ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB039

CONSTRUCTION OF A COMPACT ELECTRON INJECTOR USING A GRIDDED RF THERMIONIC GUN AND A C-BAND ACCELERATOR

T. Inagaki†, T. Fukui, T. Hara, T. Hiraiwa, H. Maesaka, H. Tanaka
RIKEN SPring-8 Center, Sayo, Japan
T. Asaka, H. Dewa, N. Hosoda, E. Iwai, C. Kondo,
T. Magome, T. Ohshima, T. Sakurai, K. Yanagida
JASRI, Sayo, Japan
S. Inoue, K. Kajimoto, Y. Minagawa, S. Nakata, T. Seno,
H. Sumitomo, R. Takesako, S. Tanaka, R. Yamamoto, M. Yoshioka,
SPring-8 Services Co. Ltd., Sayo, Japan
S. Hashimoto, LASTI, University of Hyogo, Sayo, Japan

Abstract

A compact and low-cost electron injector linac was designed and constructed for the soft X-ray synchrotron radiation facility NewSUBARU, instead of the SPring-8 injector system, which will be shutdown. The total length of the 1 GeV injector linac needs to be less than 70 m to fit into the existing tunnel. To this end, an RF electron gun with a gridded thermionic cathode directly attached to a 238 MHz RF cavity was developed and adopted. The C-band accelerator with a high accelerating gradient of 31 MV/m was used as the main accelerator to make the accelerator length compact. A highly integrated low-level RF system consisting of a MTCA.4 based high-speed digitizers and RF frontend boards has been constructed. After the beam commissioning, we obtained the aimed 1 GeV, 100 pC beam with low energy spread of 0.1%, and low normalized emittance of less than 10 mm mrad. The electron beam was injected to the storage ring with more than 90% efficiency. This electron linac sets a new benchmark for the accelerator field.

INTRODUCTION

NewSUBARU [1] is a soft X-ray synchrotron radiation facility operated by LASTI, University of Hyogo. Its electron beam energy is 1 to 1.5 GeV, the circumference is 118 m, and it is located on the SPring-8 campus. The 1 GeV beam was supplied from the SPring-8 injector linac. However, the linac will be shut down because of a part of the upgrade plan of the SPring-8 storage ring (SPring-8-II [2]). In the upgrade plan, the 8 GeV beam accelerated by the SACLA is injected directly to the SPring-8 ring. This injection procedure has been already started for usual user operation. Therefore, we decided to shut down the old injector linac and construct a new 1 GeV linac dedicated to the NewSUBARU injection.

Requirements of the new lianc are as follows; a) provides the beam energy of 1 GeV and the charge of 100 pC, b) fits to the limited construction cost, b) fits to the existing beam transport area of 70 m length, c) demonstrates the beam emittance of 10 mm mrad and the energy spread of 0.5%, which are low enough for the injection acceptance of the storage ring. To fulfil the requirements, a proven SACLA high acceleration field C-band accelerator [3] was used as the main accelerator. For the electron gun, we used a new thermal cathode RF gun [4]. This design of the electron injection linac is used for the next generation synchrotron radiation facility [5], which is currently under construction at the Tohoku University campus in Japan.

We report the configuration of the electron injector linac and the achieved beam performance.

ACCELERATOR DESIGN

Figure 1 shows the layout of the new injection linac. The following points were emphasized in the design. 1) Compact and highly efficient accelerator that can be installed in an existing beam transport tunnel. 2) Low cost of construction and operation. 3) The beam must be stable and easy to adjust. 4) High reliability and easy maintenance. In order to reduce the size and cost of the accelerator, the C-band accelerator was used as the main accelerator. The 50 MW output power of the klystron was multiplied by an RF pulse compressor to a peak power of 400 MW, supplied to the 4 columns of the accelerating structure to generate the acceleration gradient of 31 MV/m. The length of the net accelerating section is 32 m and the total acceleration energy is up to 1 GeV.

For stability and maintainability, we employed a commercially available grid-controlled thermal cathode (EIMAC, Y-845) electron gun with a pulsed 50 kV high voltage power supply. The emittance of the low energy electron beam is easily blown up. To minimize the drift length, the cathode is attached to the upstream port of the 238 MHz cavity with a thin focusing magnetic lens. This "gridded RF thermionic gun" [4] was developed for the next generation synchrotron accelerators at SPring-8 and QST [5]. Selecting an appropriate electric field design of the cathode section, the emittance increase at the grid is suppressed and the emittance growth due to the space charge effect is kept low. The electron beam energy from the gun is boosted from 50 keV to 500 keV in the 238 MHz cavity. After the halo of the beam is removed by a collimator (COL-1), the beam is energy-chirped by the -140 degree deceleration phase of the 476 MHz RF cavity, and the 200 ps bunch length is compressed to about 10 ps by

† inagaki@spring8.or.jp

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB039

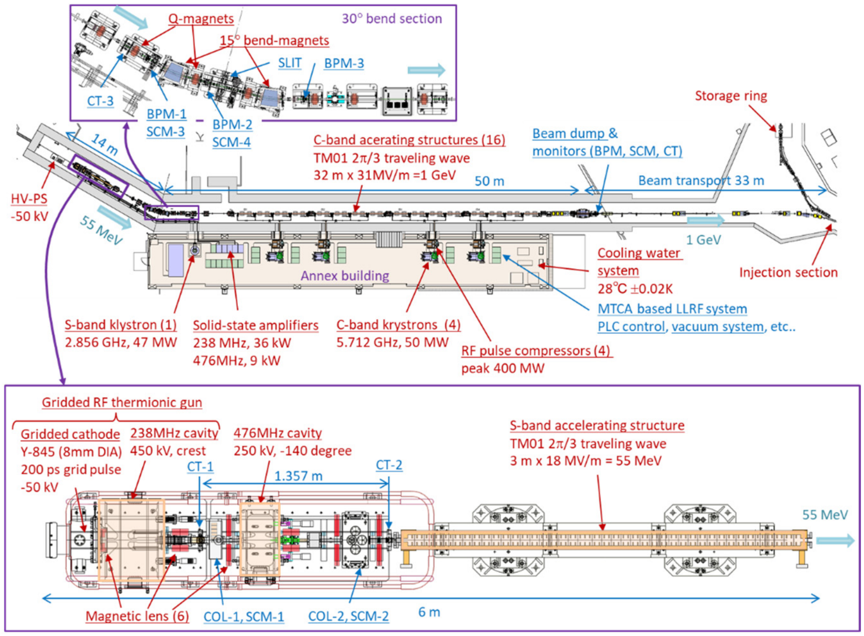

Figure 1: Layout of NewSUBARU injector linac. "COL", "SCM", "CT", "BPM" means a collimator, a screen monitor, a current transformer, and a beam position monitor, respectively.

velocity bunch compression before being injected into the 3-m long S-band (2.856 MHz) accelerating structure. The S-band accelerating structure captures the bunch and accelerate up to 55 MeV, to pass through the 30-degree bend section.

The bending section is designed to cancel out the dispersion at the following accelerator section by inserting two strong quadrupole magnets between two 15 degree bending magnets. After passing through the 30-degree bending section, 162-m long acceleration structures accelerate the beam to 1 GeV. Downstream of the C-band accelerator, a vertical bending magnet and a beam dump are installed to diagnose the electron beam without injecting the beam into the storage ring.

Two Solid-state high-power amplifiers (SSAs) and five pulsed klystrons were used as RF sources to drive the accelerator cavities. The klystrons, auxiliary power supplies, SSAs, low-power RF systems, magnet power supplies, and control equipment were installed in a 50 m long annex building along the accelerator tunnel, as shown in Fig. 1. To reduce the construction cost, the second-hand klystrons and high-voltage power supplies were reused from SACLA [3] and SPring-8 injector linac. For the low-power RF system, a digital control system, which originally developed at DESY and assembled at SPring-8/SACLA, was adopted. Using a high-speed digitizer and RTM module based on the Micro-TCA.4 standard, which had multi-input channels, the number of components was minimized which reduced the construction cost.

The cooling water for the acceleration structure and RF equipment was stabilized with an accuracy of ±0.02 K to avoid changes in RF phase and amplitude due to temperature variations. The repetition rate of the injection linac was 1 Hz, and the power consumption was less than 100 kW, resulting in low running cost.

COMMISSIONING

The new injector linac was constructed from August 2020. High power conditioning of the accelerating structure was carried out from January 2021. After one month of operation, it was able to operate stably at the nominal RF power. Then the beam commissioning was started.

The RF phase and amplitude of the 238 MHz cavity and the 476 MHz cavity were determined by measuring the time of flight between CT-1 and CT-2. The phase of the 476 MHz cavity was set to the one with the maximum signal height and minimum pulse width at CT-2. For the S-band and C-band accelerators, the crest RF phase was chosen to obtain the maximum beam energy. The beam envelope was optimized adjusting the magnetic lens and quadrupole magnets, observing the beam size with the screen monitors. Figure 2 shows the example of the quadrupole scan, to obtain Twiss parameters and the beam emittance.

Figure 3 shows a setup and an example of the vertical beam profile at 740 MeV measured by the screen monitor in the dump line. The conditions of the measurement are with the downstream C-band accelerator CB4 turned off (blue solid line), and with CB4's phase set to -90° phase, i.e., energy chirp added (red solid line). The screen is located at 379 mm downward from the initial beam axis. The sensitivity of the beam energy is 1.95 MeV/mm in vertical direction. The vertical profile of the screen presents the convolution of the spatial beam profile and the beam energy spread. If we ignore the spatial spread of the beam, we obtained an energy spread of 0.14% (FWHM) from the blue solid line, and a time length of 350 fs (FWHM) from the red solid line, indicating that we can produce a short bunch beam with a small energy spread. In addition, the

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB039

trend of the beam energy during continuous operation at 1 Hz was measured by the beam position monitors (BPM). It was confirmed that the stability of 0.04% in standard deviation was obtained. The momentum acceptance of the NewSUBARU storage ring is 0.85% and the spatial acceptance is a few mm. Therefore, the current injection beam performance is sufficient. As a result of adjusting the injection orbit, beam focusing, timing, and energy, the injection efficiency was almost 100%. The beam injection was successfully performed up to the stored beam current of 350 mA, and the top-up injection at 350 mA could be operated without any problem. Typical operation parameters are summarized in Table 1.

Table 1: Typical Operation Parameters

Beam energy	1 GeV
Bunch charge	100 pC
Normalized emittance	< 10 mm mrad
Energy spread	0.1% (FWHM)
Energy stability	0.04% (STD)
Bunch length	< 1 ps (FWHM)
Injection efficiency	> 90%
Pulse repetition	1 Hz

The user operation was started in April 2021, ahead of the original schedule. In the daily operation, the beam energy stability and orbit stability are sufficient. Although the accelerator is shut down at night and on weekends, the beam reproducibility after the shutdown is also good. This is due to the stability of the electron beam emitted from the electron gun using a thermionic cathode, the stability of the RF power supply and magnet power supply developed at SACLA, the stability of the low-level RF system using MTCA.4, which cancels fluctuations with appropriate feedback, and the stability of the cooling water temperature.

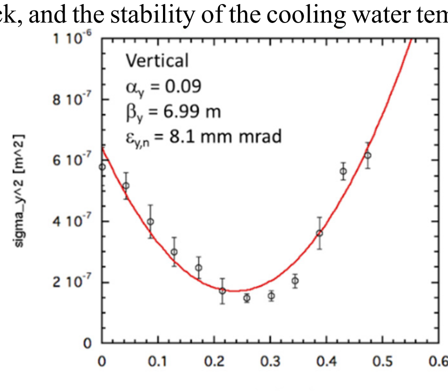

Figure 2: Example of the K-value scan of the quadrupole magnet at the exit of the S-band accelerator. The vertical axis is square of the vertical beam size (σ) measured at SCM-3 shown in Fig. 1. The error bars mean the statistic error of 10 shots in each data point. The Twiss parameters and the normalized beam emittance are calculated from the quadratic fit (red curve line) of this plot.

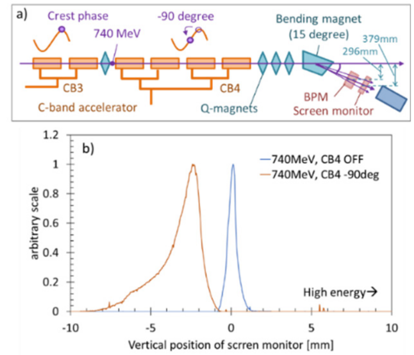

Figure 3: (a) Schematic of the diagnostic system. (b) Typical vertical beam profile, measured at the screen monitor.

CONCLUSION

A new injector linac of the NewSUBARU storage ring has been designed and constructed. The stable low-emittance electron beam from the thermionic cathode RF gun is compressed by a 476 MHz cavity and accelerated to 1 GeV by a S-band and C-band accelerators. A single bunch beam with a charge of 100 ps, a normalized emittance of less than 10 mm mrad, an energy spread of 0.1%, and a bunch length of less than 1 ps at an acceleration energy of 1 GeV was generated as designed. This beam was injected into the storage ring with an injection efficiency of more than 90%, and the user operation has been restarted with the top-up operation at 350 mA. The injector linac developed and constructed here can be used in the high-brightness synchrotron radiation ring [5] and the free electron laser facility. It is expected to be a model case for the next generation of small and medium-sized linacs.

ACKNOWLEDGEMENTS

The construction of the injection linac was greatly supported by RIKEN, JASRI and by Hyogo Prefecture. We would like to thank many staffs from RIKEN, JASRI and LASTI, University of Hyogo, SES, QST, and many other related companies, for their participation and cooperation.

REFERENCES

[1] A. Ando *et al.*, “Isochronous storage ring of the New SUBARU project”, *J. Synchrotron Rad.*, vol. 5, pp. 342-344, May 1998. doi:10.1107/S0909049597013150

[2] SPring-8-II CDR, http://rsc.riken.jp/pdf/SPring-8-II.pdf

[3] T. Sakurai *et al.*, “C-band disk-loaded-type accelerating structure for a high acceleration gradient and high-repetition rate operation”, *Phys. Rev. Accel. Beams*, vol. 20, p. 042003, Apr. 2017. doi:10.1103/PhysRevAccelBeams.20.042003

[4] T. Asaka *et al.*, “Low-emittance radio-frequency electron gun using a gridded thermionic cathode”, *Phys. Rev. Accel. Beams*, vol. 23 p. 063401, Jun. 2020. doi:10.1103/PhysRevAccelBeams.23.063401

[5] Accelerator design report for 3-GeV Next-Generation Synchrotron Radiation Facility, https://www.qst.go.jp/uploaded/attachment/18596.pdf