APPLICATION OF MAGNETIC-ALLOY-LOADED CAVITIES BEYOND 10 MHz

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Abstract

Magnetic-Alloy-loaded cavities have been used for many applications; beam accelerations of high-intensity proton and heavy ion beams, beam manipulations, medical accelerators and anti-proton decelerations. The material has a large permeability and the cavities have bandwidth below approximately 10 MHz. Using an external inductor for reducing the effective inductance of a cavity system, the cavity bandwidth can be moved beyond 10 MHz. The higher harmonic cavity is required in J-PARC Main Ring to enlarge the longitudinal beam emittance before reaching the flat-top energy. For the slow extraction, the emittance growth will be inevitable to suppress the beam instability. For Hyper-Kamiokande neutrino experiment, high-intensity beam with lower peak current will be required to avoid the event-pile-up at a new intermediate detector (IWCD). In this paper, we present the emittance control scenario with the cavity, beam effects on it, and design of a new VHF RF system.

INTRODUCTION

The construction of Hyper-Kamiokande, a next-generation neutrino observatory in Japan, is currently underway. Once completed, Hyper-Kamiokande will be one of the world’s largest and most sensitive detector for studying neutrinos, proton decays and astrophysical phenomena. The present long-baseline neutrino, T2K, experiment, will continues in an upgraded form, often referred to as ”T2HK” (Tōkai to Hyper-Kamiokande) after the start of Hyper-Kamiokande. In this experiment, a high-intensity neutrino beam is produced by the extracted proton beam with world’s largest numbers of the J-PARC facility in Tōkai-mura. The beam is then directed over a distance of about 295 km toward Hyper-Kamiokande. Compared to the original design, the beam power will be significantly increased to 1.3 MW [1]. In the Hyper-Kamiokande experiment, the Intermediated Water Cherenkov Detector (IWCD) plays a crucial role as a near detector. The IWCD is located relatively close to the neutrino source at J-PARC. It primary function is to measure the properties of the neutrino beam before oscillation occurs. The IWCD detects the cherenkov light of the charged particle produced by a neutrino reaction. When the peak intensity of neutrino beam becomes to high, unwanted pile-up of neutrino reaction will be increased in short beam pulses. The pile-up may disturb to identify the properties of neutrino beam.

To reduce the peak intensity of the neutrino beam, a task force was organized within J-PARC Main Ring group in 2020 to investigate the time structure of proton beam bunch. Several beam manipulation techniques were investigated using a simulation code to extend the beam bunch widths at the flat top energy of 30 GeV [2, 3]. Beam instability during the de-bunching process was also evaluated. An advantage of these manipulations was to extend bunch length with less cost. The disadvantages were long manipulation time to extend beam bunch and existing risk of beam instabilities. The additional time period causes the extension of cycle time and reduction of beam power to produce the neutrino beam. As an alternative idea, we proposed a higher harmonic RF to expand the longitudinal beam emittance [4–6]. This scheme can be applied during acceleration [7]. It requires wideband VHF cavities to excite a parametric resonance on the beam bunch, continuously. The resonance will be excited by a phase modulation of the VHF voltage. The previous studies have determined the VHF voltage of 40 kV to reduce the peak proton intensity by half [8] as shown in Fig. 1. The VHF scheme is also beneficial for slow extraction, since the larger momentum spread associated with increased emittance helps suppress beam instability during de-bunching [9, 10]. In this paper, we discuss a realistic scenario using the minimum required hardware for a proof-of-concept demonstration in J-PARC accelerator.

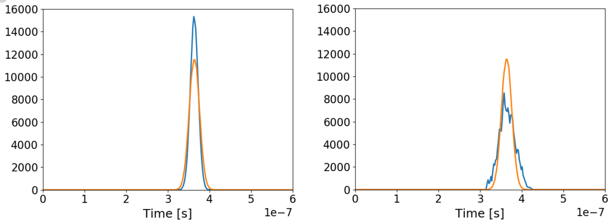

Figure 1: Effects of VHF RF. Left: without VHF, Right: 40 kV VHF voltage. Red and blue lines are bunch shapes before and after applying VHF voltage.

EMITTANCE GROWTH BY LOWER VHF VOLTAGE

In previous studies, phase modulation of the VHF voltage was applied in the second half of the acceleration, when the RF bucket area becomes much larger than the initial emittance. The total RF voltage during the modulation is

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given by Eq. (1). Here, V_0 is acceleration voltage, 400 kV during applying the VHF RF although the maximum RF voltage is 450 kV at the beginning of acceleration. The phase of VHF voltage is modulated according to Eq. (2). The total voltage is shown in Fig. 2.

$$V = V_0 \sin(h_0\omega_0 t + \phi_s) + V_{\mathrm{VHF}} \sin(h_{\mathrm{VHF}}\omega_0 t + \psi(t)) \quad (1)$$

$$\psi(t) = \Delta\phi_{\mathrm{mod}} \sin 2\pi k f_s t \quad (2)$$

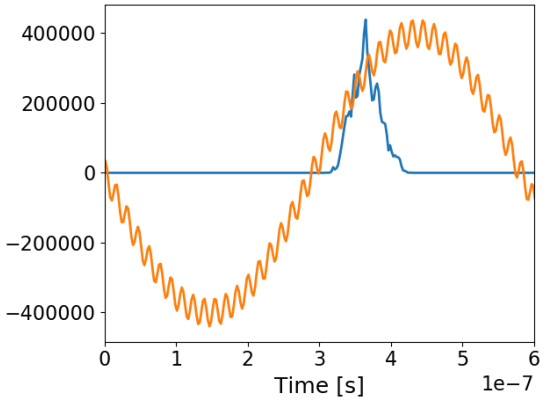

Figure 2: Sum of VHF and acceleration voltages(red) and beam bunch(blue). The VHF voltage is 40 kV.

In the previous studies, 40 MHz and 65 MHz VHF frequencies were examined. To apply it during acceleration, 65 MHz is better to obtain a good bunch shape [8]. However, 40MHz is more effective when applied to slow extraction, where it can smear the filamentation caused by a large injection phase offset and thus increase the beam emittance [9].

Figure 3 and Table 1 show the effects of phase modulation of 40 MHz and 65 MHz VHF voltages at relatively low voltages. Even with small VHF voltage, a reduction in peak intensity was observed. However, difference between these two frequencies were found. Figures 4 show waterfall plots. In case of 40 MHz VHF, only quadrupole motion was excited by the RF voltage modulation when VHF voltage is 7 kV, as shown in the left panel of Fig. 5. In case of 65 MHz VHF, small RF backets were formed, and particles were trapped and shaken, as shown in the right panel of Fig. 5.

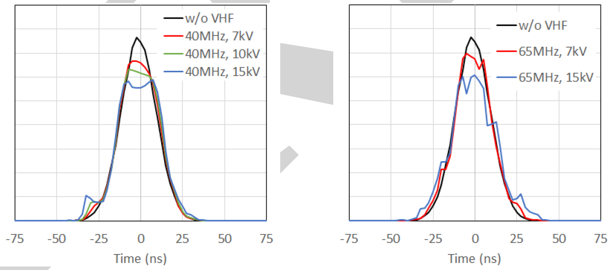

Figure 3: Effects of phase modulation of 40 MHz (Left) and 65 MHz (Right) VHF voltages during acceleration.

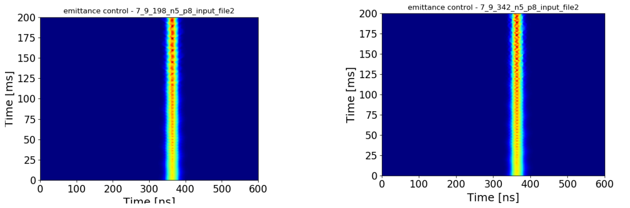

Figure 4: Waterfall plots show the effects of phase modulation of 40 MHz (Left) and 65 MHz (Right) VHF voltages during acceleration.

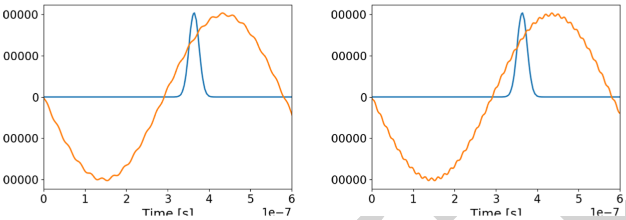

Figure 5: Total RF voltages with 7 kV-40 MHz (Left) and 7 kV-65 MHz (Right).

Table 1: Effects of Phase Modulation of VHF Voltage

Frequency [MHz]	VHF voltage [kV]	Reduction of Peak Intensity [%]
40	7	13
	15	23
	40	49
65	7	9
	15	21
	40	44

EMITTANCE GROWTH AT INJECTION

To choose 65 MHz or higher for VHF frequency, a remained issue was emittance control during injection in case of slow extraction mode. A large phase offset has been used to enlarge the beam emittance from the RCS for avoiding beam instability. Previous study showed that 40 MHz VHF was better to smear the filamentation. It was solved to enlarge the amplitude of phase sweep of 65 MHz larger than 2π. Figures 6 show the effect of the VHF RF smearing the filamentation caused by a large phase offset.

WIDEBAND VHF CAVITY SYSTEM

The wideband VHF cavity technology is based on Magnetic Alloy loaded cavity which is used in the J-PARC [11]. The J-PARC RF systems aims powerful and high RF voltage to accelerate high intensity proton bunches. Although the power-efficient direct water cooling schemes is suitable to manage high power RF, it limited a bandwidth of RF system below several MHz. To build a wideband VHF cavity, reductions of both capacitance and inductance are necessary. The inductance can be reduced by an external inductor [12]. The less capacitance can be achieved by an indirect cooling scheme which is adopted at CERN PS damper and booster cavities [13, 14]. A test cavity using the indirect

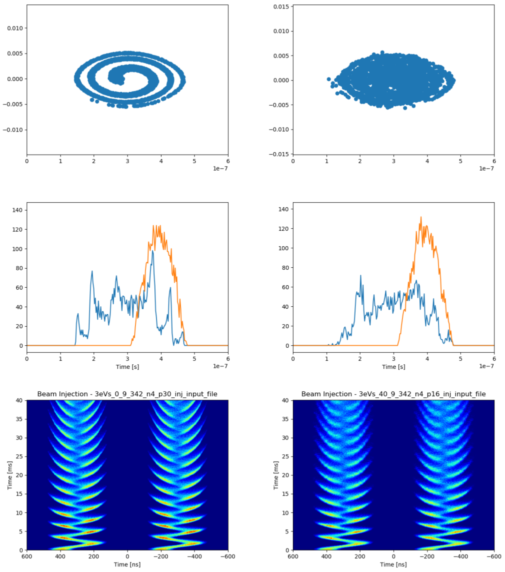

Figure 6: Left: without VHF; right: with 65 MHz, 15 kV VHF. Top: longitudinal phase spaces at 40 ms after injection. Middle: beam profiles of the injected beam (red) and at 40 ms after injection (blue). The beam bunch with 3 eV's emittance was injected with a large phase offset. Bottom: waterfall plots over 40 ms. The VHF RF smears the filamentation as seen in the right-hand panels.

cooling shows a good impedance to generate VHF voltage and less inductance at the acceleration frequency as shown in Fig. 7 [8].

The VHF cavity is driven by a tube amplifier, which must also handle higher harmonic components of the beam loading. In the case of the J-PARC beam, these harmonic components are reduced because the bunch width is approximately 40 ns, as shown in Fig. 7. For 1.3 MW beam operation, the circulating beam current is 10 A and the peak current exceeds 100 A. This allows the VHF cavity system to be more compact. Since it is not necessary to cope with heavy beam loading in J-PARC, the tube amplifier and power supplies can be of moderate size. The main parameters of RF system are listed in Table 2. The design fits within the available space at J-PARC. The amplifier design depends on the cavity design. Although a two-gap design is suitable for observing the effects to the beam, the cavity cost is approximately twice that of a single-cell cavity. It is also possible to reduce the bandwidth by adding capacitance and reducing the inductance of the external inductor. The size of APS can be made very compact by adopting a three-phase full-wave rectifier as power circuit compared with the present APS using an inverter scheme.

CONCLUSION

In Hyper-Kamiokande era, controlled longitudinal emittance growth will be inevitable to avoid event pile-up at the IWCD. The wideband VHF cavity has the advantage of reducing the peak intensity without reducing the average beam power. To demonstrate its feasibility, we propose a 7.5–-15 kV cavity as a proof of principle.

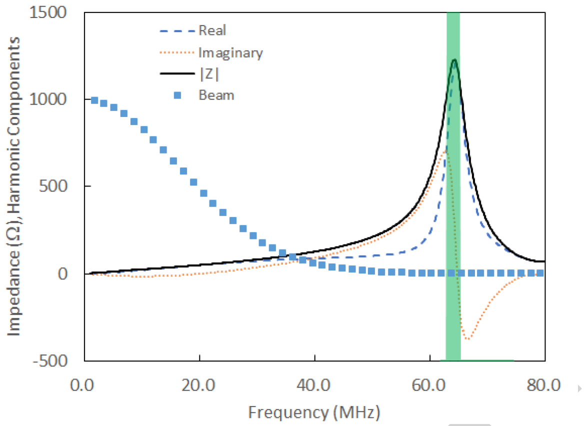

Figure 7: Cavity impedance (black, red dotted, blue dashed lines) and harmonic components (blue rectangles) of the MR beam. The required bandwidth for cavity operation during acceleration is indicated by a green line. The harmonic components in the VHF frequency range are a few percent of the beam loading at the acceleration frequency.

Table 2: RF System

Cavity	
Frequency	65 MHz
Core	Finemet FT3L 10 µm thickness 33 cm O.D.
Number of Cores	6
Cooling	Indirect
External Inductor	Coaxial 32 cm O.D, 35 cm tall
Tube Amplifier	
Tube	4CW30,000-4CW150,000
Frequency	63.48–65.36 MHz
RF power per Gap	16 kW
Number of Gaps to drive	1–2
Available VHF voltage	7.5 kV (single gap) 15 kV (2 gap)
Anode Power Supply*	
Voltage	10 kV
Current	6 A
Circuit	3-phase full-wave rectifier
Receiving Electricity	400 V, Three-phase
High Voltage Transformer	dry-type
Size	1 m ×1.2 m ×1.8 m

*based on the APS design used for the beam test at HIMAC

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