A BROADBAND AND HIGH GRADIENT RF CAVITY FOR A COMPACT PROTON SYNCHROTRON

Z. Fang, K. Endo, KEK, Tsukuba, Japan
T. Nagayama, Y. Kijima, Mitsubishi Electric Co., Kobe, Japan
I. I. Averboukh, BINP, Novosibirsk, Russia

Abstract

A broadband and high gradient rf cavity has been designed for a compact proton synchrotron, which has been approved to develop for radiation therapy [1-3]. A maximal high peak voltage of about 20kV will be applied in the cavity, including the fundamental from 1.7MHZ to 15MHz, and the second and possibly third harmonics. The design principle of the wideband cavity without tuning system by using high-permeability magnetic alloy (FINEMET) cores is described. Some calculation results will be presented. And a prototype will be developed and tested.

1 INTRODUCTION

According to the lattice design of the compact proton synchrotron [1-3], 2MeV protons will be injected into the ring of circumference of 11.9m and accelerated up to 200MeV within 5ms, with a maximal operation repetition rate of 10Hz. As the proton energy increases, the fundamental frequency increases from 1.7MHz to 15MHz, as shown in Fig. 1. And the required accelerating voltage as function of frequency is shown in Fig. 2. Since the second and possibly third rf harmonics will also be applied to the cavity to increase the injection efficiency, the rf system is designed to produce maximal high peak voltage of about 20kV in the cavity. Furthermore, in order to realize the compact design of synchrotron ring, the cavity length should be shorter than 0.5m. Since Magnetic alloy (FINEMET) cores have a very high permeability and a very high Curie temperature about 570°C, and they are stable to be used at rf magnetic flux density up to 2000gauss, so the FINEMET cores will be used in the our cavity to realize the wide bandwidth and the high gradient. The cavity shunt impedance, necessary rf driving current and power, and core cooling have been carefully calculated in order to determine the cavity structure. The main parameters of the rf system are summarized in Table 1.

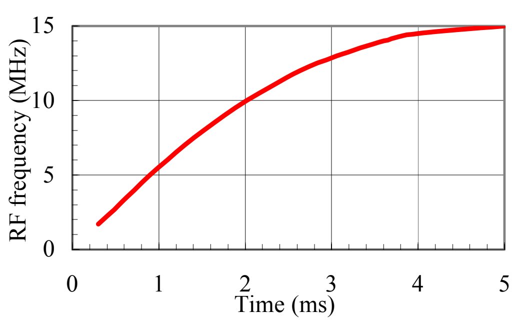


Figure 1: RF frequency as function of acceleration time.

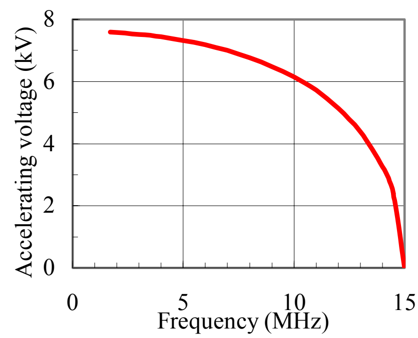


Figure 2: Accelerating voltage as function of frequency.

Table 1: Main parameters of the rf system.

Fundamental frequency range	1.7~15 MHz
Max. fundamental peak voltage	13 kV
Max. peak voltage (including fundamental, 2nd and possibly 3rd harmonics)	20 kV
Acceleration time	5 ms
Repetition rate	< 10 Hz
Length	500 mm
Number of cavities	4
Shunt impedance	~ 200 Ω × 4
Amplifier tubes	4CX20,000B × 4

2 CAVITY DESIGN

2.1 Cavity Impedance and Core Permeability

The impedance of cavity loaded with FINEMET cores is calculated by using the lumped element model, which has proved to be exactly correct by experiments. The equivalent circuit of the cavity is treated as a parallel circuit of lumped elements of cores and a gap capacitor C_g. Thus the cavity impedance is:

$$Z_{cav} = \frac{1}{\frac{1}{j\omega(u'-ju'')L_0} + j\omega C_g}$$

where $u = u' - ju''$ is the complex permeability of FINEMET cores. u' and u'' are functions of frequency, and they decrease with frequency.

$$L_0 = \frac{u_0}{2\pi} h \ln\frac{b}{a} = 2\times10^{-7} \times h \ln\frac{b}{a}$$

where a and b are the inner and outer diameters of cores, and h is the core length. $h\ln(b/a)$ is called as the filling factor of loaded cores.

The circuit can be converted to a parallel resonant *RLC* circuit:

$$R = \frac{|u|^2}{u''}\omega L_0,\quad L = \frac{|u|^2}{u'}L_0,\ C = C_g.$$

The amplitude of cavity impedance is:

$$|Z| = \frac{R}{\sqrt{1 + R^2(\frac{1}{\omega L} - \omega C)^2}}$$

And the phase of the impedance is:

$$\phi = \tan^{-1}\left[R(\frac{1}{\omega L} - \omega C)\right]$$

We have investigated the characteristics of different FINEMET (FT-3M) cores by calculating and measuring the cavity impedance from 0.5MHz to 45MHz, and got the FINEMET permeability as function of frequency:

$$\log u' = a + b\log f,\quad \log u'' = c + d\log f,$$

or $$u' = 10^a \cdot f^b \propto f^b,\quad u'' = 10^c \cdot f^d \propto f^d.$$

At 0.5MHz, u' is about from 2200 to 3700, and u'' is about from 4700 to 6500. b is about -0.93, and d is about -0.74. These data will be used in the cavity design.

2.2 Broad Band and High Gradient

Since our cavity requires a relatively wide bandwidth and a high gradient, the cavity must be designed to be of high shunt impedance over the whole operating frequency range.

At low frequency, since $\frac{1}{\omega L} >> \omega C$, the cavity impedance becomes:

$$|Z| \approx \frac{R}{\sqrt{1 + (\frac{R}{\omega L})^2}} = |u|\omega L_0 = 2\omega \times 10^{-7} \times |u| h \ln\frac{b}{a} \propto |u| h \ln\frac{b}{a}$$

While at high frequency, since $\frac{1}{\omega L} << \omega C$, so cavity impedance becomes: $|Z| \approx \frac{R}{\sqrt{1 + (R\omega C)^2}}$. In case of $R\omega C >> 1$, $|Z| \approx \frac{1}{\omega C} \propto \frac{1}{C}$.

So, at low frequency, the FINEMET cores mainly determine the cavity impedance, and the impedance increases with the filling factor and permeability of cores. In order to get high impedance at low frequency, we must load in cavity with high permeability FINEMET cores as many as possible within the permitted length. At high frequency, the gap capacitance mainly determines the cavity impedance, and the impedance decreases with the frequency and gap capacitance. So, we must reduce the gap capacitance as much as possible in the design of the cavity structure. Furthermore, using multi cavity gaps is a method to increase impedance at high frequency, since it increases with the number of gaps. On the other hand, the phase of impedance at high frequency will be also reduced by using multi gaps, since the inductance of cores loaded in each cavity is reduced. Fig. 3 shows the cavity impedance for 2 cases, 4 cores loaded in 1 and 2 cavities respectively. In the calculations, we use same cores as that used in our system (see sec. 2.3) and the gap capacitance is assumed as 60pF. We can see that the frequency response of cavity impedance of multi gap is much better than that of single gap.

By using multi cavity gaps and reducing gap capacitance in each cavity, we will obtain high shunt impedance with the broad band in our rf system. As a result, the necessary rf driving current and power will be reduced in the meantime.

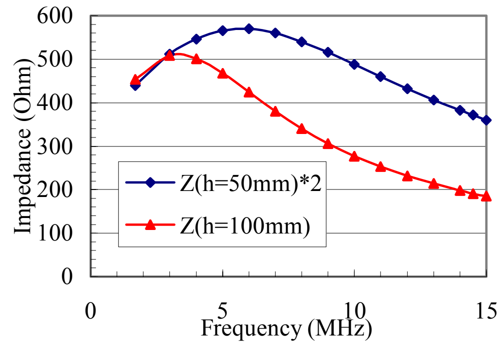


Figure 3: Cavity impedance. (upper curve, 4 cores loaded in 2 cavities; lower curve, 4 cores loaded in 1 cavity)

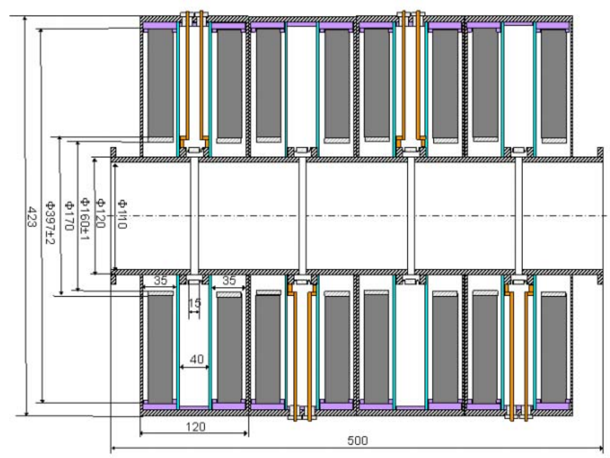
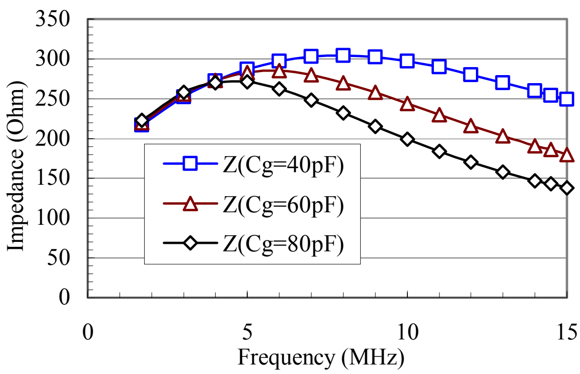


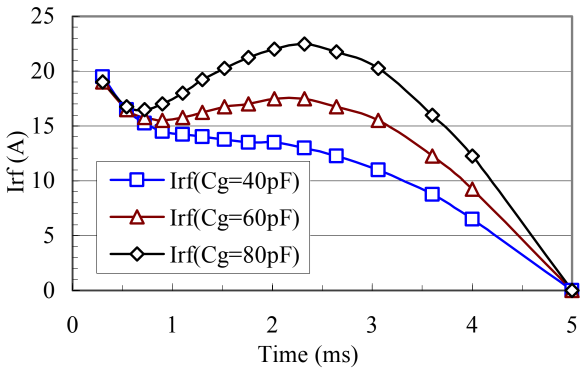
Figure 4: Cavity structure.

2.3 Structure Design and Tetrode Tubes

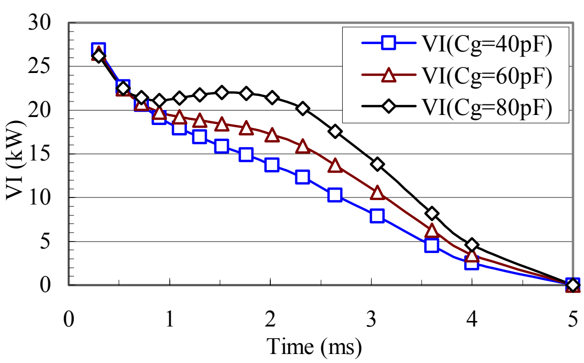
At first, the inner diameter of the drift tube of cavity is set as 110mm to satisfy the required aperture of proton beam at rf cavity. And the average value of FINEMET permeability, 3000-j5200 at 0.5MHz, is used in the design. The optimized design of rf cavity is carried out by calculating and comparing the cavity impedance, driving current and power for different cavity numbers and different core lengths in each cavity. Finally, we decide to construct the rf system with 4 cavities, loading 2 FINEMET cores in each of them, with the gap located in the center. The cavity structure is shown in Fig. 4. The length of each core is 25mm, and the outer and inner diameters are 397mm and 170mm, respectively. The length of each cavity is about 120mm, and the total length of rf system is 500mm. The calculation results are shown in Fig. 5 for each cavity. High shunt impedance is obtained with a flat curve in the whole frequency range. The cavity will work well for gap capacitance up to 70pF to keep the maximum rf current within 20A. In the cavity design, a proper space distance exists between the core and cavity wall to reduce the cavity gap capacitance less than 40pF.



a) Impedance amplitude



b) Driving rf current

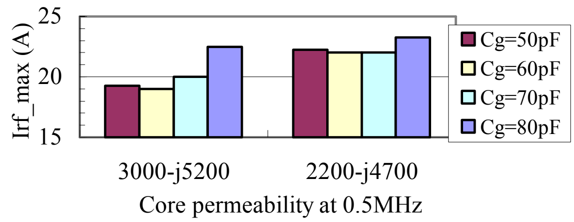


c) Driving power

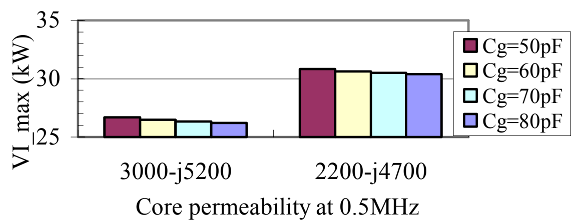
Figure 5: Calculation results for each cavity. a) impedance amplitude as function of frequency; b) driving rf current as function of time; c) driving power as function of time.

Furthermore, the effects from the permeability discrepancy of FINEMET cores have been evaluated, as shown in Fig. 6, where the permeability at 0.5MHz is assumed as 3000-j5200 and 2200-j4700 respectively in the calculation. It shows that for low permeability of cores, high rf current and power are required. To allow the discrepancy of FINEMET permeability, the maximum driving rf current and power must be higher than 22A and 31kW respectively.

Four tetrode tubes 4CX20,000B (EIMAC) are applied to drive 4 cavities, one tube to drive one cavity. The anode capacitance of tube is 25pF, and the total capacitance of the circuit will be kept within 70pF.



a) Maximum driving rf current



b) Maximum driving power

Figure 6: Calculation results of a) max. driving rf current and b) max. driving power for different permeability.

2.4 Cavity Cooling

The total average power dissipated in the cores of 4 cavities is about 2.5kW for the repetition of 10Hz, namely, 312W in each core. The cores are cooled by forced air with a total flow rate about 167 liter/sec. The maximum temperature inside cores is kept within 85°C, much lower than the Curie temperature of FINEMET cores. And FRP (fiber reinforced plastic) will be used to support the cores and guide the airflow in the cavity.

3 SUMMARY

The cavity design has been carried out with a good performance of frequency response of cavity impedance. Since this rf system works in a relatively wide frequency range, we construct the rf system with multi cavities and load in each cavity with only 2 cores, which are much fewer than that in other cavities, such as HGC at HIMAC [4] and JHF [5]. A test model is being manufactured and the high power test will be performed in the coming months.

4 REFERENCES

[1] K. Endo et al, "Table-Top Proton Synchrotron Ring for Medical Applications", EPAC2000, 2515-2517, Vienna.

[2] K. Endo et al, "Compact Proton and Heavy Ion Synchrotron for Cancer Therapy and Bio-Science", Proceedings of the 13th Symposium on Accelerator Science and Technology, 426-428, Osaka, Oct. 2001.

[3] K. Endo et al, "Compact Proton and Carbon Ion Synchrotrons for Radiation Therapy", this conference.

[4] C. Ohmori et al, "High Field-Gradient Cavities Loaded with Magnetic Alloys for Synchrotrons", PAC1999, 413-417, New York.

[5] C. Ohmori et al, "Synchrotron RF System for the JAERI-KEK Joint Project", PAC2001, 888-890, Chicago.