IAEA Technical Meeting on Uncertainty Assessment and Benchmark
Experiments for Atomic and Molecular Data for Fusion Applications
19–21 December 2016, IAEA Headquarters, Vienna, Austria
Meeting room: M02
Atomic and Molecular Data Needs for Fusion Applications 9:40–
20 min.

QST

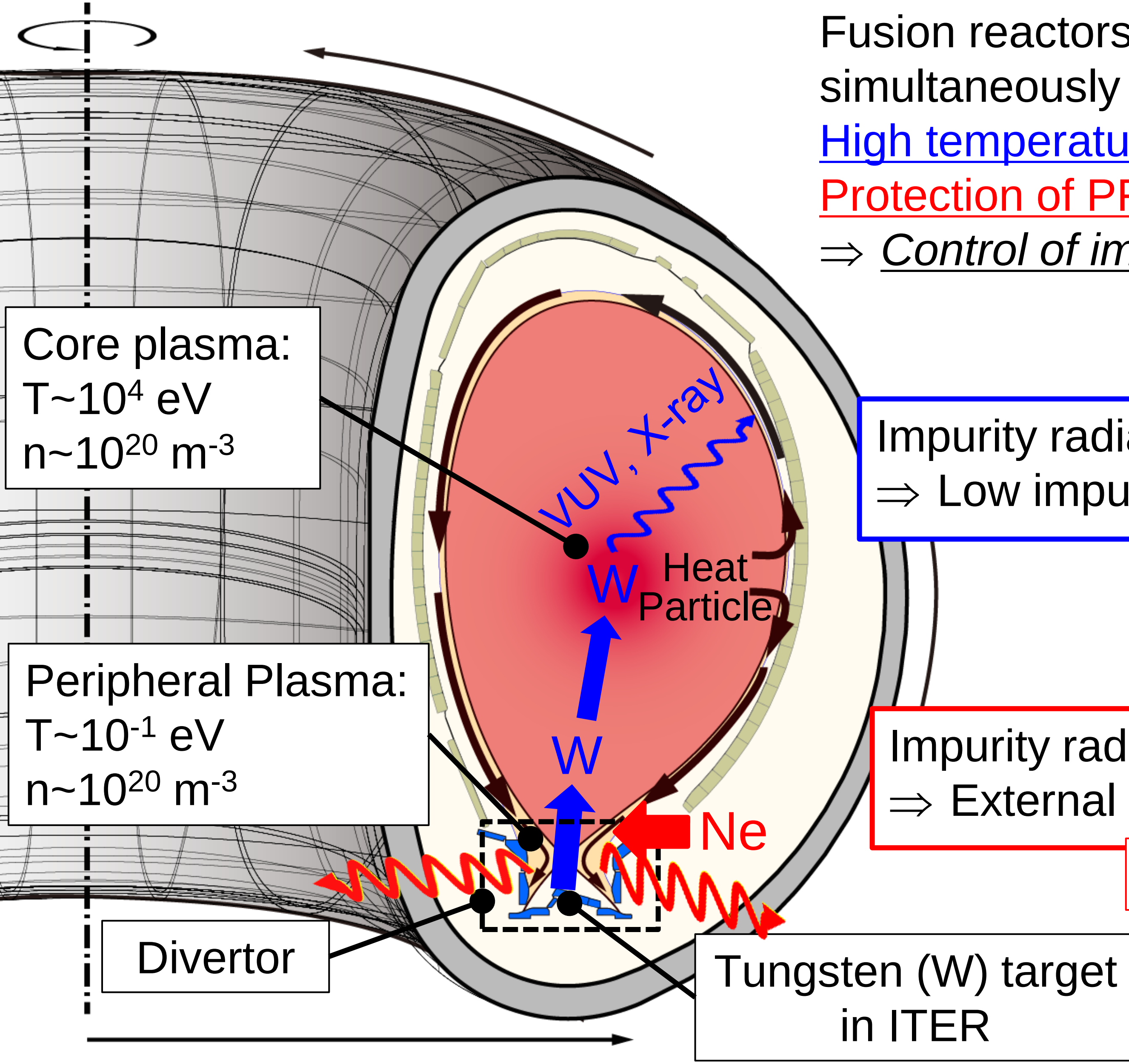
# Contribution of Quantitative Spectroscopy to Fusion Plasma Research

National Institutes for Quantum and Radiological Science and Technology
(QST)

T. Nakano

# Role of Impurities in fusion plasmas

Fusion reactors requires simultaneously
High temperature plasma and
Protection of PFCs
⇒ *Control of impurity radiation*




**Core plasma**

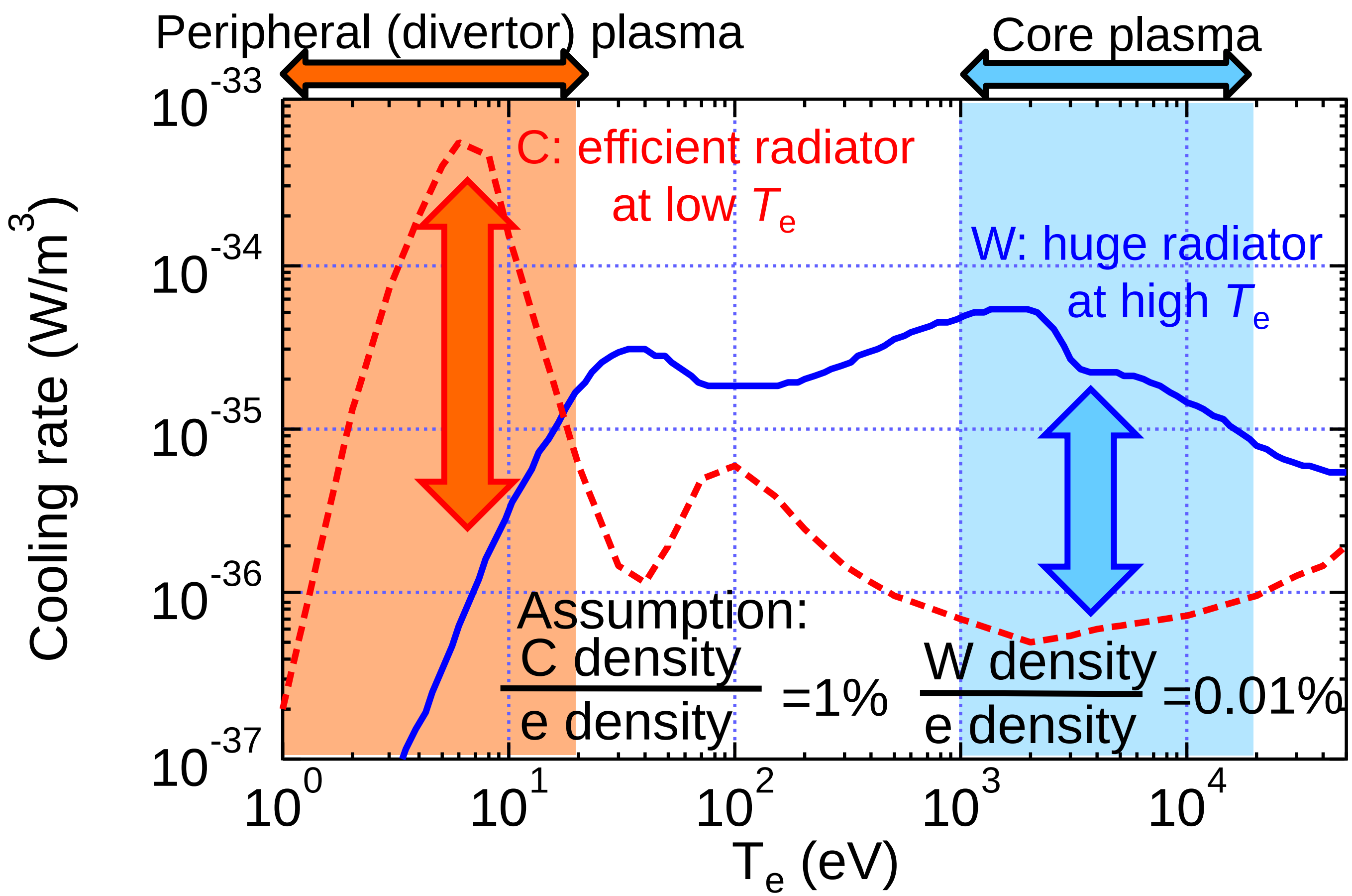
Impurity radiation *suppressed*
⇒ Low impurity concentration

**Conflicting**

Impurity radiation *enhanced*
⇒ External impurity seeding

**Peripheral plasma**

# Impurity control: needs to understand radiation properties




W: useless in divertor and harmful in core

⇒ Only demerit. Particularly W core density needs to be suppressed

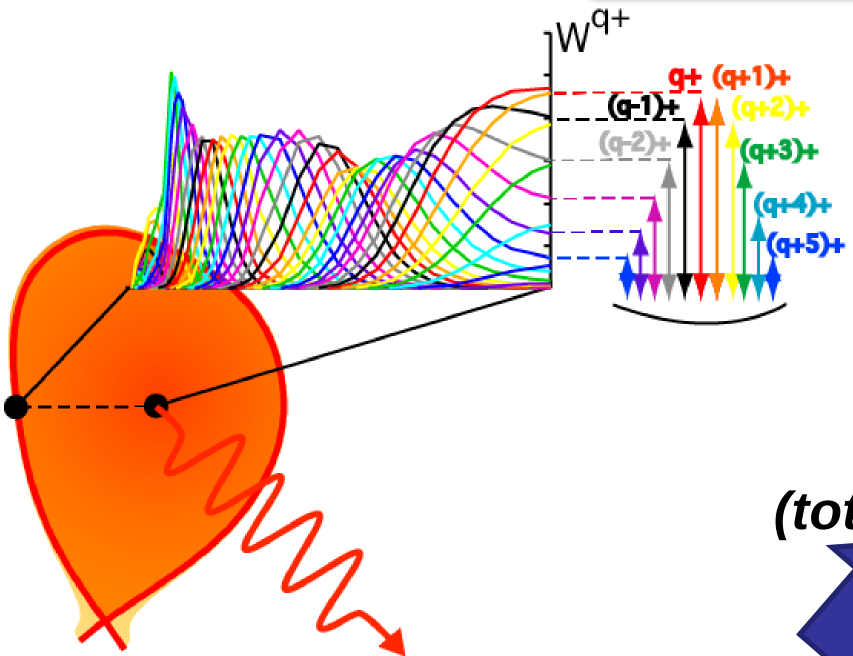
C: useful in divertor and not harmful in core

⇒ Significant merit as a radiator in divertor plasmas

# 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)***

$P_W$
***(W radiation)***

**Cooling rate**

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

$I^{q+}$

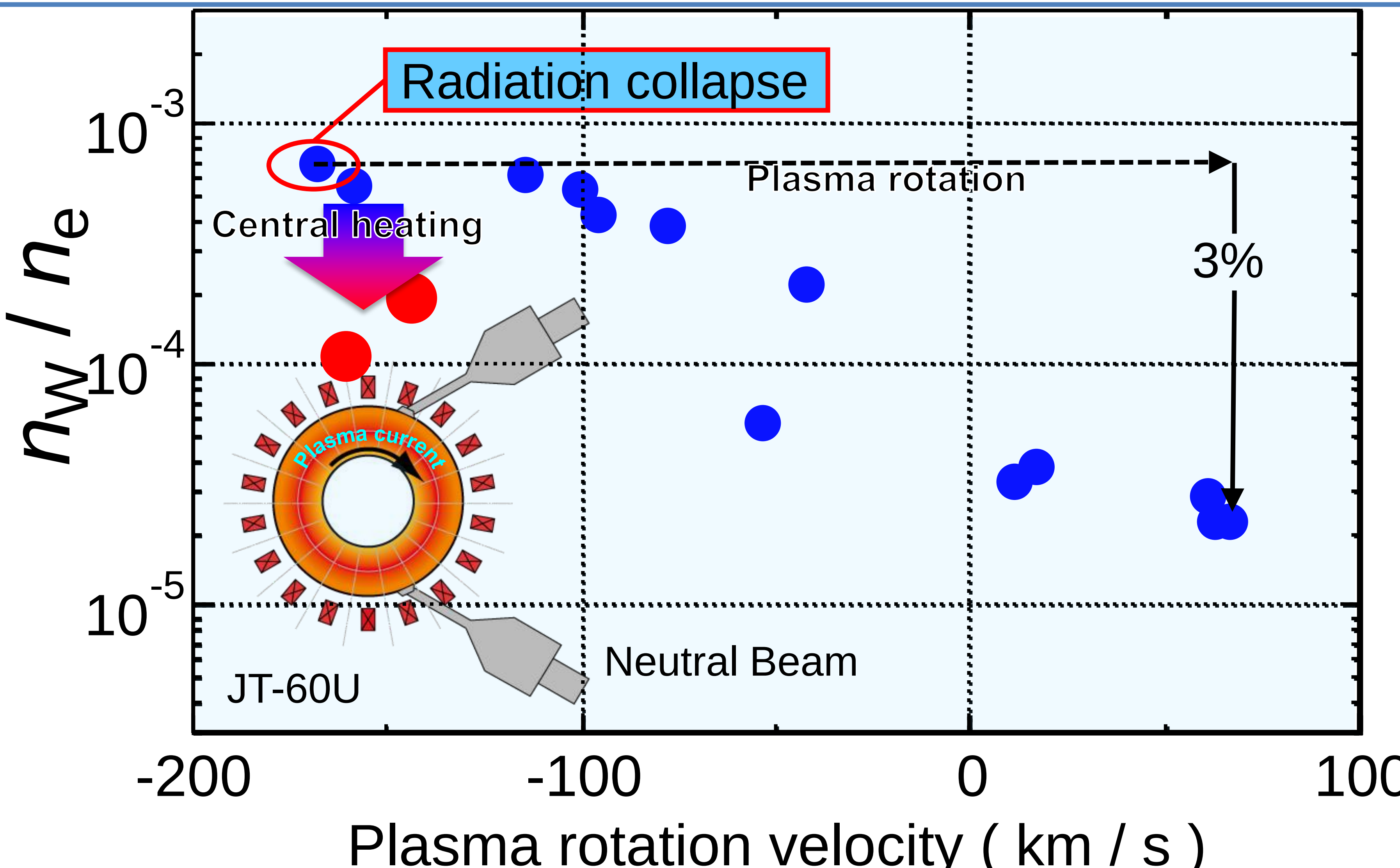
$nW^{q+}$
*($W^{q+}$ density)*

**Line identification**
<= spectral data

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

**$W^{q+}$ Collisional-Radiatve model**

# Plasma rotation and central heating effective in avoiding W accumulation




T. Nakano and the JT-60 team, *J. Nucl. Mater.* S327 (2011) 415.

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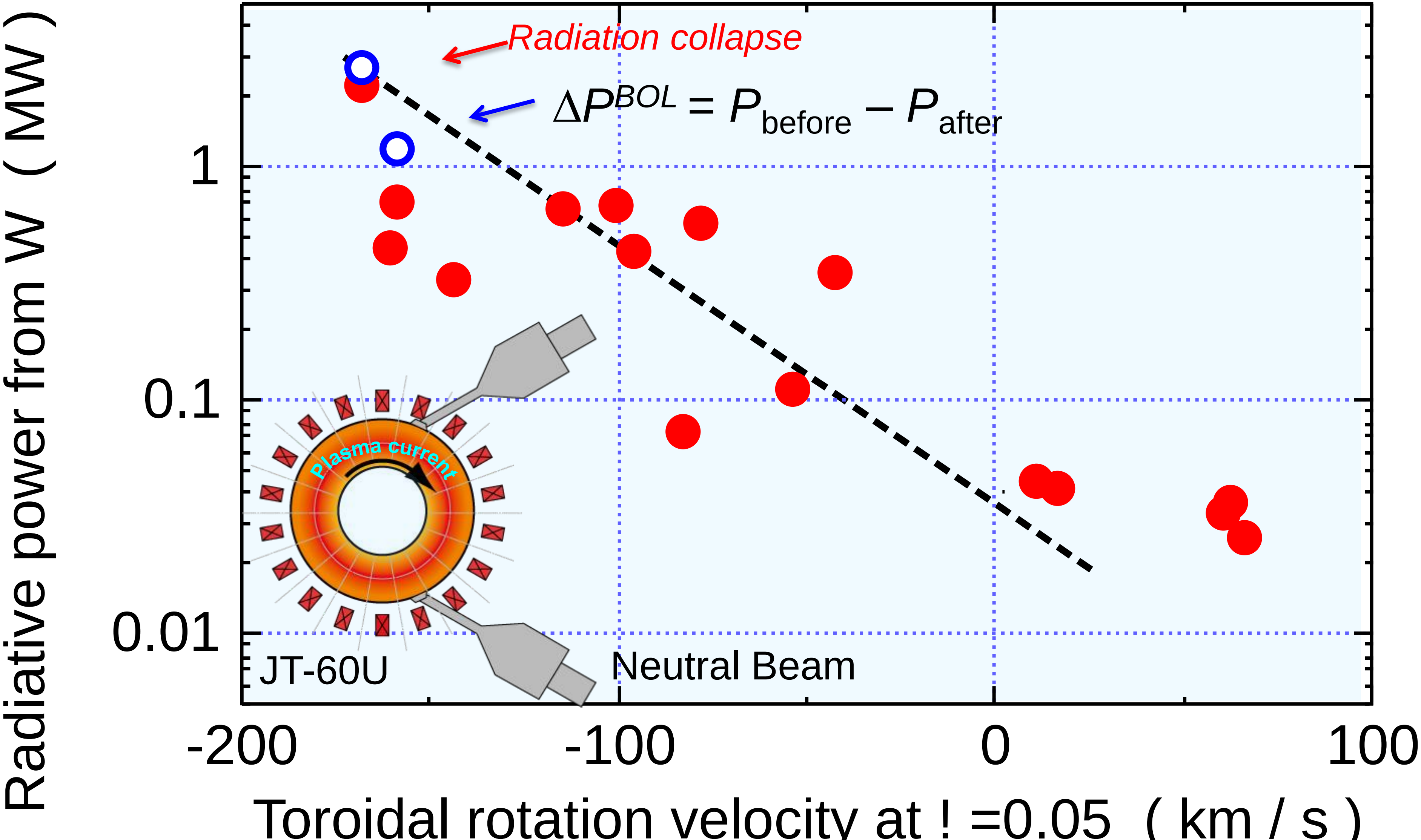


T. Nakano and the JT-60 team, *J. Nucl. Mater.* S327 (2011) 415.

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W charge state distribution
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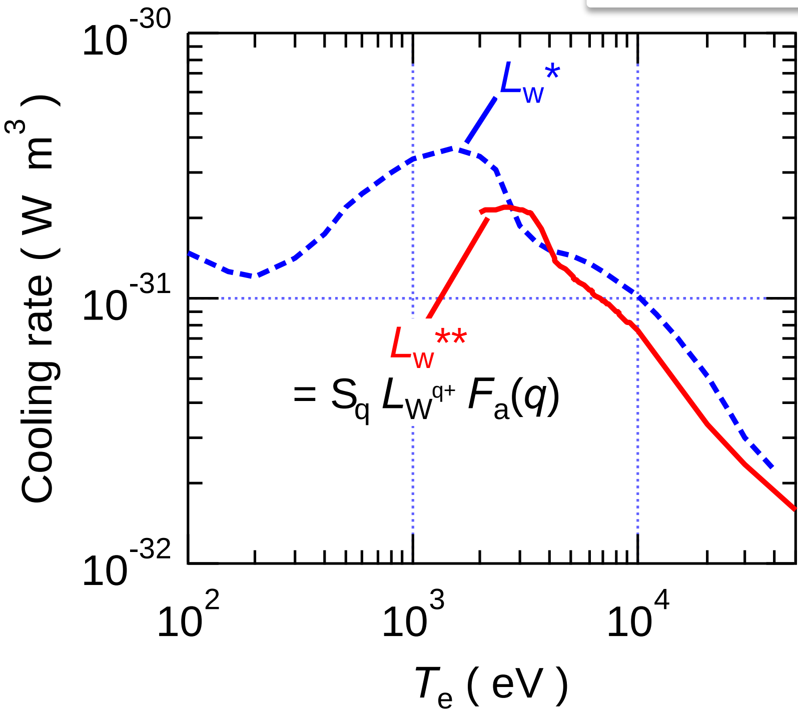
Ioniz. Equilibrium model




$\frac{nW^{q+}}{nW}$

(Fractional abundance of $W^{q+}$)

2x deviation

***nW***

***tal W density)***

4x deviation

$P_W$

***(W radiation)***

Cooling rate

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

2x deviation

$I^{q+}$

*(W^{q+} density)*

Line identification

Photon Emission Coefficient

<= excitation rate, A coef, Energy

$W^{q+}$ Collisional-Radiatve 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.

QST

**Measurement**

$$\frac{I^{W45+}(6.2\ \mathrm{nm}):\ 4s\ ^2S_{1/2} - 4p\ ^2P_{3/2}}{I^{W44+}(6.1\ \mathrm{nm}):\ 4s4s\ ^1S_0 - 4s4p\ ^1P_1} = \frac{C_e^{45+}(4s,4p)}{C_e^{44+}(4s,4p)} \cdot \frac{nW^{45+}(4s)}{nW^{44+}(4s)} \cdot \frac{n_e}{n_e}$$

Excitation rate

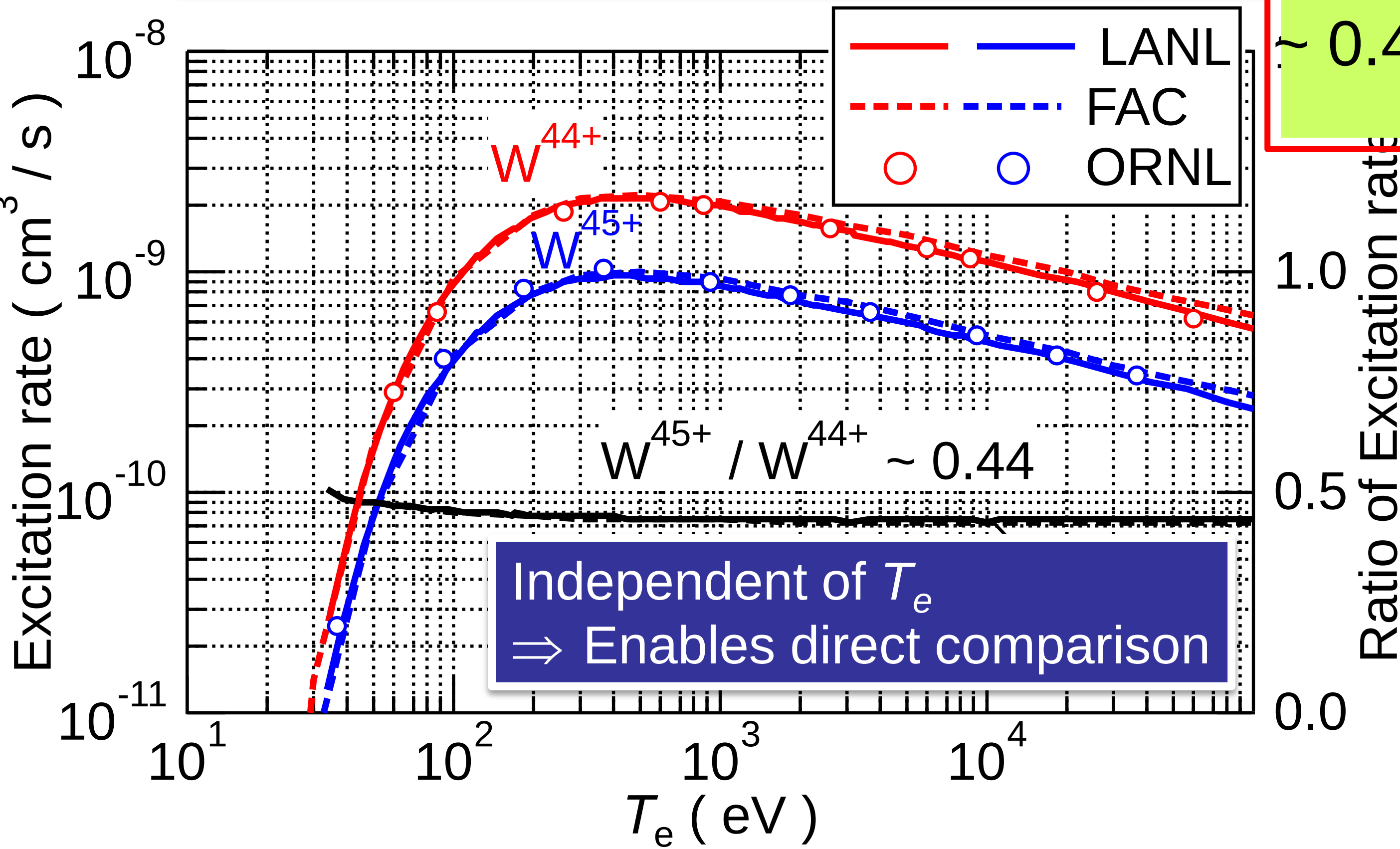
Ioniz. Equi.

$$\sim 0.44 \cdot \frac{S^{44+\rightarrow 45+}\ \text{(Ioniz.rate)}}{a^{45+\rightarrow 44+}\ \text{(Recomb.rate)}}$$

**Calculation**

Simlar excitation energy (199 ev and 204 eV)

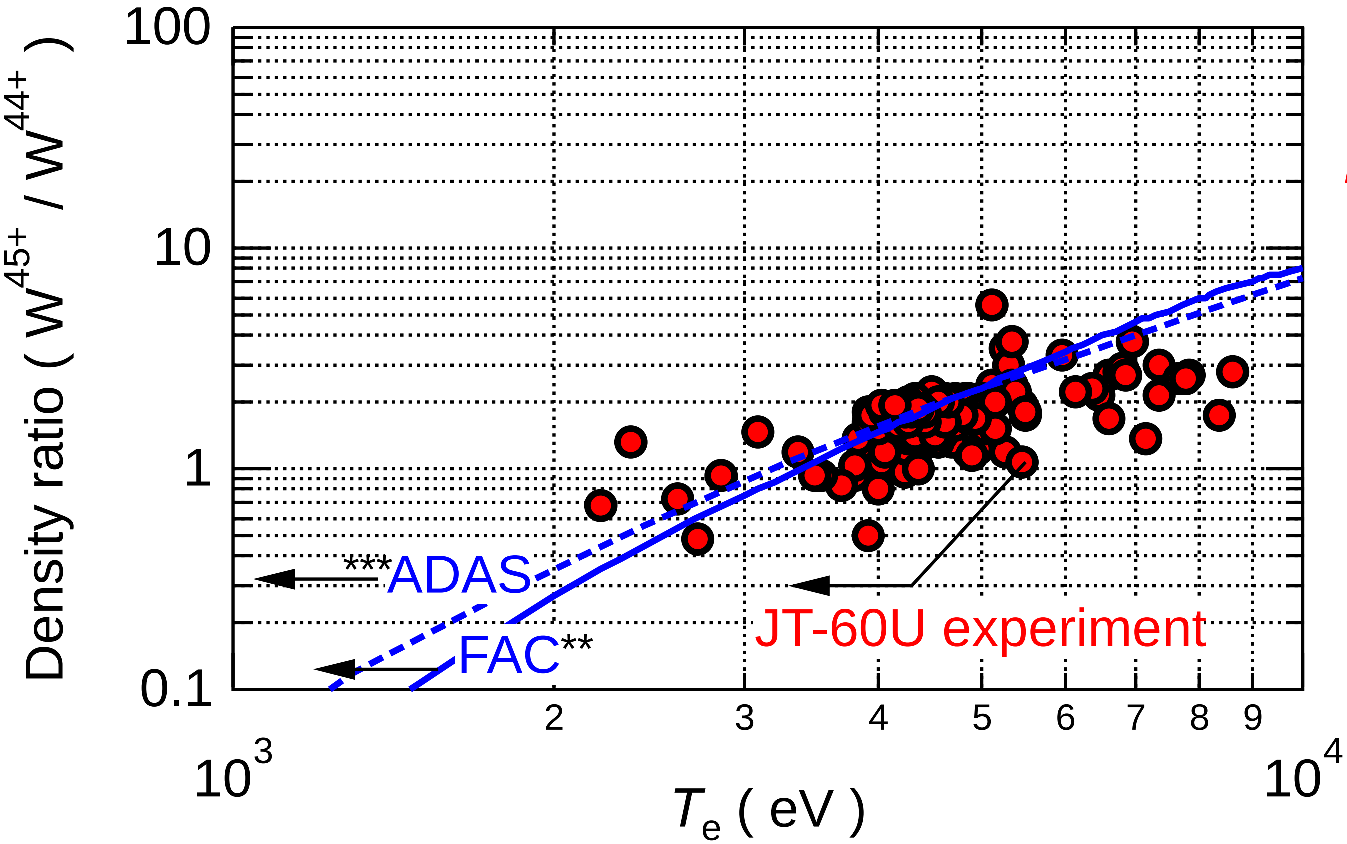
⇒ Similar temperature dependence of $C_e$




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%

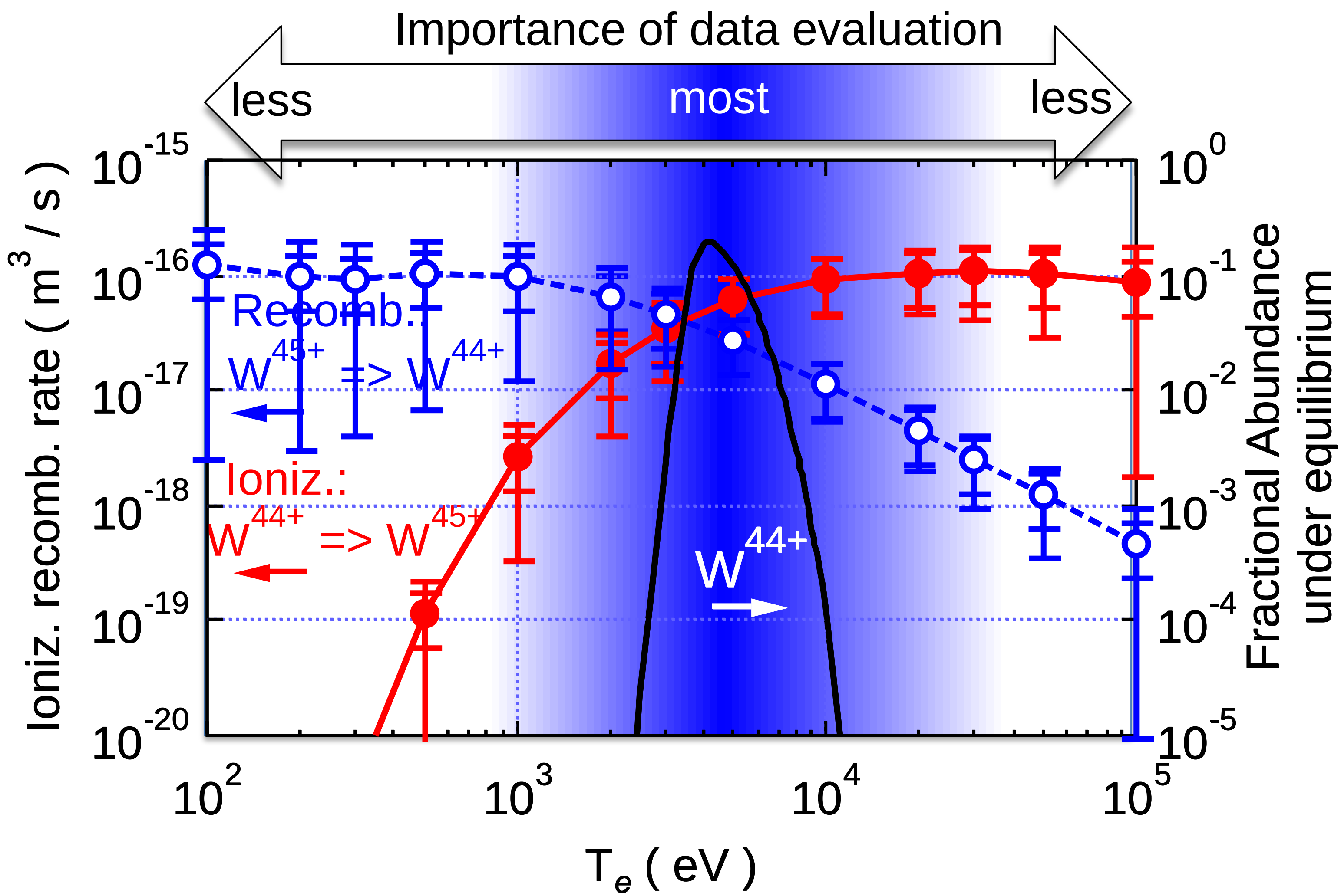
⇒ Accuracy of $S^{44+}$ to $\alpha^{45+}$ evaluated

**M.F.Gu, Can. J. Phys. **86** (2008) 675

*T Nakano et al J. Nucl. Mater **415** (2011) S327

***http://open.adas.ac.uk

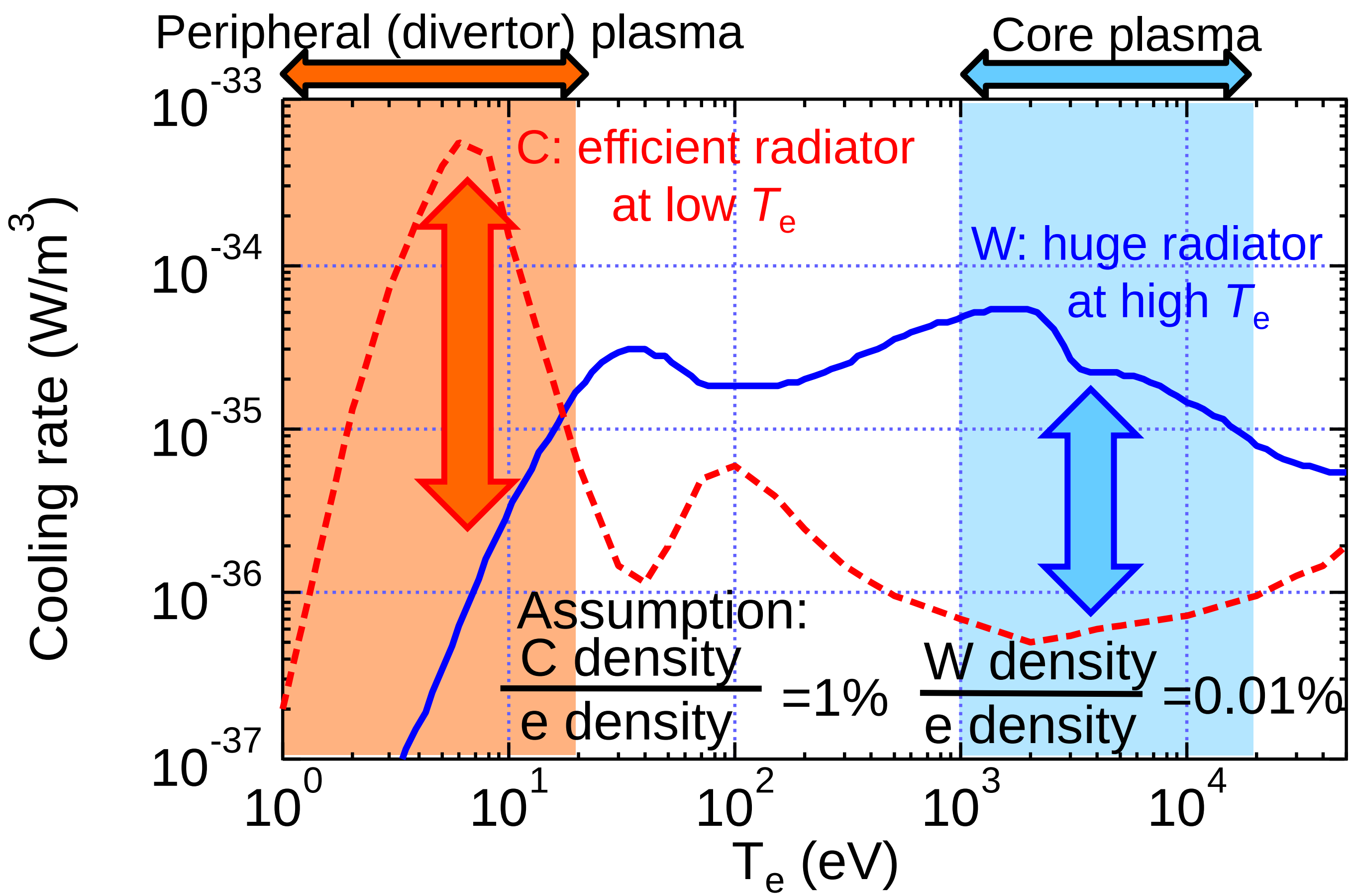
# $W^{44+}$ ioniz. & $W^{45+}$ recomb. rates should be evaluated around 4 keV.




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

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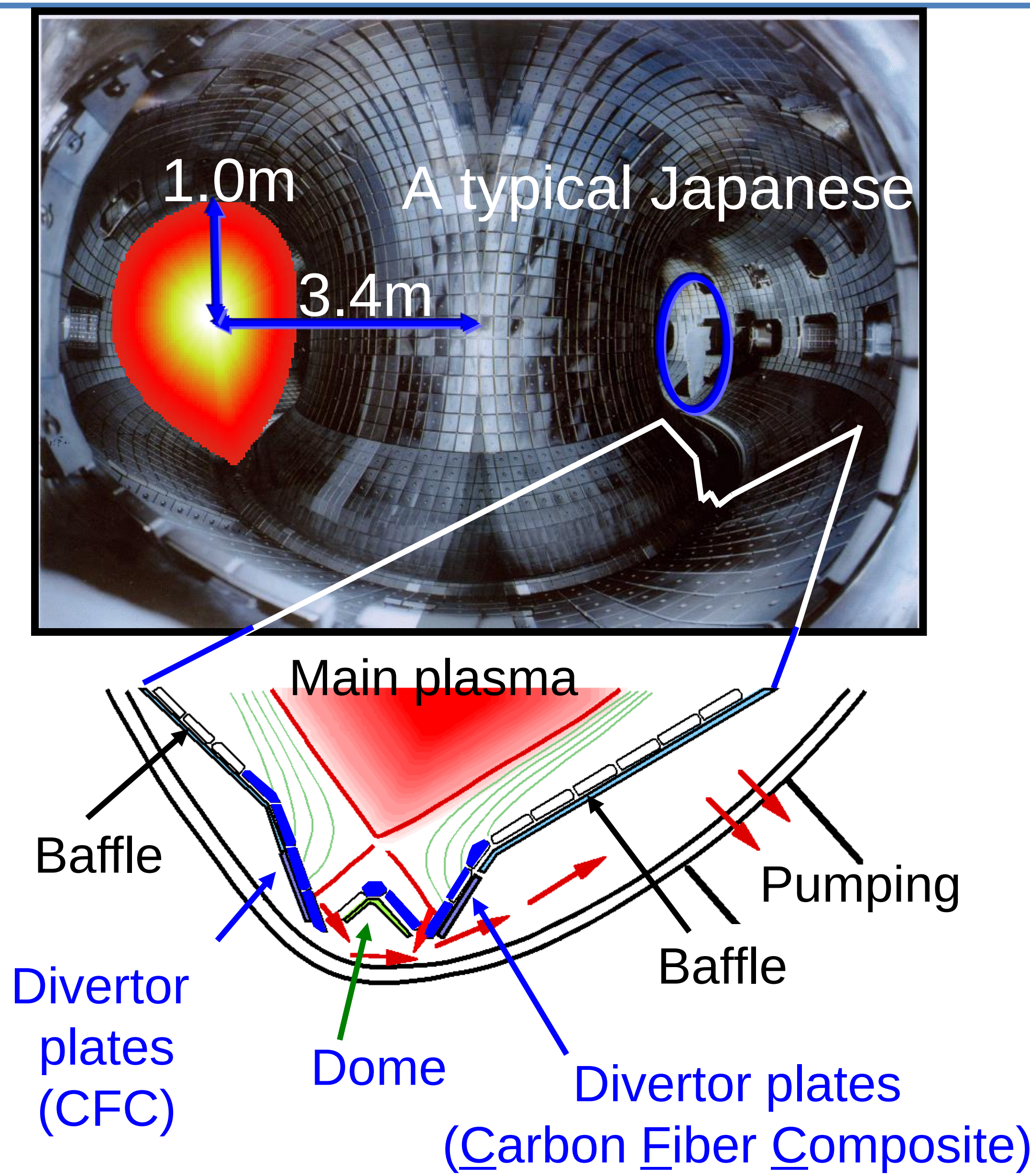
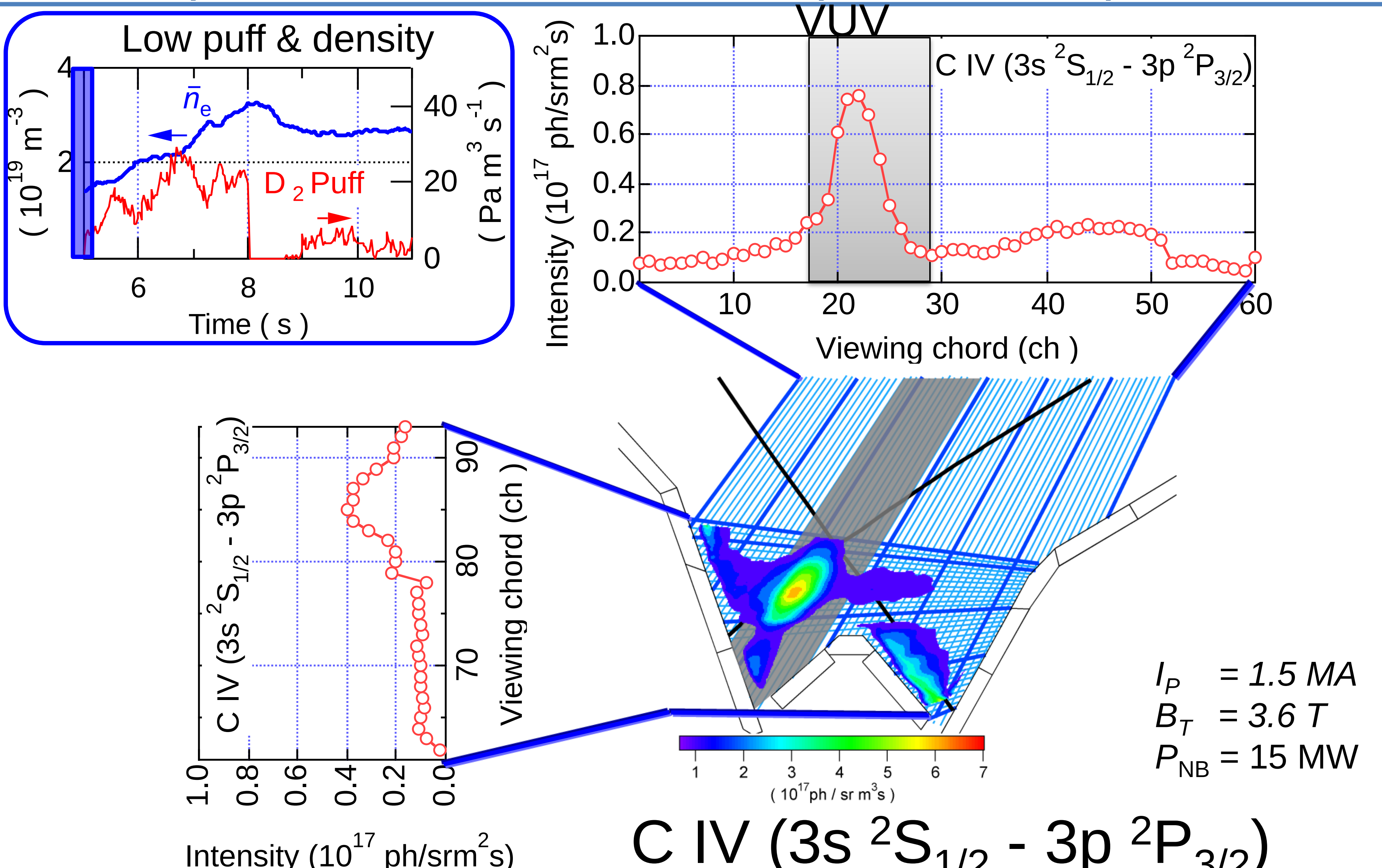
# JT-60U tokamak




- Plasma current: < 2.5 MA
- Toroidal Magnetic field: < 4.1 T
- Discharge duration: < 65 s
- Heating
  ( Neutral Beam )< 25 MW
  ( Waves) < 8 MW

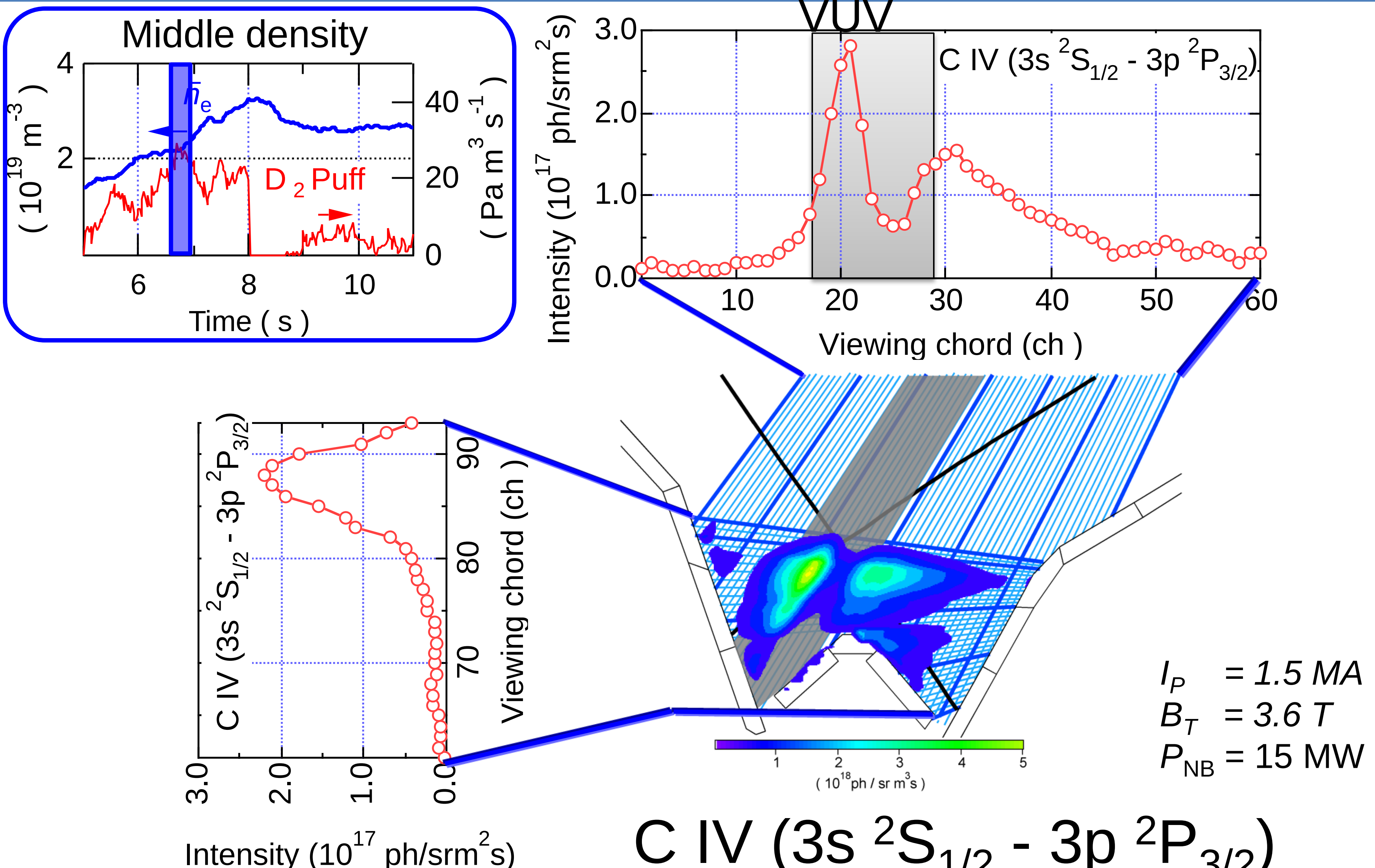
# At low gas puffing (low density): CIV peak between inner strike point and X point




$I_P$ = 1.5 MA
$B_T$ = 3.6 T
$P_{NB}$ = 15 MW

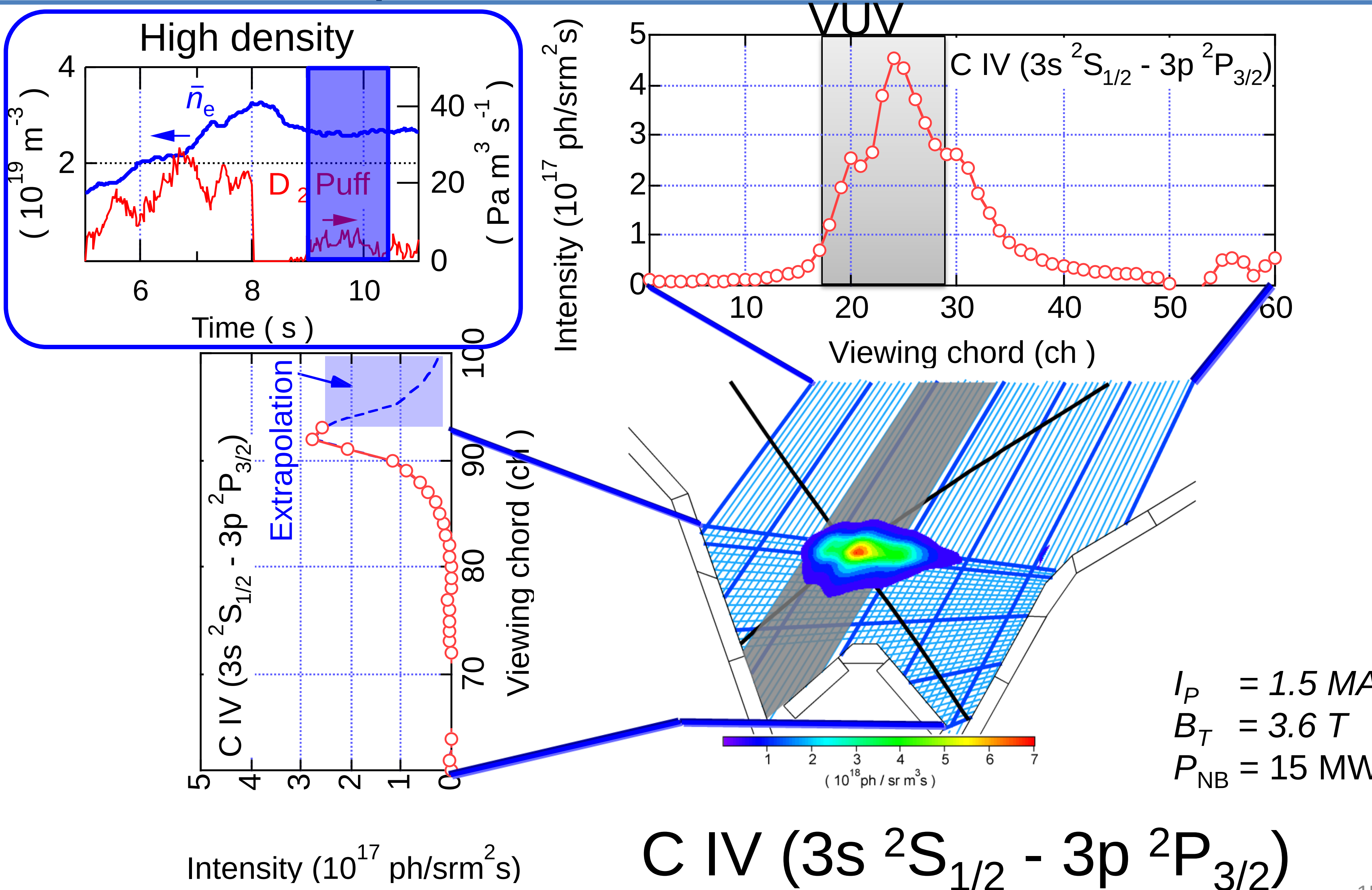
C IV (3s $^2S_{1/2}$ - 3p $^2P_{3/2}$)

# At middle density: Two C IV peaks near X point

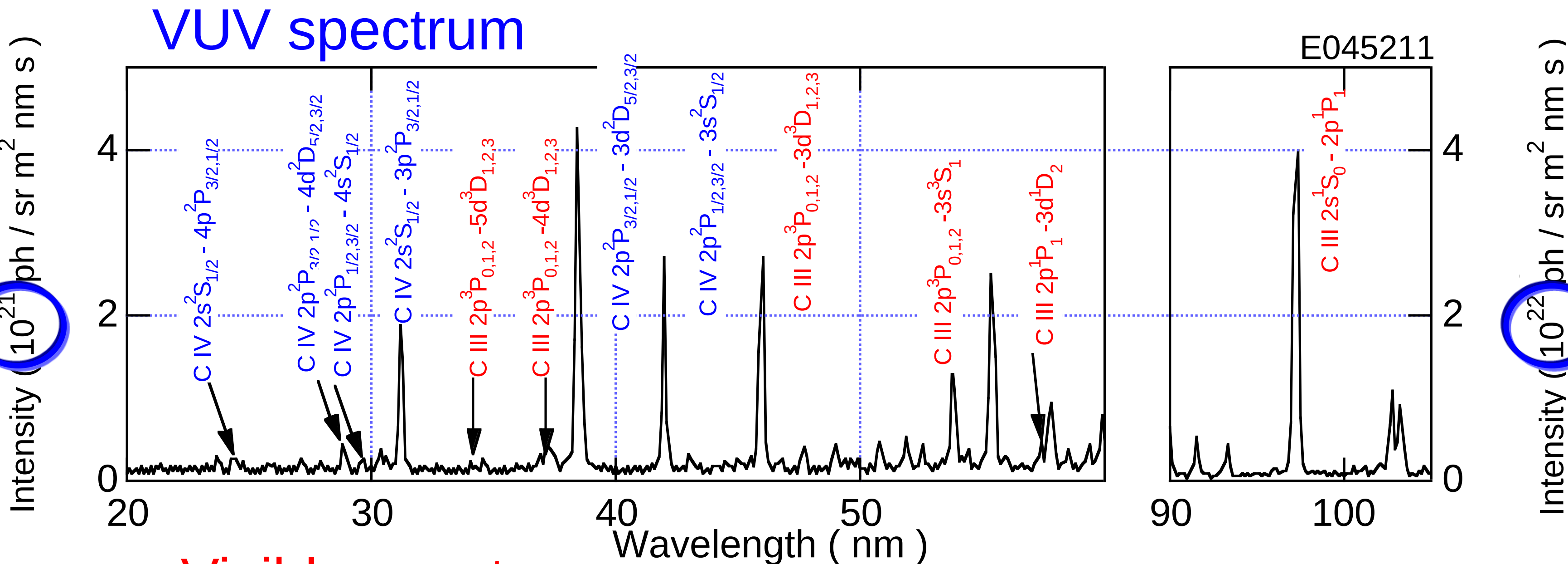


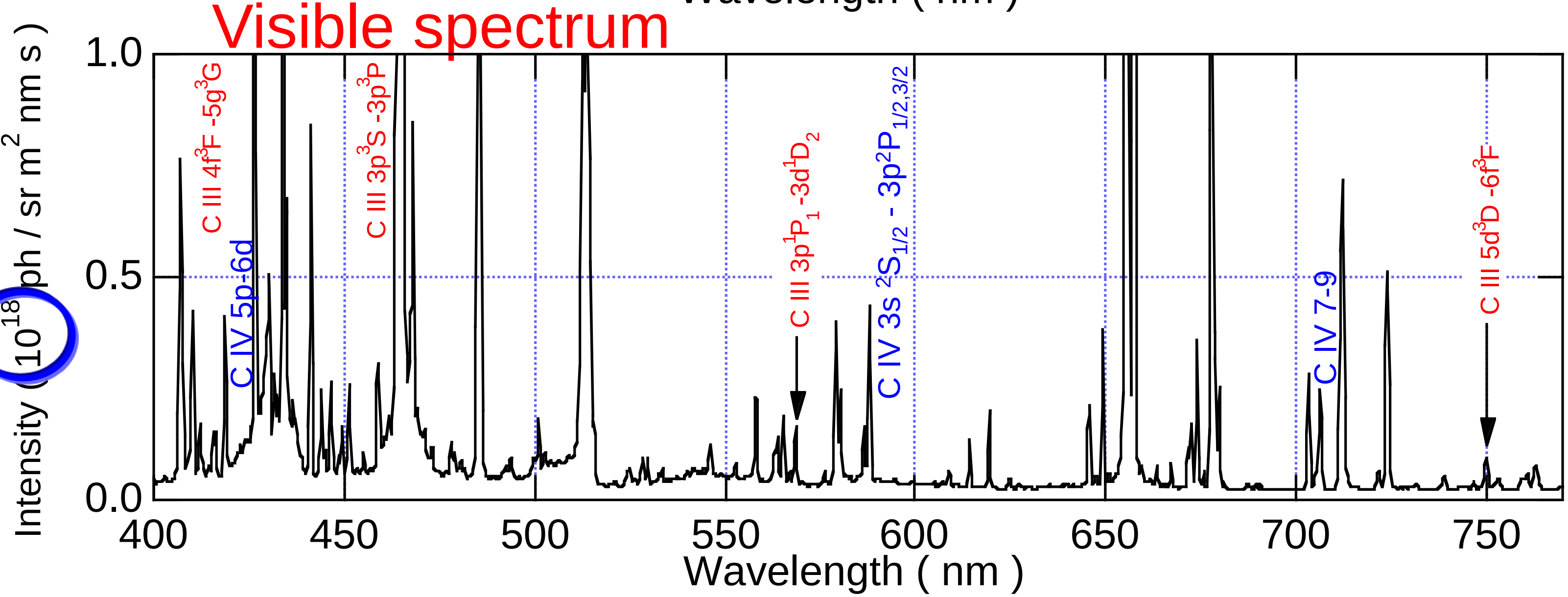

C IV (3s $^2S_{1/2}$ - 3p $^2P_{3/2}$)

# During high radiation: Peak at X point

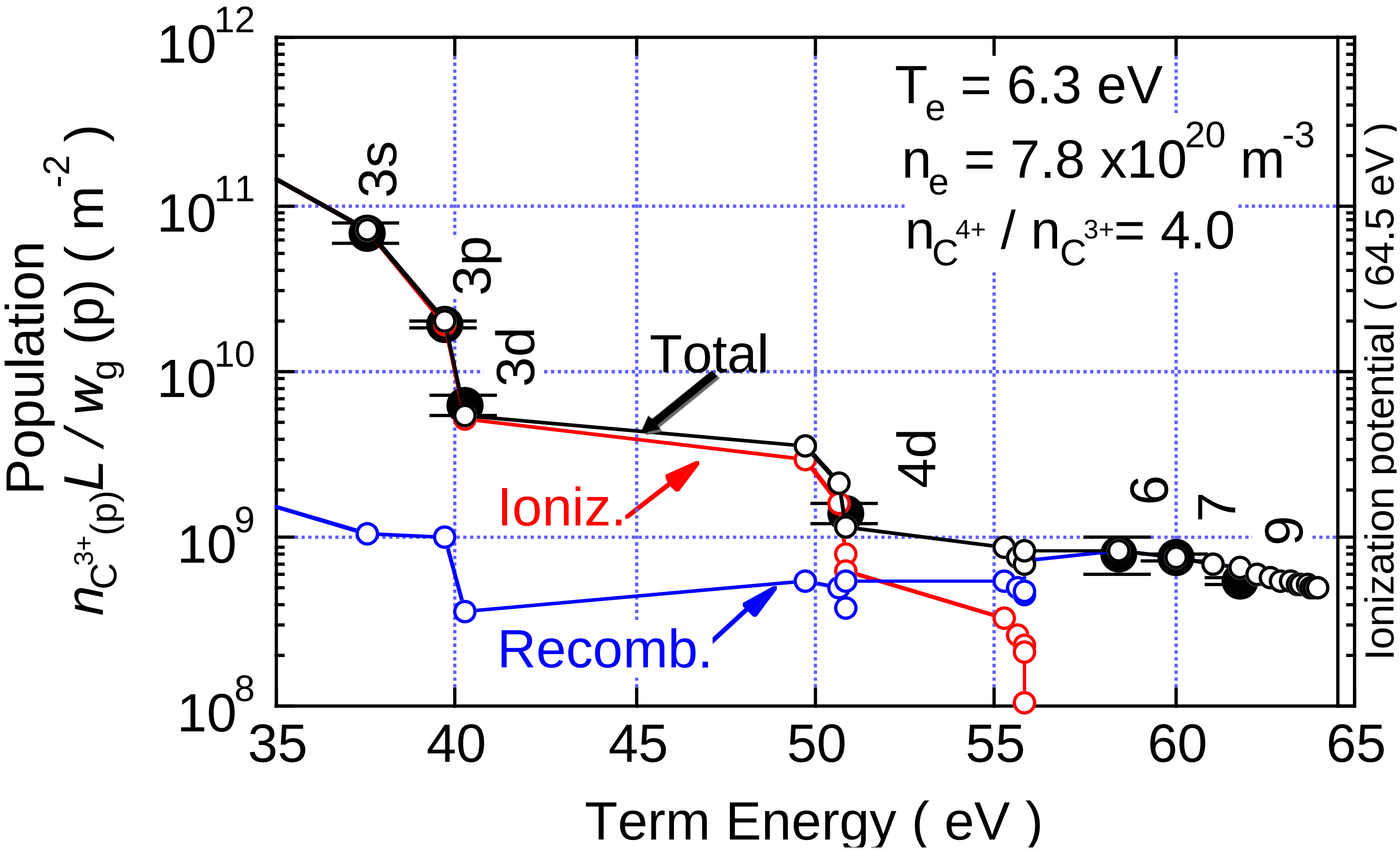


# C IV and C III lines observed in VUV and visible range



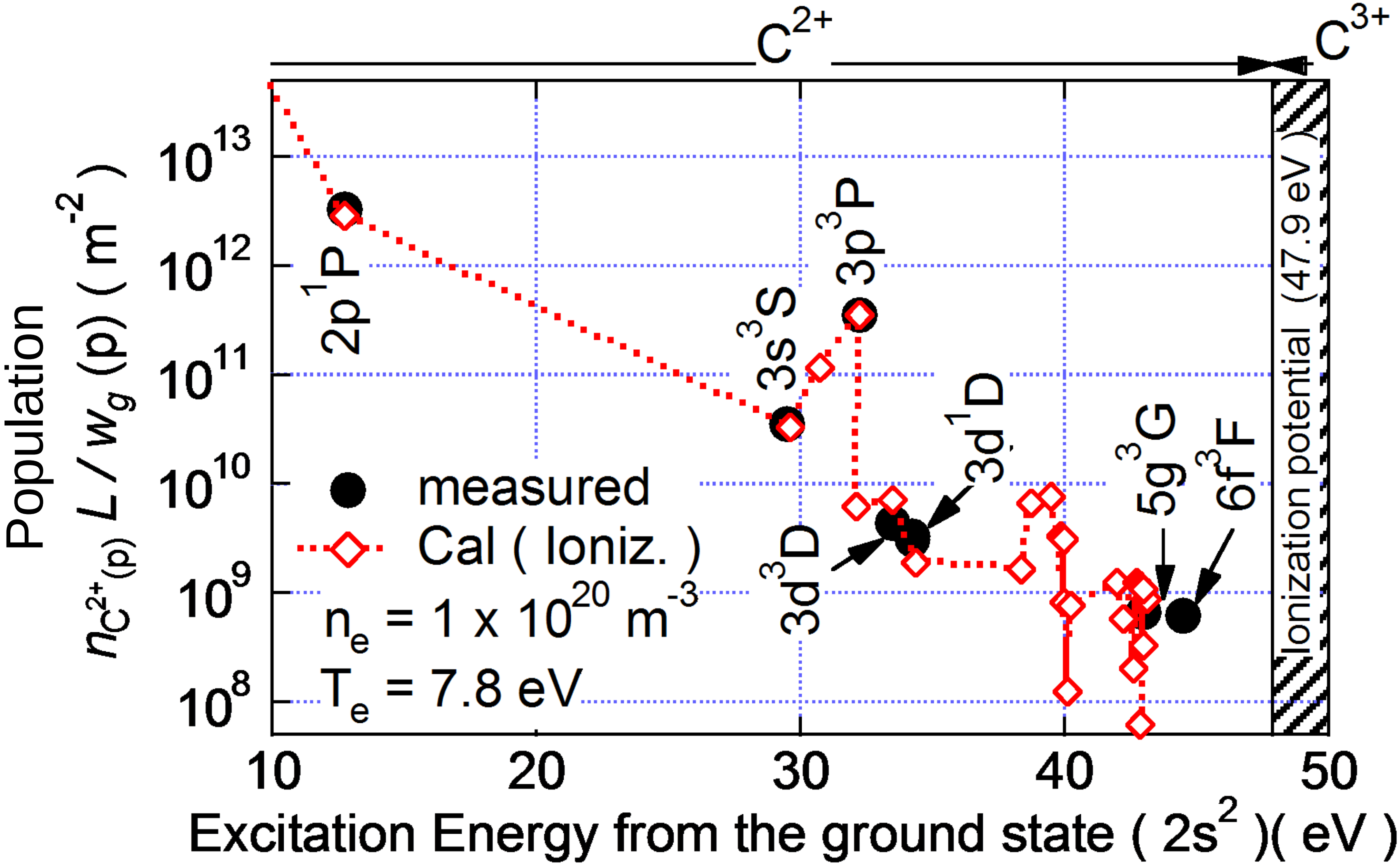



# C IV($C^{3+}$): n < 5 : Ionizing component
# n ≥ 5 : Recombining component



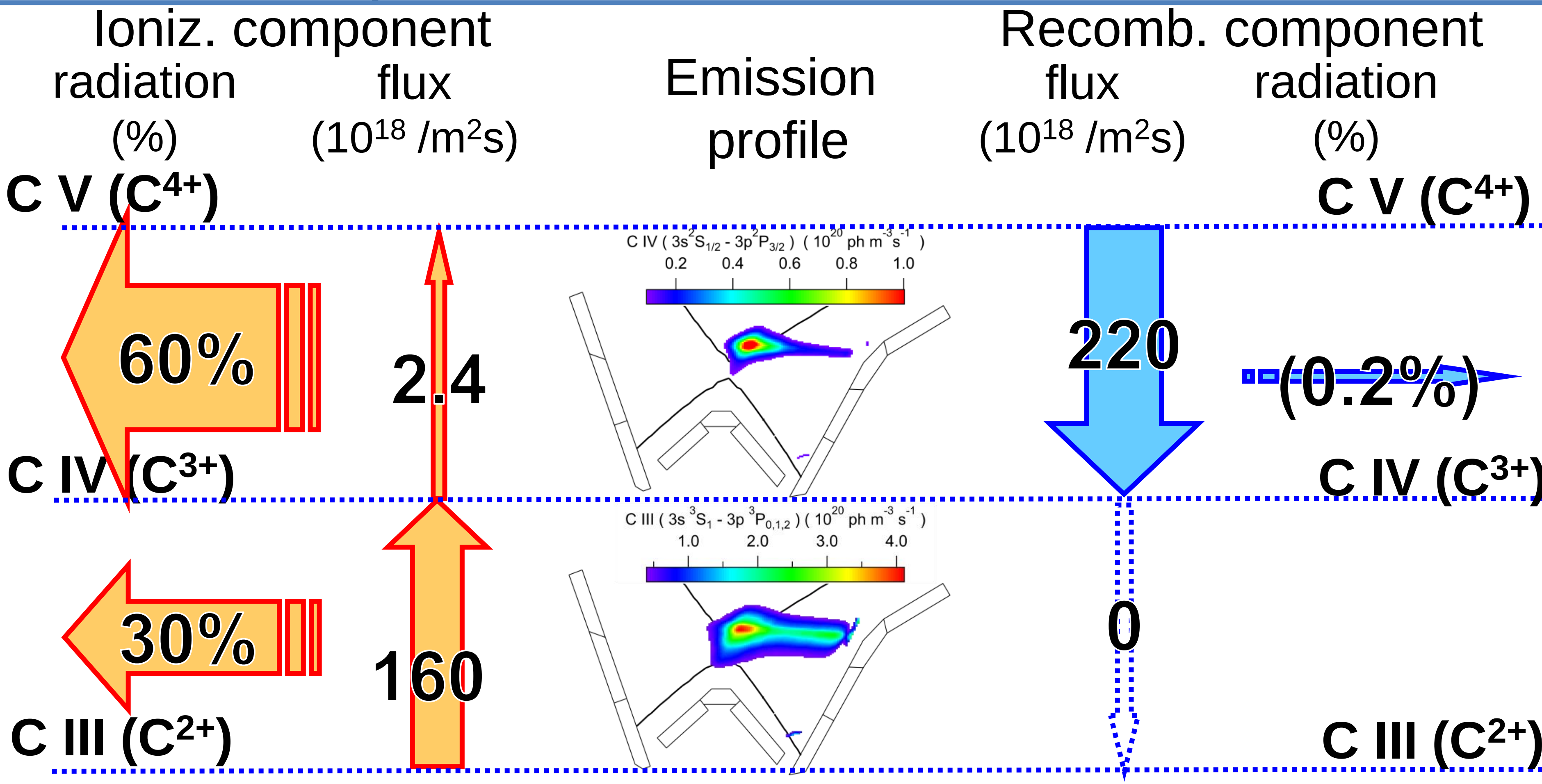

**Volume recombination of $C^{4+}$ is observed for the first time**

# C III ($C^{2+}$): Ionization component dominates




**No recombination of $C^{3+}$ is observed for unlike $C^{4+}$**

# Ionization/recombination flows and radiative power



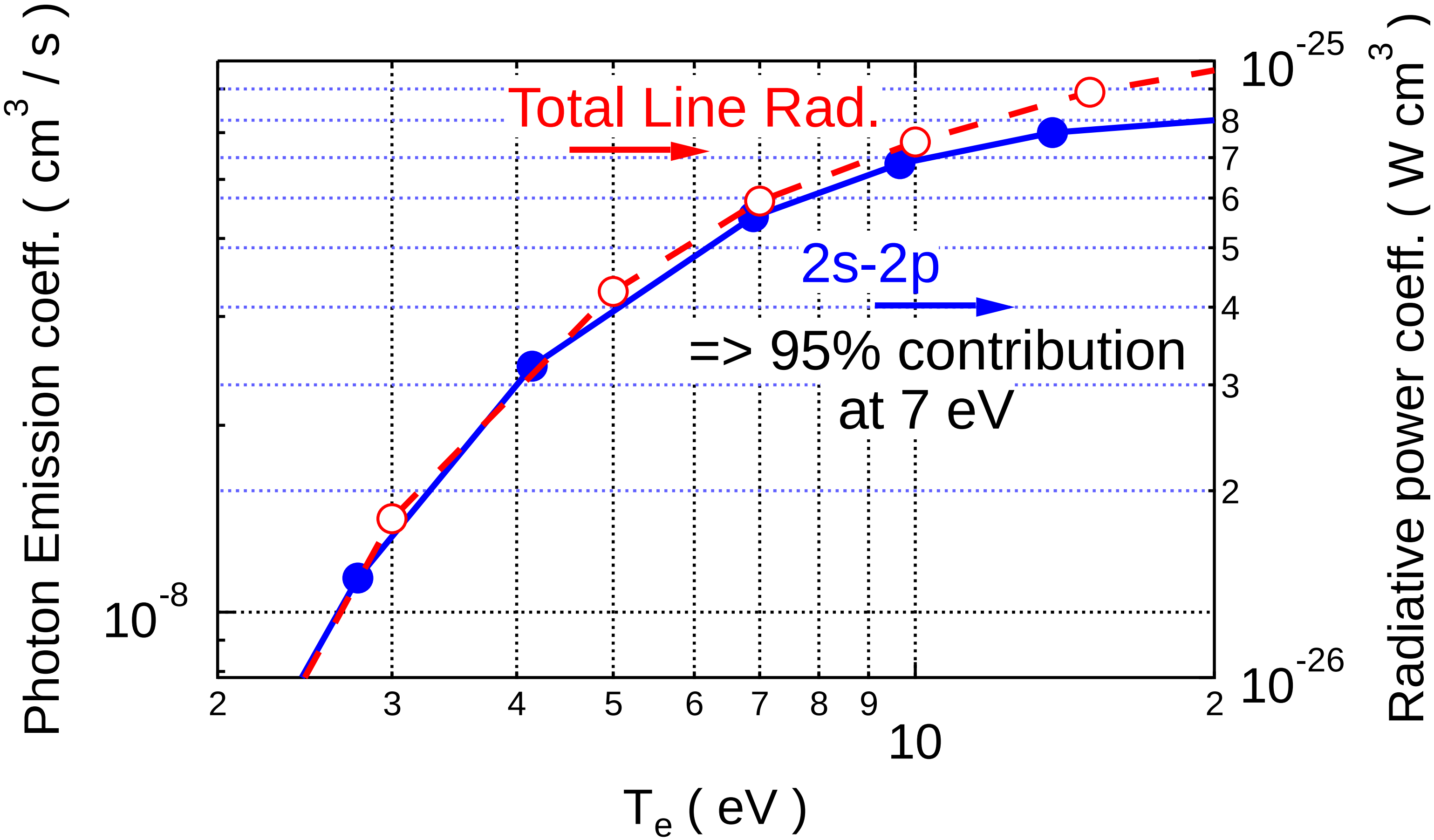

✓ $C^{3+}$ is the biggest radiator.

✓ $C^{3+}$ is produced by ionization of $C^{2+}$ and recombination of $C^{4+}$ .

⇒ Recombination converts inefficient radiator, $C^{4+}$ into efficient radiator, $C^{3+}$.

Recombination of $Ne^{8+}$ was observed in Ne seeded plasmas.

# Which line of C IV contributes the most to the total radiation?

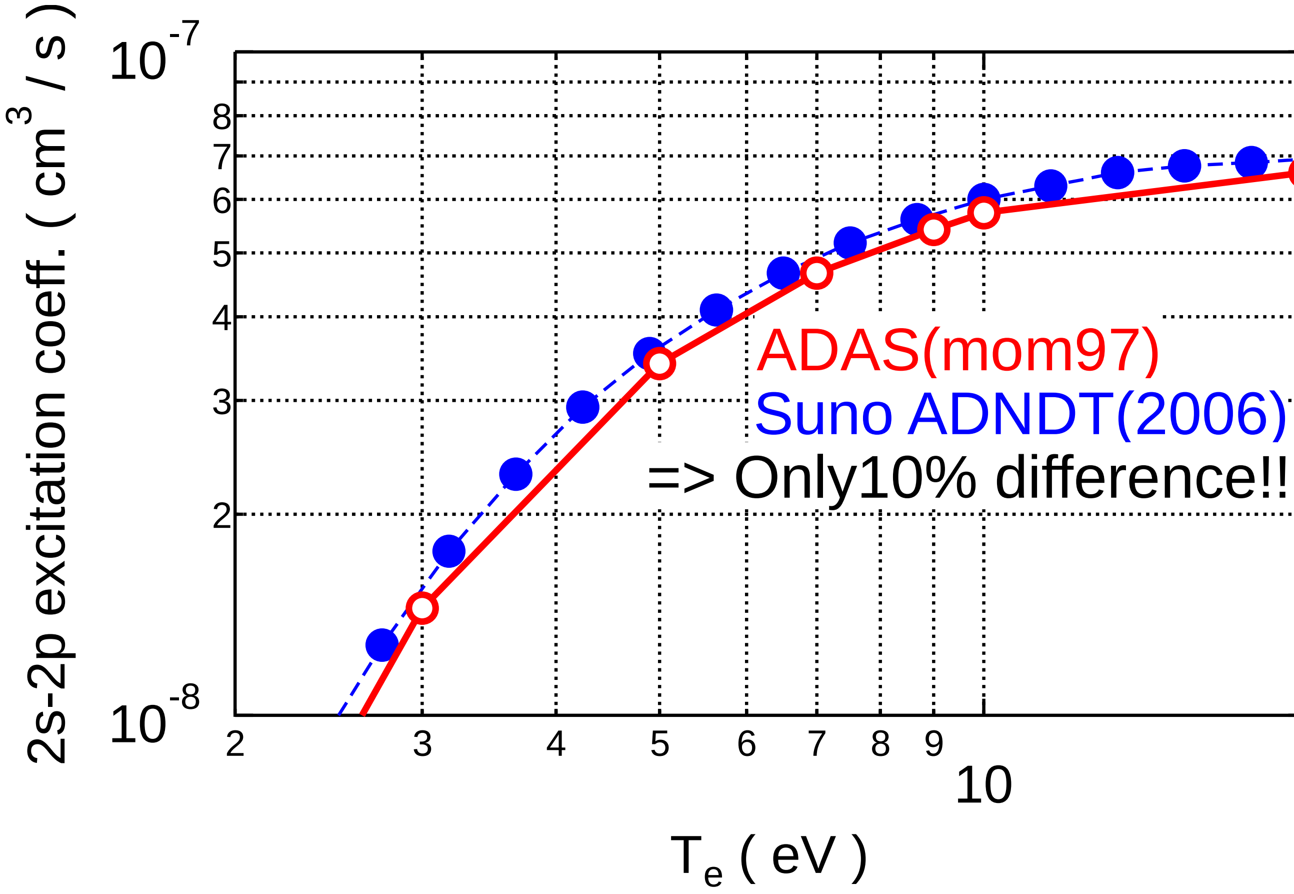



Collisional-Radiative model => Photon Emission Coefficient
x photon energy
=> Radiative power Coefficient (2s-2p,,,,& total )

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 ~ Collisional excitation rate from 2s to 2p, $C_e$(2s, 2p)

⇒ Uncertainty of $C_e$(2s, 2p) ~ equal to that of the Photon Emission coef.

~ 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