SUPPRESSION OF LONGITUDINAL INSTABILITY AT NanoTerasu

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Abstract

NanoTerasu is a newly constructed 3 GeV synchrotron radiation light source located in Sendai, Japan. The compact normal-conducting RF cavity operating in the TM020 mode with higher-order mode (HOM) dampers is employed for beam acceleration. However, a longitudinal coupled-bunch instability was observed during the storage ring commissioning in 2023 at a beam current of approximately 150 mA. The energy spread was continuously monitored using the stored beam profile monitor to detect the longitudinal coupled-bunch instability. Although partial suppression was achieved by adjusting the RF cavity temperature, the stored beam current during user operation remained limited to 200 mA in 2024. To overcome this limitation, a compact waveguide-overloaded kicker cavity and longitudinal bunch-by-bunch feedback (LBBF) system were developed and installed. The commissioning of the LBBF system in July 2025 enabled stable beam storage at the design current of 400 mA. The longitudinal coupled-bunch instability was perfectly suppressed. The stored beam current for user operation was subsequently increased, and routine user operation at 400 mA with high reliability began in November 2025. The longitudinal instability suppression at NanoTerasu was reported.

INTRODUCTION

The NanoTerasu is a compact 3 GeV synchrotron radiation light source newly constructed in Sendai, Japan [1, 2]. The circumference of storage ring (SR) is 349 m and the natural emittance is 1.14 nm rad, which is realized by a double-double-bend achromat lattice. The designed stored beam current is 400 mA.

The normal-conducting accelerating cavity adopts the world's first compact cavity that accelerates the stored beam in the TM020 mode [3]. The ferrite-based RF absorbers are installed inside the slot which is placed at the magnetic field node of the axially symmetric TM020 mode. This structure is designed to attenuate higher-order mode (HOM) components that can induce coupled-bunch beam instabilities. To reduce the HOM components, the superconducting or normal-conducting HOM free cavities were widely used in various synchrotron radiation facilities. At NanoTerasu normal-conducting TM020 HOM-damped cavity with a higher unloaded quality factor (Q_0) and accelerating gradient was employed. In contrast to the conventional HOM-damped cavities employed at European light sources such as BESSY [4] and ESRF [5], which operate in the TM010 accelerating mode and rely on strong broadband HOM absorbers, the TM020 cavity utilizes a higher-order accelerating mode with intrinsically lower R/Q_0, where R is the shunt impedance. Consequently, the beam-cavity interaction is significantly reduced. This feature reduces beam loading and longitudinal coupling impedance, while allowing efficient HOM damping by absorbers placed at field nodes without degrading the fundamental mode performance.

The commissioning of the storage ring started in June 2023 [6]. Although HOM-damped cavity was employed, the longitudinal coupled-bunch instability was observed when the stored beam current exceeded 150 mA in August 2023. As a result of investigating the accelerating cavity, this instability was attributed to the growth of a 1.9 GHz component of HOM.

To suppress the longitudinal instability, the temperature of TM020 HOM-damped cavity was adjusted. However, the stored beam current was limited to 200 mA due to the longitudinal instability in 2024. To increase the stored beam current, we started to develop the waveguide-overloaded kicker cavity and the LBBF system. The waveguide-overload kicker cavity was developed at DAΦNE in 1990s [7]. This type of kicker cavity was used in the various facilities to suppress the longitudinal coupled-bunch instability. We also developed a compact kicker cavity with low quality factor and wide bandwidth.

The kicker cavity was installed in the storage ring in May 2025. The commissioning of LBBF system was carried out in July 2025. We achieved the designed 400 mA stable beam accumulation using TM020 HOM-damped cavity and LBBF system in July 2025. The suppression of longitudinal coupled-bunch instability using TM020 HOM-damped cavity and LBBF system was reported.

LONGITUDINAL INSTABILITY

The some HOM field components exhibit nodal points of the HOM damper in the TM020 cavity, which limits the effectiveness of the damper and leads to residual unabsorbed HOM power. Among the residual HOM components, the 1.9 GHz component caused significant longitudinal coupled-bunch instability and limited the stored beam current to 200 mA.

Figure 1 shows the spectrum of the 1.9 GHz HOM from the pickup of the accelerating cavity, as well as the frequency spectrum of the beam position monitor (BPM), during the occurrence of longitudinal beam instability. In the BPM signal spectrum, sideband frequency components shifted by

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approximately 134 MHz from 508.76 MHz were observed, indicating that the coupled-bunch mode number of the longitudinal instability was 156. Considering the temporal evolution of the spectrum intensity due to the longitudinal instability and the effect of the radiation damping, the growth rate of the 1.9 GHz HOM was estimated to be approximately 5.8 msec in 2023. At the energy dispersive section the X-ray pinhole camera (XPC) was installed to monitor the stored beam profile [8]. When the longitudinal beam instability increases the energy spread of the stored beam, the horizontal beam size also increases as shown in Fig. 2. The horizontal beam size without instability was approximately 84 μm (σ).

The bunch phases of all 550 bunches are also monitored using the high-speed digitizer ADQ7 developed by Teledyne SP Devices, which also measures the bunch currents of all 550 bunches. The horizontal beam size and bunch phases are continuously monitored to detect the occurrence of the longitudinal instability.

To suppress the growth of the 1.9 GHz HOM, the cooling water condition of the SR accelerating cavity was adjusted, and user operation was being conducted at a stored beam current of 200 mA. Although parameters for stable long-term operation above 200 mA have not yet been identified, the HOM growth rate was estimated longer than 6 msec at 200 mA. The growth rate is close to the radiation damping time and has significantly slowed compared to the growth rate in 2023.

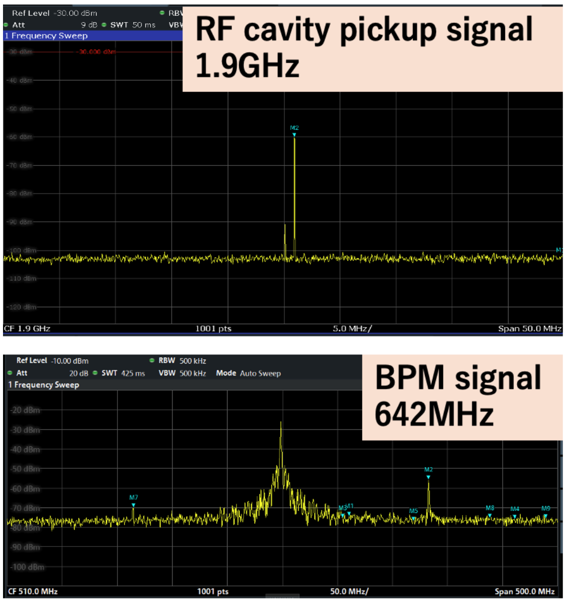

Figure 1: 1.9 GHz HOM signal from the pickup of the accelerating cavity (top) and spectrum of BPM signal (bottom).

LBBF SYSTEM

The waveguide-overloaded kicker cavity and LBBF system were developed to suppress the coupled-bunch instability. The longitudinal beam instability is detected by the BPM. The BPM sum signal is sent through a FBE-509LT and iGp12 developed by Dimtel Inc. The DAC output is

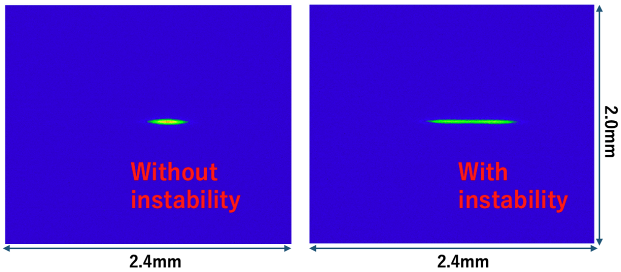

Figure 2: The stored beam profile without instability (left) and with instability (right).

sent to the back-end circuit of FBE-509LT. The back-end output signal is amplified by a 500 W solid-state amplifier developed by R&K. The output signal of 500 W AMP is fed into LBBF kicker cavity via a four-way splitter. The kicker cavity was designed based on the waveguide-overloaded kicker cavity, which has been widely used in longitudinal BBF systems [7, 9–12]. The kicker cavity was designed with a driving frequency of 1.65 GHz, which corresponds to $(3 + \frac{1}{4})f_{\mathrm{RF}}$. The f_{RF} is 508.76 MHz. The 1 dB bandwidth was set to more than 255 MHz. In order to apply accurate kicks to each bunch, the loaded quality factor (Q_L) was designed to be less than 10. A compact kicker cavity was designed with four input and four output ports. The total length between both ends of the back cavity is 133 mm as shown in Fig. 3.

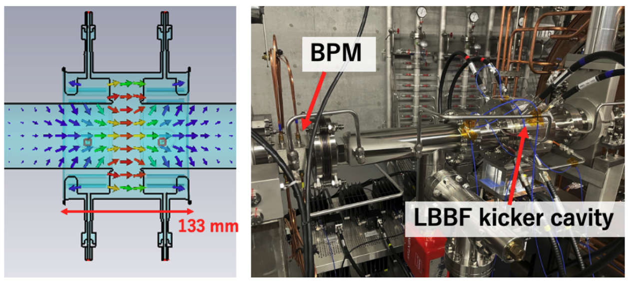

Figure 3: The RF simulation of the LBBF kicker cavity (left). The installed LBBF kicker cavity and BPM to monitor the longitudinal instability (right).

The S-parameters measured after welding and assembly of the LBBF kicker cavity were close to designed values as shown in Table 1. The Q_L value estimated from the S11 parameter was approximately 3.0. After fabrication, the shunt impedance was estimated to be approximately 700 Ω by the bead ball perturbation measurement.

Table 1: RF Characteristics of Developed LBBF Kicker Cavity

	Designed value	Measured value
Center frequency	1.652 GHz	1.609 GHz
1 dB Bandwidth	317 MHz	271 MHz
Q_L	3.4	3.0

LBBF Commissioning

The developed LBBF kicker was installed in the storage ring in May 2025. The commissioning of the LBBF system was carried out in July 2025. The damping time of LBBF system was estimated by the grow damp method. Without LBBF, the damping time was approximately 7 msec corresponding to radiation damping time. By increasing the LBBF gain, the damping time was shortened to approximately 2.5 msec. Considering the radiation damping time, the effective LBBF damping time was estimated to be 3.9 msec in case the BBF gain is 4. The damping time of developed LBBF system is shorter than the growth rate of the 1.9 GHz instability observed in 2023. We confirmed that the LBBF system provided sufficient feedback performance.

The feedback phase of LBBF system was adjusted, and a beam accumulation test was carried out up to 400 mA. The number of taps for instability detection was set to 32. To efficiently detect the instabilities caused by synchrotron oscillation, the down sampling factor was set to 5. As a result, the LBBF system successfully suppressed the coupled-bunch instability caused by the 1.9 GHz HOM. We achieved the stable beam accumulation up to 400 mA as shown in Fig. 4.

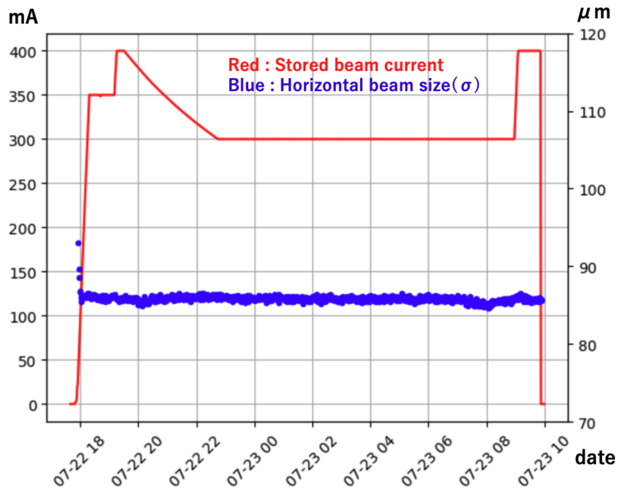

Figure 4: The stored beam current and horizontal beam size distribution with the suppression of longitudinal instability.

By applying the LBBF system, the phase spread of each bunch was significantly improved. Even at a stored beam current of 400 mA, the phase spread of all 550 bunches was suppressed to 0.5 psec (std) as shown in Fig. 5. The stored beam current for user operation was subsequently increased from September 2025, and routine user operation at 400 mA with high reliability began in November 2025 as shown in Fig. 6.

SUMMARY

We successfully developed the LBBF system to suppress the longitudinal coupled-bunch instability at NanoTerasu storage ring. The 400 mA stable beam accumulation using LBBF system was achieved. In addition, the user operation at 400 mA with high reliability began in November 2025.

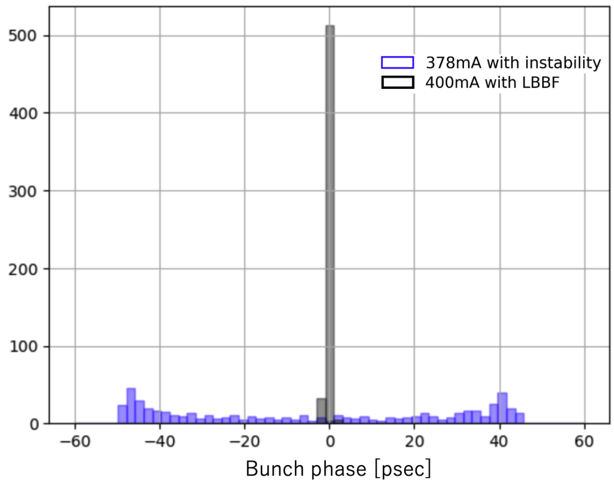

Figure 5: The bunch phase distribution of all 550 bunches.

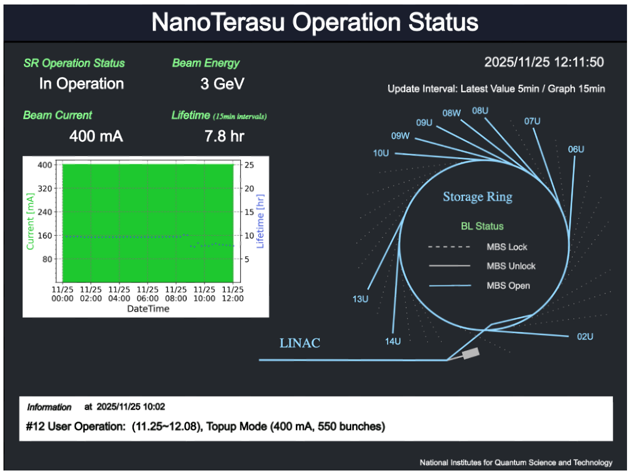

Figure 6: First 400 mA user operation.

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