ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUBI1

COMMISSIONING OF THE BEAM DIAGNOSTIC SYSTEM FOR NanoTerasu: A NEW 3 GeV LIGHT SOURCE IN JAPAN

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Abstract

NanoTerasu is a 4th generation 3 GeV light source newly constructed in Sendai, Japan. The storage ring circumference is 349 m and the natural emittance is 1.1 nm rad, which is realized by a double-double-bend lattice. The commissioning of the storage ring started in June 2023. The beam diagnostic system for NanoTerasu mainly consists of button BPMs to monitor both single-pass and COD beam orbit, a DCCT to monitor the stored current and an X-ray pinhole camera to measure the beam size. To suppress collective instabilities, a transverse bunch-by-bunch feedback (BBF) system is also in use. The BBF system can also measure the betatron tune. Using the BBF system, the stored beam current reached more than 100 mA with designed emittance in August 2023. The commissioning of the beam diagnostic system were performed smoothly. In addition, the first user operation at NanoTerasu was started on schedule with high reliability and high performance. The stored beam current was set to 160 mA with top-up beam injection. The operation availability was 99.5 % for first 1560 hours user operation period.

INTRODUCTION

The NanoTerasu is a compact 4th generation 3 GeV light source newly constructed in Sendai, Japan [1, 2]. The NanoTerasu construction was started in 2019. At the first phase, 10 beamlines were constructed. In total, 28 beamlines can be constructed. The accelerator system of NanoTerasu consists of full energy injector Linac and storage ring (SR) as shown in Fig. 1. The Linac system consists of 40 MeV pre-injector system and C-band accelerator system. The length of the Linac is only 110 m due to the high acceleration gradient of C-band accelerator. The 3 GeV C-band full-energy injector Linac enables the extension to the soft X-ray (SX) free electron laser in the future.

The SR circumference is 349 m and the natural emittance is 1.14 nm rad, which is realized by a 4 bend lattice as shown in Fig. 2. Four B-Q combined bending magnets, 10 quadrupole magnets and 10 sextupole magnets were installed in one unit cell. The SR consists of 16 cells in total. The new type of TM020 mode RF cavity with higher-order-mode dampers was developed [3]. In the beam injection point at SR, the in-vacuum off-axis beam injection system

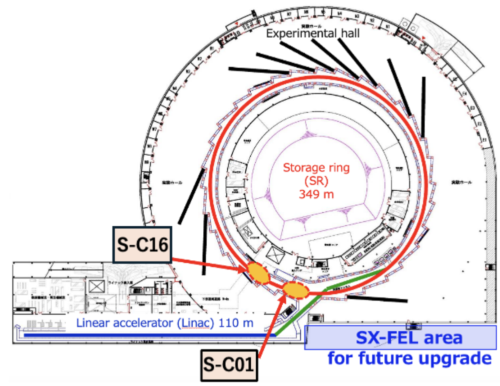

Figure 1: The layout of NanoTerasu accelerator system.

was installed for the stable top-up beam injection [4]. The beam diagnostic systems were installed in the two short straight sections (S-C01 and S-C16) [5]. Bunch-by-bunch feed back system (BBF) and BPM for bunch current monitor were installed in S-C01. Two DCCT sensor cores and a 3-pole wiggler (3PW) were installed in S-C16. The beam commissioning was started in April 2023 [6, 7].

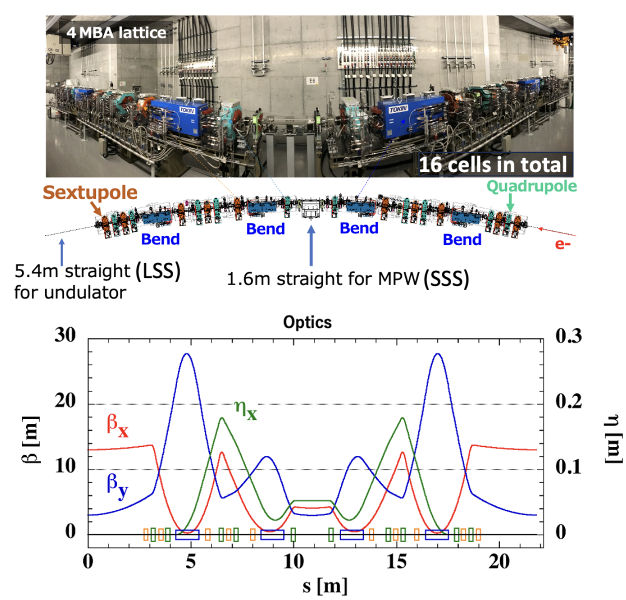

Figure 2: The magnets layout (top) and Lattice functions (bottom) in the one unit cell.

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Proc. 13th International Beam Instrumentation Conference,Beijing JACoW Publishing
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COMMISSIONING TIMELINE

The beam commissioning timeline is summarized in Fig. 3. The Linac beam commissioning was started on April 17th in 2023. After 10days, we confirmed 3 GeV electron beam. The SR beam commissioning was started on June 8th. The off-axis beam injection was achieved just adjusting the position and angle of injected beam. The injected beam turned around 300 turns without the supply of RF power on the first day of SR beam commissioning. Due to the precise alignment of the magnets by the vibrating-wire-method (VWM) [8], the first turn steering was not needed. After the RF conditioning of RF cavity, the electron beam was stored in SR on June 16th. On the same day, the first light from the 3PW was observed. Twenty four hours beam operation was started for vacuum conditioning on August 1st. The stored beam current reached more than 100 mA with designed emittance in August. In September the insertion device (ID) commissioning was started. The first user operation could be started on schedule.

Date	Event
2019	Start construction
Apr.17th 2023	Start Linac beam commissioning
Apr.27th	Confirm 3 GeV beam
Jun.8th	Start SR beam commissioning,turn around 300 turns w/o FTS
Jun.16th	First light observation of stored beam
Jul.7th	Stored beam profile observation
Aug.1st	Start 24hr beam operation for vacuum baking
Aug.10th	Stored beam current reached 100mA with designed emittance
Sep.	Start ID commissioning
Dec.	First beam observation in experimental hall
Apr.9th 2024	Start First user operation
Aug.6th	Finish first user operation (1560 hours, availability 99.5%)

Figure 3: The beam commissioning timeline.

COMMISSIONING OF BEAM DIAGNOSTIC SYSTEM

The beam diagnostic systems in storage ring are summarized in Table 1.

Table 1: Beam Diagnostic Systems

Monitor instruments	units
BPM	112 (7/cell)
Stored beam current monitor (DCCT)	2
Stored beam profile monitor (XPC)	1
Bunch-by-Bunch Feedback system (BBF)	1
Bunch current monitor	1
Injected beam position monitor (BPM)	3
Beam loss monitor	32 (2/cell)

X-ray Pinhole Camera

The stored beam profile was measured using a X-ray pinhole camera (XPC) [9] as show in Fig. 4. A compact 3PW with 1.27 T peak magnetic field was installed as a light source of XPC. The integrated magnetic field (ByL) of 3PW was reduced to 0.056 T mm not to affect the orbit of stored beam. The stored beam profile was monitored with magnification of 3.66. The designed horizontal and vertical beam size at S-C16 were 80 µm and 6 µm, respectively. The pinhole aperture was set to 13 µm square taking account the effect of diffraction. The emittance and x-y coupling ratio were evaluated from the observed beam size.

In July 2023, the stored beam profile could be fortunately observed without the adjustment of the pinhole angle and position (Fig. 4). The stored beam current and the exposure time of CMOS camera were 2.5 mA and 50 msec, respectively. After the XPC adjustment, we could confirm the stored beam profile with the designed emittance. The resolution of camera unit was estimated by knife edge method. Using hard X-rays with the peak energy of about 50 keV, the stored beam profile was monitored with about 5 µm resolution [10]. The beam size, position and tilt are monitored every second. The bunch length is also planed to measure using the visible light emitted by 3PW and a streak camera.

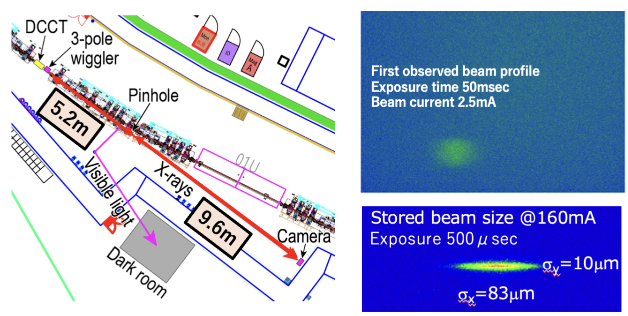

Figure 4: The XPC layout (left) and observed beam profiles (right).

Beam Position Monitor

To measure the stored beam position, 7 BPMs were installed in one unit cell. In total 112 BPMs were used for monitoring the closed-orbit distortion (COD) and single pass trajectories (SP). To measure injected beam trajectories precisely in the early stage of commissioning, the required position resolution of SP mode was set to less than 0.1 mm (std) for a 0.1 nC bunch. The BPM consists of four-button type electrodes developed for SPring-8-II project [11] as shown in Fig. 5. The beam position was calculated in the MTCA.4 based electronics using the voltage detected by BPM electrode [12]. BPM electrode and readout electronics were connected using coaxial cables. To avoid radiation damage, the semirigid cables with dielectric materials of PEEK were used at the high radiation dose position near the vacuum chamber. The corrugated coaxial cables were used from the bottom of magnet girders in the accelerator tunnel to the outside.

The stored beam COD was monitored with several data acquisition methods such as turn-by-turn (TBT) with 859 kHz, fast data (FA) with 10 kHz and slow data (SA) 10 Hz. The MTCA.4 based electronics were installed in the water-cooling 19-inch rack. The temperature in the rack was stable within ± 0.1 deg for 4 months. In June 2023, SP timing of

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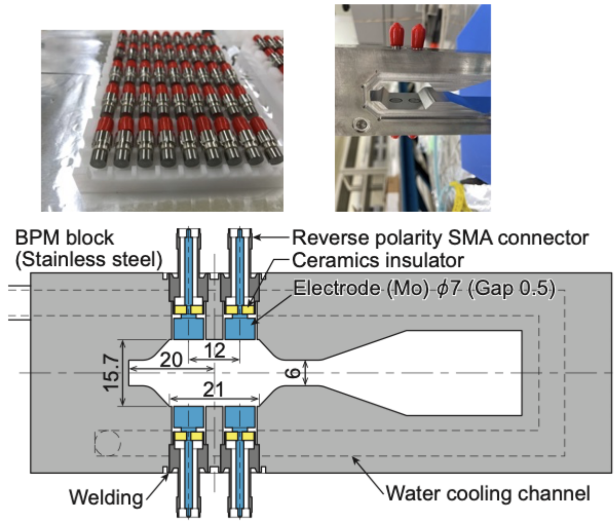

Figure 5: Picture of button electrodes (top) and schematic view of BPM (bottom).

all BPMs was adjusted during RF cavity conditioning. The SP BPM data could be taken just after electron beam was stored as shown in Fig. 6. Using the SP data, the frequency of the synchrotron and betatron oscillation were estimated.

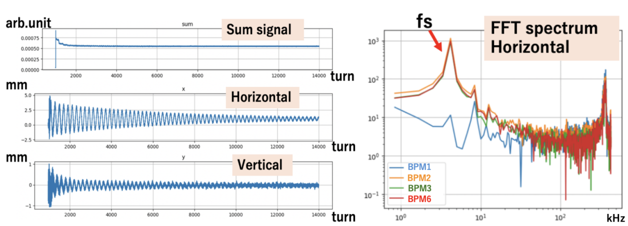

Figure 6: SP BPM data (left) and Fourier transformed spectrum (right). The BPM2, 3 and 6 were installed at an energy dispersive section. The BPM1 was installed at a non-dispersive section.

The beam based alignment (BBA) [13] of all BPMs was performed to adjust the beam optics parameters precisely in September 2023. The BPM offset against the magnetic field center of the nearest quadrupole was measured with an accuracy of 10 µm. The position correlations between BBA target BPM and another BPM were measured before and after magnetic field change of quadrupole as shown in Fig. 7. The COD was measured with FA data for 48 BPMs. In case the stored beam passed through the center of quadrupole magnetic filed, the COD was not changed. The 47 intersection points were obtained as a BPM offset. To avoid the effect of insensitive BPMs, the intersection points within $\pm 1\sigma$ were selected to evaluate the BPM offset. Figure 8 shows the all BPM offsets distribution. The horizontal and vertical standard deviation depending on the accuracy of BPM electric center were 147 µm and 138 µm, respectively.

The COD results before and after BBA correction are shown in Fig. 9. The vertical COD was especially reduced to $\pm$ 0.05 mm. It took many hours to obtain BPM offset for

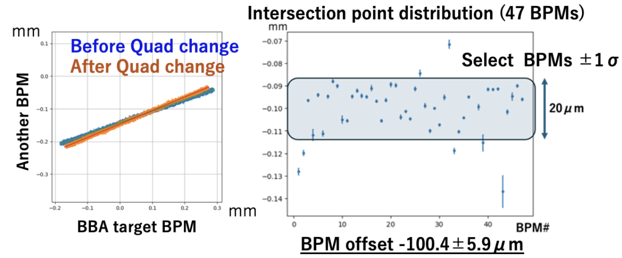

Figure 7: The position correlations plot of 2 BPMs before and after magnetic field change (left). Intersection point distribution as a result of BBA for one BPM (right).

all BPMs last year. The BBA measurement time was reduced to 100 minutes now by improving the BBA sequence.

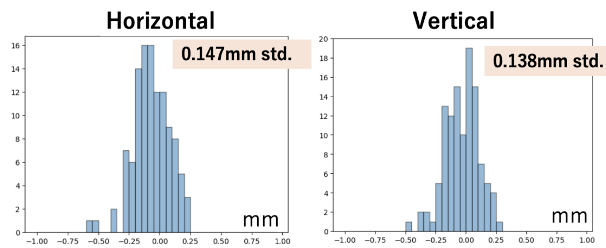

Figure 8: All BPM offsets distribution.

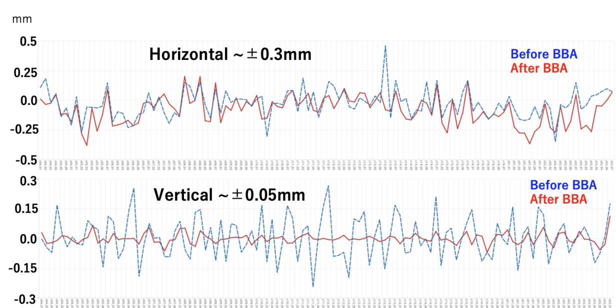

Figure 9: COD result before and after BBA correction.

Bunch by Bunch Feedback System

To suppress the transverse instability, the BBF system was installed. At the S-C01 a 4-electrode stripline kicker and a stripline BPM were installed as shown in Fig. 10. The beam position signal was picked up and the counter kick signal was calculated by the fast signal processor iGp12 developed by Dimtel Inc. The horizontal and vertical kick signals were calculated independently and combined in the back-end electronics. The kick signal was amplified by the wide-band power amplifier.

The BBF commissioning was started in August 2023. In case the stored beam current reached about 10 mA, the stored beam size was increased due to the transverse instability. The parameters of horizontal and vertical BBF systems were adjusted to suppress the transverse instability. After the target COD was decided, the attenuator and phase shifter

Proc. 13th International Beam Instrumentation Conference,Beijing JACoW Publishing
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of each electrode were adjusted so that the $\Delta X(=V1+V4-V2-V3)$ and $\Delta Y(=V1+V2-V3-V4)$ differential signals were small. By exciting the stored beam, the sampling point was set at most fluctuating timing with an accuracy of about 20 psec. The kicker timing was adjusted not to affect the neighboring bunches. The BBF damping time depending on BBF gain was measured by grow damp method as shown in Fig. 11. The horizontal and vertical damping time were confirmed less than 10 µs and 20 µs, respectively. The phase shift of the FIR filter at the betatron frequency was adjusted with an accuracy of about 5 deg so that the baseline of the spectrum notch was flat.

The BBF resolution and dynamic range were measured using local bump as shown in Table 2. After the BBF commissioning was performed, the stored beam current reached more than 100 mA with designed emittance in August 2023. In addition, the fluctuation of the stored beam at the beam injection could be settled below beam size within 10 turns after the beam injection using BBF system.

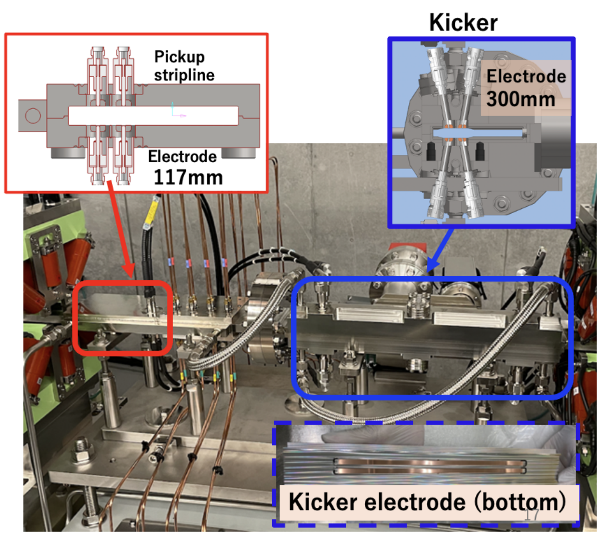

Figure 10: BBF kicker and pickup BPM.

Table 2: BBF Resolution and Dynamic Range

	Resolution	Dynamic range
Horizontal	14 cnt/mA/µm	±146 µm (1mA/bunch)
Vertical	12 cnt/mA/µm	±170 µm (1mA/bunch)

The horizontal and vertical fractional betatron tune values were monitored using BBF systems. BBF was disabled for only one bunch to measure the fractional tune. The bunch was shaken by a swept sine with 20 kHz span to measure the tune variation. Horizontal and vertical tune were corrected every 30 seconds to achieve stable beam operation.

Beam Abort System

In NanoTerasu the vertical beam size was increased using beam shaker at beam abort to avoid the vacuum accident.

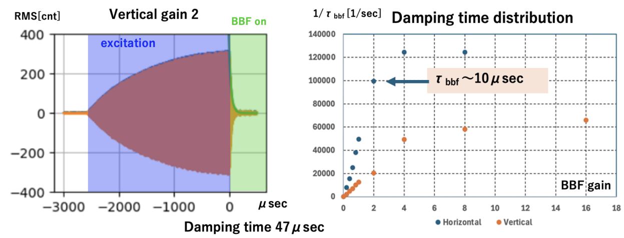

Figure 11: BBF grow damp measurement (left) and damping time distribution depending on the BBF gain (right).

The interlock signal of RF was transferred to BBF backend electronics and the kick signal was switched from BBF to beam shaker with vertical betatron frequency.

In addition, to protect beamline and frontend equipment the COD was always monitored using FA data. In case the COD exceeds the orbital interlock threshold, the stored beam is immediately aborted within 1 msec. The orbital interlock was enabled in case the stored beam current was more than 3 mA. The thresholds of the orbit interlock for each ID were set to upstream and downstream BPMs of each ID. Even though the interlock threshold was set to ±0.14 mm at severest BPM, the stable beam operation was achieved.

Figure 12 shows the SP BPM data at energy dispersive section taken by the orbit interlock trigger. After the orbit interlock signal was triggered, the RF power was turned off and the horizontal orbit was shifted toward the center of the storage ring. The beam shaker was immediately turned on by the transferred RF interlock signal and the vertical beam size was increased. The aborted beam is gradually stretched in the phase space due to the decoherence effect and the phase space distribution becomes like a ring [14]. Because the pickup BPM can be measured only the center of beam, so the vertical oscillation amplitude looks like reducing before the beam abort. The stored beam was gradually lost about 400 µs later after the orbital interlock was triggered.

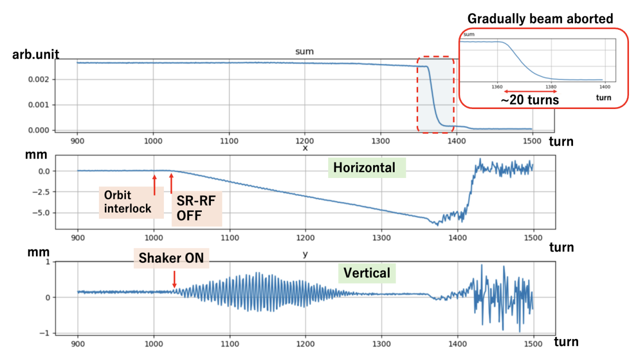

Figure 12: SP BPM data when the orbit interlock was triggered.

USER OPERATION STATUS

The first user time operation was started on April 9th in 2024. The stored beam current was set to 160 mA with top-up beam injection. The optics parameters are listed in Table 3. The stored beam profile was monitored using

ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUBI1

the XPC as shown in Fig. 13. The horizontal and vertical beam size were stable within 1 µm. In addition, the position variations were also stable within 5 µm.

In total the scheduled user operation time was 1560 hours until August 6th. The down time was only 7.3 hours as shown in Fig. 14. The user availability reached 99.5 %. The mean time between failures (MTBF) was 222 hours.

Even though the stored beam current is limited by the longitudinal coupled bunch instability, the RF cavity parameters are being adjusted to increase the stored beam current. The stored beam current was increasing to 200 mA with designed emittance on July 26th. The highly brilliant SX beam with a high coherent ratio and high reliability has been started to be provided to users.

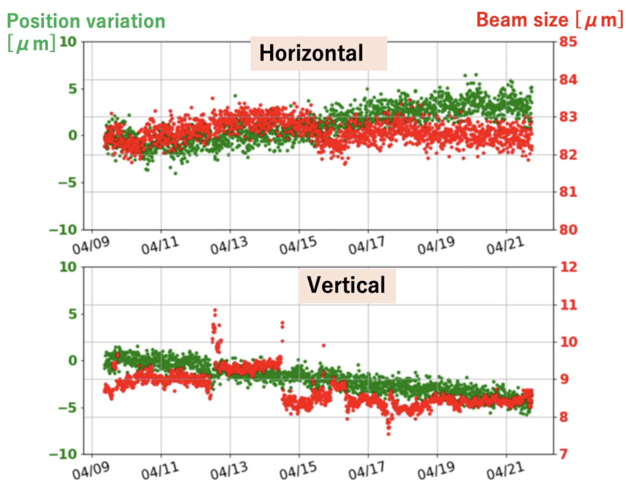

Figure 13: The horizontal (top) and vertical (bottom) stored beam stability during 12 days user operation period.

Table 3: Designed and Measured Beam Parameters in SR (160 mA)

Ring parameters	**Designed value**	**Measurement**
Horizontal emittance	1.14 nm rad	1.14 nm rad *
Vertical emittance	0.01 nm rad	0.02 nm rad
x-y coupling	1 %	2.1 %
Energy spread	0.084 %	0.097 %
Betatron tune(ν_x, ν_y)	(28.17,9.23)	(28.17,9.23)
Chromaticity(ξ_x, ξ_y)	(1.38,1.53)	(1.98,1.98)

*assuming the designed value

SUMMARY

The commissioning of the beam diagnostic system, including the start-up of BPM data acquisition system, BBA, XPC adjustment, BBF adjustment and beam abort system, was completed ahead of schedule. The stored beam current was reached more than 100 mA with designed emittance in

Cycle	period	Current	User time	Down time	Availability
#1	April 9~21	160mA	296 hours	111 min	99.38%
#2	May 19~31	160mA	272 hours	218 min	98.66%
#3	June 4~14	160mA	248 hours	0	100%
#4	June 19~28	160mA	224 hours	0	100%
#5	July 9~19	180mA	248 hours	108 min	99.27%
#6	July26~Aug.6	200mA	272 hours	0	100%

Figure 14: User operation status.

August 2023 due to the suppression of transverse instability using the BBF system.

The first user operation was started on schedule. The operation availability was 99.5 % for first 1560 hours user operation period. The highly brilliant SX beam with high reliability has been started to provide users in Japan.

ACKNOWLEDGEMENTS

With the great support of SPring-8/SACLA accelerator team, the design, fabrication, and installation of NanoTerasu accelerator were completed. The NanoTerasu beam commissioning progressed much earlier than scheduled thanks to their invaluable support.

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