P7-12

Development of Heat Flow Measurement Using Thermal Probe Method in Divertor Simulator MAP-II

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16th International Toki Conference @ Ceratopia Toki

Abstract

We are improving the measurement method of the heat flow (*Q*)– the sheath potential (*V*) characteristic for the thermal probe method.

The method of biasing the thermal probe

Time constant to achieve the steady state is 123 ± 18 sec.

The following measurement method is applicable.

1. **change the bias in a stepwise manner**
2. **deduce the temperature at the steady state by a functional fit of the temperature variation.**

Q-V curve and the analysis for T_i and R_E

Q_{exp} from the temperature gradient has the V-dependent difference (Q_{dif}) compared to Q_{cal} from the calculation using the sheath theory.

The V dependence of Q_{dif} enables us to analyze T_i and R_E.

→ **The error of T_i is large caused by the error in Q_{exp}.**

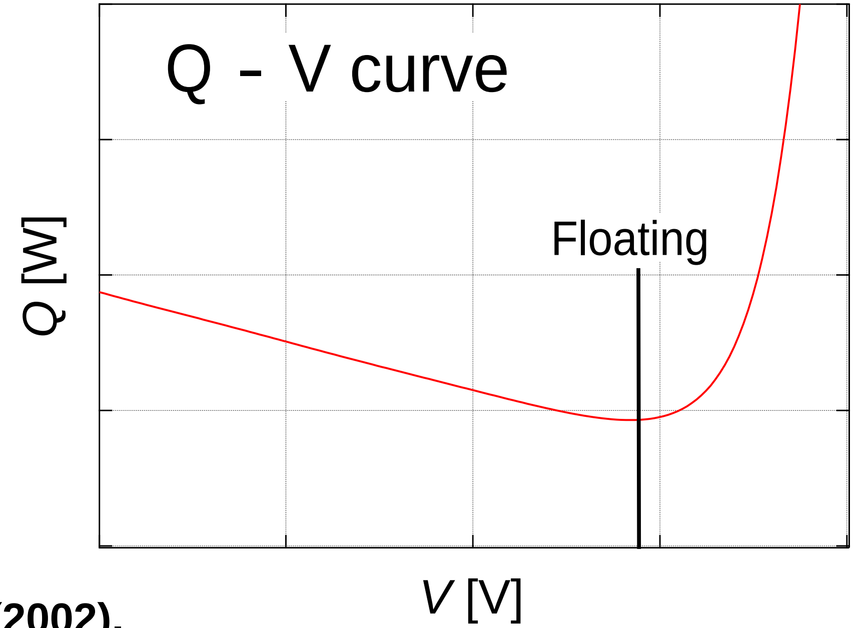
Reliable in-situ calibration of the heat flow is required.

Background

The thermal probe method uses the heat flow (*Q*) – the sheath potential (*V*) characteristic in order to deduce the various plasma parameters.

-- negative ion density [1]

-- ion temperature [2,3]



[1] E. Stamate *et al.*, Appl. Phys. Lett. 80, 3066 (2002).
[2] H. Matsuura and K. Michimoto, Contrib. Plasma Phys. 44, 677 (2004).
[3] K. Kurihara and S. Kado *et al.*, Trans. Fusion Sci. Tech. (2007) *in press*

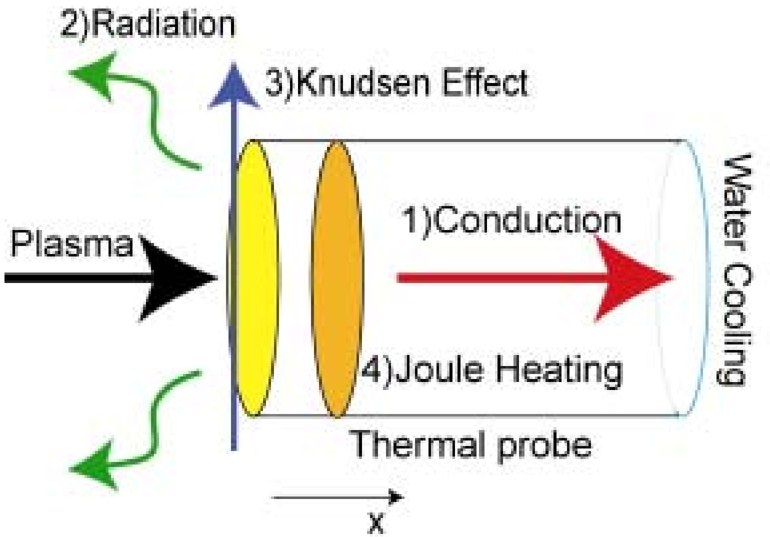
The time resolution of the thermal probe method is poor in nature because of the long transient time in thermal phenomena.

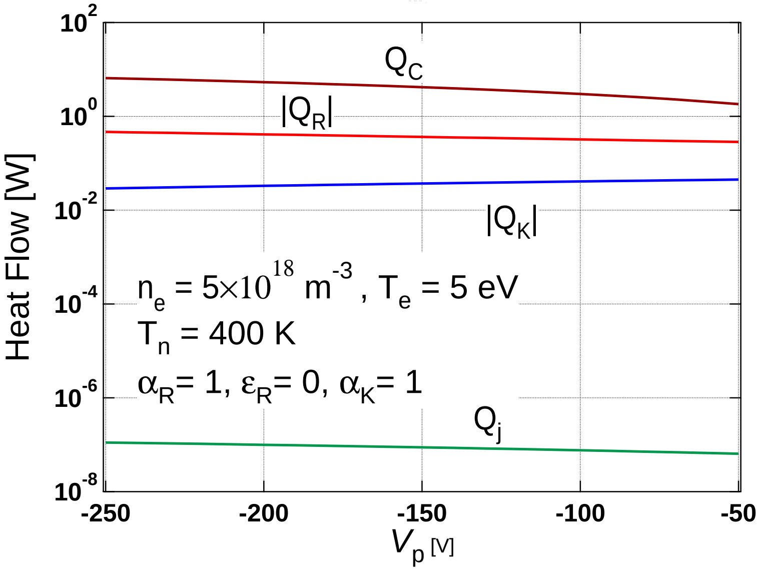
It is necessary to improve the time response of the thermal probe.

- **The measurement of the time constant to achieve the steady state**
- **The improvement in the *Q*-*V* characteristic measurement methods**

Heat transfer in thermal probe

Heat transfer in the thermal probe





1)Heat Conduction

$$Q_C = -S\kappa \left.\frac{dT_p}{dx}\right|_{x=Surface}$$

κ: thermal conductivity

2)Heat Radiation

$$Q_R = S\sigma\left(\varepsilon_R T_p^{\,4} - \alpha_R T_n^{\,4}\right)$$

ε_R: emissivity **α_R: absorptivity**

3)Knudsen Effect

$$Q_K = Sp\frac{1}{4}\frac{\gamma+1}{4(\gamma-1)}\sqrt{\frac{8kT_n}{\pi m_i}}\alpha_K\left|\frac{T_p}{T_n}-1\right|$$

α_K: Accommodation coefficient

4)Joule heating

$$Q_j = \rho\frac{L}{S}I_p^{\,2}$$

Heat conduction is dominant.

Temperature variation

1-dimensional heat equation

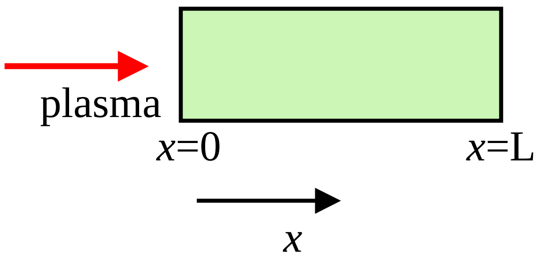
$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

α: the thermal diffusivity

under the boundary condition

$$\left.\partial T / \partial x\right|_{x=0} = \text{const.}$$

$$\left.\partial T / \partial t\right|_{x=L} = 0$$



Considering the sign of $\partial T / \partial t$ **doesn't change with any** x

$$T(x_1, t) = T(x_1, \infty) + \{T(x_1, 0) - T(x_1, \infty)\} \exp\left(-\frac{t}{\tau}\right)$$

where

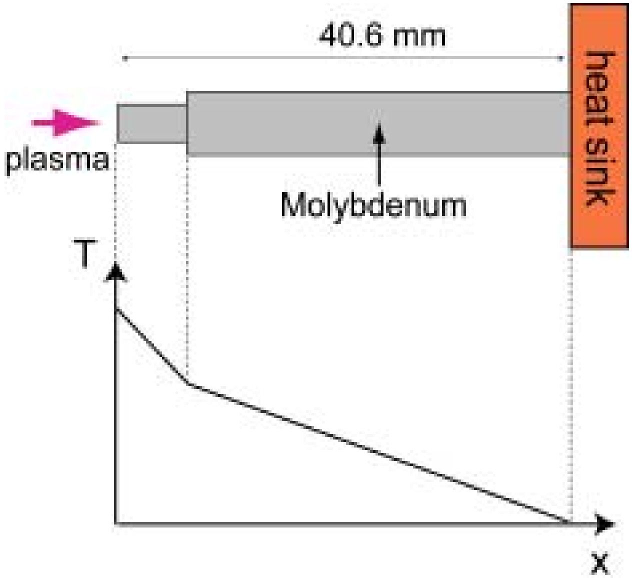
x_1: one point in the thermal probe, τ: the time constant to archive the steady state

$$\tau = \frac{1}{\alpha} \frac{4L^2}{\pi^2}$$

(τ depends only on the probe length for a given material)

Q-V characteristic

Since the heat conduction is dominant in the thermal probe, $Q(V)$ can be written as



$$Q(V) = -\kappa \frac{\Delta T(x, \infty, V)}{\Delta x} S$$

From the sheath theory [1], Q can be written as

$$Q(V) = \underline{I_{\mathrm{is}}(V)} \times \left[\left\{ \underline{2T_{\mathrm{i}}} \, \underline{-V} \right\} (1 - R_{\mathrm{E}}) + \underline{E_{\mathrm{rec}}} \right] + \left\{ \underline{I_{\mathrm{p}}(V) - I_{\mathrm{is}}(V)} \right\} \times 2T_{\mathrm{e}}$$

Ion current | **Thermal motion** | **Acceleration by sheath** | **recombination** | **Electron current**

I_{is}: ion saturation current (measurement value)

I_p: Probe current (Electron current + Ion current)

V : Sheath potential

R_E: energy reflection coefficient (ALADDIN database [2])

E_{rec}: recombination energy (constant)

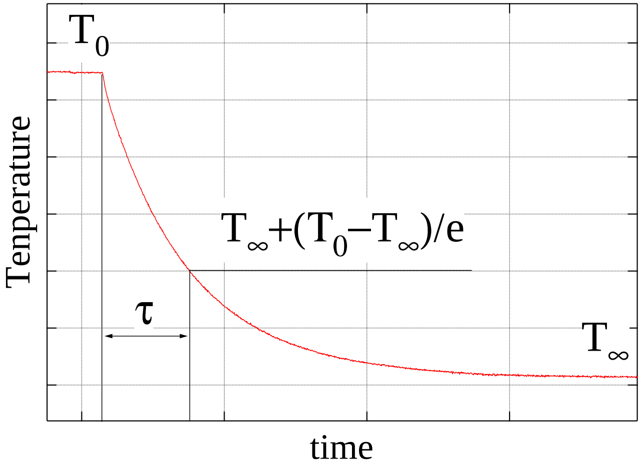
[1] P.C. Stangeby *Physics of plasma-Wall Interactions in Controlled Fusion*, eds. D.E. Post and R. Behrisch (Plenum Press, New York, 1984) p. 41.

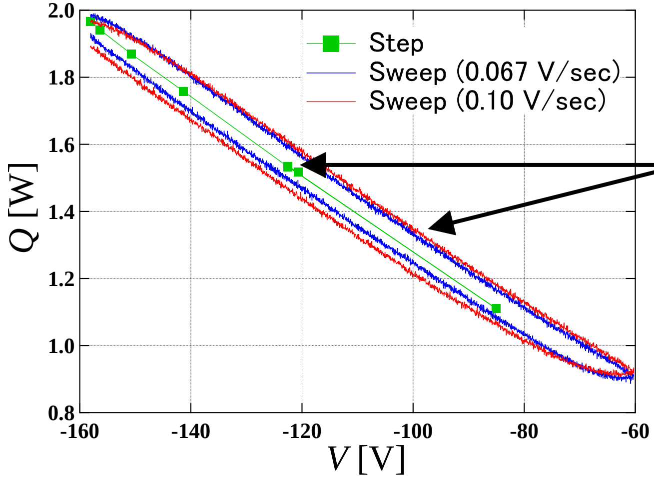
[2] IAEA AMDIS ALADDIN database

http://www-amdis.iaea.org/ALADDIN/

Q-*V* characteristic measurement

Two methods for the *Q*-*V* characteristic measurement





The results of the method 2 don't agree with those of the method 1.

1. Changing the bias in a stepwise manner: $T(x,\infty)$ is obtained by fitting.

- **The temperature at the transient state is measured.**
- **Only finite data points can be obtained.**

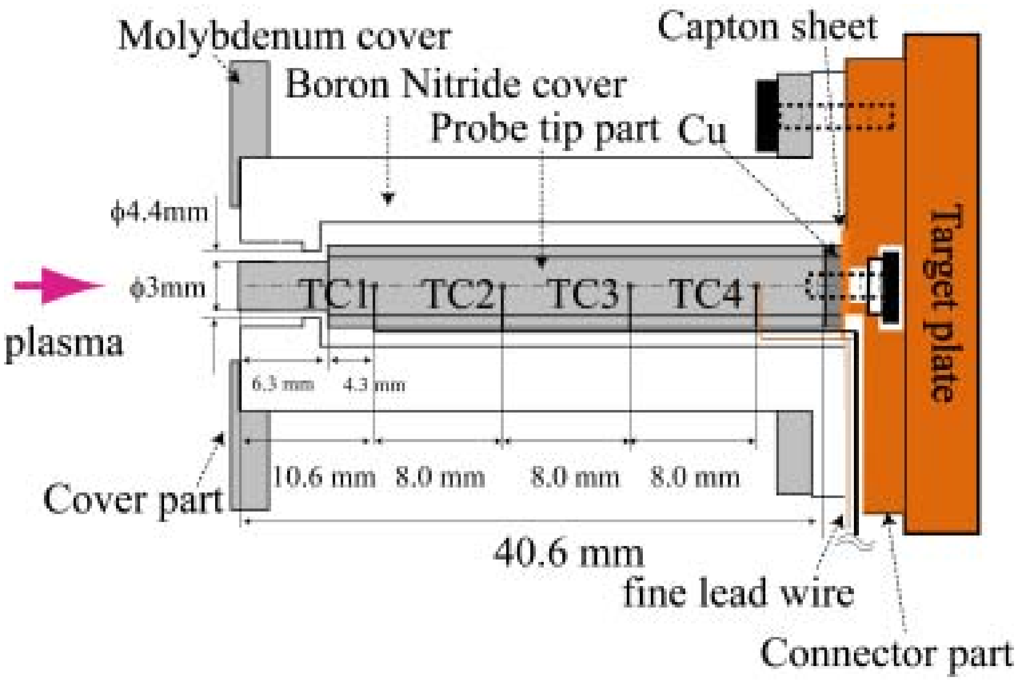
⇨ **This improve the time response**

2. Sweeping the bias continuously: $T(x,\infty)$ is directly measured.

- **Continuous *Q*-*V* curve can be obtained. (reliable analysis)**
- **If the sweeping speed is fast against the heat transfer phenomena, the temperature at the steady state is not measured.**

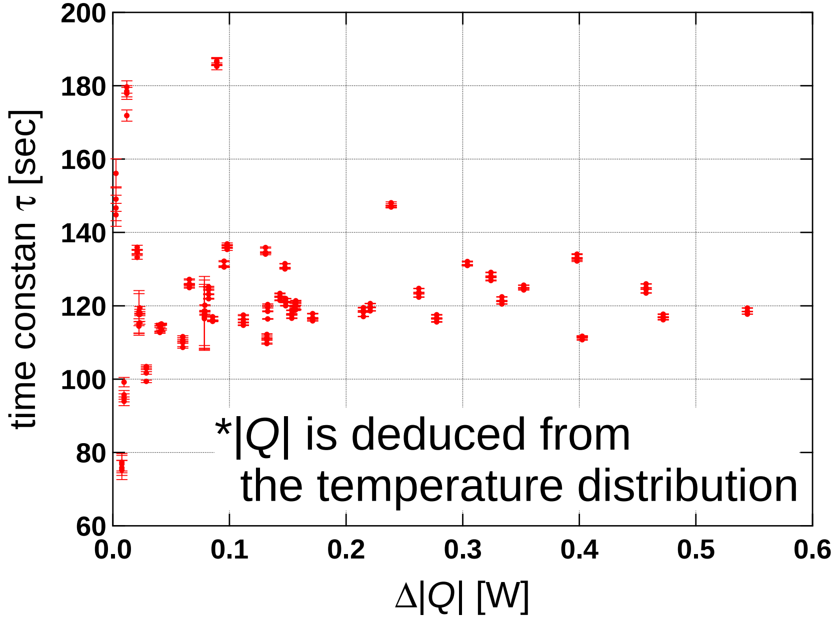
➡ **The method 1 is more applicable than the method 2 under the long time constant (~125 s under our condition).**

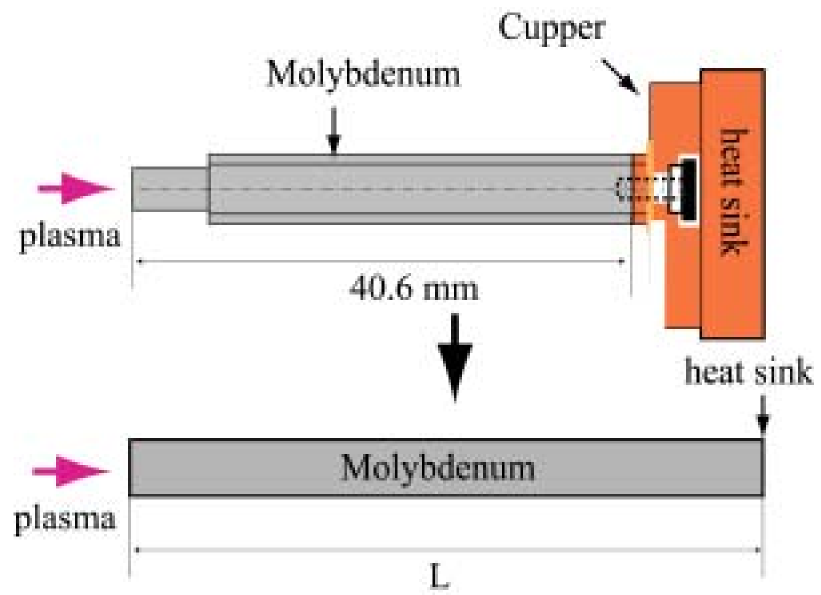
Apparatus - thermal probe -



- The probe tip is made of Mo（3 mmϕ (Left part), 5 mmϕ (Right part), 40.6 mm$L$）.
- The thermal probe is equipped with four K type thermo-couples for the temperature gradient measurement and with a fine lead wire for biasing the thermal probe as well as the probe current measurement.
- The Q-V characteristic and I-V characteristic can be obtained simultaneously.
- The probe tip is insulated from both Mo cap and Cu heat sink using an boron nitride cover and double capton sheets, respectively.
- Cu target plate is cooled by an incubator and two external coolant tubes.

Time constant and Virtual probe 1





The time constant is independent of Δ|*Q*|. τ is 123 ± 18 sec.

The deviation of τ becomes small for Δ|*Q*| > 0.1 W

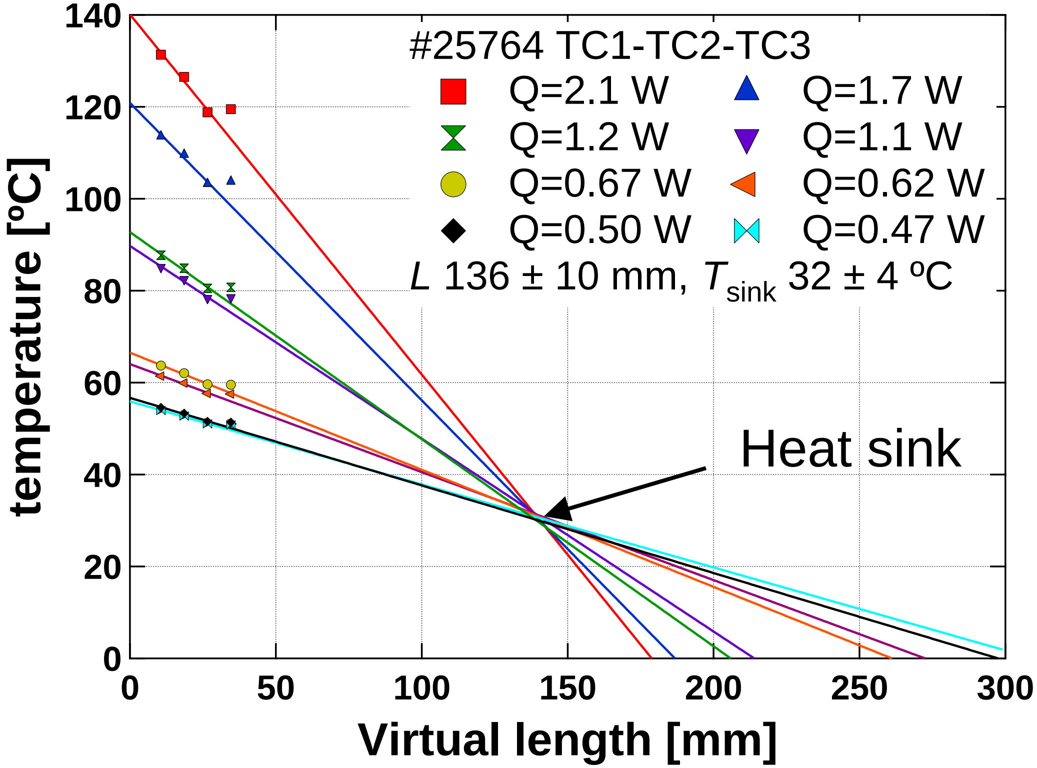
The length of the real probe is 40.6 mm (Mo part).

If the right edge is heat sink, τ = 12 sec from $\tau\ [s] = 7.55\times10^{9} L^{2}\ [\mathrm{mm}]$

The practical probe length should be interpreted as that of an equivalent probe made of the uniform material

The length of the virtual probe *L* = 128 ± 49 mm from $L\ [\mathrm{mm}] = 1.15\times10\sqrt{\tau}$

Virtual probe 2



*Thermo-couple = TC

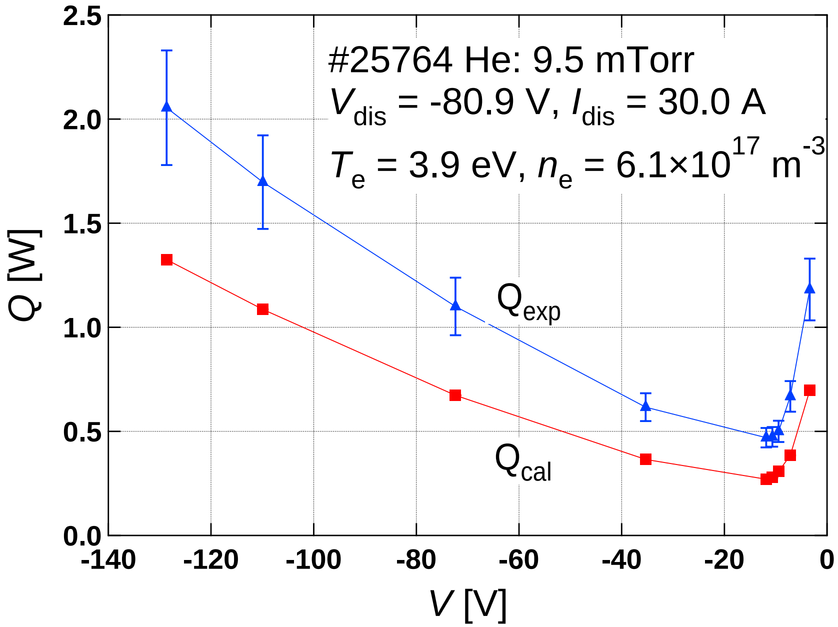
TC set	L [mm]	T_{sink} [ºC]
12	177 ± 14	30 ± 5
13	135 ± 10	32 ± 4
14	218 ± 14	28 ± 4
23	114 ± 7	33 ± 4
24	245 ± 12	26 ± 3
123	136 ± 10	32 ± 4
124	221 ± 14	28 ± 4
1234	196 ± 13	29 ± 4
τ	123 ± 18	

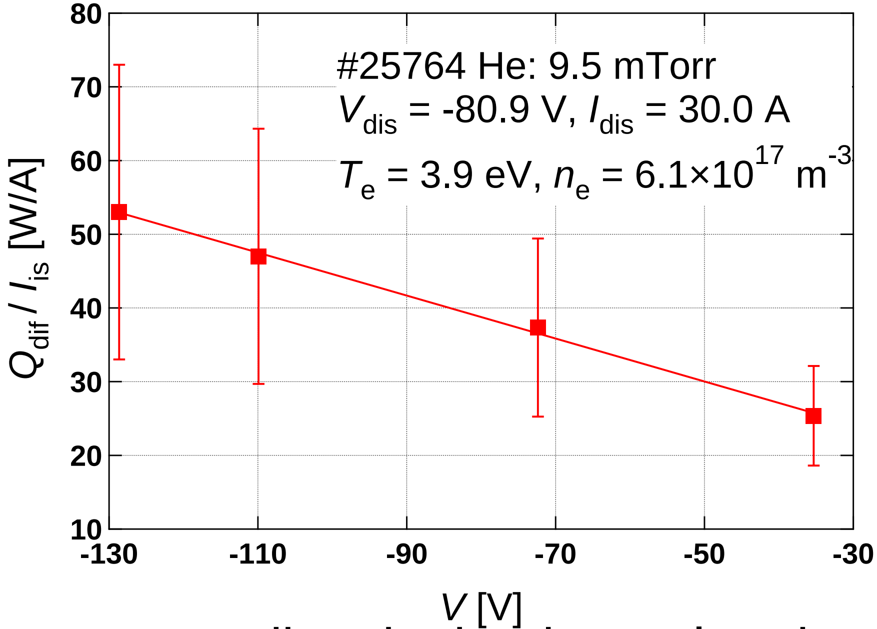
***L* from the TC set except TC4 has good agreement with that from τ.**

We choose the set of TC1-TC2-TC3 because the value deduced from 3TCs is more reliable than that from 2 TCs.

*The errors are deduced from the means of all cross point, not including the error of the cross point.

Q-V characteristic and T_i





Q_{exp}: heat flow deduced from the temperature gradient in the thermal probe

Temperature distribution of TC1-TC2-TC3 is adopted.

Q_{cal}: heat flow deduced from the sheath theory using experimental data of I_p.

I_p: measured by thermal probe, R_E: interpolated from the database, T_i: assuming T_i = 0.

Between Q_{exp} and Q_{cal}, there is the V-dependent difference Q_{dif} .

Q_{dif} / I_{is} has the linear dependence on V.

***The process of Q_{dif} is now under investigation.**

T_i and R_E can be deduced assuming this dependence.

The procedures to deduce T_i and R_E

1. Assuming Q_dif / $I_\mathrm{is.}$ is linear to *V* in the ion dominant region, the slope *a* and intercept *b* ($Q_\mathrm{dif} / I_\mathrm{is} = a \times V + b$) can be deduced from Q_dif / I_is – *V*.

Adding to the contribution of Q_dif, we have

$$Q_{\exp} = I\left\{\left(2T_i - V\right)\left(1 - R_E\right) + E_{rec}\right\} + Q_{dif}$$

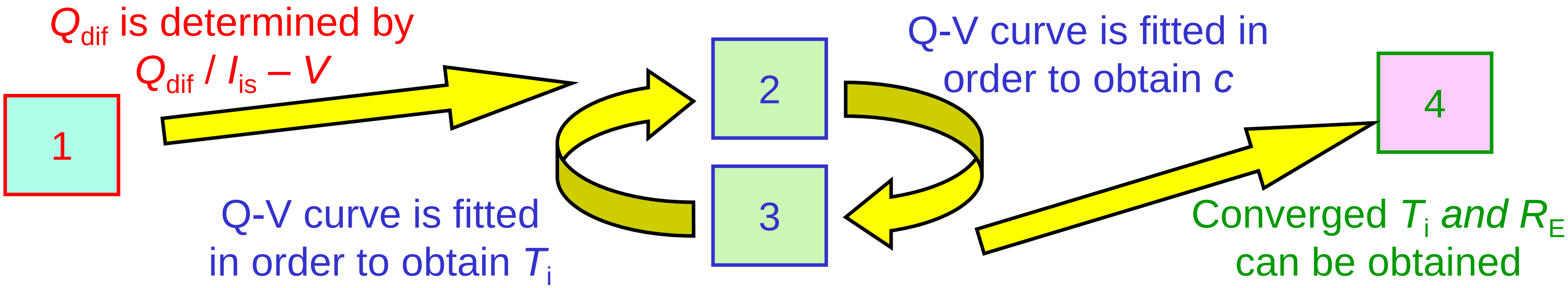
$$= I\left\{\left(2T_i - V\right)\left(1 - cR_E\right) + E_{rec} + aV + b\right\}$$

**c* is the calibration factor for R_E, introduced to make use of the *V* dependence of R_E.

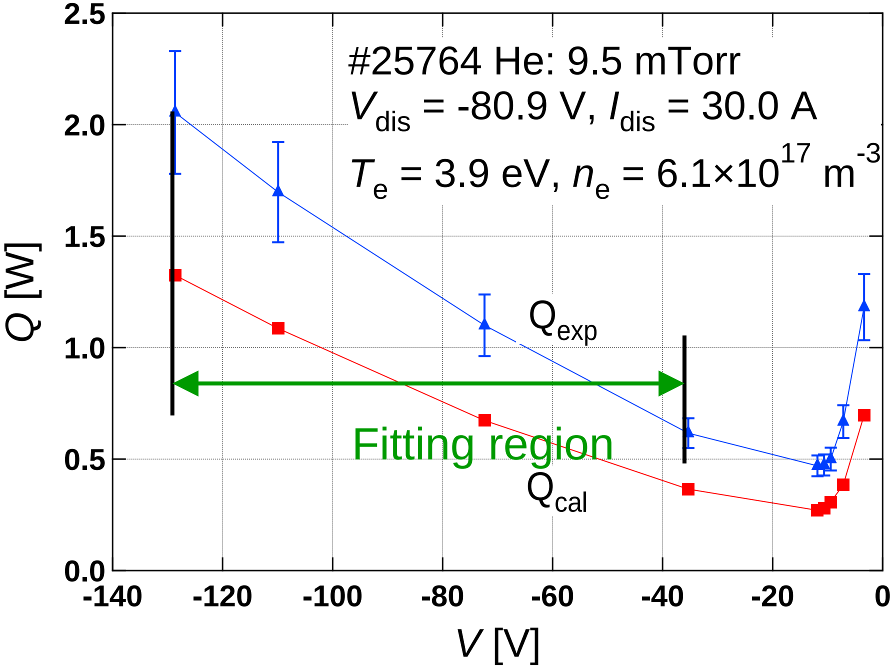
2. *Q*-*V* curve is fitted to the equation in order to obtain *c* (T_i is fixed).

3. *Q*-*V* curve is fitted again in order to obtain T_i using *c* obtained in 2.

4. The procedures of 3 and 4 are repeated until T_i and *c* converge.



Error estimation of T_i



T_i and c obtained from the analysis in the fitting region.

T_i = 0.17 ± 41.6 eV

c = 1.0 ± 0.8

The error of T_i and c is too large.

This is because the large error in Q_{exp} influences those in a, b, c and T_i.

Without the error in I_{is} and V, δTi is written as

$$\delta T_i = \sqrt{\left(\frac{\partial Ti}{\partial Q_{\text{exp}}}\delta Q_{\text{exp}}\right)^2 + \left(\frac{\partial Ti}{\partial a}\delta a\right)^2 + \left(\frac{\partial Ti}{\partial b}\delta b\right)^2 + \left(\frac{\partial Ti}{\partial c}\delta c\right)^2}$$

	13 eV	**13 eV**	**19 eV**	**31 eV**	δT_i = 41.6 eV
1/10 of δQ_{exp} ⇒	**1.3 eV**	**1.6 eV**	**2.3 eV**	**3.6 eV**	δT_i = 4.8 eV

⇒ We have to improve the accuracy of the Q_{exp} for the reliable T_i.

Conclusion

We are improving the measurement method of the *Q*-*V* characteristic for the thermal probe method.

1) The time constant τ and the method of biasing the thermal probe

τ = 123 ± 18 s, and was independent of the $\Delta|Q|$.

→ The stepping method is more applicable than the sweeping method.

2) *Q*-*V* curve and the analysis for T_i

Q_{exp} has the difference Q_{dif} compared to Q_{cal}. The process of Q_{dif} is under investigation.

T_i and R_E can be analyzed by using the linear *V* dependence of Q_{dif} / I_{is}.

But the errors of T_i and *c* are too big because of the error of Q_{exp}.

→ We have to improve the accuracy of Q_{exp}.

<u>Future plan</u>

- **Reliable in-situ calibration of the heat flow**
- **Clarifying the process of the Q_{dif}**

***This work was supported in part by a NIFS Collaborative Research Program (NIFS04KOAB009) directed by the second author.**

Appendix -differential equation-

<u>Considering the sign of</u> $\partial T / \partial t$ <u>doesn't change with any</u> x

$$\left.\partial T / \partial t\right|_{x=L} = 0 \quad \Rightarrow \quad \cos(\lambda L) = 0$$

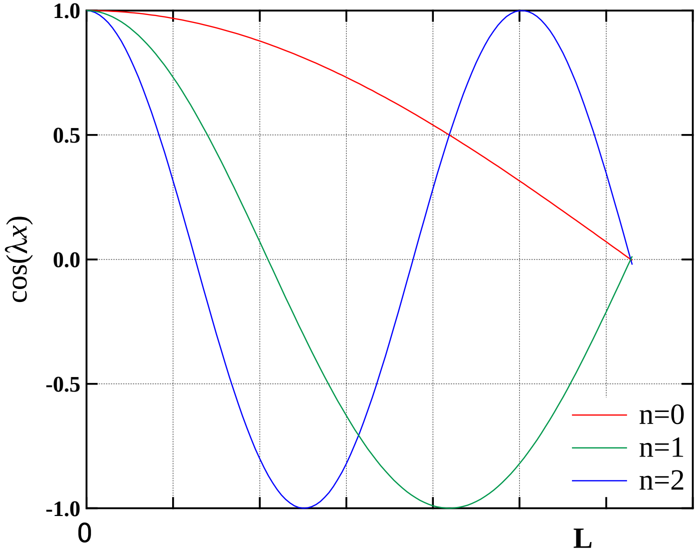
$$\Rightarrow \quad \lambda L = \frac{\pi}{2} + n\pi \quad (n \in \mathbf{N})$$

The sign of $\partial T / \partial t$ is determined by cos(λ*x*)

Considering the sign of $\partial T / \partial t$ doesn't change with any x

(The temperature always varies toward the *T*(x,∞))

⇒Only n=0 is satisfied with this condition.



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