SINGLE BUNCH ACCELERATION AND DETECTION
IN S-BAND ELECTRON LINEAR ACCELERATOR

J. Tanaka, I. Sato, S. Anami, S. Fukuda, H. Matsumoto
KEK   Tsukuba Japan
Y. Tabata, H. Kobayashi, S. Tagawa, M. Washio
Nuclear Engineering Research Lab. Univ. of Tokyo.

Summary

Single bunches have been accelerated and directly monitored for pulse radiolysis studies since June 1977, at the 35-MeV S-band electron linac of the Nuclear Research Laboratory of the Univ. of Tokyo.

An extremely short, picosecond-range single electron pulse was attained by means of a beam compressing injector and an ordinary TW type accelerator guide system. The measured maximum charge density of the single bunches was 1 nanocoulomb and the detected pulse duration was 16 picoseconds which is the limit of the monitoring detector. This report also describes the low jitter (less than 20 ps) triggering system for the detectors and the injector, and a few of the monitors to detect such a short pulse.

Introduction

Picosecond-range single bunches accelerated by an S-band electron linear accelerator provide a powerful means not only for the study of pulse radiolysis in radio chemistry and of other transient phenomena but also for the study of the performance of the accelerator itself.

Sub-nanosecond range single bunches accelerator by an L-band electron linear accelerator have been reported previously.[1,2,3] The short pulse beams produced by an electron gun (with duration corresponding to one cycle of a sub-harmonic frequency) were compressed by means of a subharmonic buncher, a prebuncher and an ordinary accelerator guide, and were detected by a coaxial type Faraday cup and a Bi-planer photodiode. However, the detected pulse durations were in the 50-picosecond range.

In order to study picosecond-range transient phenomena a 35-MeV S-band (2856 MHz) electron linear accelerator capable of accelerating picosecond-range single bunches, nanosecond and microsecond range pulse beams was constructed at the Nuclear Engineering Research Laboratory at the University of Tokyo.[4] In addition to ordinary physical, chemical and engineering research, the linac has two main special research purposes. The first is to produce intense neutron pulses by link operation with the fast neutron reactor "Yayoi", for studies in reactor physics and engineering. The second is to get extremely short electron pulse beams to study transient phenomena including picosecond-range pulse radiolysis.

General Description of the Linac

The NERL linac is composed of an injector which consists of an electron gun, a sub-harmonic frequency buncher(476 MHz), a traveling wave type prebuncher (2856 Mhz) and focusing magnetic lenses, two 2/3π mode TW type accelerator guides(1.7 m and 2 m in length) and three beam channels including a beam transport line extending to the reactor "Yayoi".

To be as flexible as possible for research purposes, especially for pulse radiolysis using picosecond range single bunches, careful attention was paid to the design and construction of the very short pulse, high current electron injector and the triggering system which synchronize the injector and detectors with the accelerator wave.

The general parameters of the machine are shown in Table I and the schematic layout is shown in Fig. 1.

Table I General parameters of the linac

1. Ordinary pulse mode operation

Energy	38 MeV(no load)
	26.8 MeV(at 200 mA)
Beam current	230 mA(at 25 MeV)
Pulse duration	0.1, 0.6, 1.1, 4.5 μs
Repetition rate	single shot∿200 pps
Size of beam spot	2∿3 mm

2. Nanosecond pulse mode operation

Energy	37 MeV
Beam current	2 A
Pulse duration	2.0, 10, ns
Beam current stability	1.5%/5min., 3%/60min.

3. Picosecond pulse mode operation

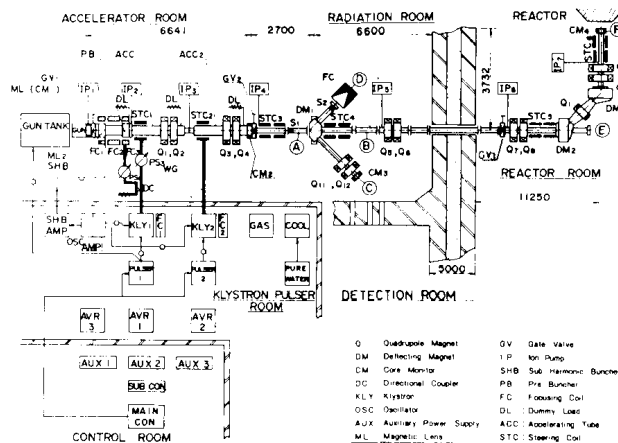|		
3.1	2,100 ps interval pulses (with S.H.B.)	
	Charge per bunch	1 nc
3.2	Single bunch	
	Bunch width	16 ps
	Charge	1 nc

Fig. 1 Layout of the NERL facility

Injector

The injector is composed of an electron gun and a dc biased grid-cathode pulse generator placed on a −90kV, 5μs pulse transformer high potential deck, a 476-MHz (1/6·2856 MHz) subharmonic buncher, a 2856-MHz TW type 6-cell prebuncher and focusing system. The schematic diagram of the injector is shown in Fig.2.

In order to attain an intense single bunch isolated from the fine-structure of the 2856-MHz

accelerating frequency (350 ps interval satellites), a very short pulse electron gun is required capable of ·2.1 ns pulses corresponding to one cycle of the sub-harmonic frequency (476 MHz). The electron gun is of the triode type and the grid-cathode structure is similar to that of a planer triode tube. The grid and cathode connections are coaxial and have matched coaxial ceramic seals. The impedance is 25 ohms and the VSWR is less than 1:1.5 over the frequency range from 500 MHz to 1,300 MHz. As the output of the grid-cathode
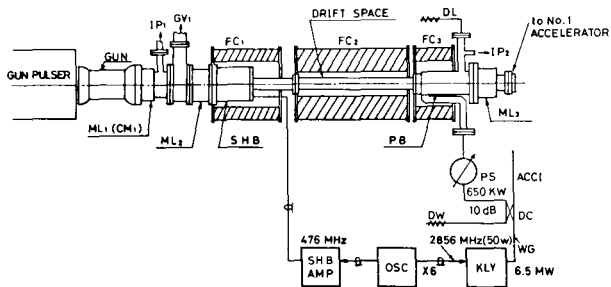

Fig. 2 Schematic diagram of the injector

pulse generator is designed for 50-ohm cable, a tapered coaxial transient adapter is inserted between the pulse generator and grid-cathode connections.

The present cathode of the electron gun is an impregnated cathode,and the duration of the electron beam pulse is 1.6 ns at a peak current of 2.5 A. However, development of a new grid-cathode assembly is proceeding, which uses a grid-cathode assembly of a commercial planer tube and will be able to attain higher currents.

To obtain a clean single bunch without satellites, a triangular electron pulse form is preferable over a rectangular pulse beam.

The grid-cathode pulse amplifier,which consists of 6 UHF planer triodes coupled together in series by broad-band coupling transformers is placed on the -90 kV high potential deck. The trigger pulse for the fast pulse amplifier is supplied from a synchronized trigger system working at ground potential via an isolation choke wound of semirigid coaxial line.

The sub-harmonic buncher is a tunable re-entrant type cavity; the loaded Q value is 700 at a coupling coefficient of 1.4. Due to the operation of the sub-harmonic buncher and prebuncher, a 2-nanosecond electron pulse is compressed to less than 100 picoseconds prior to injection into the accelerator guide. Consequently, to reduce the strong space-charge effects it is necessary to accelerate the beam to higher velocity. The prebuncher is a $2/3\pi$ mode TW type 6-cell accelerator guide and the phase velocities of the first 3 cells and the last 3 cells are $0.7c$ and $0.75c$ respectively.

The output beam is accelerated to 540 keV with 600 kW of rf power and is compressed into the acceptance angle of the first accelerator guide, which has a short bunching section.

The focusing system of the injector is

composed of three magnetic lenses and three solenoids, surrounding the sub-harmonic buncher, the first drift space and the prebuncher.

Synchronized Triggering System

In a single bunch electron linac, one of the important requirements is to generate fast rise-time, low jitter trigger pulses synchronized with the accelerating rf waves in order to accelerate an intense and clean single bunch and to be able to observe the details of the picosecond-range short pulses.

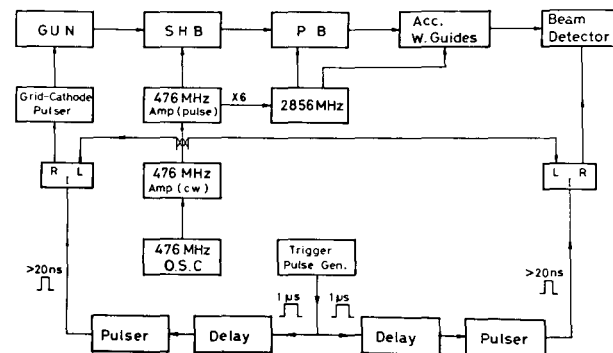A new simple, stable and low jitter synchronized trigger system was developed.[5] (Fig.3)

Fig. 3 Schematic diagram of synchronized trigger system

In this system, a 476 MHz sub-harmonic frequency wave, delivered from the cw preamplifier of the modulated signal, is used directly for the trigger signals. A double balanced mixer (HP 10514A) is available to slice the UHF continuous wave into wave trains of more than 20 nanoseconds duration, where the leading wave crest is used as the trigger pulse. The rise-time of the modulation pulse should be as fast as possible; however, a risetime of 10 nanoseconds was sufficient, because, even if the amplitude of the first crest was too low to trigger the gun pulse generator or the detectors, the succeeding wave crests would have an amplitude exceeding the trigger levels.

This triggering scheme enabled successful acceleration and stable measurements of single bunches with a Cerenkov-light and streak camera system and other detectors using a sampling scope with jitter of less than 20 picoseconds. This scheme is also applicable for observation of successive bunches or the fine structure in ordinary beam pulses by adjusting the trigger delay time.

When the NERL linac was first operated, trigger pulses shaped from a 119 MHz signal (the 4th sub-harmonic of 476 MHz) were used because of restrictions due to the electronic circuitry. However, the trigger system had a time-jitter of about 50 pico seconds.

The new system made the triggering not only stable and reliable for the single bunch operation and detection, but is also simple and low cost.

Performance of Single Bunch Operation

In single bunch operation of the machine, in order to obtain the optimum conditions, it is

important to be able to monitor the details of the bunches with sufficiently rapid response time to allow tuning the machine.

There are several methods to observe sub-nanosecond pulses. They are roughly classified into three groups. The first is the optical method, that is a light-photodetector combination. Cerenkov, synchrotron and transition light serve as the light sources, bi-planer photo-diodes and streak cameras are used for the photodetectors. The second is the electro-magnetic method in which fast coaxial Faraday cups, wall current monitors, etc. are used. These sensors are usually connected to a fast oscilloscope or sampling scope.

The third is an indirect method. It is based on measurements of the energy spread, higher frequency components and phase detection of the bunches.

However, at present, the most intuitively appealing, rapid and exact method for the above mentioned radio-chemical purposes is the Cerenkov-
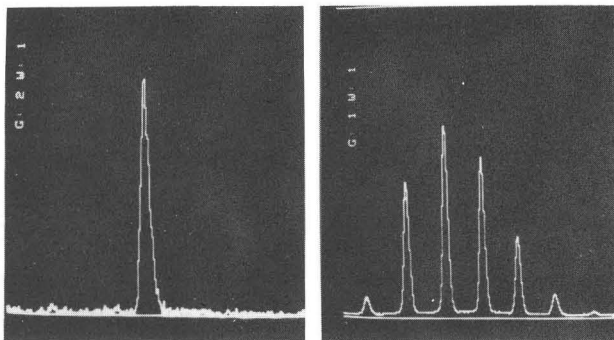

Fig. 4 (a)   16 ps single bunch by streak camera with S.H.B.
(b)   Fine structure of 2 ns beam without S.H.B.

light-streak camera scheme. With this detection system, intense and clean single bunches or bunch trains are easily and rapidly obtained by adjusting machine parameters, for example the phase and power level of the sub-harmonic buncher, pre-buncher or the grid-cathode bias voltage of the electron gun. Figure 4(a) shows an example of a single bunch detected with the Cerenkov light-streak camera system; the pulse width is 16 pico-seconds, which is the limit of the detector system. Figure 4(b) shows the case of a 1.8 ns gun pulse and no sub-hamonic bunching which shows 350 ps interval bunches. Figure 5(a) shows small satellites around the main bunch. Figure 5(b) shows a picture aver-aging 100 single bunches. The half width is about 40 ps which shows that the time jitter of the system is less than 20 ps.

The charge per bunch measured by averaging current into a coaxial type Faraday cup was 1 nC, under optimum conditions.

At the NERL, the bunch monitoring system is used as a simple and powerful means for the tuning of the machine.
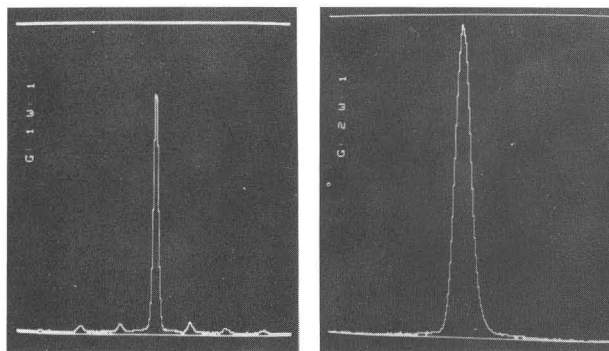

Fig. 5 (a)   Single bunch with small satellites with S.H.B.
(b)   100 shots of single bunches

Development of Bunch Monitors

In order to study sub-nanosecond or nano-second range short pulse beams accelerated by an electron linac and to operate the machine as a single bunch accelerator at the optimum conditions, it is important to nondestructively monitor the fine-structure of the beams at the appropriate positions of the machine. To monitor the fine structure bunches of the S-band linac routinely, the nondestructive sensors are required to have a time resolution of less than 100 ps and are desired to be of simple structure, small size and low cost. To meet the requirements, new bunch sensors were developed jointly by KEK and NERL.

One sensor is a "One turn core monitor" which originated from an ordinary "Ferrite core beam current monitor". However, to increase the resolution down to the 100-ps range, the secondary coil is one turn and is formed like a re-entrant-type cavity as shown in Fig. 6.

The gap is closed by a low resistance ring-shaped solid resistor. In the prototype sensor, the gap resistance was 1 ohm and the inside space of the secondary coil was filled with a high frequency ferrite core ring. The gap signal voltage induced by a bunched beam was extracted by a loop and was transmitted to a sampling scope via
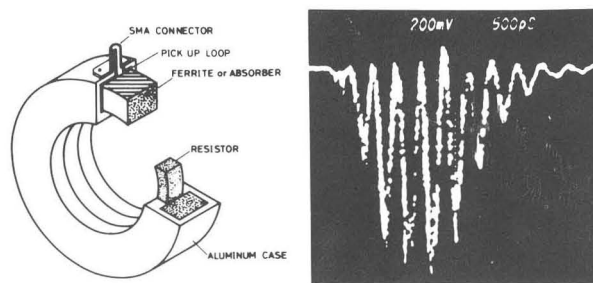

Fig. 6   One turn ferrite core monitor
Fig. 7   Fine structure by Fig. 6 monitor

a semi-rigid coaxial cable 9 m in length. The sensor was able to resolve the fine structure of the bunched beam with a resolution of better than 200 ps. (Fig.7).

The experiments showed that the ferrite core acts more as an absorber than as a magnetic material for such a high frequency range, and the gap should be made as small as possible to increase the resolution.

Consequently, three different size sensors were tested, and the ferrite cores were replaced by materials which absorb the waves from 1 GHz to 10 GHz, and a tap length of 3 mm was chosen because the bunch length is about 3 mm and that length is at the manufacturing limit for the resister ring thickness. The monitors and the measured single bunches are shown in Fig.8.
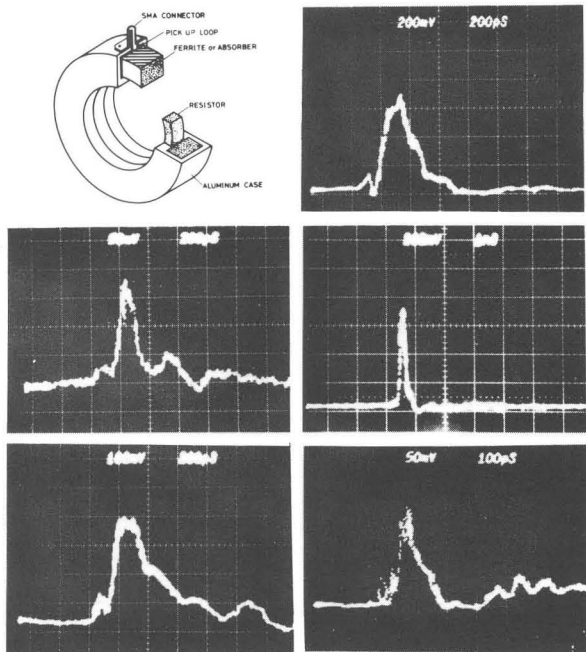

Fig. 8 (a) (b) (c)   (d) (e) (f)
(a) One turn absorber loaded monitor
(b) ID 40 mm, gap 5 mm, 1Ω, 500 mv/div, 200 ps/div
(c) ID 18 mm, gap 3 mm, 1Ω, 1 V/Div, 200 ps/div
(d) ID 8 mm, gap 3 mm, 1Ω, 2 V/div, 200 ps/div
(e) ID 8 mm, gap 3 mm, 1Ω, 2 V/div, 1 ns/div
(f) ID 8 mm, gap 3 mm, 0.1Ω, 500 mV/div, 100 ps/div

The second type of sensor is a "Micro-stripline monitor", placed perpendicularly to the beam line. The sensor is made on a glass epoxy board (printed circuit) etched as shown in Fig.9.

Type A has a risetime of 60 ps and a half width of 80 ps. However, as shown in Fig. 10, ghost signals appear behind the real signal which are caused by multiply reflected waves from the borders of the strip line, and the first ghost is delayed 600 ps (600 ps corresponds to the path difference of 9 cm inside the line).

In Type B, the width of the line around the beam hole is rather small compared with Type A. Although the ghost signal levels were reduced, the half width of the real signal is wider than Type A due to the close approach of the first ghost to the real signal (Fig.11).
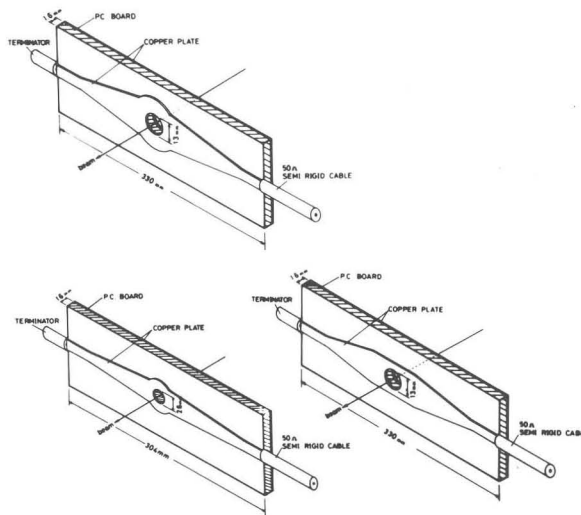

Fig. 9 Micro-stripline monitor, above (A), middle (B), bottom (C)

Type C has a reduced width and beam hole. It was placed behind a collimator with a 2-mm hole diameter; consequently the signal voltage was reduced to about half. As shown in Fig.12 the rise time and half width are 50 ps and 70 ps, respectively and the ghost signals were fairly reduced

Both kinds of sensors as described above seem to be kinds of wall current monitors having very narrow longitudinal dimensions at the limit of the very high frequencies involved in the bunches.

The resolution depends roughly on the longitudinal size but does not depend on the vertical size of the sensors. However, to remove the reflections of the concentrically propagating signal wave, it is necessary to place good absorbers around the gap for the one-turn monitors and on the outer borders for the micro-strip line monitors.
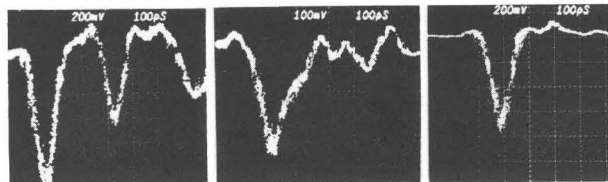

Fig. 10   Fig. 11   Fig. 12

Discussion

Penner, NBS: The last monitor you showed, the version C, had practically no reflection. I'd like to ask, how small is the beam hole to get it to behave like that?

Tanaka: This has a very small hole – the beam size is about 2 or 3 mm and the hole is 2.8 mm.

Penner: What is the sensitivity; how many volts per ampere do you use?

Tanaka: About 4 volts.

Penner: For how much current?

Tanaka: One or two amperes.

Stein, LASL: Have you measured the emittance or the energy spread of the beam from that machine?

Tanaka: We did not measure the emittance. The usual energy spread is very small as can be seen from the narrow width of the single bunch beam.

Witkover, BNL: The figures that you showed indicated a 16 pico-second width. What did you use for the monitor?

Tanaka: Cerenkov light and a streak camera.

Miller, SLAC: You said the input impedence to your gun was 25 ohms and was a good match over a wide frequency range. Is that a resistive matching and is the resistor internal to the gun or external?

Tanaka: This is measured to be resistive. It's the actual beam due to beam interception of the grid, or cathode current.

References

1 N.J. Norris and R.K. Hanst, IEEE Trans. Nucl. Sci., NS-16, 323 (1969).

2 W. Gallagher, K. Johnson, G. Mavrogens and W. Ramler, IEEE Trans. Nucl. Sci., NS-18, 584 (1971).

3 G. Mavrogens, W. Ramler, W. Wesolowski, K. Johnson and G. Clifft, IEEE Trans. Nucl. Sci., NS-20, 830 (1973).

4 Y. Tabata, J. Tanaka, S. Tagawa, K. Katsumura, T. Ueda and K. Hasegawa, J. of the Faculty of Eng., The Univ. of Tokyo, Vol. XXXIV, No. 4.

5 S. Fukuda, H. Matsumoto, I. Sato and J. Tanaka, Proc. of the 2nd Symposium of Acc. Sci. and Tech, INS. Univ. of Tokyo, March 23-25, 45 (1978).