# High Power and High Efficiency Operation of 77 GHz Gyrotrons by Stepwise Raising of the Anode Voltage

Hiromi TAKAHASHI, Takashi SHIMOZUMA, Satoshi ITO, Shin KUBO, Yasuo YOSHIMURA,
Hiroe IGAMI, Masaki NISHIURA, Sakuji KOBAYASHI, Yoshinori MIZUNO, Kohta OKADA,
Yasuyuki TAKITA, Shinya OGASAWARA[1)], Ryohei MAKINO[1)], Takashi MUTOH,
Tsuyoshi KARIYA[2)], Ryutaro MINAMI[2)] and Tsuyoshi IMAI[2)]

*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
[1)]*Department of Energy and Technology, Nagoya University, Nagoya 464-8463, Japan*
[2)]*Plasma Research Center, University of Tsukuba, Tsukuba 305-8577, Japan*

(Received 7 November 2011 / Accepted 13 October 2012)

High power and high efficiency operation of 77 GHz gyrotrons was achieved by the stepwise raising of the anode voltage. In particular, a stable MOU output power of 1.8 MW was obtained for 1 s. The effect of beam-charge neutralization on the oscillation characteristics was examined. The intended beam acceleration voltage was not initially reached due to the space-charge effect but was achieved over time through the charge neutralization process. By applying the stepped anode voltage, the gyrotron operational parameters were able to be optimized for the sufficiently accelerated electron beam, leading to the improvement of the output power and the electric efficiency.

Keywords: gyrotron, ECRH, space-charge effect, charge neutralization, LHD

DOI: 10.1585/pfr.7.1205154

Since 2006, the installation of triode-type 77 GHz gyrotrons with an output power of over 1 MW each has progressed in the Large Helical Device (LHD) in collaboration with University of Tsukuba [1,2]. At present, three 77 GHz gyrotrons are operational for plasma experiments [3]. The total injection power of ECRH to the plasma has significantly increased due to the installation of the 77 GHz tubes and has reached a value of 3.7 MW.

An active control of operational parameters is a key for an improvement of oscillation efficiency on gyrotrons. In JAEA, high efficiency operations in the hard excitation region have been achieved on 110/170-GHz gyrotrons by the active control of the anode voltage and the cavity field during the oscillations [4,5].

On the 77 GHz gyrotrons, the anode voltage ($V_A$) can be adjusted and the improvement of the output power and the electric efficiency were successfully achieved by the stepwise raising of $V_A$. Figure 1 shows the time evolution of (a) the applied voltage for collector $V_C$, for body $V_B$ and for anode $V_A$, (b) the beam current $I_C$, the anode current $I_A$ and the body current $I_B$ and (c) the MOU output power for the most recently installed 77 GHz gyrotron. In Fig. 1 (c), the MOU output power is represented as the averaged power over the oscillation of 1 s evaluated from the temperature change of the cooling water of a dummy load and the Schottky-diode signal is also attached as the reference data. In the first step period of $V_A$, a small voltage (~27 kV) was applied for 100 ms, in which 60 A of the electron beam flowed inside the tube but RF was not generated. After that, $V_A$ was increased to ~40 kV to start oscillation. In this operation, a stable MOU output power of 1.8 MW (the window output of 1.9 MW) was obtained

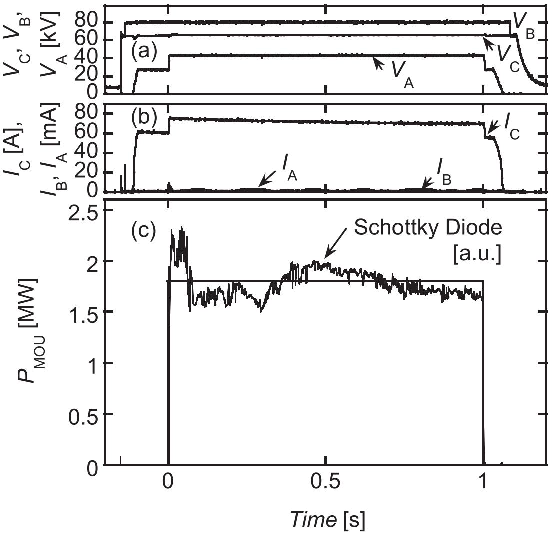

Fig. 1 The time evolution of (a) the applied voltage for collector $V_C$, for body $V_B$ and for anode $V_A$, (b) the beam current $I_C$, the anode current $I_A$ and the body current $I_B$ and (c) the MOU output power $P_{MOU}$ for the oscillation of 1.8 MW / 1 s.

---

*author's e-mail: takahashi.hiromi@lhd.nifs.ac.jp*

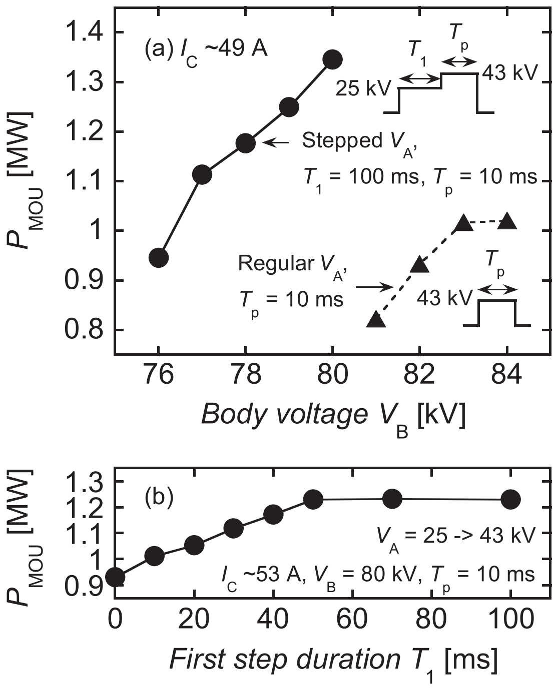

Fig. 2 The dependence of $P_{\mathrm{MOU}}$ on (a) $V_B$ and (b) the duration of the first step in the stepped $V_A$.

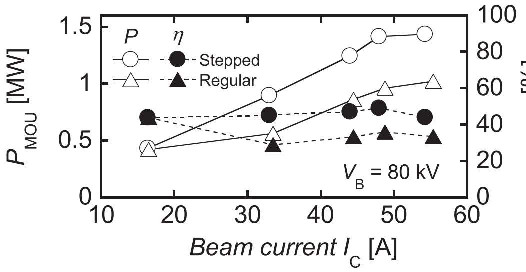

Fig. 3 The dependence of $P_{\mathrm{MOU}}$ and $\eta_{\mathrm{MOU}}$ on $I_C$ for the operation with stepped $V_A$ (circles) and rectangular $V_A$ (triangles).

for 1 s even though the beam current $I_C$ decreased from 76 A to 70 A. The averaged value of $I_C$, $I_A$ and $I_B$ during the oscillation were 72 A, 2.3 mA and 1.4 mA, respectively. The collector voltage was set at 65 kV and the electric efficiency $\eta_{\mathrm{MOU}}$ was evaluated as 38% ($\eta_{\mathrm{window}}$ = 40%). A higher output power was obtained by a further increase of $I_C$. Although the pulse duration was short, the oscillation with $P_{\mathrm{MOU}}$ = 1.9 MW/100 ms ($\eta_{\mathrm{MOU}}$ = 37%) was achieved at the time-averaged $I_C$ of 77 A ($P_{\mathrm{window}}$ = 2 MW, $\eta_{\mathrm{window}}$ = 39%).

In the operation with the stepped $V_A$, the charge neutralization phenomenon of the gyrotron electron beam [6] is considered to be critical for the improvement of the output power and the electric efficiency. Figure 2 shows the dependence of the MOU output power on (a) $V_B$ and (b) $T_1$, where $V_B$ corresponds to the beam acceleration voltage and $T_1$ denotes the duration of the first step in the waveform of the stepped $V_A$. The circles and triangles in Fig. 2 (a) represent the output power for the operations with the stepped $V_A$ and the regular $V_A$ (rectangular waveform), respectively. $T_1$ was fixed at 100 ms for the operation in Fig. 2 (a). In the series of operations shown in Figs. 2 (a) and (b), the oscillation duration $T_p$ was set at 10 ms and the gyrotron operational parameters, such as the strength of the magnetic field of the cavity/gun coils, the value of the applied high voltages and the cathode heating condition were not changed except for $V_B$ or $T_1$. As can be seen from Fig. 2 (a), the operation with the regular $V_A$ required 5 ~ 6 kV higher $V_B$ to generate an output power similar to that of the stepwise $V_A$ case. This shows that the acceleration voltage, which influences the electron beam in the tube, became lower than the set value due to the space charge effect. Although such a drop in the voltage might arise in both operations, the voltage recovered in the case of stepped $V_A$. Charge neutralization of the electron beam is a possible explanation of this result. The electron beam collided with the molecules of the residual gas inside the tube and ionized them in the first step phase of $V_A$. Then the electron beam was partially neutralized due to the presence of the ions and the acceleration voltage influencing the beam was considered to increase. Figure 2 (b) shows that the output power increased with the extension of the duration of the first step and was saturated for a duration longer than 50 ms, implying that the space charge was sufficiently neutralized for ~50 ms in the operation.

The operation using the stepped $V_A$ with adequate $T_1$ has the advantage that the gyrotron operational parameters are able to be optimized for the sufficiently accelerated electron beam, leading to the improvement of the output power and the electric efficiency. Figure 3 shows the dependence of the MOU output power and the electric efficiency on the beam current. The triangles correspond to the data for the rectangular $V_A$ case and the circles are those for the stepped $V_A$ case with $T_1$ = 100 ms. In both operations, the gyrotron operational parameters were optimized to obtain high power and high efficiency at each beam current. As can be seen from Fig. 3, the electric efficiency was improved by 10 to 16% for $I_C > 33$ A by applying the stepped $V_A$. In particular, for the operation at $I_C$ ~48 A, the SC coil current for the cavity could be decreased by 0.5 A and the anode voltage could be increased by 1.3 kV in comparison with regular $V_A$ operation. Consequently, high power and high efficiency ($P_{\mathrm{MOU}}$ = 1.4 MW, $\eta_{\mathrm{MOU}}$ = 49%) operation was successfully achieved with a pulse duration of 1 s.

This work was supported by NIFS grants, NIFS10UJRR001, 10ULRR002 and NIFS11ULRR701.

[1] H. Takahashi *et al.*, Fusion Sci. Technol. **57**, 19 (2010).
[2] T. Kariya *et al.*, J. Infrared Millim. Terahertz Waves **32**, 295 (2011).
[3] T. Shimozuma *et al.*, Fusion Sci. Technol. **58**, 530 (2010).
[4] K. Sakamoto *et al.*, Nat. Phys. **3**, 411 (2007).
[5] T. Kobayashi *et al.*, Nucl. Fusion **51**, 103037 (2011).
[6] G.S. Nusinovich *et al.*, Phys. Plasmas **13**, 083106 (2006).