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THE NEW FABRICATION METHOD FOR A PERIODIC PERMANENT MAGNET (PPM) C-BAND (5712 MHZ) KLYSTRON

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Abstract

PPM focusing is quite an attractive scheme, since it eliminates the focusing solenoid (and its power supply) from the klystron. However, one technical difficulty lies in how to integrate the magnetic-circuit, which is relatively complicated, into the vacuum tube. We have solved this problem by introducing a new fabrication technique of metal-to-metal diffusion-bonding by hot-isostatic-pressing (HIP). After simply stacking alternatively the disks made of magnetic stainless-steel (Mag-SUS) and oxygen-free-copper (OFC) without any brazing-material, they were bonded together by pressing with a high-pressure (1200-kgf/cm^2) at a high temperature (800-°C) for 2 hours. Machining this bonded block produces the drift-tube for the PPM-klystron. We chose the neodymium magnet because of its high maximum BH-product (>40 MGOe), while still having relatively low cost. A 50-MW class C-band PPM klystron is under fabrication. Already magnetic field measurement has been performed, and the axial-field profile was confirmed to be within tolerance. A high power test is scheduled in July 2000.

1 INTRODUCTION

Hardware R&D on the C-band (5712-MHz) RF-system for the Japan Linear Collider (JLC) started in 1996 at KEK. For Phase-I (500-GeV C. M. energy), the JLC will use 3500 klystrons of 50-MW output power [2], [3]. No laboratory has ever built such a large-scale accelerator, and nobody has any experience in fabricating such a large number of accelerator components. Therefore, it is very important to design the machine to provide the following key features: high reliability, high machine-availability and good maintainability, lower construction cost, reasonably high power-efficiency and operationally ease.

We have already developed three 50-MW class klystrons in the three years 1996-1998. All of them successfully generated rf output power as high as 50-MW or more. After long test runs (>5000 hours each), we confirmed performance as being acceptable for the JLC-I project [3].

The rf power efficiency of existing high-power klystrons is usually less than 50%, which is the main limit for the total power-efficiency of the RF-acceleration system. PPM focusing is a very attractive scheme, since it improves the system power-efficiency by eliminating the electrical power for the focusing solenoid, and also improving the beam-to-rf power conversion efficiency.

The PPM focusing scheme was first applied to a high-power klystron by D. Sprehn [4] in 1996 at SLAC in the course of R&D for the X-band NLC. They demonstrated stable operation at an output power level over 50-MW and a beam-to-rf power-efficiency as high as 60%. In spite of this promising result, industrialization of this type of tube seems to be not easy, because (1) we have to integrate the relatively complicated magnetic circuits into the vacuum tube; at least 20 pole-pieces are required in one tube and (2) the pole-pieces are usually made of iron which is troublesome for the brazing process due to its thermal expansion coefficient being lower than copper, and the iron easily becomes rusty.

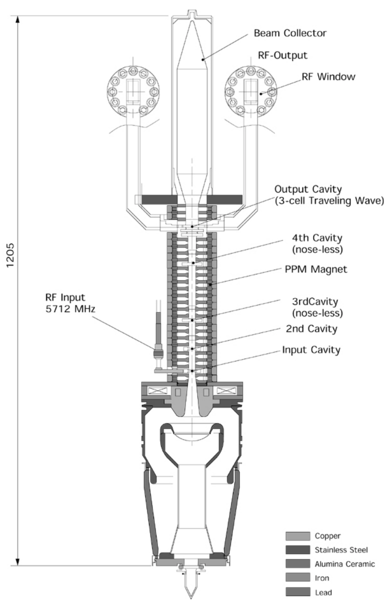

Fig. 1: Cut away view of the first C-band (5712 MHz) 50 MW-class PPM type klystrons (TOSHIBA E3747).

We have solved these problems by developing a new fabrication technique for metal-to-metal diffusion-bonding by hot-isostatic-pressing (HIP). Figure 1 shows the first C-band PPM klystron now under fabrication at TOSHIBA Co. In this paper, we will describe the basic design of the C-band PPM klystron and the new fabrication technique for the magnetic circuit.

2 PPM KLYSTRON DESIGN

In order to minimize the required R&D items, we decided to upgrade the existing design of our C-band klystron (No.3-tube). Thus we kept the same design for the electron gun, the output cavity (traveling-wave structure) and the beam collector, limiting the new design to the drift-tube part in order to implement the PPM scheme.

2.1 Electrical Design

We used the FCI-code [5] to find the optimum magnetic-field profile. The simulates the beam dynamics in

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the drift-tube using a PIC-method, which takes into account the space-charge field, interaction with RF-cavities, and the external focusing PPM-field. The electrical parameters for the design are listed in Table-1.

Table 1: Main parameters for the PPM klystron.

Frequency	5712	MHz
Output rf power	50	MW
RF pulse width	2.5	μsec
Beam voltage	350	KV
Beam current	317	A
RF power efficiency	48	%
Perveance (10^{-6})	1.53	$A/V^{1.5}$
Drift tube radius(up/down stream)	7.5/9.0	mm
Beam radius (up stream)	5.0	mm
Brillouin field (relativistic)	1.9	kG
Peak field (on axis, upstream)	2.0	kG
Plasma wavelength (λ)	82.3	mm
PPM pitch (λ)	30	λ.PPM
Cutoff voltage (α=66)	23	kV
Permanent Magnet 1) Residual Induction: Br Coercive force: Hc	Neodymium 1.2 11	N40A Tesla k-Oe
Pole-piece 2)	Mag-SUS: Fe+14%Cr+C (20-ppm)	

Note: 1) Shin-Etsu Chemical Co., Ltd., type N40A.
2) NKK Co., special order material.

2.2 Design of PPM Focusing System

We chose "Mag-SUS" for the pole-piece instead of pure iron. The principle chemical composition is Fe+14%Cr, which avoids the rust problem. The carbon content is controlled to be below 20-ppm; this is important in preserving the ferrite-phase after the heat-cycles from the HIP and conventional brazing processes.

We chose a neodymium magnet ($Nd_2Fe_{14}B$) because of its excellent performance. Fortunately it has become lower in cost, because it is widely using in high-tech devices like computers, electro-mechanical devices, transportation and consumer electronics.

The magnet module is made of a half-ring shaped permanent magnet sandwiched between two iron pole-pieces and an aluminum guard ring as shown in Figure 2. The permanent magnet is nickel plated to avoid degradation of field property due to oxidation. After assembling the parts in one module using "Epoxy-Bond", it is magnetized. Handling the fully magnetized neodymium magnet without shields is sometimes risky due to the very strong attractive force. But since the pole-piece acts as a magnetic shield, we can safely handle the magnetized module, and easily mount it onto the klystron body.

Left: each magnet comprises of 2 of half rings. Right: assembled PPM magnets comprises of 24 modules.

Fig. 2: PPM magnet mounted on the main body of klystron.

Figure 3 shows the magnetic-field patterns from the simulation. Since there is a rather long path through the Mag-SUS disks, which are relatively wide, a large amount of the total field flux is bypassed between them, and only a fraction remains which can reach into the beam pipe. While this design results in an inefficient field usage, it does generate a fairly axial-symmetric field in the beam pipe. This is quite an important feature for achieving stable beam transport. Additionally, the thick body serves as a radiation shield for the neodymium magnet, and provides space for the cooling water channel and enough mechanical rigidity to support the gun parts.

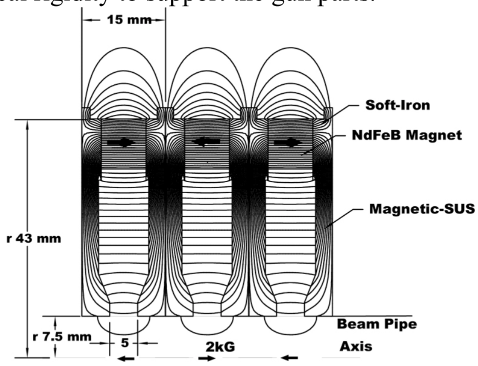

Fig. 3: Cutaway view of the PPM structure and the magnetic-field pattern.

In order to verify the quality of the permanent magnets and the magnetic circuits, field measurement was performed before welding on the electron gun and beam collector. All of the magnet modules were mounted on the klystron body as also shown in Figure 2. Figure 4 shows the measured field profile along the axis. The large positive swing around z=550 mm corresponds to the output cavity of the three-cell traveling wave structure. The measured data is within tolerance of the expected profile.

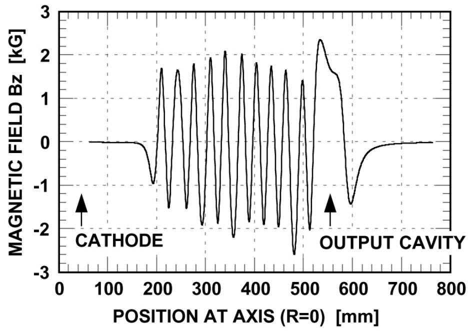

Fig 4: Measured field profile along the axis at the center. (Bz, r=0)

3 FABRICATION OF PPM CIRCUIT

3.1 Diffusion bonding

In order to transfer the magnetic flux to the beam from the permanent magnet, which is mounted outside of the klystron, we need a periodic magnetic-circuit. And in order to integrate the magnetic components into the klystron body, usually made of OFC copper, we decided to use the HIP process [6] as follows:

(1) Prepare disks made of "Mag-SUS" and OFC with purity better than 99.99%.
(2) Stack them alternatively, without any brazing material.
(3) Put them in a vacuum capsule made of OFC as shown in Figure 5, and seal the end caps with an electron-beam welder (EBW) in vacuum.

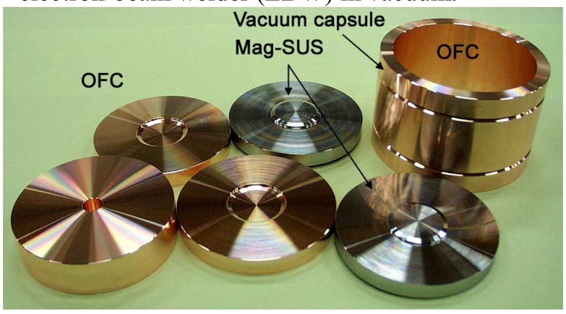

Fig. 5: PPM components before assembly. They are stacked together and then inserted into the vacuum capsule.

(4) HIP process at a 1200-kgf/cm^2 pressure and 800-°C temperature for 2 hours in Ar-gas. The process is shown schematically in Figure 6.

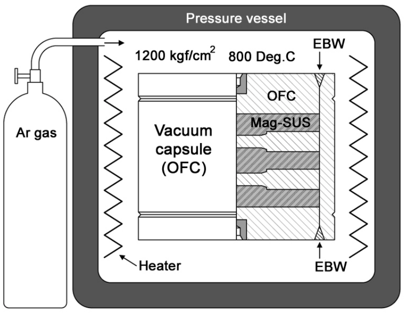

Fig. 6: HIP diffusion bonding process.

(5) Remove the capsule with a turning lathe, then drill the beam hole at the center, four water channels. Finally machine the rf-cavity and the waveguide port. The resulting module is shown in Figure 7.

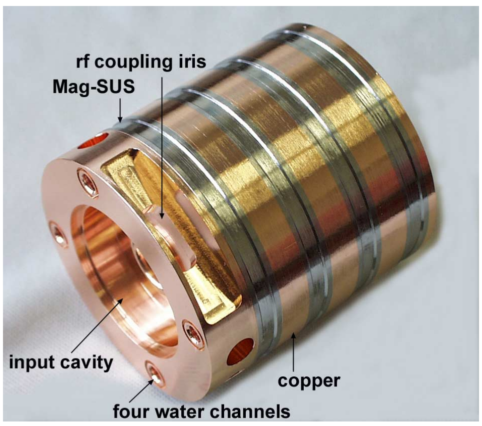

Fig. 7: The diffusion bonded PPM modules, after machining an input rf-cavity, an iris, the beam hole and four water channels.

(6) Braze the modules together using brazing wire placed radially at each rf-cavity.

To do HIP, great care has to be taken with regard to surface roughness and cleanness of all materials to be bonded. A surface flatness of ±25-μm and a roughness of around ±0.6-μm is good enough, both can be easily obtained using today's standard turning lathe.

A big technical advantage in using HIP is that one can obtain perfect metal-to-metal bonding even if the pair of materials has different properties [6]. In the present case, the thermal expansion coefficients are quite different (Mag-SUS is 1.2 x 10^{-5}, and the copper is 1.7 x 10^{-5}); even so the bonding process is still performed very well under HIP. We believe that the external pressure applied from the Ar-gas keeps the materials positioned stably form during the HIP process, and suppresses any deformation associated with the difference in thermal expansions (possibly plastic-flow in copper also helps this process). A schematic view of the HIP process is shown in Figure 6.

3.2 Experimental results

After HIP, the bonding zone at the interface between Mag-SUS and copper was found to be 3-μm in thickness. The bonding zone showed a tensile strength in the range of 213-221 N/mm^2, which is comparable to the strength of bulk copper. The tensile strength of the bonding zone will gradually increase with lengthening of the HIP and the baking cycle.

After a 10 minute 1000 °C and 40 hour 500 °C heat-treatment in a hydrogen furnace, no leak was found using a He-leak detector at a sensitivity better than 10^{-10} Atm・cm^3/sec. There was no evidence of dimensional change after the heat cycle. An assembled PPM module ready for brazing is shown in Figure 7.

4 CONCLUSIONS

The first C-band PPM klystron which uses the unique fabrication technique described here is under fabrication. Its first high power test is scheduled in July 2000.

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