cooling rate
  Efforts should be concentrated on data at important $T_e$ range

- $C^{3+}$ was the biggest radiator, in divertor plasma
- $C^{3+}$ was produced by ioniz. of $C^{2+}$ and recomb. of $C^{4+}$.

Recombination converted inefficient radiator, $C^{4+}$ (He-like) to efficient one, $C^{3+}$.
⇒ Recombination is another channel for enhancing radiation.

Light elements (such as C, N, Ne,..,) data needs:
Evaluated charge specific cooling rates for analyses of non-equilibrium plasmas
Evaluated excitation rates for radiation-responsible lines, ex 2s-2p of Li-like ions