JAERI-Research
96-017

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March 1996

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編集兼発行　日本原子力研究所
印　　刷　いばらき印刷㈱

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(Received February 27, 1996)

A superconducting magnet (SCM) using a persistent current for a 110 GHz gyrotron was developed to reduce liquid-helium loss, the boiled-off rate of 0.13 liter/hour was attained in a persistent current operation. It shows that the continuous operation for 50 days is capable without additional liquid-helium supply. Moreover, the 3040 liter in a year is used for a gyrotron test during five months and for the maintenance during seven months and liquid-helium savings of 65% was successfully demonstrated. The SCM is capable to excite the maximum magnetic field of 5.0 T in the persistent current mode. A mirror ratio between resonant cavity and magnetron injection gun (MIG) is 20 for operating the main coils in the persistent mode, since cavity coils and gun coils are connected in series. Auxiliary coils are equipped independently to control the mirror ratio, the mirror ratio of 13.6 - 37.0 at the 110 GHz is available. A two-stage refrigerator using helium gas was also installed and made liquid-nitrogen for cooling thermal shield of 80 K free. By developing this new type SCM, the number of routine works was drastically decreased in one time per 22-50 days, while routine works of a few times per week was needed up to now.

Keywords: 110 GHz Gyrotron, Persistent Current, 5T Magnet, Liquid He

JAERI-Research 96-017

# 永久電流による110GHz帯ジャイロトロン用超伝導マグネットの特性

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（1996年2月27日受理）

110GHz帯ジャイロトロン用超伝導マグネットにおいて、液体ヘリウムの消費を減らすために、永久電流を採用したことによって、電流導入端子からの熱侵入を軽減でき、永久電流による運転において、0.13リッター／時間の消費を達成した。この消費量は、液体ヘリウムの補給なしに、50日間の連続運転ができることを示す。さらに、5カ月間のジャイロトロン出力試験と7カ月間の非励磁に使用した液体ヘリウム量は、約3040literであり、約65％の液体ヘリウムの低消費化を達成した。この超伝導マグネットは、永久電流で最大5Tの励磁が可能である。永久電流によって磁界を保持するために、キャイビティ部及び電子銃部のコイルが直列に配線されるために、電子銃部とキャビティ部間のミラー比は、一定の20である。このミラー比を調整するために、独立に補助コイルが設けられ、110GHz時に13.6から37.0のミラー比を調整することができる。この超伝導マグネットでは、ヘリウムガスによる2段式冷凍機を採用して、80Kシールドを冷却する液体窒素の供給を不要とした。この新型超伝導マグネット開発により、今迄1週間に数回必要であったルーチンワークの作業回数が、22日～50日間に一回と大幅に削減された。

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## 1. Introduction

Theoretical studies of electron cyclotron resonance heating (ECH) and current drive (ECCD) using a millimeter wave have been done for fusion application[1～3], and experimental studies of the ECH and ECCD using a gyrotron have been carried out on small and medium size tokamak machines[4～10]. In the International Thermonuclear Experimental Reactor (ITER), an injection power of 50 MW at a frequency of 150～170 GHz has been considered as one of heating and current drive methods[11]. The gyrotron generating, the output power of 1MW with continuous-wave operation, is a key component of EC system and now under development[12～15].

A mechanism of the gyrotron is based on electron resonance maser (CRM)[16] that kinetic energy of electrons is transformed into electromagnetic wave energy due to interaction between electron cyclotron motion and electromagnetic waves at a resonant cavity. In order to make electron beam gyrate, an axial magnetic field is externally applied from MIG to the cavity. The magnetic field strength at the cavity is dependent on electron cyclotron frequency fc where fc = 28 B(T)/$\gamma$ GHz, B is the strength of the magnetic field and $\gamma$ is the relativistic factor. At the frequency more than 28 GHz, a superconducting magnets have been generally used, since it is difficult to cool coils under the magnetic field more than 1.0 T.

A conventional SCM consists of four solenoid coils and each coil is excited by each power supply. Heat invaded into a cryostat through each current lead is large, but the SCM has advantage of making an axial magnetic field freely. Near the level of 0.7～1.0 liter/hour of liquid-helium and liquid-nirogen are consumed for cooling their coils and thermal shield of 80 K[17]. Therefore, their supply is needed a few times in a week. For the ECH system using 70 gyrotrons such as ITER, it is essential to reduce number of the supply to maintain reliable operation. For this purpose, a newly SCM equipped with a persistent current system was developed to lessen heat loads invaded into a cryostat through current leads of feed through. A closed-circuit to excite the persistent current in the cryostat is capable to remove just one line of the conventional SCM. Even though auxiliary coils are equipped to control a mirror ratio, it is capable of suppressing the heat loads by minimizing auxiliary magnetic field strengths and then using a small diameter for their current lead. Moreover, a two-stage refrigerating device is installed to simplify routine works to keep the cryostat, too. The two-stage refrigerator does not require the liquid-nitrogen to cool the thermal shield at 80 K.

This paper presents characteristics of the SCM using the persistent current and the liquid-helium consumption. In the next section, outline of the SCM is described, and in the third section coupling effects between main magnetic field and auxiliary magnetic fields. Liquid-helium consumption is presented in the fourth section, conclusion is given in the last section.

## 2. Outline of the SCM using a Persistent Current

Conceptual view of a SCM using a persistent current is shown in Fig. 1. The SCM consists of four main coils, three auxiliary coils, and two steering coils. Main coils of Mu, Ml Gu and Gl are connected in series as the circuit diagram illustrated in Fig. 2. They are excited by one power supply. The Gu coil is a back turning coil. Current can be flowed into a closed circuit only by a persistent current switch and main magnetic field can be kept by the persistent current. Therefore, the current lead connected at the service port can be removed and then thermal barrier is installed instead of the current lead. Heat load through the current lead into the cryostat, therefore, can be drastically reduced. On the other hand, the main coils produce the constant mirror ratio of 20 between cavity and MIG. However, the mirror ratio can be controlled by auxiliary coils (Gua and Gla coils), which are equipped independently at the outside of Gu and Gl coils as shown in Fig. 2. In the cavity field of 4.35 T, the mirror ratio can range from 13.6 to 37.0.

The rated current of main coils is 113.4 A, the maximum field strengths at the cavity and the gun are 5.0 T and 0.25 T, respectively. The specification of SCM for 110 GHz gyrotron design is demanded as shown in Table 1. The design value of the magnetic field at the cavity is 4.35 T. The axial magnetic field profile measured is shown in Fig. 3. The axial length between cavity and MIG is 400 mm and the bore diameter is $\phi$220 mm. In order to control accurately the cavity field, auxiliary cavity coil of Mua is also equipped at the outside of Mu coil. The cavity field can be controlled with the accuracy of 1.0 Gauss, which is about 4 times greather than that of main coils. These rated currents are 15 A. Their axial field to be excited independently is shown in Fig. 4, and the maximum field strengths are shown in Table 2. A current lead with a diameter of $\phi$ 1.0 mm between thermal shield of 20 K and liquid-helium vessel is used to suppress heat loads invaded into the cryostat through these current leads. Steering coils are also equipped for beam alignment under the same lead diameter and rated current as those of auxiliary coils.

The cryostat consists of two thermal shields of 80 K and 20 K and liquid-helium vessel of 4.2 K. A two-stage refrigerating device using helium gases is equipped with the cryostat. The cooling power and the ultimate temperature are 85 W and 30.9 K, the third section coupling effects between main magnetic field and auxiliary magnetic fields. Liquid-helium consumption is presented in the fourth section, conclusion is given in the last section.

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Heat loads from the service port into the cryostat are caused by monitor cables, current leads and thermal barrier. The heat fluxes are transmitted by heat radiation, heat conduction from residual gas and support structures. The cryostat was designed so as to operate continuously for a fifty-days without liquid-helium supply under a persistent current operation. To attain this specification, heat loads to be injected into liquid-helium vessel is required to be suppressed at the level of 0.05 W. The value is estimated from a useful liquid-helium volume of 186 liters and the latent heat of helium vaporization by Mr. Konno and Mr. Yasukawa et al.[18], but it involves a margin of two times.

## 3. Coupling Effects of Main Magnetic Field with Auxiliary Magnetic Fields

When auxiliary coils are excited independently in persistent mode, the main magnetic coils and the auxiliary magnetic coils couple each other so that inductive current flows in the opposite direction to cancel out auxiliary magnetic fields. Inductive current $\Delta I$ is given by $\Delta I = - M\, i/L$, where L, M and i are self-inductance, mutual-inductance and auxiliary current intensity, respectively. The total self-inductance L of main coils is 91.0 H, mutual-inductance of Mua, Gua and Gla coil with auxiliary coil are 2.47, 0.231 and 0.352 H, respectively. When their rated current of 15 A are excited independently, their inductive current $\Delta I$ to Mua, Gua and Gla coil are 0.407 A, 0.038 A and 0.058 A. In the case that auxiliary gun fields are applied in the same direction, the rate of inductive current at 4.35 T are 0.0973%, and then the variant field at the cavity corresponds to 42.3 gauss. However, the real variant field reaches near 90 gauss, since a tail of the applied field affects the magnetic field region at the cavity. If the variant field within 20 gauss is permitted, the mirror ratio within 18.6 ∼23.7 can be controlled under persistent current mode. In the case that Mua coil is excited, the real variant field is a few gauss at the cavity, since the mutual-inductance of Mua coil is large. Thus, the adjustment has to be done under taking off persistent current operation. In this normal operation, main coils are excited by the regulated power supply and thus inductive current can be cancelled out. After the adjustment, the magnetic field can be kept again by persistent current mode under the proper arrangement field. Under such operation, the mirror ratio of 13.6∼37.0 can be respectively, at the first stage, 8 W and 9.2 K at the second stage. Liquid-nitrogen used for cooling thermal shield of 80 K in the conventional SCM, is not required. The volume of liquid-helium in the vessel is 299 liters, the volume of 186 liters is useful.

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## 4. Liquid-helium Consumption

There are four operations of the SCM that yield different losses of liquid-helium. One is a current step up/down mode of main coils. In this mode, current heater is activated to turn the persistent current switch off and then the power of 21.4 W is generated in the liquid-helium vessel. A duration time of the current step up/down is limited by a rate less than 5 A/sec to avoid a quench. The second is quasi persistent current mode (Quasi-PCS mode). In this mode, current lead of main coils is still connected to the service port without power supplying and a magnetic field is held by the persistent current. This mode is useful for adjusting the magnetic field, but heat loads through the current leald invaded into cryostat. The third mode is persistent current operation (PCS mode) that the current lead is removed from the service port and thermal barrier is installed into the service port. Thus, main heat loads are caused by conductor of monitor cables and current lead of auxiliary coils. For a long pulse operation of gyrotron with the magnetic field optimized, this mode is effective. The last one is a static mode that a magnetic field is not excited, the other condition is the same as the PCS mode.

In the 110 GHz gyrotron test, liquid-helium loss is measured as shown in Fig. 5. The consumption was monitored by a level meter. In the current set up during 35 minutes, liquid-helium of 14.5 liter is consumed and the boiled-off rate is 24.8 liter/hour. In the Quasi-PCS mode, the boiled-off is 0.30 liter/hour. It is shown that the SCM is capable to operate continuously of the 22-days per one supply of liquid-helium. When heat load of 1 W invaded into liquid-helium vessel, the boiled-off of 1.41 liter/hour is consumed by the latent heat of helium vaporization under one atmosphere. Thus, it is indicated that heat load of 0.21 W is generated into the liquid-helium vessel in Quasi-PCS mode. In the PCS mode, the boiled-off is 0.13 liter/hour, the supply is not needed for fifty-days. This means heat load of 0.092 W at the liquid-helium vessel. The heat load is within the margin value of 0.1 W. The boiled-off in the static mode was almost the same as that in PCS mode.

For a gyrotron test during five months and a static mode during sevenths month, the total liquid helium of about 3040 liter is used. The average boiled-off in a year is equivalent to 0.35 liter/hour, which indicated liquid-helium savings of 65%.

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## 5. Conclusions

To reduce liquid-helium loss, a newly SCM using a persistent current was developed for a 110 GHz gyrotron. Using this SCM, an output power of 400 kW-4.0 sec under total efficiency of 50% with a collector potential depression is successfully performed[12-13,19]. An optimization of a magnetic field in the gyrotron test is conducted on almost the same time as that using a conventional one. There are not an inopportune evidence in the SCM using the persistent current. A Quasi-PSC mode was used for adjusting the main magnetic field, and then the boiled-off of 0.30 liter/hour was obtained. In this operation, liquid-helium supply was needed one time per 22 days. The SCM was operated for a long pulse test of the gyrotron under the PCS mode after the optimization. In the PCS mode, the boiled-off is 0.13 liter/hour and continuous operation for 50 days was demonstrated without additional supply of the liquid-helium. For the gyrotron test during five months and a static mode during sevenths month, the average boiled-off in a year is equivalent to 0.35 liter/hour. This average boiled-off is 65% less than that of a conventional them. Moreover, a two-stage refrigerator device installed did not require liquid-nitrogen for cooling thermal shield of 80 K. Up to now, the supply of liquid-helium and liquid-nitrogen was needed more than a few times per week in a conventional SCM. However, these routine works are drastically decreased in just one time per 22～50 days for the newly SCM. Specially, a current set up/down in every day are not needed, since a magnetic fields can be kept by Quasi-PCS mode and PCS mode. In ECH system using a number of gyrotrons, not only less routine works but also this development will contribute for a lower cost performance.

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Table 1 Design values of the magnetic field by main coils under the rated current

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Cavity region : ( 390 mm ≤ z ≤ 410 mm )

$$\left|\frac{dB_z}{dz}\right| \le 1.25\,[\,\mathrm{T/m}\,]$$

Electron gun region : ( – 10 mm ≤ z ≤ 10 mm )

$$0 \le \frac{dB_z}{dz} \le 0.875\,[\,\mathrm{T/m}\,]$$

The region between Electron gun and Cavity :
( 0 mm ≤ z ≤ 400 mm )

$$\mu = \rho_\kappa \sqrt{\frac{B_\kappa}{B_z}}\,\frac{1}{B_z}\,\frac{dB_z}{dz} \le 0.1$$

where $\rho_\kappa = 0.9$ mm, $B_\kappa = 0.25\,[\,\mathrm{T}\,]$

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Table 2 Maximum magnetic field strength due to their rated current

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Main coil system

Bz = 5.00 [T] ( z = 400 mm ; Center of cavity )
Bz = 0.25 [T] ( z = 0 mm ; Center of gun )

Auxiliary coils

Mua coil ; Bz = ± 184 [ gauss ] ( z = 463 mm )
Gua coil ; Bz = ± 593 [ gauss ] ( z = 72 mm )
Gla coil ; Bz = ± 569 [ gauss ] ( z = – 23 mm )

Steering coils

STx ; Bx = ± 61 [ gauss ] ( z = 400 mm )
STy ; By = ± 61 [ gauss ] ( z = 400 mm )

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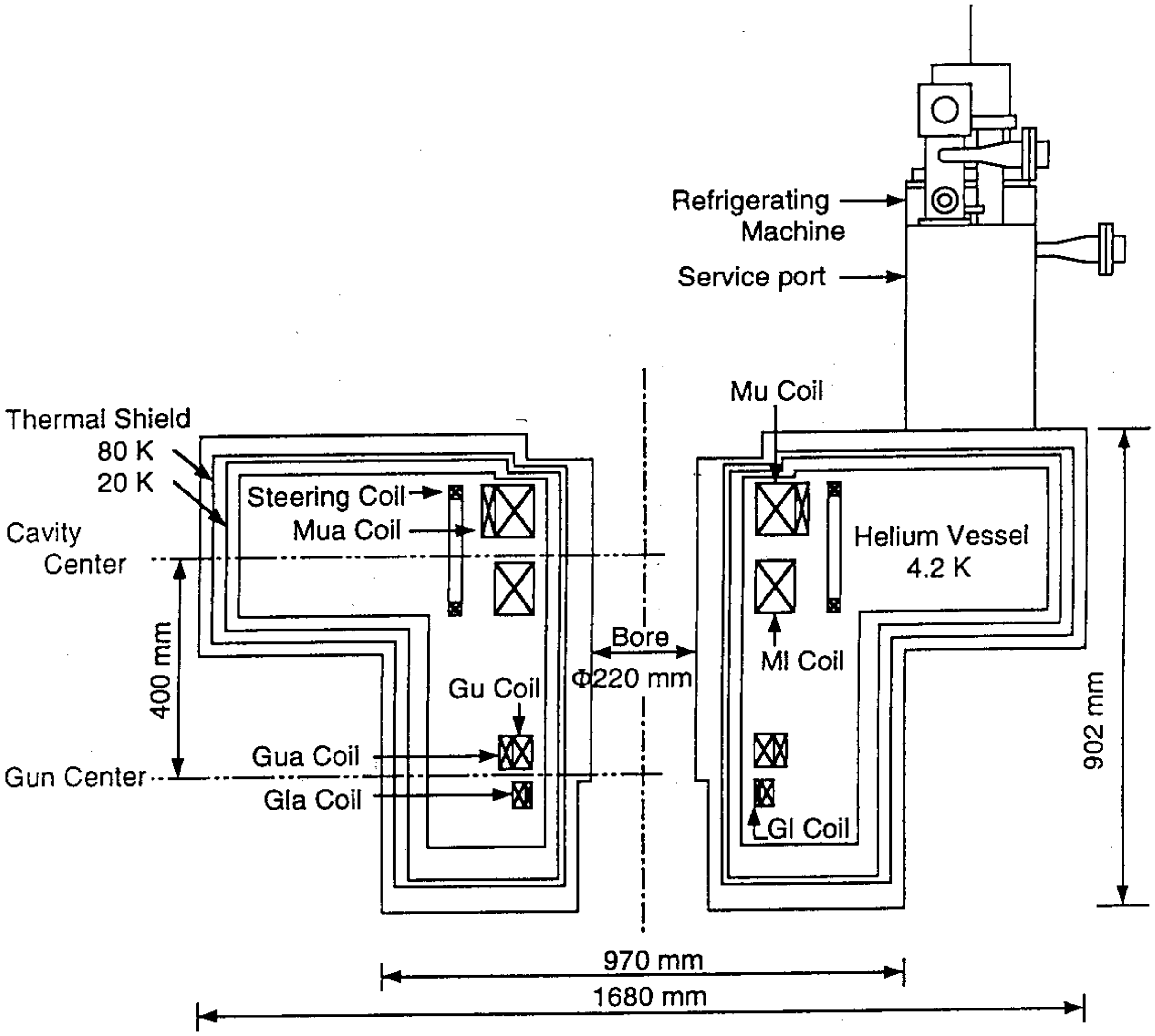

Fig. 1 Conceptual view of the SCM using a persistent current

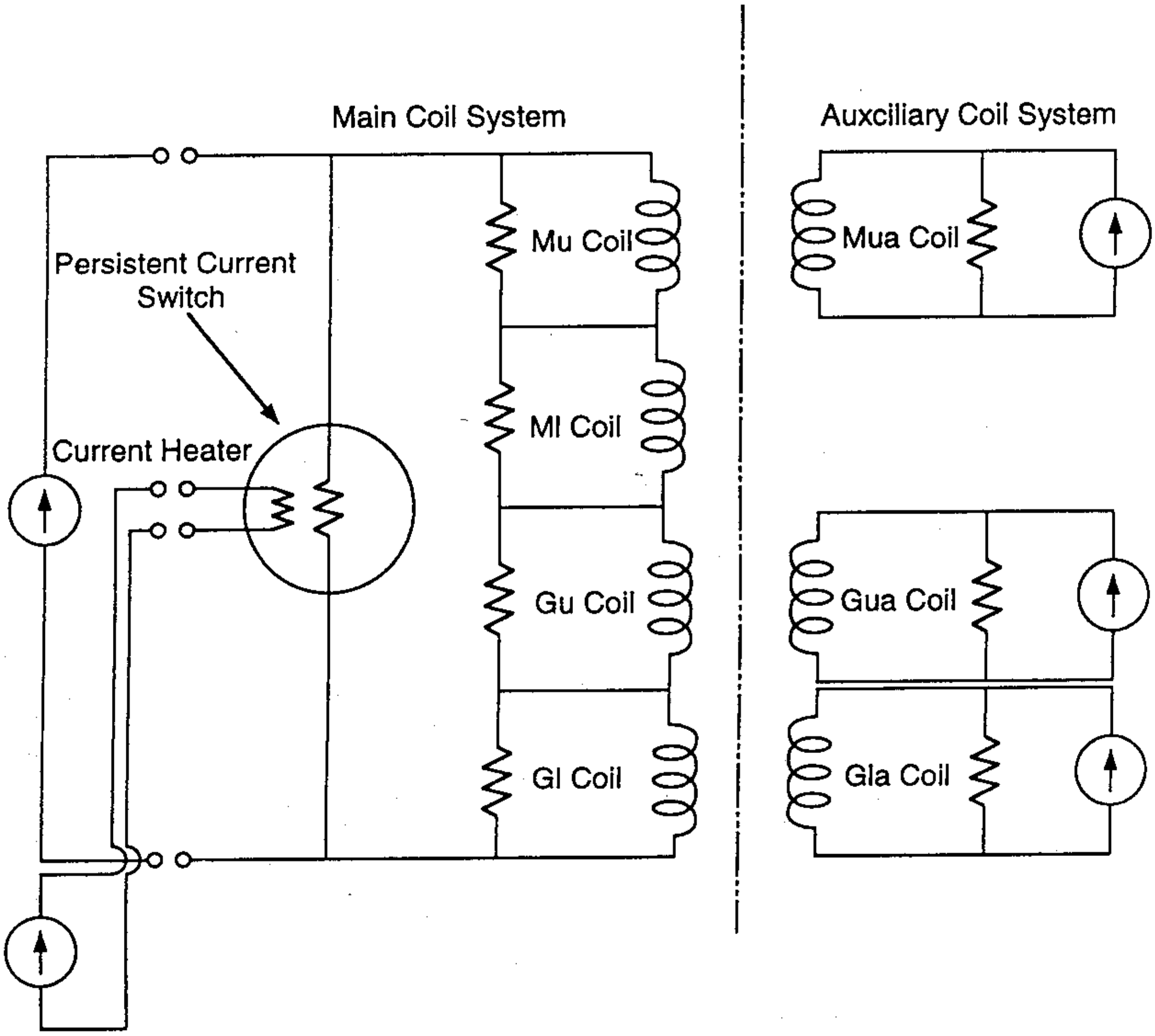

Fig. 2 The circuit diagram of main coil system and auxiliary coil system

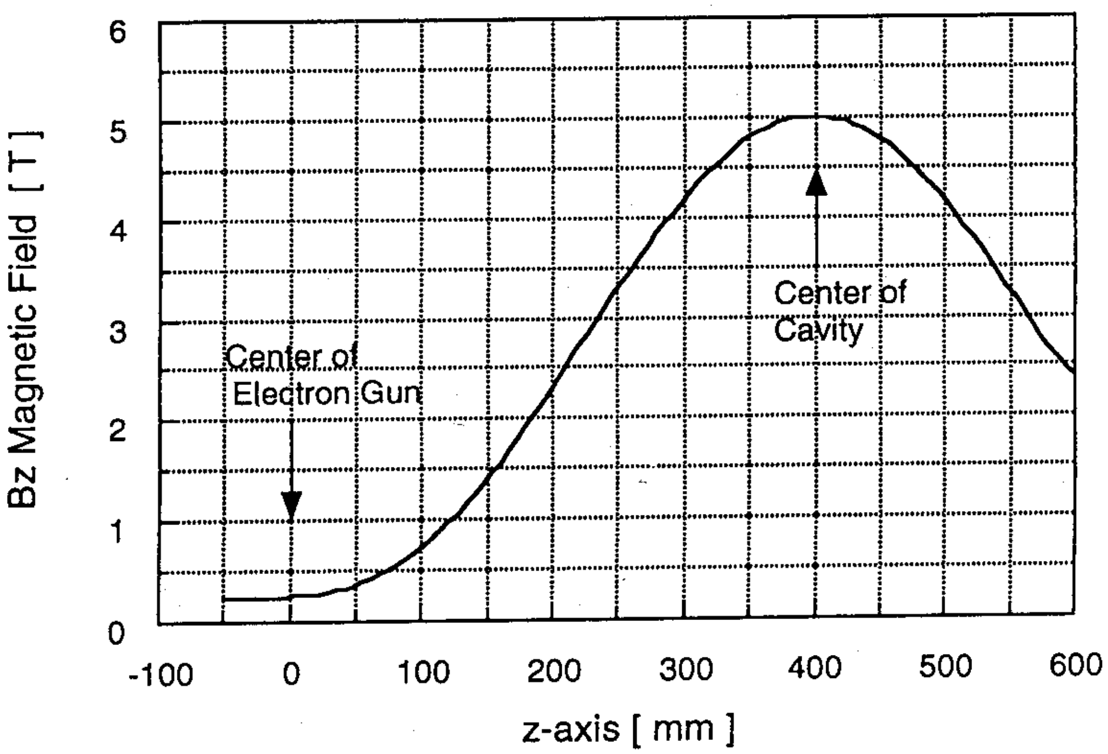

Fig. 3 The magnetic field profile by main coils along z-axis

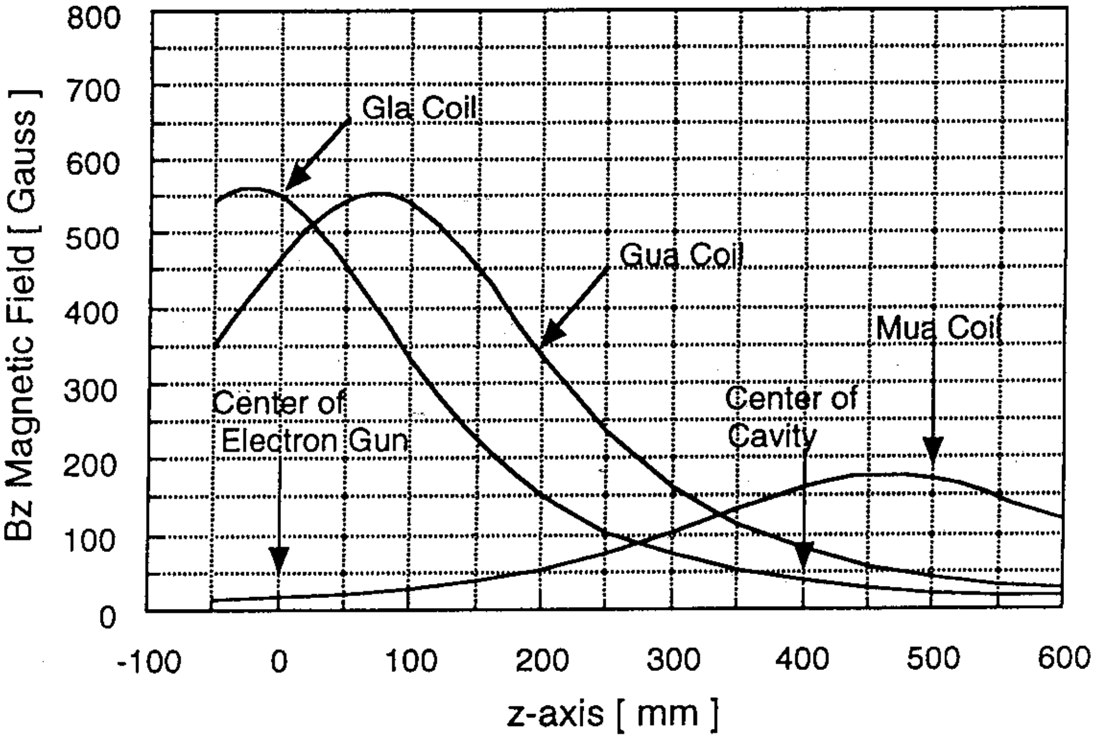

Fig. 4 The magnetic field profile by auxiliary coils along z-axis

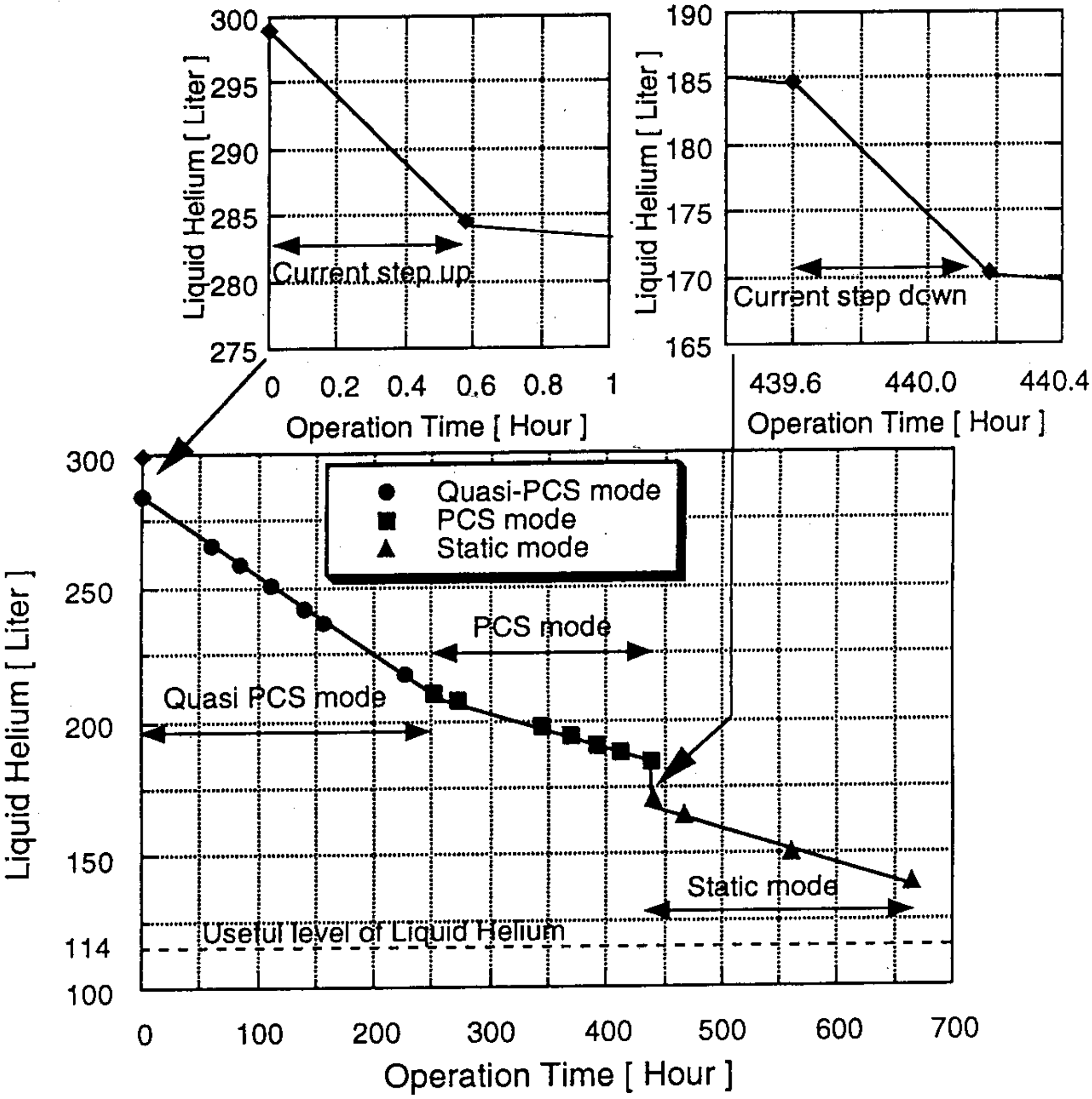

Fig. 5 Liquid helium consumption in several operation mode