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A direct digital control of temperature for the VENUS vertex chamber at TRISTAN

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Abstract

A trial to introduce the DDC (Direct Digital Control) system has been carried out in order to stabilize the temperature of the VENUS vertex chamber so as to obtain a spatial resolution better than $50\text{ }\mu\text{m}$. The temperature is controlled to within 0.1°C in the gas near to the chamber endplates.

1. Introduction

A vertex drift chamber[1] has been installed into the VENUS detector[2] at TRISTAN in order to make it possible to detect decay vertex points of fundamental particles such as c, b-quarks and τ -lepton. The vertex chamber is a cylindrical jet-type drift chamber, located at the center of the VENUS detector, and surrounded by other detectors, such as the trigger chamber and the central drift chamber, as shown in the cross-sectional view of Fig.1.

In an unsaturated gas, such as a mixed gas of CO_2 (92 %) and C_2H_6 (8 %), with which the vertex chamber is operated under a pressure of 3 atm, the drift velocity of an electron in the electric field depends on the temperature of the gas. It is necessary to keep the gas temperature stable to within 0.3°C during data-taking in order to obtain the spatial resolution of the particle tracks with a precision better than $50\text{ }\mu\text{m}$. However, the temperature of the chamber gas changes intensively with the beam status because the beam pipe with a hybrid structure of Be and stainless steel, which comprises a part of the pressure vessel of the vertex chamber, is affected by radiation and the wake field due to both electron and positron beams of TRISTAN. Unfortunately, the vertex chamber does not have any space to insert an apparatus for cooling the beam pipe. In addition, the vertex chamber has two heat sources at both aluminum endplates of the pressure vessel. Namely, one comprises

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12 sets of pre-amplifiers with a total wattage of 22 W, which are mounted on what we call the D-side endplate; the other 6 pairs of resistor chains with 26 W, are mounted on the C-side endplate.

Both aluminum endplates of the pressure vessel have heat exchangers with a water coolant in order to not only remove the heat due to the pre-amplifiers and the resistor chains from the chamber, but also to compensate for any temperature disturbance due to the radiation and wake field. The flow rate of the water coolant is controlled by the DDC method. The temperature around a point in the gas near to the endplate, where a thermo-sensor is also located, is controlled by a PI(Proportional and Integral)-control loop to within 0.1°C .

2. Temperature control system

The concept of the temperature control system is shown in Fig.2, and details concerning a heat exchanger comprising two copper pipes and an aluminum endplate of the C-side are given in Fig.3. Since both endplates are separated from each other by 80 cm, they are assumed to be thermally isolated. The water as a coolant comes from a reservoir, in which the water temperature is controlled, and to the endplates through two pairs of thermally insulated pipes for each side. Most of the control apparatus, including the water reservoir and the automatic valves, are situated far from the vertex chamber. The distance between them effectively reaches at least 10 m. Suppose that the flow rate of the water is simply 100 cc/min; in this case it takes as much as 10 min for the water, itself, to move from the valve to the chamber. The large dead time on the way makes the loop response diverge, even if the temperature of the water in the reservoir responds sufficiently quick. On the other hand, the flow rate of water immediately changes after the valve operation, since the water is a non-compressive fluid. As discussed in a later section, temperature control of the chamber gas must be done by adjusting just the flow rate of water.

The gas temperatures at two points near to each endplate are detected by two resistance thermo-sensors having stability of better than $\pm 0.1^{\circ}\text{C}$ [3]; their mean value is then calculated and compared with a reference temperature at the entrance of the computer in order to produce a driving signal for the valve. The driving signal is fed in parallel to two automatic valves located on the way to each endplate in the corresponding loop.

3. Block diagram and transfer functions

Since the wattage generated at both endplates is similar, the chamber has two pairs of the same kind of feedback control loops. In case of a system with a relatively large time constant, such as the vertex chamber, the temperature can be sufficiently controlled by only PI functions without the D (Differential) function[4]. Figure 4 shows a block diagram of a control loop with the PI-control system. If the computer directly shares both roles of P and I in the feedback loop (so called DDC), the over-all transfer function ($G(s)$) is described as a product of three terms, based on the assumption that the chamber has effectively just a simple transfer function with the 1st-order lag element (T_C), and that

there exists a slight mechanical dead time (L) at the valve in Fig.4. Namely,

$$G(s) = \{K_P(1 + \frac{1}{T_I s})\}\{K_V \exp(-Ls)\}\{\frac{K_C}{1 + T_C s}\}, \quad (1)$$

where, K_P is the proportional gain, T_I the integral time constant of the computer, K_V the valve gain including the DAC (Digital to Analog Converter) and VIC (Voltage to Current Converter) after the computer, and K_C the gain of the vertex chamber, including the thermo-sensor.

The transfer function expressed in the form of eq.(1) is called type I (or position type) based on the degree of the denominator[5, 6]. The loop responds perfectly for a step input without a position-error, since

$$\lim_{s \rightarrow 0} \{s \frac{1}{1 + G(s)} \frac{1}{s}\} = 0.$$

This loop is also practical, except for a short time during the transition, although the velocity error remains for a ramp input, as the following equation shows:

$$\lim_{s \rightarrow 0} \{s \frac{1}{1 + G(s)} \frac{1}{s^2}\} = \frac{T_I}{K},$$

where K is the product of K_P , K_V and K_C .

(1) Valve gain (K_V)

Generally, a valve used as a regulator in a loop is often of the equal-percent type. An automatic equal-percent valve has been adopted for the present purpose[7]. The valve property corresponding to the output voltage (dv) from the computer to the DAC is in differential form,

$$\frac{dq}{q} = A_V dv,$$

where q is the flow rate of the valve and A_V is a constant of the valve. Since the flow rates are 1000 cc/min for an input signal voltage of 1 V and 50 cc/min for 5 V, respectively, at a pressure difference of 1 kg/cm² between the entrance and the exit of the valve (according to the catalogue), the constant A_V (V⁻¹) is

$$A_V = \frac{\ln 50 - \ln 1000}{5 - 1} = -0.7489.$$

Then, the valve gain (K_V (cc · min⁻¹ · V⁻¹)) becomes

$$K_V = \frac{dq}{dv} = A_V q = -0.7489q.$$

(2) Chamber gain (K_C)

When the chamber at a gas temperature of θ_C is exposed to radiation equivalent to

heat of Q (J/min) and is cooled by water of q (cc/min), the equilibrium condition of heat is

$$C(\theta_C - \theta_W)\rho q = Q,$$

where C is the specific heat, ρ the density, and θ_W the temperature of incoming water. Upon differentiating the above equation, the next equation is derived as

$$\frac{d\theta_C}{\theta_C - \theta_W} = -\frac{dq}{q},$$

when $\rho = 1$ (g/cc). This suggests that the temperature of the chamber changes in proportion to a percent flow rate of water (dq/q). The above equation, however, in the real system should be reformed to $\eta(\theta_C - \theta_W)$ multiplied by the efficiency (η) instead of $(\theta_C - \theta_W)$, because the heat exchange at the endplates is not ideal.

On the other hand, the sensitivity of the thermo-sensors used here is $dv_C/d\theta_C = 0.2$ (V/°C). Therefore, the gain (K_C (V · cc⁻¹ · min)) is

$$K_C = \frac{d\theta_C}{dq} \frac{dv_C}{d\theta_C} = -0.2 \frac{\theta_C - \theta_W}{q} \eta.$$

Though each gain (K_V or K_C) depends on q , the product of K_V and K_C finally becomes independent of q as below:

$$K_V K_C = (-0.7489q)(-0.2 \frac{\theta_C - \theta_W}{q} \eta) = +0.14978(\theta_C - \theta_W)\eta. \quad (2)$$

Thus, the product of three gains, $K = K_P K_V K_C$, is also independent of q .

(3) Computer algorithm

Since the vertex chamber is surrounded by other detector components with large heat capacities, the chamber temperature is considered to be mostly stable around the equilibrium temperature ($\Theta_0(s)$ or $\theta_0(t)$). Temperature $\Theta(s)$ or $\theta(t)$ described below is measured on the basis of $\Theta_0(s)$ or $\theta_0(t)$.

Generally, the relations between the computer input voltage ($E(s)$) and output ($V(s)$) are given as follows:

$$V(s) = K_P(1 + \frac{1}{T_I s})E(s), \quad E(s) = 0.2\{\Theta(s) - \Theta_0(s)\}.$$

They are translated into real time as

$$v(t) = K_P\{e(t) + \frac{1}{T_I} \int e(t)dt\}, \quad e(t) = 0.2\{\theta(t) - \theta_0(t)\}.$$

By introducing a sampling time of T_S , the above equation for $t = t_n$ can be written in "position form",

$$v_n = K_P(e_n + \frac{T_S}{T_I} \sum_{k=1}^n e_k).$$

However, for this purpose, a more convenient "incremental form" is often applied [10,11,12]. It is easily derived as the difference between v_n and v_{n-1}

$$\Delta v_n = K_P\{(e_n - e_{n-1}) + \frac{T_S}{T_I}e_n\} = e_{out}. \quad (3)$$

When we bring the chamber from the equilibrium temperature ($\theta_0(t)$) to a set temperature (θ_{set}), starting from a pair of initial values, $e_{out} = 1$ (V) and $\theta = \theta_0$ ($^{\circ}\text{C}$) at $t = 0$ (in eq.(3)), the following equations are obtained:

$$\begin{aligned} e_{out} &= K_P\{(e_1 - e_0) + \frac{T_S}{T_I}e_1\}, \\ &= K_P 0.2\{(\theta_1 - \theta_{set}) - (\theta_0 - \theta_{set}) + \frac{T_S}{T_I}(\theta_1 - \theta_{set})\}, \\ &= K_P 0.2\{(\theta_1 - \theta_0) + \frac{T_S}{T_I}(\theta_1 - \theta_{set})\} \quad \text{at } t = t_1, \\ e_{out} &= K_P 0.2\{(\theta_2 - \theta_1) + \frac{T_S}{T_I}(\theta_2 - \theta_{set})\} \quad \text{at } t = t_2, \\ &\vdots \\ e_{out} &= K_P 0.2\{(\theta_n - \theta_{n-1}) + \frac{T_S}{T_I}(\theta_n - \theta_{set})\} \quad \text{at } t = t_n. \end{aligned}$$

The computer in the feedback loop continues until e_{out} becomes zero at the equilibrium state. Since this operation is DDC, the output of the computer must be held during the sampling time (T_S). The output is transferred to the DAC through a holding function, then into the VIC in order that the output is sent by a current signal of 4 to 20 mA (corresponding to 1 to 5 volts at the output of the computer) to the control valve via a twisted cable of about 20 m.

4. Closed-loop gain and indicial response

The closed-loop transfer function [5, 6, 8, 9] of this feedback is calculated from eq.(1) as

$$\frac{G(s)}{1 + G(s)} = \frac{K(1 + T_I s) \exp(-Ls)}{(1 + T_C s)T_I s + K(1 + T_I s) \exp(-Ls)}. \quad (4)$$

As long as the dead time (L) is (if any) small, eq.(4) becomes

$$\frac{G(s)}{1 + G(s)} = \frac{K}{T_I(T_C - KL)} \left\{ -LT_I + \frac{\frac{T_I T_C + L(T_I - T_C)}{T_C - KL}s + \frac{T_C}{T_C - KL}}{\Lambda} \right\}, \quad (5)$$

where

$$\Lambda = s^2 + \frac{(1+K)T_I - KL}{(T_C - KL)T_I}s + \frac{K}{(T_C - KL)T_I}. \quad (6)$$

In the closed loop shown in Fig. 4, the indicial response ($\Theta(s)$) for the step input $\Theta_{in}(s) = 1/s$ is

$$\Theta(s) = \frac{G(s)}{1+G(s)}\Theta_{in}(s) = \frac{G(s)}{1+G(s)}\frac{1}{s}. \quad (7)$$

The response of $\Theta(s)$ is important for DDC when the characteristic equation,

$$\Lambda = 0, \quad (8)$$

has imaginary solutions, since this case is generally often used to control the feedback loop quickly. The case in which eq.(8) has real solutions is discussed in the appendix.

Since eq.(6) is reformed as

$$\Lambda = (s + A)^2 + B^2,$$

where

$$A = \frac{(1+K)T_I - KL}{2(T_C - KL)T_I}$$

and

$$B = \left[\frac{K}{(T_C - KL)T_I} - \left\{ \frac{(1+K)T_I - KL}{2(T_C - KL)T_I} \right\}^2 \right]^{1/2},$$

the indicial response is

$$\begin{aligned} \Theta(s) = \frac{K}{T_I(T_C - KL)} & \left[-LT_I \frac{1}{s} + \frac{T_IT_C + L(T_I - T_C)}{T_C - KL} \left\{ \frac{1}{(s + A)^2 + B^2} \right. \right. \\ & \left. \left. + \frac{T_C}{T_IT_C + L(T_I - T_C)} \frac{1}{(s + A)^2 + B^2} \frac{1}{s} \right\} \right]. \end{aligned}$$

The response ($\theta(t)$) is obtained with the Laplace transformation as follows:

$$\begin{aligned} \theta(t) = \frac{K}{T_I(T_C - KL)} & \left[-LT_I + \frac{T_IT_C + L(T_I - T_C)}{T_C - KL} \left\{ \frac{1}{B} \exp(-At) \sin(Bt) \right. \right. \\ & \left. \left. + \frac{T_C}{T_IT_C + L(T_I - T_C)} \left(\frac{1}{A^2 + B^2} + \frac{1}{B} \frac{1}{\sqrt{A^2 + B^2}} \exp(-At) \sin(Bt - \phi) \right) \right\} \right], \quad (9) \end{aligned}$$

where $\sin \phi = B/\sqrt{A^2 + B^2}$ or $\tan \phi = -B/A$.

An indicial response of the vertex chamber has been taken and compared with eq.(9), in order to determine how the feedback loop responds. It has been attempted based on

the following conditions:

- The equilibrium temperature (θ_0) of the chamber is 24°C before the step input T_{in} is added.
- The θ_{in} has a small value around θ_0 , so not to over-swing the automatic valves.
- The water (coolant) temperature (θ_W) is 17°C .
- The cooling efficiency (η) is assumed to be 0.5.
- The product of the valve and the chamber gains ($K_V K_C$) is $0.14978 \times 7 \times 0.5$, according to eq.(2).
- The proportional gain of the computer (K_P) is 33.
- Consequently, the over-all loop gain (K) is 17.3.
- The integral time of the computer (T_I) is 1.67 min.
- The sampling time (T_S) is 2 sec.

The cross marks in Fig.5 show the observed indicial response for $\theta_{in} = -0.2^\circ\text{C}$ at the C-side of the vertex chamber when every detector around the vertex chamber is in the normal condition without the TRISTAN beam. On the other hand, the curve indicated by the solid line in Fig.6 is the indicial response calculated by putting the parameters $L=0$ and $T_C=75$ min into eq.(9). The transfer function of the vertex chamber is well presented simply by the 1st-order lag element (T_C), in spite of its complicated structure.

5. Bode diagram of the loop

Figure 7 is a Bode diagram of the loop when the parameters are $K=17.3$ and $T_I=100$ sec (1.67 min). The constant $K (= K_P K_V K_C)$ in eq.(1) is expressed by a line of 20 log $K (= 24.76)$ parallel to the angular frequency ω axis. The absolute value of the next part, $(1+1/T_I s)$, is represented by $\sqrt{1 + (1/\omega T_I)^2}$, which has a slope for the region of ω less than $\omega = 1/T_I$. Namely, the gain curve in Fig.7 is

$$-20 \log \left\{ 1 + \left(\frac{1}{\omega T_I} \right)^2 \right\}^{1/2} + 24.76.$$

In the same way, the absolute value for the last part of $1/(1 + T_C s)$ is given as

$$-20 \log \left\{ 1 + (\omega T_C)^2 \right\}^{1/2} + 24.76.$$

(Exactly speaking, the above formulae are smooth curves without a kink at $\omega = 1/T_I$ or $\omega = 1/T_C$). After all, the gain curve of eq.(1) is expressed by a solid line drawn on the basis of 24.76 in Fig.7, since the absolute value of $\exp(-Ls)$ is unity.

As for the phase given in Fig.7, we first of all consider the case without a dead-time element. The phase (ϕ_I) for $(1+1/T_I s)$ changes from -90° to 0° around the inflection point of $\omega = 1/T_I$ according to the formula $-\tan^{-1}(1/\omega T_I)$, depending on ω . The phase (ϕ_C) for $1/(1+T_C s)$ is from 0° to -90° according to $-\tan^{-1}(\omega T_C)$ with the inflection point $\omega = 1/T_C$. Therefore, the overall phase curve without a dead time becomes like the solid line in the figure. In this case, the loop would be absolutely stable, because the phase never exceeds -180° . When the gain curve crosses over the 0 dB line at $\omega = 6.5 \times 10^{-3}$

(sec^{-1}) in the figure, the loop has a sufficient positive phase margin.

If the loop had a dead-time element (L) as large as 10 min somewhere, the phase curve of $\exp(-Ls)$ with dead time of L decreases rapidly in the region higher than $\omega = 1/L = 1.67 \times 10^{-3} (\text{sec}^{-1})(L = 10 \text{ min})$, as shown by the dash-dotted line in Fig.7. Then, the overall phase of the feedback loop becomes the dashed line in the figure, which would cross over -180° at $\omega = 5.5 \times 10^{-4} (\text{sec}^{-1})$. The loop has a large negative phase margin at a gain of zero. In other words, the gain is still positive for a phase of -180° . Namely, the loop is unstable. This is the reason why we can not choose the temperature regulation of water which creates a much large dead time from the valve to the chamber.

6. External disturbance

The beam pipe of the vertex chamber is always exposed to the radiation, the amount of which depends on the TRISTAN beam status. Consequently, the beam pipe affects the temperature of the chamber gas. The response of the loop, when a temperature disturbance enters the chamber, can be estimated based on assumption that it comes in just before the chamber, as shown in the block diagram of Fig.8. The response of the chamber for both the input ($\Theta_{in}(s)$) and the disturbance ($D(s)$) is written as

$$\Theta(s) = \frac{G_1(s)G_2(s)}{1 + G_1(s)G_2(s)}\Theta_{in}(s) + \frac{G_2(s)}{1 + G_1(s)G_2(s)}D(s),$$

where $G_1(s)$ denotes the transfer function including the computer, DAC and VIC; $G_2(s)$ denotes that of the chamber and thermo-sensor (Fig.8). Since the pattern of the disturbance to the chamber is not so clear, we assume the disturbance is equivalent to the pattern of the valve output in order to simplify the calculation. Namely, a disturbance of $D(s) = K_V/s$, for example, enters when the loop is working at a setting temperature ($\Theta_{in}(s)=0$), the temperature $\Theta(s)$ will respond as

$$\Theta(s) = \frac{G_2(s)}{1 + G_1(s)G_2(s)} \frac{K_V}{s} = \frac{K_V K_C}{T_C - K L \Lambda} \frac{1}{s}.$$

In this case also, when eq.(8) has imaginary solutions, the following are obtained:

$$\Theta(s) = \frac{K_V K_C}{T_C - K L} \frac{1}{(s + A)^2 + B^2}$$

and

$$\theta(t) = \frac{K_V K_C}{T_C - K L} \frac{1}{B} \exp(-At) \sin(Bt). \quad (10)$$

The temperature ($\theta(t)$) of the chamber should respond like the solid line in Fig.9 according to eq.(10). It is not easy experimentally to confirm the suppression effect against the external disturbance though a good result is expected.

Figure 10(a) is an example of the gas temperature at the D-side when the D-side end plate is cooled with a constant flow of water without any feedback loop. Comparing with

the record of the total beam current shown in Fig.10(b), it is clear that the temperature corresponds to the total beam current of TRISTAN. Finally, Fig.11(a) shows that the temperature of the gas is beautifully controlled by this feedback loop within 0.1 degree. On the contrary, the flow rate of water used to compensate the heat due to the beams changes as can be seen in Fig.11(b), corresponding to the total beam current shown in Fig.11(c).

7. Discussion

As mentioned above, the indicial response of the chamber is almost consistent with a calculation of $L = 0$. However, at the start-up point on the indicial response, there is an indication that the loop includes a 2nd-order lag element due to L , though it is small. If the loop has absolutely only the 1st-order lag element, the response must show a sharper start-up property. The transfer function of the vertex chamber may not be expressed by a simple form, such as $1/(1 + T_C)$, without the 2nd-order lag element. It is difficult to tell where the dead-time element (L) exists exactly, except for the valve.

The temperature stability around the sensors is almost perfect, as can be seen in Fig.11(a). However, the important thing is to stabilize the gas temperature in the fiducial volume of the vertex chamber to be constant for a long time. Unfortunately, since there is no space to put even a sensor in the middle part of the chamber, because of the strong electric field, the status is still not clear.

8. Conclusion

A temperature control system has been constructed using the DDC PI-loop in order to keep the gas temperature of the VENUS vertex chamber constant to within 0.1°C. The obtained indicial response is in good agreement with the calculation. Though the gas temperatures around both endplates are almost perfectly controlled, the temperature distribution inside the chamber is still unknown. Now, under the well established boundary conditions, the temperature distribution in the chamber is under study in order to obtain a better spatial resolution for the particle tracks.

Acknowledgement

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Appendix

Mathematically, the characteristic equation (eq.(8)) can have either a pair of real solutions or a double solution, except for the imaginary ones, as discussed previously. In the case of real solutions, the response of the feedback loop is relatively dull, compared with the case of the imaginary solutions. Therefore, in general, parameters K_P and T_I are so chosen that eq.(8) has imaginary solutions.

(I) When eq.(8) has two real solutions (α and β).

From eqs.(5) and (7), the indicial response of $\Theta(s)$ is derived as follows:

$$\begin{aligned}\Theta(s) &= \frac{G(s)}{1 + G(s)} \Theta_{in}(s) \\ &= \frac{K}{T_I(T_C - KL)} \left\{ -LT_I \frac{1}{s} + \frac{T_I T_C + L(T_I - T_C)}{T_C - KL} \frac{1}{(s - \alpha)(s - \beta)} \right. \\ &\quad \left. + \frac{T_C}{T_C - KL} \frac{1}{(s - \alpha)(s - \beta)} \frac{1}{s} \right\}.\end{aligned}$$

Therefore, the response $\theta(t)$ in real time is finally obtained by Laplace transforming as below:

$$\begin{aligned}\theta(t) &= \frac{1}{\alpha - \beta} \frac{1}{(T_C - KL)^2} \frac{K}{T_I} \left[\left\{ T_I T_C + L(T_I - T_C) + \frac{T_C}{\alpha} \right\} \exp(\alpha t) \right. \\ &\quad \left. - \left\{ T_I T_C + L(T_I - T_C) + \frac{T_C}{\beta} \right\} \exp(\beta t) \right] + 1.\end{aligned}$$

For the response against the disturbance, the results are given by

$$\Theta(s) = \frac{K_V K_C}{T_C - KL} \frac{1}{(s - \alpha)(s - \beta)}$$

and

$$\theta(t) = \frac{K_V K_C}{T_C - KL} \frac{1}{\alpha - \beta} \{ \exp(\alpha t) - \exp(\beta t) \}.$$

(II) When eq.(8) has a double solution.

The indicial response $\Theta(s)$ and $\theta(t)$ are given by

$$\begin{aligned}\Theta(s) &= \frac{K}{T_I(T_C - KL)} \left[-LT_I \frac{1}{s} + \frac{T_I T_C + L(T_I - T_C)}{T_C - KL} \left\{ \frac{1}{(s + A)^2} \right. \right. \\ &\quad \left. \left. + \frac{T_C}{T_I T_C + L(T_I - T_C)} \frac{1}{(s + A)^2} \frac{1}{s} \right\} \right],\end{aligned}$$

and

$$\theta(t) = \frac{K}{T_I(T_C - KL)} \left[-LT_I + \frac{T_IT_C + L(T_I - T_C)}{T_C - KL} \right. \\ \left. \left\{ t \exp(-At) + \frac{T_C}{T_IT_C + L(T_I - T_C)} \frac{1}{A^2} (1 - \exp(-At) - At \exp(-At)) \right\} \right],$$

respectively. For the response against the disturbance, the results are described as

$$\Theta(s) = \frac{K_V K_C}{T_C - KL} \frac{1}{(s + A)^2}$$

and

$$\theta(t) = \frac{K_V K_C}{T_C - KL} t \exp(-At).$$

Even if the parameters giving real solutions are taken for some other reasons, the system still works better than that without feedback loop, as mentioned above.

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Fig. 2 Concept of the cooling. Numbers, 1, 2, 3 and 4 indicate the thermo-sensors.

Fig. 1 Cross-sectional view of the vertex chamber in the VENUS detector.

Fig. 4 Block diagram of the PI-control system.

Fig. 3 Structure of the end plate at the C-side.

Fig. 6 Calculated indicial response at the C-side of the vertex chamber.

Fig. 5 Observed indicial response for $\theta_m = -0.2$ °C at the C-side of the vertex chamber when all detectors around the vertex chamber are in normal conditions without the TRIS-TAN beam.

Fig. 8 Block diagram when a disturbance enters the loop.

Fig. 7 Bode diagram of the loop.

Fig. 9 Estimation that how effectively the PI control suppresses a disturbance at the C-side.

Fig. 10 (a) Example of the gas temperature at the D-side without any control.
(b) Total beam current of TRISTAN when (a) has been recorded.

Fig. 11 (a) Gas temperature at the D-side controlled by the PI feedback loop.
 (b) Flow rate of the water to compensate. (c) Total beam current of TRISTAN.