

SCSS RF CONTROL TOWARD 5712 MHz PHASE ACCURACY OF ONE DEGREE

Yuji Otake, Hirokazu Maesaka, Masanobu Kitamura, Tumoru Shintake, RIKEN, Harima Institute
 1-1-1 Kouto, Sayo-tyou, Sayo-gun, Hyogo, 679-5148, Japan
 Takashi Ohshima, Naoyasu Hosoda, Toru Fukui, Toru Ohata, Japan Synchrotron Radiation
 Research Institute (JASRI/SPring-8), Kouto, Sayo-tyou, Sayo-gun, Hyogo, 679-5198, Japan

Abstract

A 250 MeV prototype accelerator was built. Its low-level rf system, which mainly controls a 5712 MHz pulsed rf signal, was built to achieve very tight requirements: phase stability and a setting resolution of less than 1 deg.. These requirements correspond to a beam energy variation of 10^{-4} at the crest acceleration for the 5712 MHz rf. To realize the requirements, IQ-modulators/demodulators and arbitrary wave form generators/digitizers of VME modules (D/A, A/D) to handle an IQ-function were developed. The PID control method was employed to compensate for any time drift, such as an rf phase. We finally achieved phase setting and a detecting resolution of the IQ-modulators/demodulator of +/- 0.5 deg. at 5712 MHz. Decreasing the phase drift with in +/- 0.5 deg. was also achieved by a PID control program. By this control performance, a beam energy variation of 0.06% was achieved.

INTRODUCTION

To check the feasibility of X-FEL(SCSS),[1] the 250 MeV prototype accelerator was constructed at SPring-8 [2]. The construction was started from October, 2004, and finished in December, 2005. After construction, we confirmed 49 nm SASE light by the prototype accelerator with 250 MeV, 0.2 nC electron beams, and 10 Hz repetition [2,3]. This 60 m long accelerator comprises a 500 kV CeB6 mono-crystal thermionic electron gun with a beam deflector for making a 1ns (FWHM) beam pulse width, a 238MHz pre-buncher cavity and a 476 MHz booster cavity for bunching and accelerating beams, a 2856 MHz APS cavity and a 2856 MHz/2m long accelerator guide to obtain 50 MeV beams, four 1.8 m

long/5712 MHz accelerator guides to make the beam energy up to 250 MeV, and two 3 mm gap in-vacuum undulators to generate 49 nm laser light. In the case of the prototype accelerator, the pulse width of the beams should be compressed to 1 ps by a magnetic bunch compressor to obtain about a 1 kA peak current for generating SASE [3]. Therefore, a low-level RF system of the accelerator was built to achieve very tight requirements, which were 5712 MHz phase stability and a resolution of less than +/-0.5 deg., as well as 5712 MHz amplitude stability and a resolution of less than 10^{-4} [4]. These requirements correspond to a beam energy variation of less than 10^{-4} at a crest acceleration of a 5712 MHz rf. This phase value corresponds to time stability and a resolution of less than 500 fs. Such stability and a resolution are necessary to achieve 100 μm pointing stability of electron beams and to generate laser light for the undulator section of about 10 m long [5]. This paper gives a summary and describes the performance of the low-level rf system and its key components, such as an IQ-demodulator and an IQ-modulator as well as the PID control method to obtain long-term phase and amplitude stability.

RF SYSTEM

The low level rf system of the prototype accelerator was built as shown in Fig. 1 [6]. CW signals of 238 MHz, 476 MHz, 2856 MHz, and 5712 MHz for acceleration are provided with a signal source having a very low noise level, which causes an rf phase jitter. These signals are transmitted to rf components through phase-stabilized coaxial cables having a temperature coefficient corresponding to an electrical length of 10 ppm/°k.

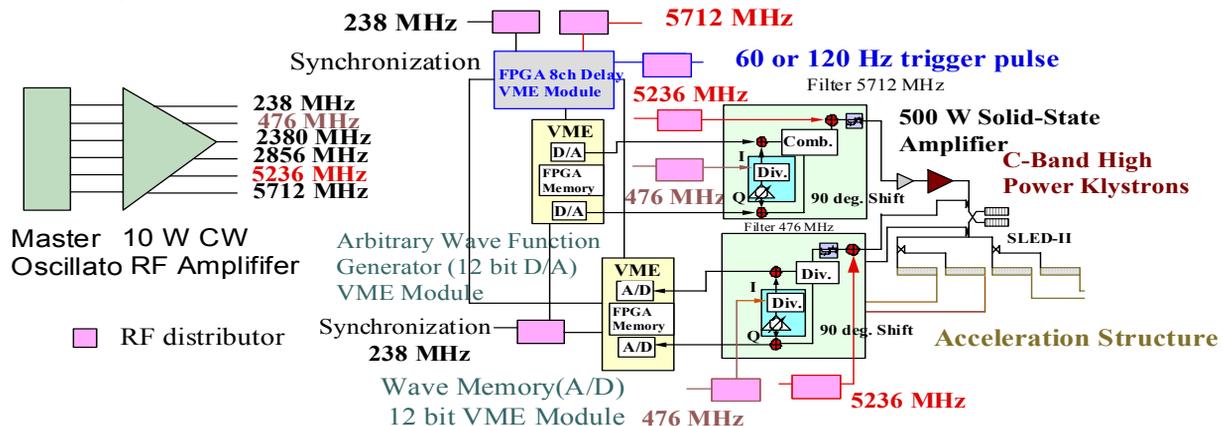


Figure 1: SCSS rf system. The system mainly comprise a very low-noise signal source, IQ-modulators/demodulators, A/Ds and D/A's to control IQ- instruments, and 600 w solid state klystron driver amplifiers.

The signals drive rf components, such as a 5712 MHz klystron with 50 MW output power and a 2 μs pulse width. Because of using coaxial cables, we should take care of any rf loss. Therefore, 10 W rf amplifiers of these signals, stabilized by PLL (Phase Locked Loop) and ALC (Auto Level Control), should be used. To drive the C-band 50 MW klystron, the signals should be modulated to make a 2 μs pulsed rf, and rf phase and amplitude control to the signals is necessary. These signal manipulations are achieved with an IQ-modulator and a VME-D/A module. The output of the IQ-modulator is applied to a 600 W solid state amplifier to drive the klystron. The phase and amplitude of the output rf from the klystron are monitored with an IQ-demodulator and an VME-A/D module though an 60 dB rf waveguide directional coupler.

COMPONENTS OF LOW LEVEL RF SYSTEM

Master Oscillator

The master oscillator,[6] which generates 238, 476, 2380, 2856, 5236, and 5712 MHz stable rf signals, is a time reference source. The circuit configuration of the oscillator is shown in Fig. 2. It comprises a very stable reference generator (stability of 10⁻¹¹) of 10 MHz, which has a low-noise characteristic in the frequency region below 1 kHz measured from 10 MHz, a 2856 MHz signal generator having a low-noise characteristic in the frequency region over 1 kHz measured from 2856 MHz, a frequency doubler instrument to make 5712 MHz from 2856 MHz, and frequency dividers to generate the above-mentioned frequency signals. Both low-noise signal generators are connected by a PLL circuit to make the very low SSB (Single Side Band) phase noise over the whole frequency range, as shown in Fig. 3. The noise level is -140 dBc/Hz at 1 MHz, measured from 2856 MHz.

IQ-modulator and demodulator

The IQ-modulator and demodulator [6] employs a Gilbert Cell, which has a very good rf phase and amplitude stability to any temperature change as well as nice rf isolation, as a mixer. Figure 4 shows an example of a developed 5712 MHz IQ-demodulator. The IQ-modulator also uses a similar circuit. The cell can handle up to 2.7 GHz, because of technical limitation when we designed them. Therefore, the IQ-modulator and demodulator use detection in 476 MHz, which is the frequency of the booster cavity, and employ the heterodyne method to make 476 MHz by mixing 5712 MHz and 5236 MHz. An amplifier having a noise level of nV/Sqrt(Hz) is used at the input/output stage of the modulator/demodulator. To prevent the effect of external noise, a 100 ohm differential signal transmission is employed for connection between the modulator/demodulator and the A/D/D/A modules to read/write the IQ-data. Figure 5 shows the phase-detection characteristic of the IQ-demodulator. The

phase-modulation characteristic of the IQ-modulator is also of comparable performance. The phase-detection resolution is about +/- 0.5 deg. at 5712 MHz, and the relative amplitude resolution is less than 0.1%.

VME-A/D and D/A module

The VME-A/D, [6, 7] as shown in Fig. 6, was developed to digitize the IQ-detection signal. A VME-D/A [6,7] module was also developed to manipulate the IQ-modulator. Both modules have 12-bit resolutions, wave-data generation driven by 238 MHz clock, and a 30 MHz base band width at the input/output.

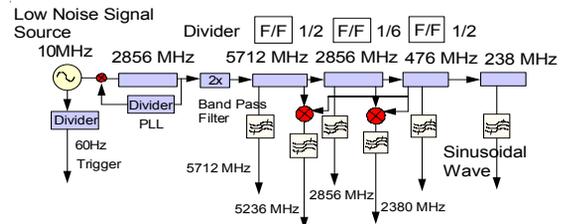


Figure 2: Circuit diagram of the master oscillator. The oscillator uses frequency dividing, a very low-noise power supply and PLL connection between the 10 MHz and 2856 MHz sources to achieve low noise.

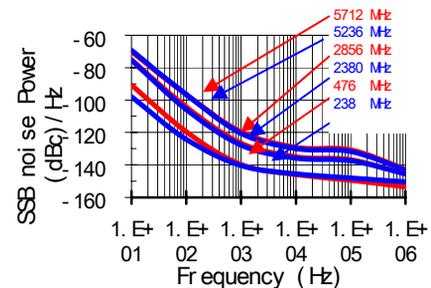


Figure 3: SSB noise power spectra of the master oscillator. The decreasing noise level at individual frequencies is proportional to the dividing ratio.

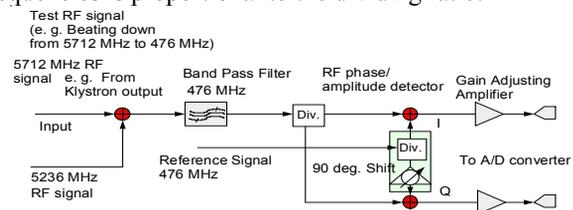


Figure 4: Block diagram of the IQ-demodulator. The demodulator uses the heterodyne method for detection at 476 MHz. The 476 MHz signal is made from mixing the 5712 MHz and 5236 MHz signals.

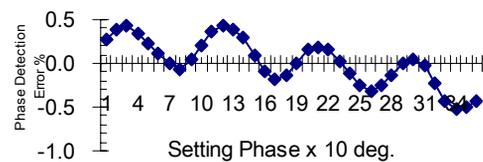


Figure 5: Phase Detection Error of the IQ-Demodulator. The detection error is within +/- 0.5 deg.

The D/A has functions that make a pulse of an arbitrary wave form such as 2 μ s in a width, and a PSK(Phase Switch Keying) operation during the rf pulse to realize rf pulse compression with SLED. One set of the two output channels of the D/A module can manipulate the IQ-function to control the IQ-modulator. This D/A module each time generates the arbitrary shape pulse triggered by an external pulse synchronized to an accelerated electron beam. The A/D module is like an oscilloscope without a display to digitize an arbitrary wave form. The VME A/D module can detect an error wave form out of tolerance referred to a reference wave form that is memorized in advance. The tolerance is such as 10% defined in advance. For example, by this function, the module can automatically catch a large thyatron jitter that shows its replacement. We finally obtained a dynamic range devoid of noise in the A/D and D/A modules is about 11 bit (5×10^{-4} V resolution).

Stabilization of rf phase and amplitude

To stabilize the long-term rf phase and amplitude, PID (Proportional Integrate Differential) feedback control [8] of the rf phase and amplitude in the acceleration cavities was employed. The method uses the equation

$$y = K \left(e_n + \frac{\theta}{T_i} \sum e_n + T_d (e_n - e_{n-1}) \right), \quad (1)$$

where K is the gain value, e_n and e_{n-1} are the deviation values between a target value and the output of equipment at each sampling time, θ is the sampling period, T_i is the integration factor, T_d is the differentiation factor, and n is the sampling number. Y is the output value to a control target (the equipment). This equation is a quantized equation to apply to computer control. This method was achieved with the A/D and D/A modules, and a LINUX computer connected via Giga-bit Ethernet. The maximum response frequency of the method is about one tenth of the maximum repetition of the accelerator, because of the Nyquist Frequency. Figure 7 shows example stabilization data of an rf phase in the 238 MHz prebuncher cavity. The rf phase was controlled within 0.5 deg. for more than 2 hours. The control parameters of K , T_i , T_d , and θ were 0.1, 0.001, 0, and 1 s.

SUMMARY

We achieved generating non-linear amplification of a 49 nm VUV laser by the SCSS prototype accelerator using the above-mentioned low-level rf system. A pulse-by-pulse acceleration voltage (energy) jitter of 10^{-4} , which is caused by noise of the signal source, was estimated by integrating the noise spectrum (-140 dBc/Hz at 1MHz offset frequency) shown in Fig. 3 by applying a weight function described in Ref. [9]. The +/-0.5 deg. phase and amplitude resolutions of the IQ-detection and modulation were effective to satisfy our requirement to realize a beam energy stability of 10^{-4} . The PID control method stabilized the 238 MHz cavity rf phase within +/-0.3 deg. for a long period. This fact also satisfies our requirements. We finally applied this PID method to controlling the rf

phase and amplitude of the 238 MHz and 476 MHz cavities, and the rf phase of the 2856 MHz cavities. All controls worked well. We finally obtained a beam energy variation of 0.06% (peak-to-peak) in the prototype accelerator.

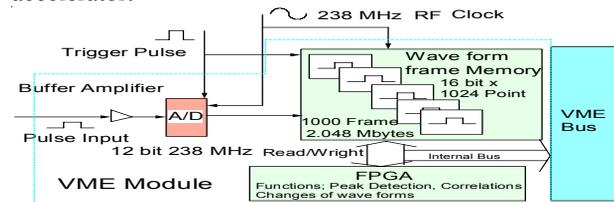


Figure 6: Schematic diagram of the A/D module. It has a 12-bit dynamic range, a data taking speed driven by a 238 MHz clock, and a 30 MHz input base bandwidth.

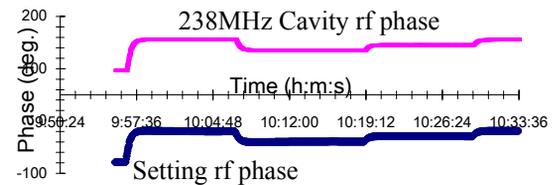


Figure 7: Example of PID feedback control performance of the 238 MHz cavity phase. This graph shows the cavity phase follows the setting phase purposely changed by an operator. The 238 MHz cavity phase is controlled within 0.5 deg. The phase difference between the cavity and setting phase is artificial.

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