BEAM STABILIZATION IN THE SPring-8 LINAC

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Abstract

The beam stability of the SPring-8 linac has been improved by means of reducing RF variations, providing beam energy compensation, and reinforcement of monitor systems: Variations in the RF power and phase have been reduced by improving the voltage regulation system for the klystron modulator, and by stabilizing the temperature drift of the atmosphere and cooling water in order to reduce the phase variation. These improvements realized a greatly reduced energy fluctuation of 0.03% rms. A new synchronous oscillator synchronizes a beam trigger pulse and a 2856 MHz reference signal. Variation in the beam charge was reduced by this synchronizing technique; the stabilized beam loading consequently resulted in the beam energy fluctuation of 0.01% rms. A beam energy compression system (ECS) was installed to compensate for accidental energy variation and reduce the energy spread due to beam loading. The reduced energy spread enabled the high-current injection without increasing beam loss. A BPM system employing shared memories for synchronized fast data acquisition has been constructed. A quasi nondistractive profile monitor using OTR was installed in a chicane section of the ECS to observe the beam energy and energy spread during the beam injection. These monitors greatly aid in both beam diagnosis and beam adjustment.

INTRODUCTION

The SPring-8 linac, which is an injector for the 1.5 GeV NewSUBARU storage ring of the Himeji Institute of Technology as well as the SPring-8 booster synchrotron.

The SPring-8 users expect a uniform bunch pattern in the stored beam; that is, every shot of the beam injection must have a stable beam current and energy. SPring-8 will soon initiate their top-up operation and will continue it for 1 month; the injector linac must be able to supply stable beams any time without interruption.

The NewSUBARU storage ring has a narrower beam acceptance than that of the booster synchrotron; the NewSUBARU's acceptance provides the energy variation range of ± 0.1% as a goal.

There are two general approaches to stabilization of a linac:

Stabilization of each device.

Introduction of feedback control.

The KEKB linac has mainly used the latter technique to realize the energy stability of 0.2% p-p[1], for example. The Spring-8 linac has adopted the former approach and has no feedback control at present.

The following program has been our strategy for stabilizing the beam:

- Investigate the variation chains which result in beam instability
- Fix origins of the variation chains
- Synchronize the linac RF and the ring RF
- Introduce an energy compression system (ECS)
- Reinforce the monitor and control system

The last item does not directly contribute the stabilization; however, it is quite important to maintain the stability during a long-term operation of the linac and the reappearance of the beam. In this paper, we describe only important devices of the monitor system.

We have carried out this program step by step since 1998[2,3]. As a result, a minimum beam energy fluctuation of 0.01% rms has been achieved and the reduced energy spread has allowed realization of a high-current injection into the synchrotron. Present performance of the linac with an operation of the ECS is given in Table 1.

Table 1: Beam parameters for SPring-8 linac (with ECS)

	Synchrotron		NewSUBARU
Pulse Width	1 ns	40 ns	1 ns
Repetition	1 pps	1 pps	1 pps
Current	2 A	70 mA	200 mA
dE/E (p-p)	0.6%	1%	0.4%
Energy Stability (rms)	0.02%	–	0.01%
ε_n (90%, mm·mrad)	<240π	<360π	<200π

Figure 1 shows a simplified diagram of the present linac's RF system. Thirteen 80 MW S-band klystrons (Toshiba E3712) feed pulsed RF power to the accelerating structures. The first klystron drives the next eleven klystrons via the 90 m waveguide drive line, as well as the injector section. A part of the RF power generated by the thirteenth klystron is also fed to an energy compression system (ECS). The ECS requires phase stability, and therefore the ECS's klystron is driven by a dedicated PLL-stabilized drive system. Details of the ECS will be explained in a later section.

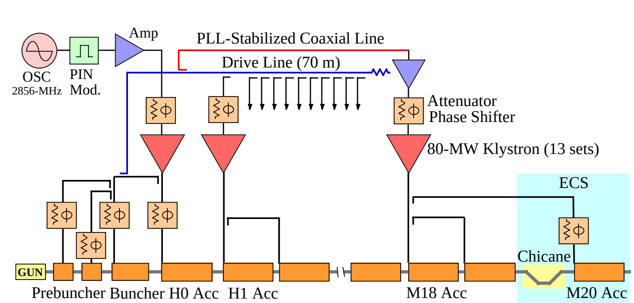

Figure 1: Diagram of improved RF system.

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VARIATION SOURCES

Variation Chains

Variation in an injection current into a synchrotron is mainly caused by its energy variation; here we consider the beam energy variation only.

In an accelerating structure, RF fields accelerate an electron beam and then give the energy gain E to the beam. The energy gain is expressed as $E = k\, P_{kly}^{0.5} \cos\varphi$, where P_{kly} is the RF power fed to the accelerating structure, φ the RF phase where beam bunches are accelerated, and k a coefficient depending on the resonant frequency of the structure and the beam loading of the RF power.

There are two typical cases for the RF phase φ; $\varphi \approx 0$ and $\varphi \approx -90$ degrees. A regular accelerating structure requires a maximum accelerating field at the crest of the RF field, then φ is adjusted to around 0 where cos φ is almost one. An ECS's accelerating structure has to compensate for the energy distribution of a bunch stretched in the chicane section. Therefore the phase φ is set to be around –90 degrees where the field gradient with respect to the phase is the maximum. Then the energy variations for the two cases can be given as follows:

$$\frac{\delta E}{E_m} \approx \frac{1}{2}\frac{\delta P_{kly}}{P_{kly}} + \frac{\delta k}{k} - \frac{1}{2}\delta\varphi^2 \quad \text{for } \varphi \approx 0$$

$$\frac{\delta E}{E_m} \approx \delta\varphi \qquad \text{for } \varphi \approx -90 \text{ degrees,}$$

where E_m is the maximum energy gain when $\varphi = \tilde{0}$

The second formula means that the ECS directly transfers the phase variation to the energy variation.

The following items are the important primary sources of energy variation in the SPring-8 linac:

1) Air temperature in a klystron gallery
2) Cooling water temperature
3) AC line for klystron modulators
4) Phase noise of the RF source
5) Asynchronousity of a beam trigger pulse and a 2856 MHz RF signal

Items 1 through 3 vary slowly; their variation periods are longer than 1 second. Items 4 and 5 cause shot-by-shot (random) fluctuation of the beam energy.

Long-Period Variation[2]

The air temperature dominates the electric length of the RF transmission line. The RF phase at the end of a transmission line consequently varies along with the temperature variation. The 90 m waveguide of the SPring-8 linac is not temperature stabilized; the temperature coefficient of the RF phase at the end of the waveguide is approximately 2.5 deg./˚C.

It is well known that the temperature of a travelling wave structure has to be highly stable, to avoid causing variation of the phase shift. The RF phase of a klystron's RF output power is also sensitive to its body temperature. The temperature coefficient of the RF phase has been estimated to be 0.74 deg./˚C for an 80 MW klystron.

A cooling system for the SPring-8 linac's accelerating structures maintains its temperature at 30 ± 0.1 ˚C. The klystrons, however, had not been temperature stabilized; their temperature variation was approximately 3 ˚C.

At the SPring-8 site, the AC line voltage varies by 5% throughout a day. Most electronic devices are not affected by this variation. The de-Q'ing circuit of a modulator, however, cannot sufficiently suppress this large variation, and thus it results in variation of a modulator's pulse forming network (PFN) voltage. This voltage variation often causes nonnegligible RF-amplitude and phase variations in a klystron's output.

Phase Noise

RF signals generated by an oscillator system have phase noises around the center frequency of 2856 MHz. The phase fluctuation of the RF signal is simply given by integrating the phase noise density, as is well known. Practical phase variation of the accelerating RF fields with respect to the beam must be introduced in order to estimate the actual energy fluctuation.

Suppose that a CW electron beam is accelerated. A beam ejected by an electron gun is bunched in the buncher section and then the timing of the bunches are determined at this stage. That is, the phase noise of an RF field in the buncher cavity is transferred to the electron beam, and thus the bunched beam takes on a phase jitter. When the electron bunches pass into a travelling wave structure, the actual RF phase where the beam is injected is determined by combination of two phases: One is the instantaneous phase shift of the accelerating RF caused by the phase noise, the other is that of the beam given in the buncher section, as mentioned above.

Suppose that we follow a specific phase from an oscillator to an input coupler of a specific accelerating structure, by two routes A and B: Route A leads to the end via a buncher and accelerating structures, that is, the phase travels in the form of an electron bunch. Route B leads via an RF transmission line and a klystron to the specific accelerating structure where route B meets route A. The time difference τ between the phase transmission times along the two routes determines the contribution of the phase noise density in a low-offset-frequency region by the following formula. The relative phase fluctuation θ between the RF fields and beam bunches is expressed as

$$\theta_{rms}^{\ 2} = \int_{f1}^{f2} \left[S_{beam} + S_{rf} - 2\sqrt{S_{beam} \cdot S_{rf}} \cos 2\pi f\tau \right] df$$

where S_{beam} is the phase noise density of the beam bunches and S_{rf} is that of the RF fields.

In the case of the SPring-8 linac, the following five assumptions determine the phase noise density S_{beam} and the frequency region from $f1$ to $f2$:

The phase jitter in the ECS accelerating structure dominates the energy fluctuation because the beam is injected on the zero-cross phase of the RF field, as mentioned above. Therefore, we consider only the ECS which varies the beam energy linearly along with the phase variation.

The buncher is a standing-wave type and its cavity's loaded Q value is approximately 5000; the buncher functions as a narrow band-pass filter. Hence, we simply assume that $S_{beam} = 0$ for $f > 200$ kHz and $S_{beam} = S_{rf}$ for $f < 200$ kHz.

The time difference τ was calculated to be about 40 ns for the ECS; $\cos 2\pi f\tau = 1$ for $f < 1$ MHz.

Combining these three assumptions yields the result that the integrand is negligibly small for $f < 200$ kHz.

The low power RF system including a 2856 MHz reference generator determines the phase noise of the klystron's output power; the phase noise S_{rf} of the accelerating RF is equal to that of the low power system.

The upper frequency $f2$ is determined by the bandwidth of the klystron or the accelerating structure; $f2 = 10$ MHz.

We finally obtained a simple approximation of the relative phase fluctuation:

$$\theta_{rms}{}^{2} \approx \int_{0.1\,\mathrm{MHz}}^{10\,\mathrm{MHz}} S_{rf}\, df$$

RF Asynchronousity[4]

A trigger pulse for the electron gun is generated by counting the 508.58 MHz master signal for the ring. Therefore, a 1 ns beam ejected from the gun has not been synchronized with the linac's 2856MHz RF, which has no harmonic relation with the ring's frequency.

The SPring-8 linac is not equipped with a subharmonic buncher which would modulate the beam velocity and then maintain the uniform phase relation between the 1 ns beam and the 2856 MHz RF in the buncher. Thus the asynchronous 2856 MHz RF formed two or three bunches along with the gun trigger timing. This unstable bunching caused random variation of the beam loading of accelerating RF field, and then the beam energy center was consequently varied shot by shot.

The SPring-8 linac also accelerates a 250ps beam and supplies a single-bunch beam to the synchrotrons. The RF asynchronousity mentioned above was not able to sustain the injection of the 250 ps beam at a specific phase of the RF fields in the buncher. That is, the buncher could not continuously capture the whole charge of the 250 ps beam, and thus the current of the accelerated single bunch beam consequently became unstable, as illustrated in Fig.4.

IMPROVEMENT AND RESULTS

Strategy for Beam Stabilization

We have developed the following strategy for reducing the beam energy fluctuation:

- Reduce the temperature variations to minimize the RF-phase drift.
- Stabilize the PFN voltage to minimize the RF amplitude and phase variations at the klystron's output.
- Synchronize the linac RF with the ring RF to stabilize the phase relation between the gun trigger and the linac's RF.
- Introduce an ECS to compensate for uncontrollable energy variations and compress the beam energy spreading to achieve reduction of injection beam losses at high current.

Reduction of Long-Period Variation[2]

We have readjusted the air conditioners in the klystron gallery to stabilize the room temperature. The temperature variation was consequently reduced to 1˚C. Heat jackets are also used to cover the 90 m waveguide to prevent it from being directly struck by air flows from the air conditioner. These improvements finally minimized the RF phase variation at the end of the 90 m waveguide to less than 1 degree.

We recently observed that the temperature variation has increased to 5˚C and a nonnegligible phase fluctuation has reappeared. Therefore, we are now developing a plan to stabilize the waveguide's temperature by using cooling water.

The temperature regulation of the water cooling system for the klystrons was improved by applying an inverter control method in the cooling unit. The improved regulation results in the phase variation of less than 0.5 degrees at the klystron's output.

In order to stabilize the modulator's PFN voltage, we reexamined the entire regulation circuit, aiming to improve the control of the induction voltage regulator (IVR), which coarsely adjusts the dc high voltage. The improved controller regulates the IVR's output voltage such that it is maintained within a ± 1% variation. This improved regulation consequently reduced the previous long-period variation to 0.03% rms over a week-long period, which corresponded to the RF power and phase variation of about 0.08% rms and 0.2 degrees rms, respectively.

These improvements realized the energy fluctuation of 0.03% rms; a full range of the variation, which is assumed to be 6σ, satisfies the request mentioned in the section of introduction.

New Synchronous RF Reference[4]

A new method was developed to realize the complete synchronization of the beam trigger and the linac RF as expressed in Fig. 3[5]: A beam trigger of 1 Hz is produced by counting the 508.58 MHz reference for the ring. Sinusoidal waves of 89.25 MHz with duration of 290 μs, whose frequency is 2856 MHz divided by 32, are programmed in an arbitrary waveform generator. The 1 Hz beam trigger causes the generator to start oscillating by referring to the external 508.58-MHz clock, and thus a 89.25 MHz burst signal is created which synchronizes with the 508.58 MHz reference. This intermediate signal is filtered by a high-Q crystal filter with a bandwidth of 12 kHz, to reduce phase noises. Finally, the filtered signal is multiplied by 32 to generate the 2856 MHz reference. Note that this RF reference signal is not CW but burst waves.

The formula introduced in section *Phase Noise* gives the relative phase fluctuation of about 0.2 degrees rms by integrating the measured phase noise density S_{rf}.

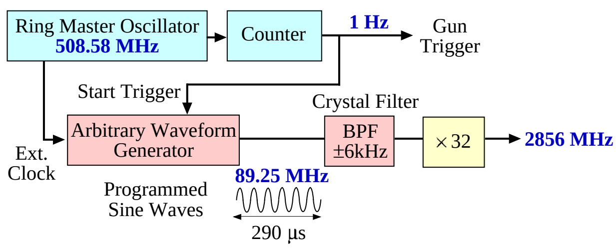

Figure 3: Block diagram of RF reference generator.

The electron gun can generate a 250 ps beam. The buncher compresses a part or of the beam, and then forms a single bunch. Figure 4 shows an example of beam current measurement during single bunch acceleration. The fluctuation of current observed when using the previous asynchronous system does not appear in the new synchronous system. This measurement clearly demonstrates that the new 2856 MHz reference signal synchronizes with the beam trigger.

The RF synchronization also improves the beam energy stability since the beam loading remains almost constant: The energy fluctuation of 0.03% rms was reduced to 0.009% rms when the previous system was replaced with the new synchronous system.

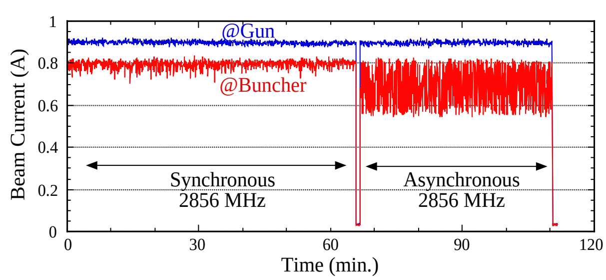

Figure 4: Stability of single-bunched beam.

ECS[6]

We introduced a conventional ECS which is mainly composed of a magnetic chicane section and an accelerating structure to provide the energy modulation of the electron bunches. The ECS compresses the energy spread from ±1.0% (full width) to ±0.3% (full width) for the 1 GeV beam with a bunch length of 20 ps, when the accelerating structure of the ECS holds the electric field strength of 7 MV/m.

The beam center energy varies along with the phase of the RF fed to the ECS's accelerating structure; the estimated rate is 0.35% per 1 degree. However, the minimum energy spread is estimated to continue over the range of 40° of the phase. Since the beam energy is sensitive to the phase of the RF fed into the ECS's accelerating structure, this phase should be precisely synchronized with the phase of the beam bunches formed in the bunching section, as mentioned in section *Variation Chains*.

In order to reduce the phase fluctuation of the ECS's klystron, a phase-locked-loop technique was applied to an independent drive system for the klystron, as shown in Fig. 1. The PLL system illustrated in Fig. 5 was designed to maintain good stability of the RF phase in a 120 m coaxial cable which feeds the RF to an amplifier for the thirteenth klystron providing an RF power to the ECS.

We observed that the PLL achieved the phase stability of 0.2 degrees rms at the output of the klystron over a period of one week. The combination of this phase stability and the phase fluctuation of the new synchronous oscillator described in section *New Synchronous RF Reference* gives the estimated total phase variation of 0.3 degrees rms, which results in the energy variation of 0.01% rms.

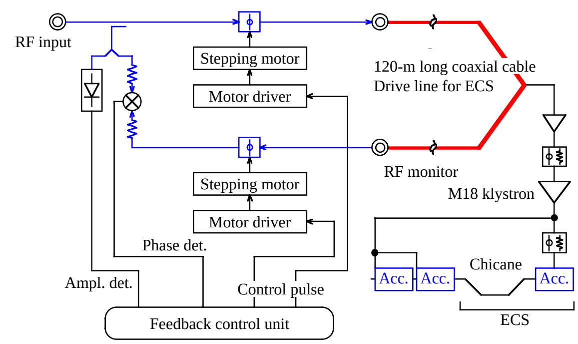

Figure 5: Diagram of PLL system for long drive line.

When the 40 ns beam at the high current of 350 mA was accelerated, we observed that the ECS compressed the full energy spread from 3.6% to 1.4% which is narrower than the synchrotron's energy acceptance, and consequently the injection current was doubled as shown in Fig. 6.

The ECS can also reduce the energy fluctuation according to the same principle. For example, the ECS suppressed the energy variation of 0.06% rms down to 0.01% rms for the 1 ns beam acceleration when the synchronous generator transmitted the reference RF. Thus the ECS is effective in maintaining both shot-by-shot and long-period beam energy stability.

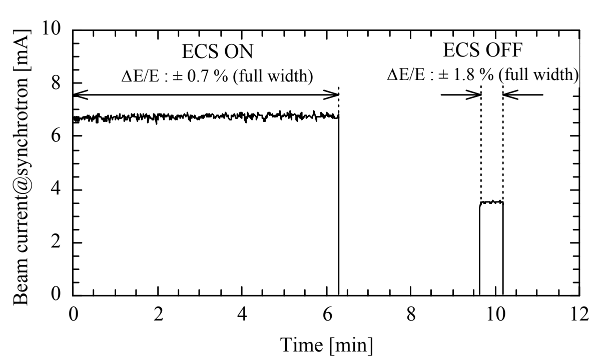

Figure 6: Stability of high-current 40 ns beam injection.

MONITORS

Beam Energy Monitor

The beam energy, before being compensated by the ECS, is monitored by a thin screen inserted in the center of the chicane where the energy dispersion is 1 m. The screen is a 12.5-μm thick Kapton film coated with 0.4-μm aluminum as shown in Fig.7. A CCD camera with a telecentric lens captures OTR (Optical Transition Radiation) lights radiated by beam irradiations on the screen. The telecentric lens corrects the trapezoid distortion of the image on the CCD. The captured beam images are analyzed to determine the beam energy and its spread. This analysis is executed automatically and the results are accumulated in the database. The 1-GeV beam has an emittance of $5\times10^{-8}\,\pi$ mrad and the screen increases it to $5\times10^{-7}\,\pi$ mrad. This emittance growth is negligible for injection into the synchrotrons. Therefore, the screen is always inserted to monitor the beam energy during the beam injection.

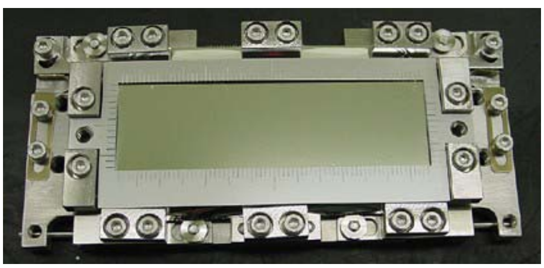

Figure 7: OTR screen to monitor beam energy.

Beam Position Monitor[7]

An electrostatic strip line type BPM was employed. The resonant frequency of 2856 MHz was chosen for the strip line, since the BPM had to detect three types of beams with the pulse widths of 1 ns, 40 ns and 1 μs. Thirty-six sets of the BPM were installed in the quadrupole magnets, and nine sets in the dispersive sections.

A signal processor for the BPM was required to have a wide dynamic range, since the 1-ns beam current ranges from 20 mA to 2 A. Therefore we employed a logarithmic detection method, which was originally capable of processing wide dynamic range signals. A practical circuit comprises 2856 MHz bandpass filters, logarithmic detectors and ADC’s. The circuit has a dynamic range wider than 45 dB and a maximum position resolution of ten and a few μm (2σ).

A data acquisition system was required to process data of all the channels synchronizing with a beam pulse to represent a one-pass beam orbit of the linac. However, the system would be composed of several VME systems distributed along the linac. Therefore, a shared memory method was introduced for synchronized data acquisition[8].

RF Power & Phase Monitor

RF power meters measure the forward-going RF powers and the reflected powers at the outputs of all the klystrons. The RF power meter is specially designed for using in accelerator sites: A differential RF detector composed of two diodes is employed in the power meter; the detector circuit can reject severe common mode noises. The power meter linearizes the measured power and display the linearized values in MW. A value of VSWR is also calculated.

Monitor of the RF phase of the high power RF is indispensable to diagnose the RF system since it is very sensitive to the RF variation in comparison with other methods. RF phase meters are installed to monitor the RF phase at the output ports of the accelerating structures.

The phase meter employs the conventional digital comparator technique, which compares two phases of the test RF and reference RF. Both 2856 MHz RF signals are converted to the intermediate signals of 230 MHz. Limiter amplifiers amplify them without phase variation along with the RF power level. A 4π digital phase comparator converts the phase difference to the pulse-width-modulated signal. A lowpass filter circuit finally provides a voltage signal proportional to the phase difference. A limiter amplifier was carefully chosen to satisfy both of a fast rise time (10-90%) of 50 ns and a small detection error of ±1 deg. in a power range of 30 dB.

ACKNOWLEDGMENT

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