RF Acceleration Systems for the JAERI-KEK Joint Project

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Abstract

The RF acceleration system has been designed for the JAERI-KEK Joint Project for High-Intensity Proton Accelerators in Japan. Main parameters for the RF system will be described. A high power RF system to drive a new type of rf cavity using MA (Magnetic Alloy) cores will be also reported.

1. INTRODUCTION

A high intensity proton beam of 15μA will be accelerated in the 50 GeV MR. Stability under heavy beam loading is the most importance issue on RF systems of both 3 GeV Rapid Cycle Synchrotron (RCS) and 50GeV Main Ring (MR). The circulating beam intensity is two orders of magnitude larger than that of the existing KEK 12 GeV-PS. However, beam loss is not allowed to be more than the level of the present KEK-PS. The linac beam will be painted naturally in longitudinal phase space. Together with painting in transverse phase space, its longitudinal emittance will be controlled so as to keep the bunching factor to be more than an appropriate value regarding space charge tune shift. The RF system is used not only for acceleration but also for bunch manipulation.

2. LONGITUDINAL EMITTANCE

2.1 General

It is very important to consider fast and slow beam losses due to space charge tune shift in a high intensity proton synchrotron. To control the incoherent tune shift growth, the longitudinal manipulation is the only way to solve the problem. The longitudinal bunch shape should be managed to conserve the bunching factor as much as possible. The required bunching factors are kept higher than 0.4 at the RCS injection and 0.3 at the MR injection, respectively. In the MR, the longitudinal emittance should be increased to be larger than 10eV·s before the top energy. The threshold of longitudinal microwave instability becomes severe. The longitudinal emittance at RCS injection is at most 3.5eV·s. Controlled emittance blow-up is necessary during acceleration. According to particle tracking so far, however, it seems difficult to manage increasing the bunching factor and longitudinal emittance simultaneously in the RCS without any beam loss. One should consider separated longitudinal manipulations of bunch shaping and emittance blow-up.

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2.2 Longitudinal Issue in RCS

The linac beam pulse is chopped to fit a longitudinal waiting bucket of the RCS. The design value of chopping duty is 56%. This is expected to minimize beam loss during bunch forming process in the RCS. The linac beam is injected at a prior timing to *Bmin*. The injection timing, pulse width, chopping duty and momentum-offset injection are the parameters to optimize the bunch formation in the RCS. In order to keep the bunching factor > 0.4 at the injection, the second harmonic RF system is necessary. Figure 1 shows the estimated tune spread with the required bunching factor simulated by particle tracking code [1]. The transverse emittance of the painted beam and the acceptance are 144 and 216 πmm·mrad. The corresponding tune shifts are 0.25 and 0.16, respectively.

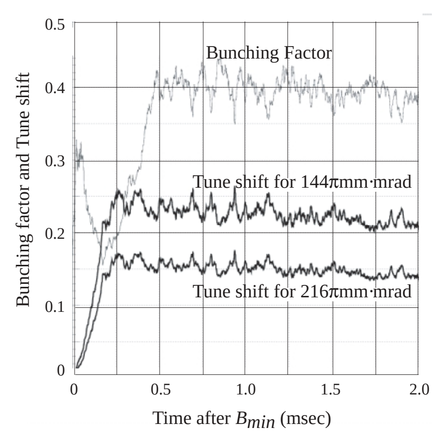

Figure 1: Time variations of the Bunching factor and Tune Shift after the RCS Injection; 0.25ms/div

Sinusoidal magnet ramping results in reduced longitudinal acceptance around 14 msec after the injection, where the synchronous phase reaches a maximum value of 45-degree. The corresponding longitudinal acceptance is roughly twice that of the beam emittance. The second harmonic RF voltage is gradually ramped down, and ramped again up at the end of the cycle for the extraction. To achieve the required bunching factor of more than 0.3 for the MR injection, each parameter for bunch manipulation has been checked carefully. Because of small synchrotron tune at the end of RCS cycle, the manipulation must start in the middle of the cycle. The adibaticity is also taken into account during the longitudinal manipulation. Reducing the accelerating voltage down to 60kV at the extraction is necessary for the longitudinal bucket matching between the two synchrotrons. In this case, the relative beam loading becomes more serious. The feedforward beam loading compensation and the counter phasing of each of the cavity voltages are appropriately applied.

2.3 Longitudinal Issue in MR

The space charge tune shift should be also considered during the long injection period in the MR. The bunching factor of 0.3 must be kept until the acceleration starts. The space charge tune shift is 0.17. On the other hand, to avoid the single bunch instability, the beam emittance should be enlarged during the acceleration. Using the Keil-Schnell-Boussard criterion, the threshold impedances are obtained as followed,

$|Z_L/n| < 285\ \Omega$ (at 3 GeV and ε_L=10 eV·s)

$|Z_L/n| < 1.9\ \Omega$ (at 50 GeV).

To keep the bunching factor of the injected beam, the second harmonic RF system is necessary. The longitudinal mismatch without the second harmonic system results in a large quadrupole oscillation. And, the oscillation may cause a periodic undesired tune shift [2].

3 BEAM LOADING

The beam loading caused by a circulating high intensity proton beam of 4.12×10^{13} protons per bunch is the most important issue when the stability of the RF system is analyzed. The RF system is necessary to supply the beam power and RF power to obtain the designed accelerating voltage. The peak beam powers are 2.8MW in the RCS and 1.5MW in the MR, which are supplied from 11 RCS RF systems and 6 MR RF systems, respectively. To keep the stability condition of the RF system, the relative loading factor [4] is chosen to be smaller than 1. However, especially, it becomes the most severe condition during the injection and extraction, because the voltage amplitude must decrease for bunch formation and longitudinal matching.

The periodic transient beam loading effect is one of the issues to be considered in the MR. This effect becomes most severe when the injected beams fill half the MR buckets. Also, during acceleration, one of nine buckets is empty for an extraction kicker system. The potential distortion caused by circulating bunches is also to be considered.

The full digital low-level control and feed-forward loading compensation systems are considered for stable and reproducible system operation and beam loading compensation [4]. The feedforward system can compensate the periodic transient effect, too.

4 HARDWARE

4.1General

The RCS ring was re-designed last year. The circumference of the ring was extended to 10/9 times of the original one. The main parameters of both synchrotrons have been updated as listed in table-1.

Table – 1. The Parameters of RF Systems

	3GeV RCS	50GeV MR
Energy (GeV): Inj.	0.4	3
Ext.	3	40~50
γ_t	9.14	j31.6*1
Cycle or period	25Hz	3.64 sec
Number of proton	8.3×10^{13}	3.3×10^{14}
Acc. Voltage (fund.*2)	450kV	280kV
Max. $\phi_{synchronous}$	45 degree	28 degree
Circumference (m)	348.3	1567.9
RF harmonic (fund.)	2	9
RF frequency (fund.)	1.23-1.67MHz	1.67-1.72MHz
Number of cavities	11 (fund. +2nd.)	6(fund)+3(2nd)
Voltage per cavity	45kV	47kV
Number of gaps	3	3
Quality factor	2-3	10-20

*1: imaginary transition energy *2: fund. = fundamental

4.2 RF Cavity

The RF accelerating cavity requires a field gradient of 20-25kV/m. The high field gradient RF systems have been designed with the Magnetic Alloy (MA) materials, instead of the conventional ferrites.

The bandwidth of the RCS cavity is 1.23MHz to 3.34MHz to cover the fundamental (H = 2) and second harmonic (H = 4) frequencies. The MR cavity will cover only the fundamental frequency of 1.67MHz to 1.72MHz (H = 9). The quality factors in the two systems have to be considered separately. In fact, the quality factor of 2-3 is selected for the RCS cavity, because of its wide accelerating bandwidth. No dynamic-tuning system is used. The combined RF signal of a fundamental to 2nd harmonic can excite the same cavity. For the MR cavity, the quality factor of 10-20 is chosen to minimize the transient beam loading. The cut-core configuration allows changing the effective quality factor of the cavity widely, without changing the shunt impedance; R/Q can be controlled [5].

Cavity cooling is the key issue to realize a high gradient cavity. The power dissipation in a core is 5kW for the RCS cavity and 9kW for the MR cavity. For effective core cooling, two different cooling methods have been considered; so-called, "*direct water cooling*" and "*indirect cooling*". In case of the direct cooling cavity, each core is put into the water-sealed tank and cooled *directly* by water. This is the most effective cooling method.

However, impedance reduction due to the high dielectricity of water should be considered, when the cores are surrounded by water. Coating the surface of the cores is also necessary to prevent corrosion. In case of the in-direct cooling cavity, each core is *indirectly* cooled by a water-cooled Copper-plate. It is possible to adjust the distance of the cut core gap mechanically from the outside. This cavity is basically tunable. The insulation between MA core and Copper-plate is necessary. And, thermal contact and Copper-plate to MA core bonding is the most important engineering issue. The details are discussed in the reference of [6].

4.3 RF Power Source & Anode Power Supply

For the RF system, each cavity is driven by one power amplifier, which is installed adjacent to it. The three gaps of each cavity are connected in parallel and directly driven by the amplifier. The plate voltage is decoupled from the cavity by dc-blocking capacitors. To find reliable capacitors is one of the difficulties in designing a low-frequency high power amplifier. The output stage of the amplifier consists of two tetrodes operated in push-pull. The RF systems supply both the circulating beam power and the RF power to obtain the designed accelerating voltage. Each of RF power sources provides two of 600kW plate dissipation tetrodes.

The anode dc-power supply for RF power source is required to operate with a low ripple voltage. The synchrotron frequency of the circulating beam (f_s) varies from a frequency of a few kHz to a few ten Hz. Good frequency separation of voltage ripple and f_s are necessary for stable and accurate longitudinal beam control. On the other hand, the anode power supply needs to provide a fast power cut-off circuit to protect the tetrodes from accidental inflow energy, for example, when arcing occurs.

A conventional crowbar circuit could quench an arc inside a tetrode within several μsec. However, the circuit cannot be free from false-firing problems due to electrical noise.

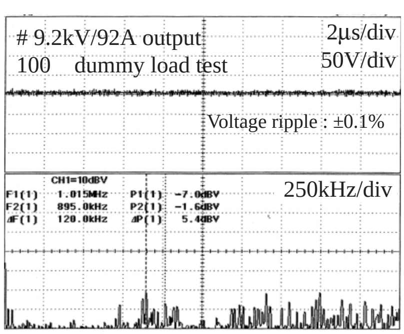

Figure 2: Voltage ripple and its Fourier spectrum

With an *IGBT* inverter power supply, it is possible to realize low ripple voltage, reliable operation, and redundancy and fast power cut-off. The total appraisement is much better compared to a conventional power supply with simple rectifiers and capacitor bank.

We have initiated to design the 1.2MW proto-type anode dc power supply for the 50GeV MR, of which the design is based on the 400kW IGBT dc-power supply for the high gradient MA RF system installed in KEK-12GeV PS [5]. The output voltage of this anode power supply was measured at the maximum current rating of 92A. A voltage ripple of ±0.1% has been achieved with a 100Ω resistor load (Figure-2).

5 SUMMARY

The tune shift dominated by space charge should be small enough to minimize beam loss during the injection. The bunching factors are required to be 0.4 at the RCS injection and 0.3 at the MR injection. Longitudinal tracking shows that the bunching factor control in the RCS seems to be possible by optimizing injection parameters and adding the 2nd harmonic system. Also, in the MR, the 2nd harmonic RF system is indispensable to avoid longitudinal mismatch. Concerning heavy beam loading, the feedforward system is essential to compensate the beam loading and to stabilize the RF system. Full-digital systems are designed to construct accurate and reproducible low-level RF controls.

The RF systems are necessary to supply both the circulating beam power and the RF power to obtain the designed accelerating voltage. The peak beam powers are 2.8MW in the RCS and 1.5 MW in the MR, which are shared with 11 RCS RF systems and 6 MR RF systems, respectively. The RF cavities are high field gradient systems with magnetic alloy cores. The designed field gradient is 20-25kV/m. The cut core configuration is applied in order to change the effective value of the cavity according to the system requirement. The quality factor of the RCS cavity is chosen to be 2-3, so that the bandwidth covers the accelerating frequency and its second harmonics. The cavity can be used as the 2nd harmonic system as well as the accelerating system. In case of the MR cavity, the quality factor is not necessary to be small, because of the small change of accelerating frequency (3%). And also, to avoid periodic transient beam loading, the quality factor of 10-20 is selected.

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