Simple and stable 3-GeV linear accelerator in high brilliance synchrotron radiation source NanoTerasu

NanoTerasu Center

National Institutes for Quantum Science and Technology

Takao Asaka

NanoTerasu QST

DAEJEON LINAC2026

Outline

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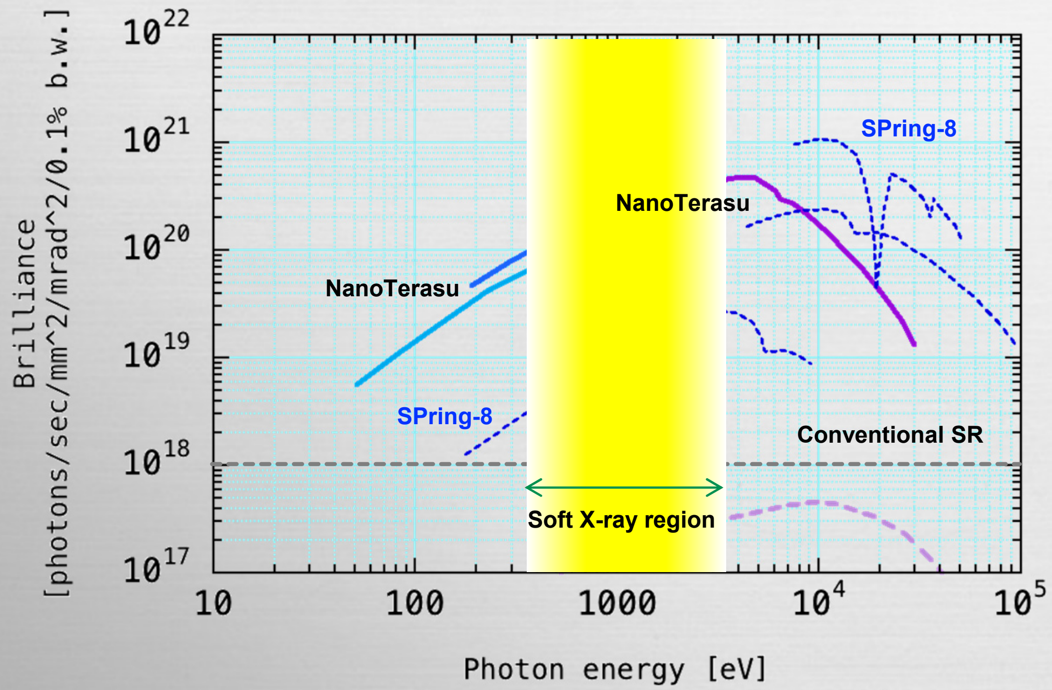
» 3 GeV Beam Performance and Top-up Injection

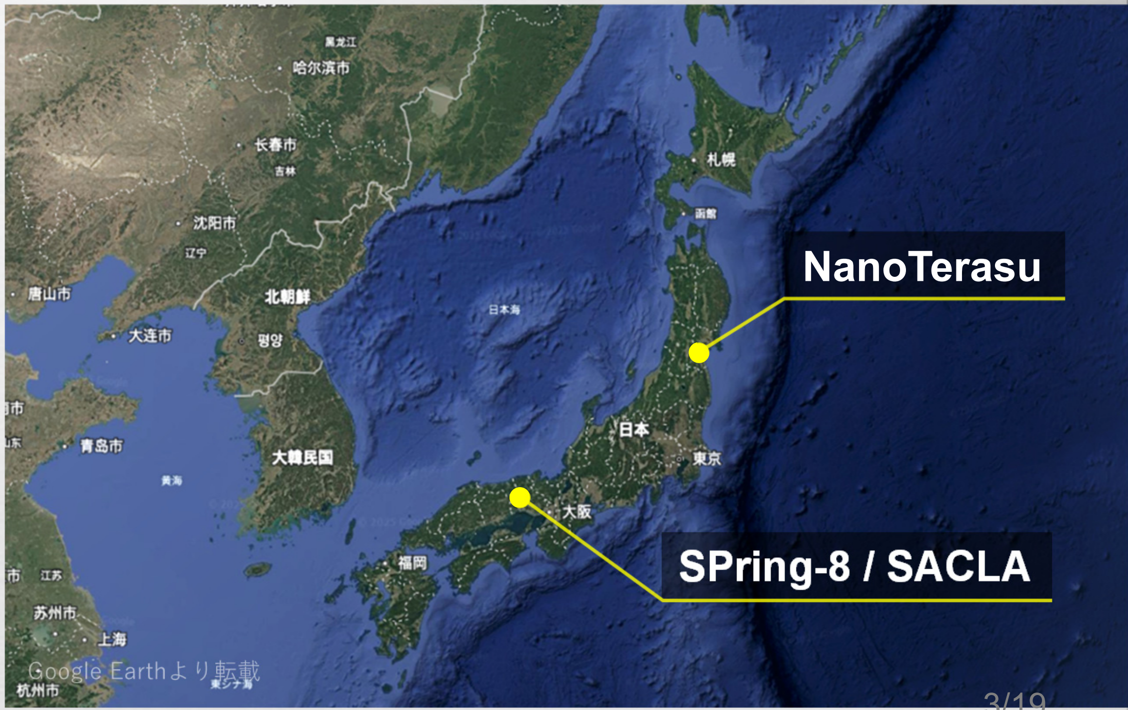
» Summary

Introduction

» NanoTerasu is a 4th generation synchrotron radiation facility optimized for the soft- to tender X-ray region.

» Together with SPring-8, Nanoterasu constitutes a national photon science platform in Japan, providing complementary capabilities across the soft- to hard-X-ray spectrum.





Construction and Operational History of Accelerator System

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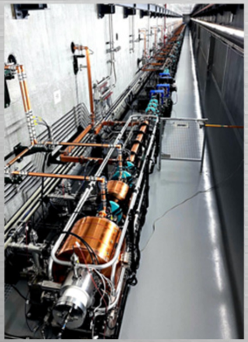
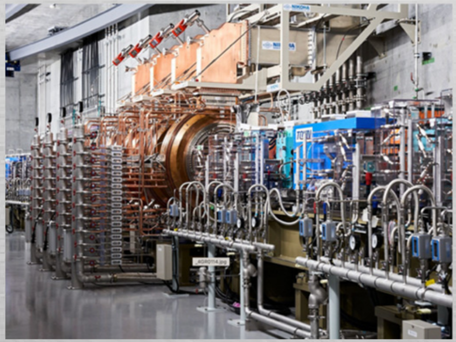
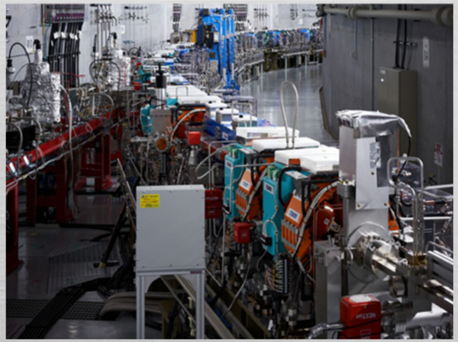
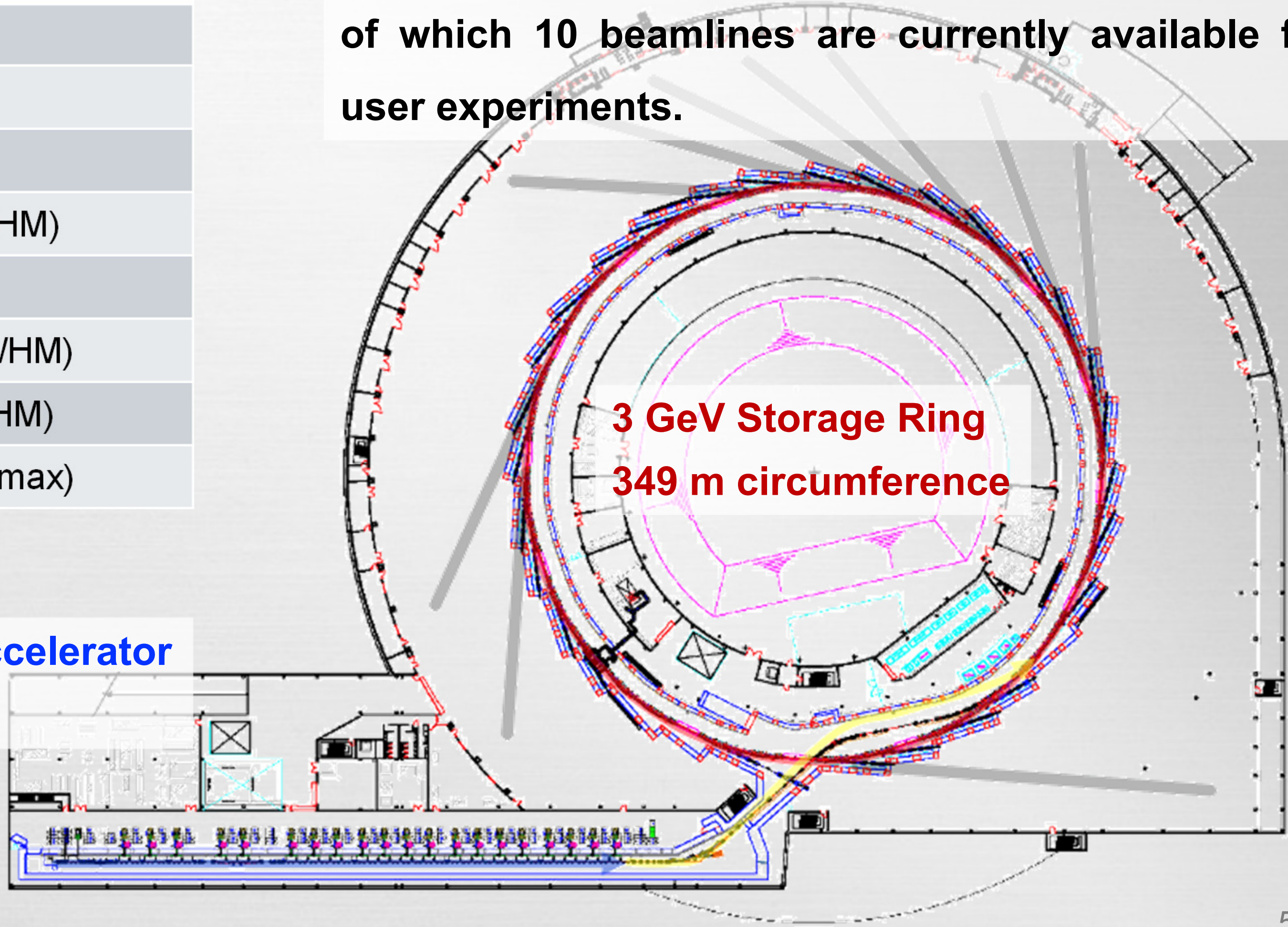
Year	Month	Major Milestones
2020	**Mar.**	Start of **Facility Building Construction**
2022	Jan.	Completion of Facility Building Construction
2023	**Jan.**	Completion of **Accelerator Installation and Alignment**
	Feb.	RF Conditioning
	Apr.	**Linear Accelerator Beam Commissioning**
	Jun.	**First Beam Stored in Storage Ring**
	Sep.	Stored Beam Current Reached 200 mA
	Dec.	**X-ray Beamline Commissioning** with Stored Beam Current of 200 mA
2024	Apr.	Start of **User Experiments with Top–up Operation**
2025	**Nov.**	**User Experiments at Design Stored Beam Current of 400 mA**


Target Beam Parameters for Linear Accelerator

Beam parameters	Design
Beam charge	**0.3 nC**
Emittance	**3 nm rad**
Normalized emittance	10 mm mrad
Bunch length	< 10 ps (FWHM)
Beam energy	3 GeV
Energy spread	< 0.16% (FWHM)
Energy stability	< 0.2% (FWHM)
Repetition rate	1 Hz (10 Hz max)

NanoTerasu can accommodate up to 28 beamlines, of which 10 beamlines are currently available for user experiments.



Design Concept of Linear Accelerator

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Minimalist philosophy

Low-emittance Electron Gun with a Gridded Thermionic Cathode

Simplified Pre-injector Composed of Functionally Separated Subsystems

Compact C-band Linear Accelerator

High-availability Operation

Improved Reliability and Reduced Operational Costs

-> High-precision RF Control based on MTCA.4

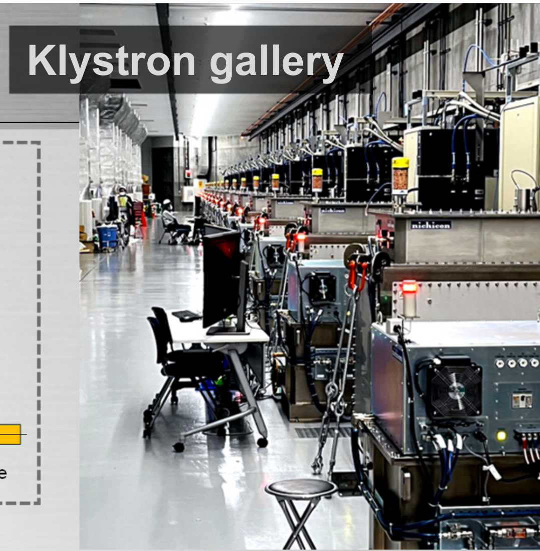
-> Simplified Beam-Tunning Procedures

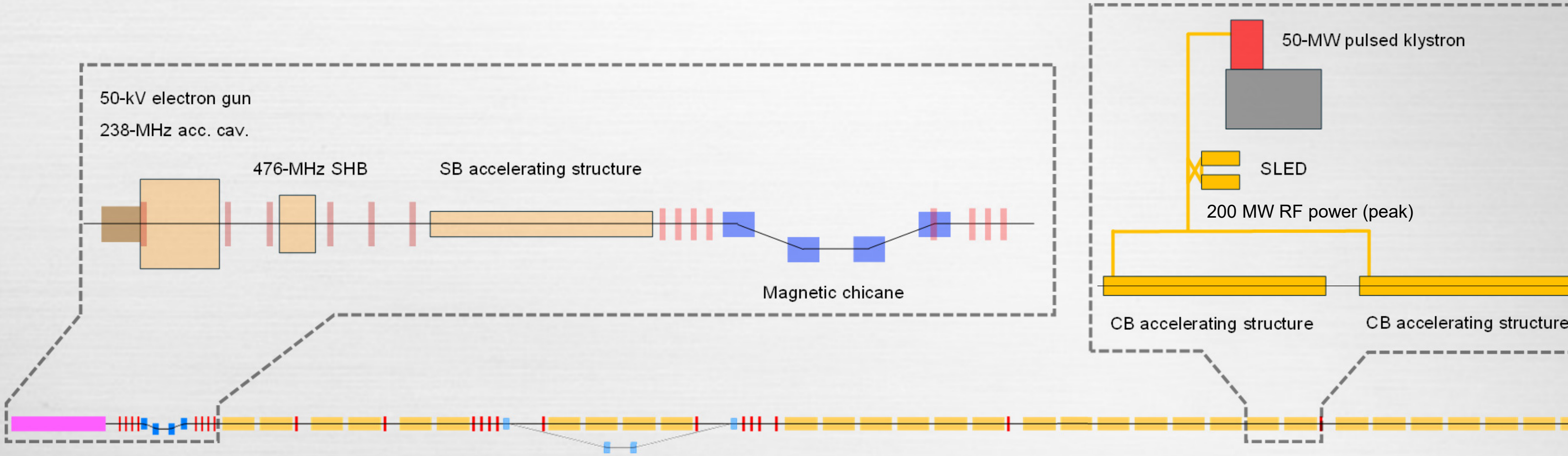
Future SX-FEL Expansion

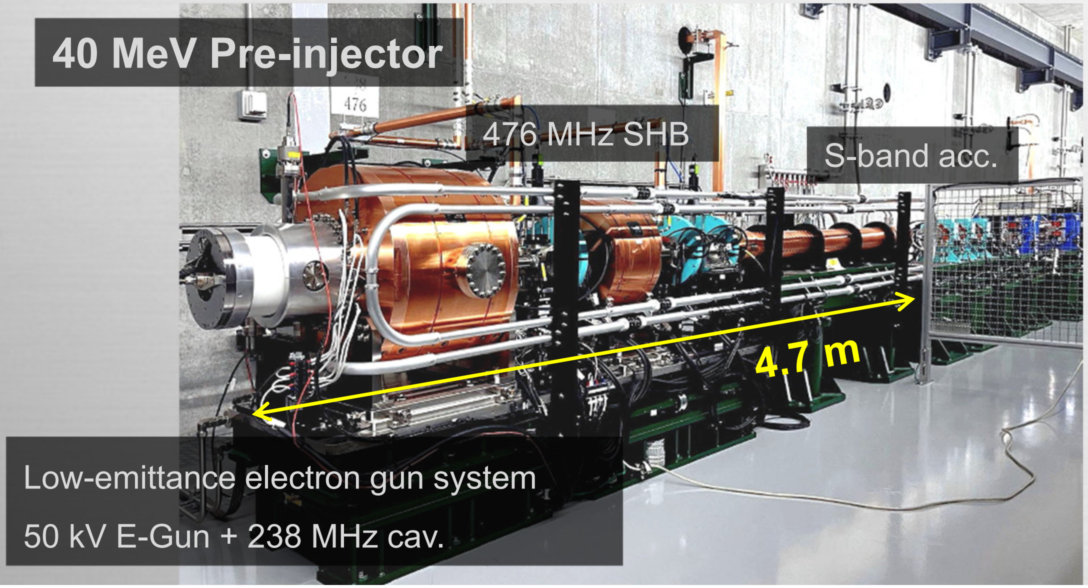
Implementation of Magnetic Bunch Compressor and Pre-injector Upgrade

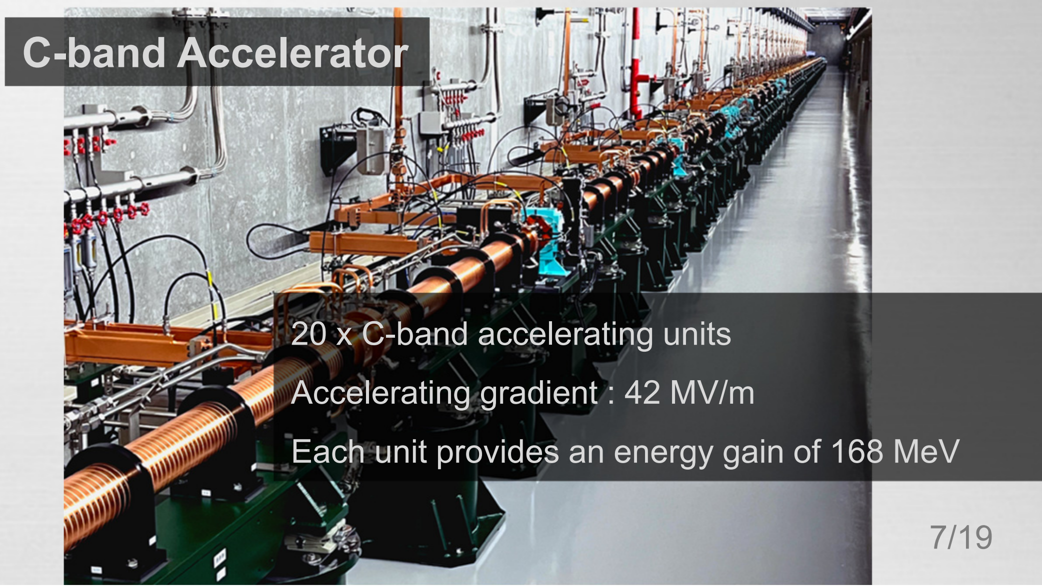
Highly Stable Beam Injection for Top-up Operation

Configuration of 3 GeV Linear Accelerator

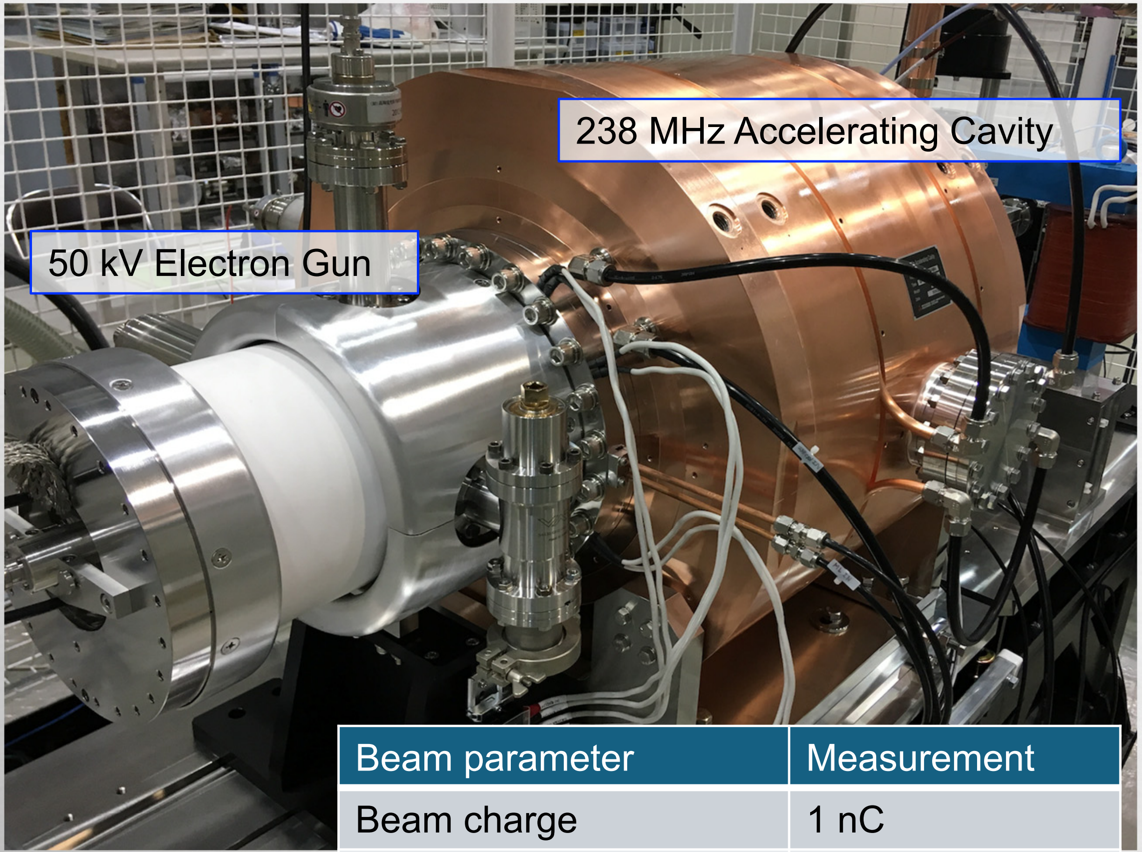








Low-Emittance Electron Gun System



Beam parameter	Measurement
Beam charge	1 nC
Bema energy	500 keV
Pulse width	600 ps
Normalized emittance	1.7 mm mrad

Low-emittance electron beams have been generated using:

Photocathode RF guns or 500-kV gridless thermionic guns

Generally:

Gridded thermionic cathodes have been regarded as unsuitable for low-emittance beam generation because of emittance growth caused by grid induced electric-field distortion

: Lens effect

Challenges and achievement:

NanoTerasu electron gun system successfully generates low-emittance beam with a gridded thermionic cathode.

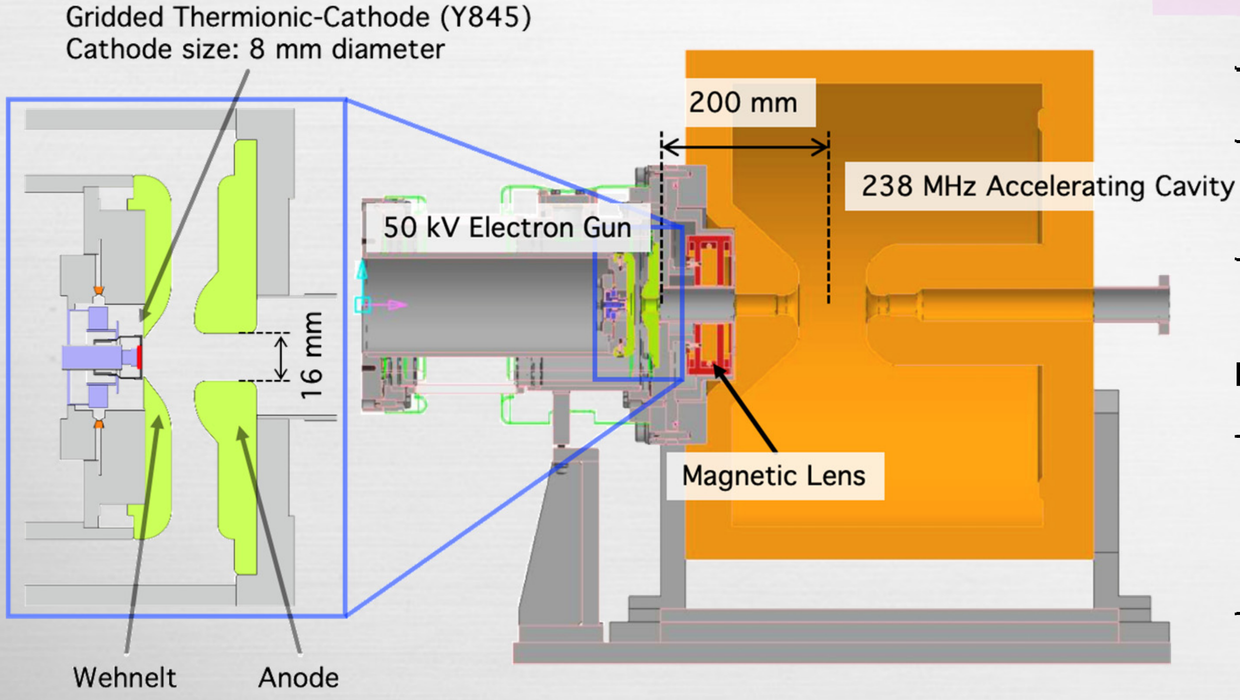
Advantages:

Gridded thermionic cathode offers several practical advantages, including ease of handling, high reliability, simple maintenance, mechanical robustness, and long operational lifetime

Future application:

Electron gun concept is planned for future SX-FEL upgrade

Low-Emittance Electron Gun System



No large-Scale Auxiliary Systems Required:

- No laser drive system required
- No high-voltage pulse modulator required

Compact and cost-effective

Low-emittance electron beam generation scheme

Transparent-Grid Scheme:

- Grid voltage optimized to compensate electric-field distortion caused by the grid mesh
- Generation of a nearly parallel beam downstream of the grid mesh

Rapid Acceleration for Space-Charge Suppression:

- To minimize emittance growth due to the space charge effects at low beam energies, 50 kV electron gun is positioned as close as possible to 238 MHz accelerating cavity
- This configuration enables the beam to be accelerated to 500 keV immediately after extraction from the anode of electron gun

Integrated Magnetic Lens:

- Magnetic lens was embedded in the electron gun structure
- Preservation of beam uniformity during transport from electron gun to 238 MHz accelerating cavity

Emittance Measurement of Electron Gun System

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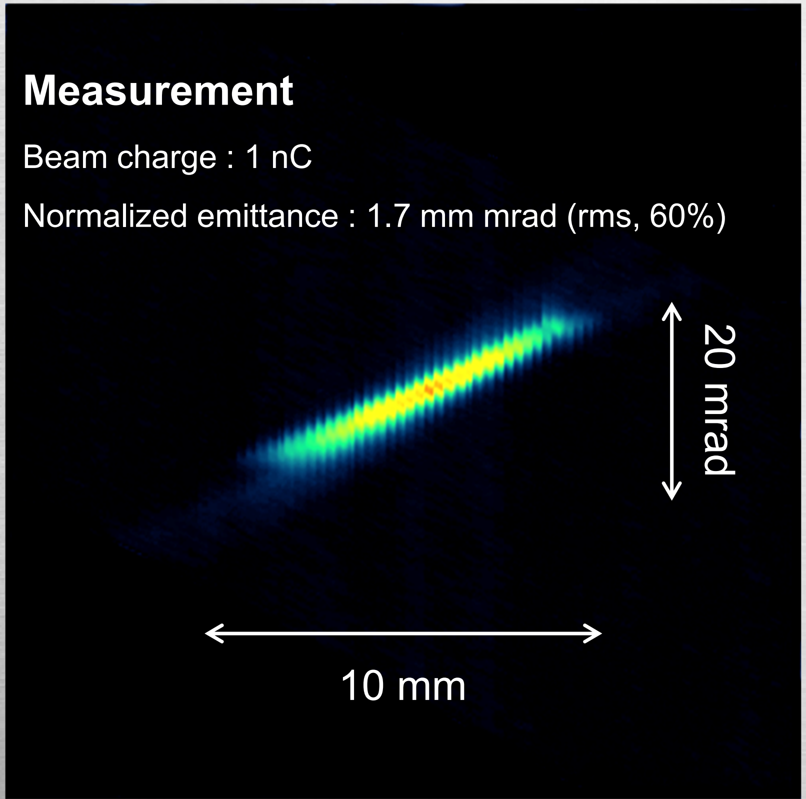

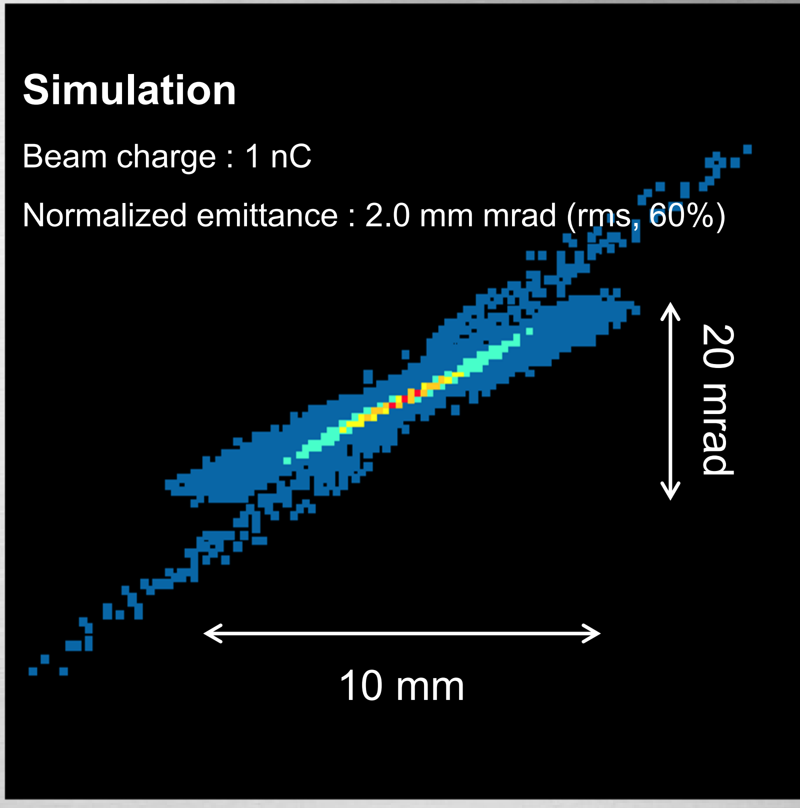

Low-Emittance Beam Demonstration:

- Horizontal phase space distribution measured using slit-scan method during the beam tests
- Normalized emittance of 1.7 mm mrad was achieved, demonstrating successful low-emittance beam generation
- Phase-space distribution and normalized emittance are in good agreement with the simulation results

40-MeV Pre-injector & Chicane

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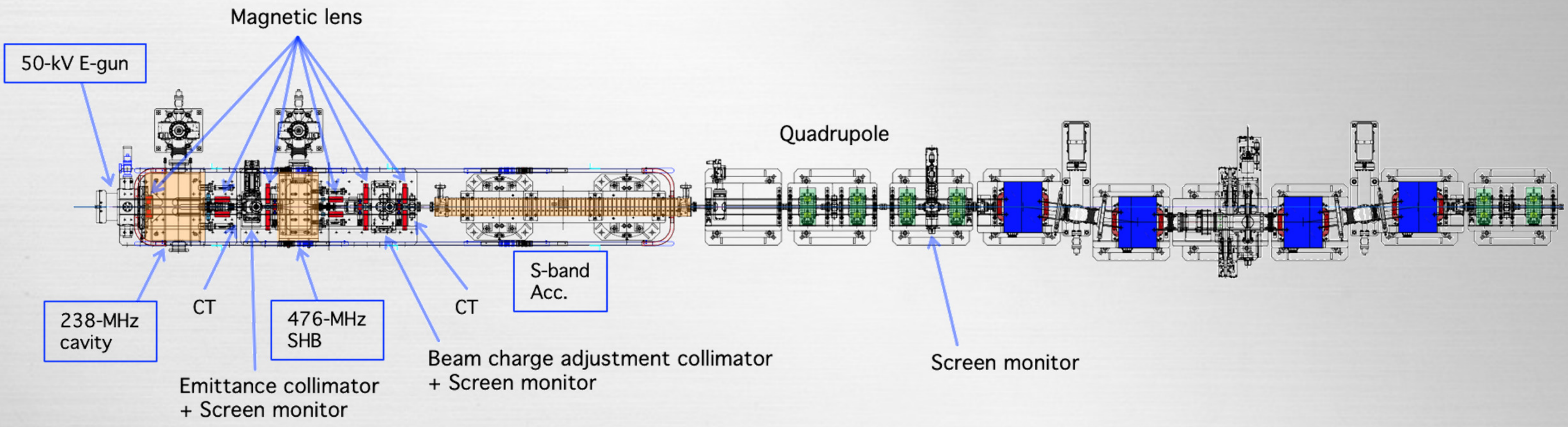


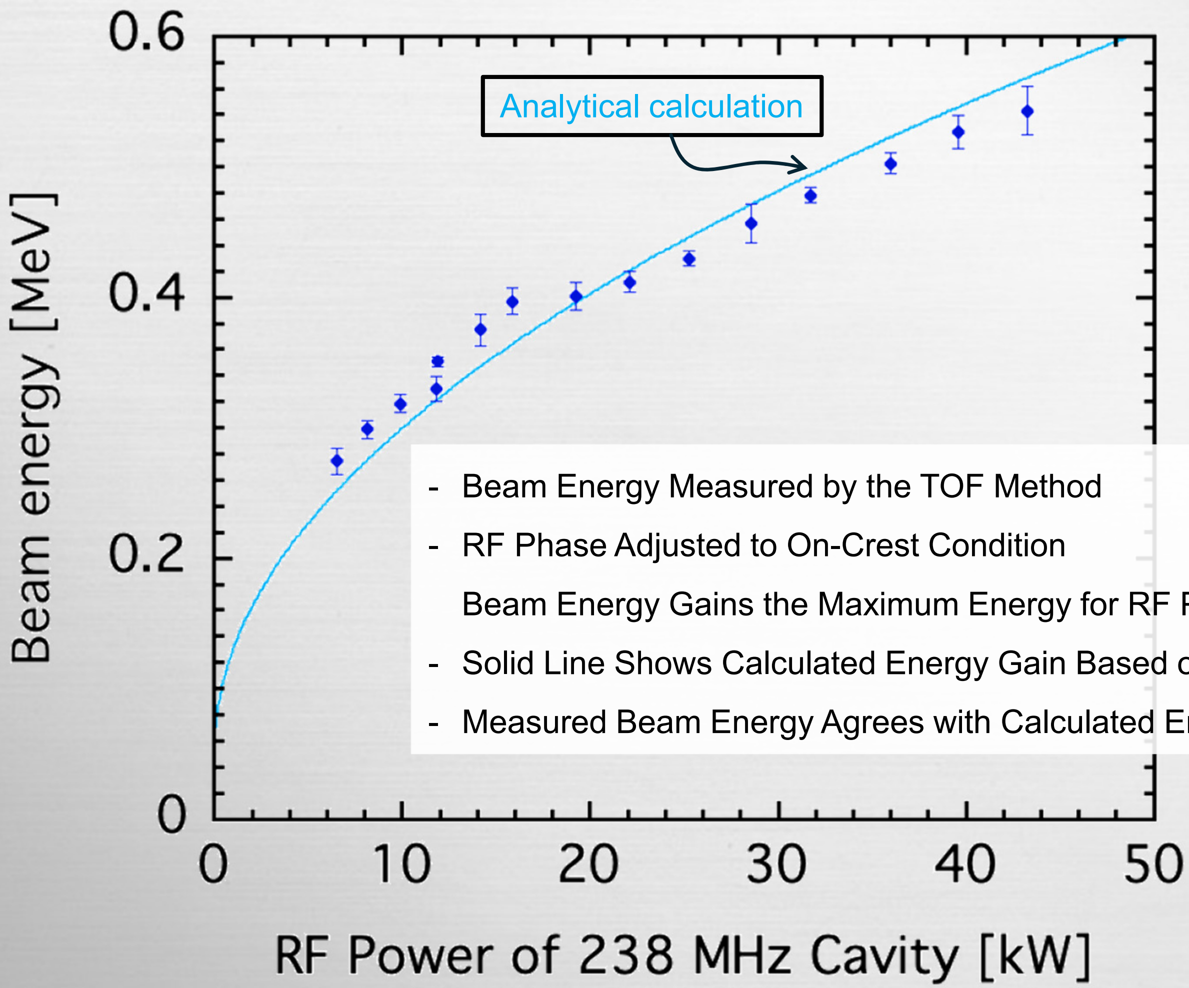
Design and Beam Tuning Strategy:

- Position and parameter settings of all components were optimized using PARMELA
- Beam monitor (Current transformer, Screen monitor) locations were selected to facilitate efficient beam tuning
- RF amplitude and phase of the accelerating cavity and SHB were optimized using time-of-flight (TOF) measurements from two CTs

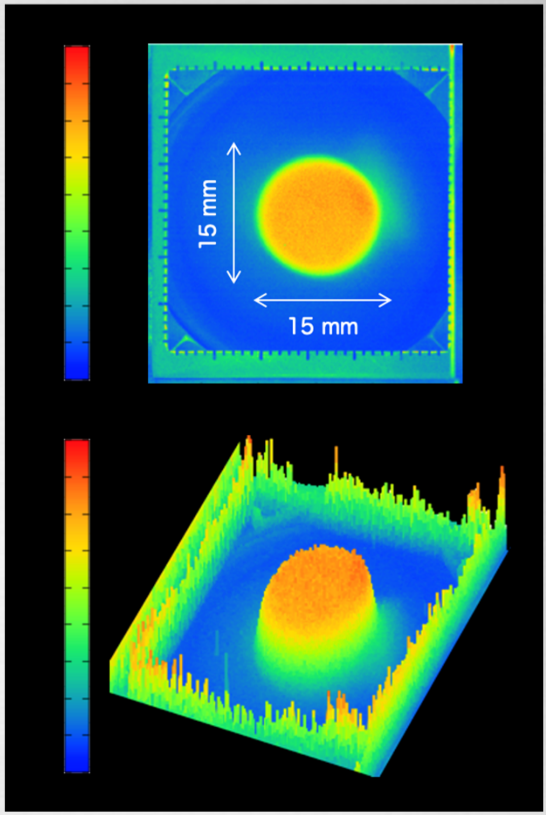
Initial Parameter Setup:

- Cathode-to-grid voltage of 50 kV electron gun set according to PARMELA
- Magnetic-lens excitation current were set to determined by PARMELA

Beam tuning of 40-MeV Pre-injector, 238 MHz cavity



- Beam Energy Measured by the TOF Method
- RF Phase Adjusted to On-Crest Condition
  Beam Energy Gains the Maximum Energy for RF Power
- Solid Line Shows Calculated Energy Gain Based on R_{shunt}
- Measured Beam Energy Agrees with Calculated Energy Gain



- Measured Beam Profile at the Exit of the 238 MHz Accelerating Cavity
- A Homogeneous Beam Distribution Was Obtained

Beam tuning of 40-MeV Pre-injector, 476 MHz SHB

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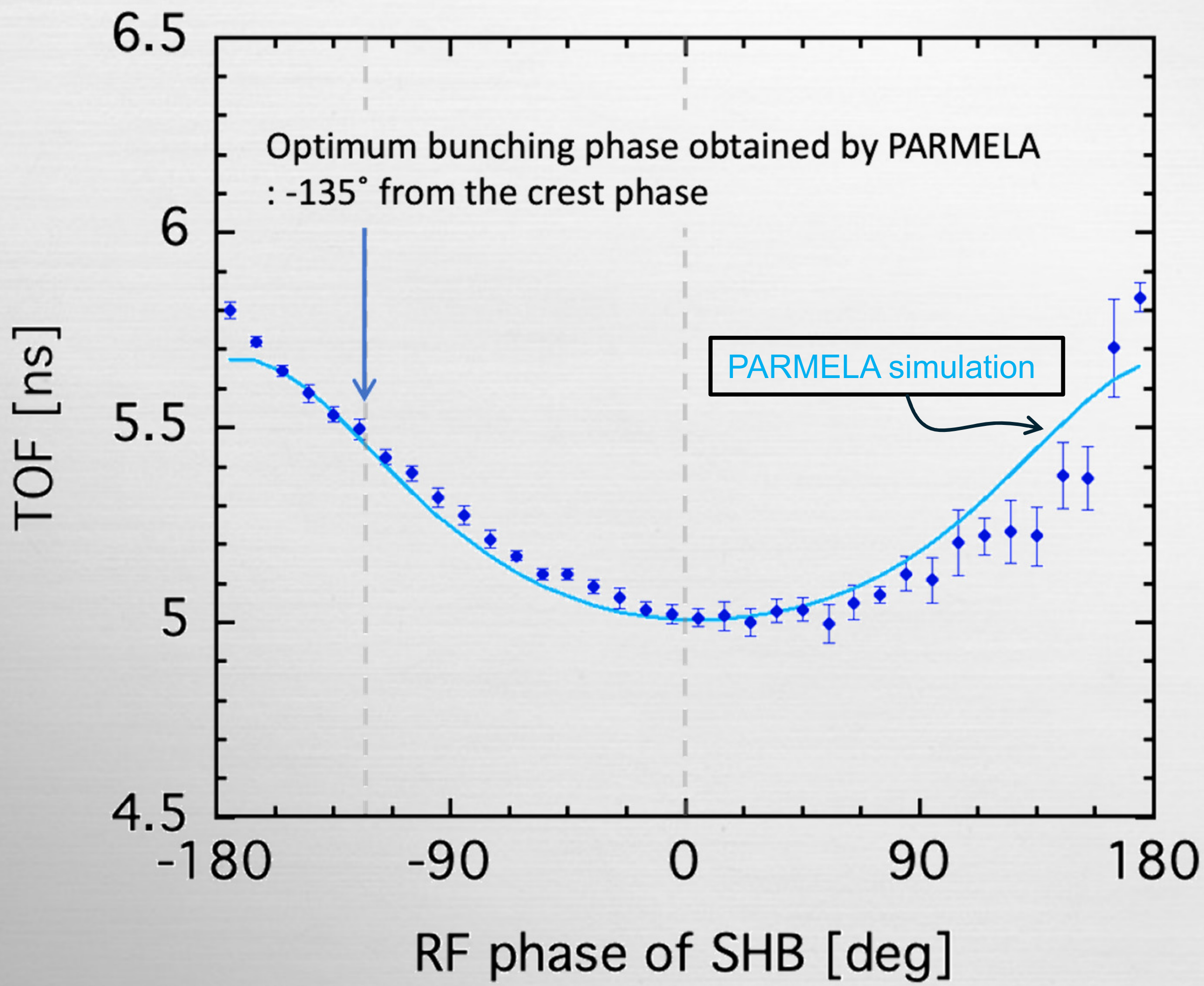


Optimization of RF parameters of 476 MHz SHB:

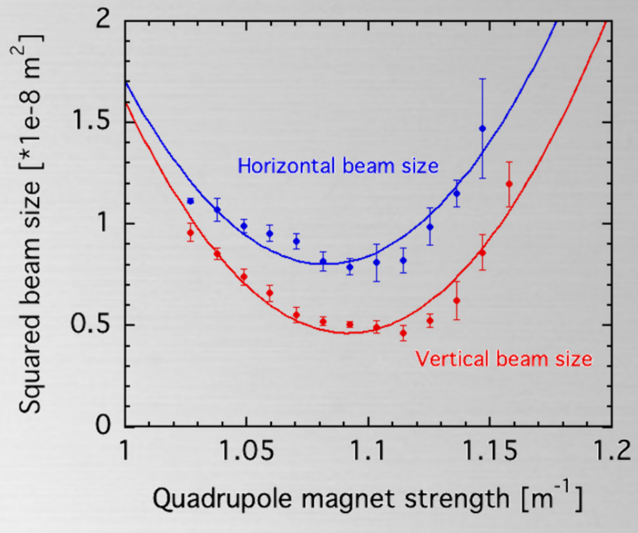
- Measured TOF as function of RF phase for 6.8 kW
- TOF variation depends on RF power and phase
- Measured results are in good agreement with PARMELA simulations

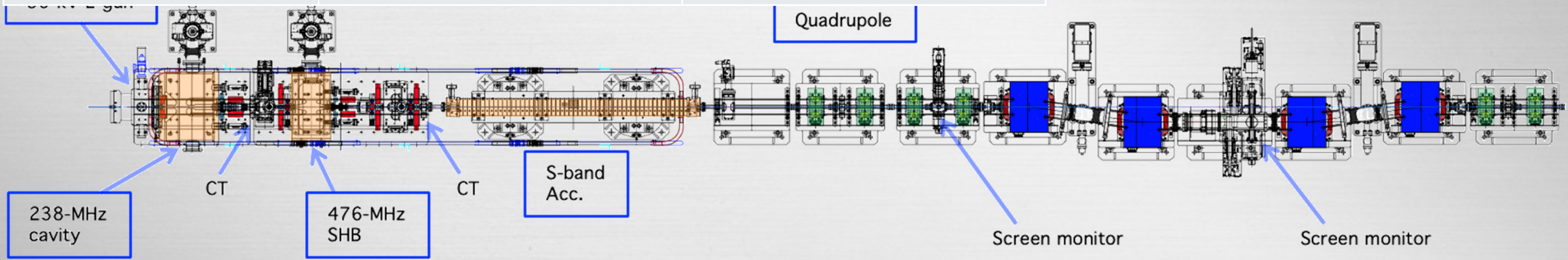
Optimum Bunching Condition:

- According to the simulation, optimum bunching phase : -135˚ relative to the on-crest phase
- Bunch-centroid energy: ~ 320 keV
- Optimal injection conditions for the S-band accelerating structure

40 MeV Beam Parameters

Beam parameters	Design	Measurement
Beam charge	0.3 nC	0.4 nC
Normalized emittance	10 mm mrad (rms)	8.4 ± 0.9 mm mrad (rms, x) 6.5 ± 0.2 mm mrad (rms, y)
Bunch length	< 10 ps (FWHM)	~ 5 ps (FWHM)
Beam energy	40 MeV	40 MeV





- RF power and phase of SB accelerating structure were optimized based on the measurement of beam energy profile
- Twiss parameters were measured to established the design optics for C-band accelerator
- All measured beam parameters satisfy the design parameters

3 GeV Beam Parameters

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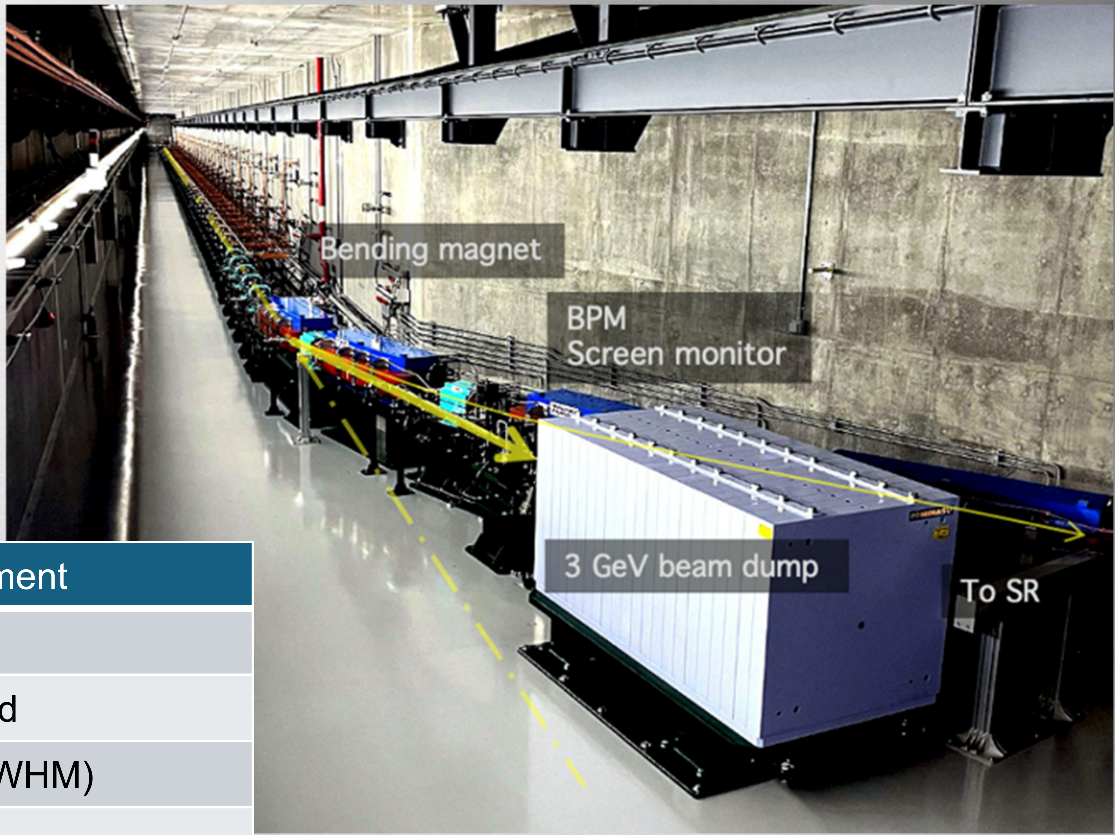
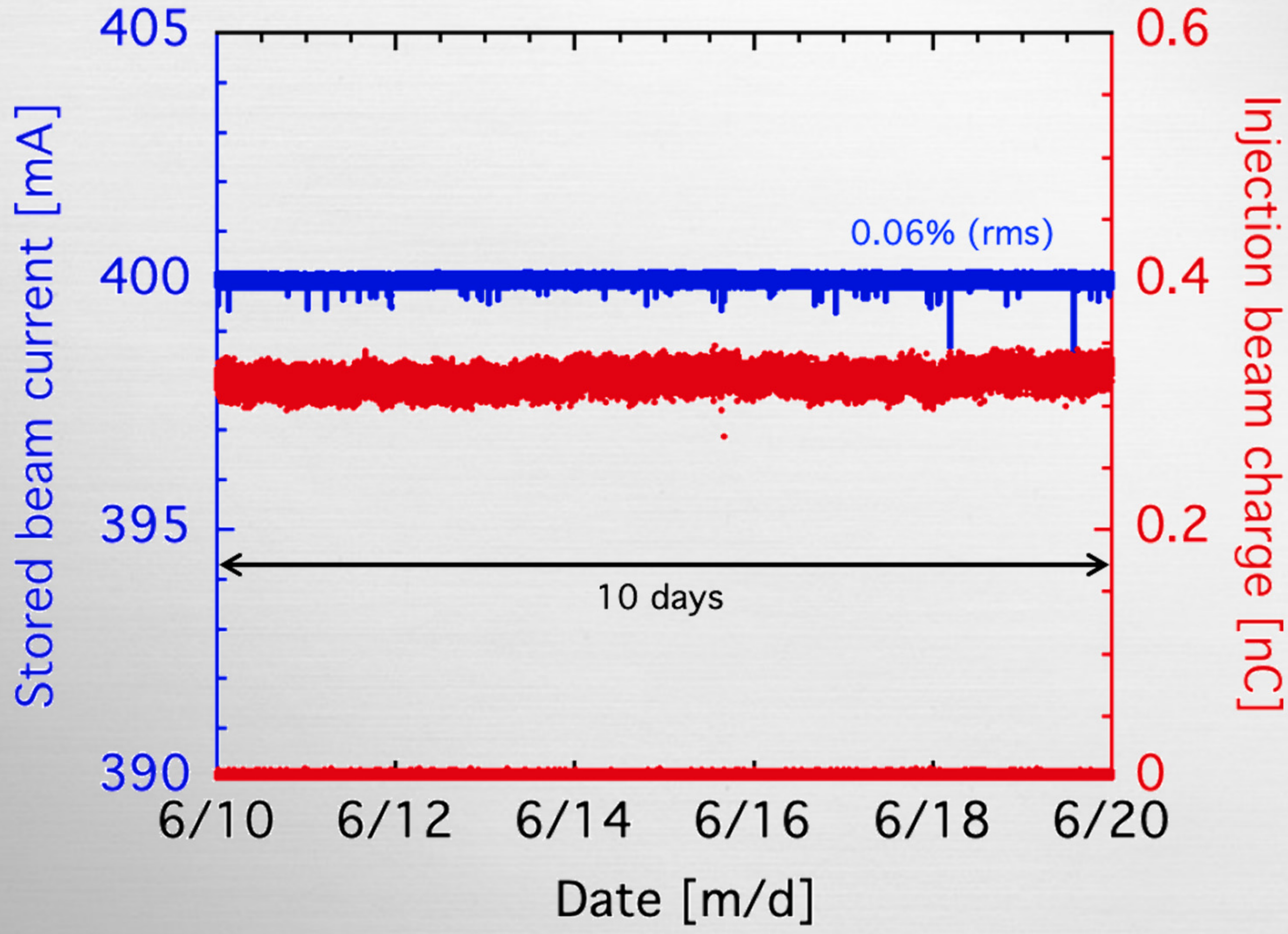
Design and Beam Tuning Strategy:

- RF phase of each C-band accelerating unit was determined using beam-induced voltage measurements
- Beam energy is fine-tuned using screen monitor installed downstream of BM
- Energy spread of 0.04 % was achieved
- Corresponding bunch length was estimated to be 5 ps from $\Delta E/E$
- Beam transmission through linear accelerator was > 90 %



Beam parameters	Design	Measurement
Beam charge	0.3 nC	0.35 nC
Absolute emittance	< 3 nm rad	2.5 nm rad
Bunch length	< 10 ps (FWHM)	~ 5 ps (FWHM)
Beam energy	3 GeV	3 GeV
Energy spread	< 0.16% (FWHM)	0.04 % (FWHM)

Top-up Operation and Energy Stability



Top-up injection performance:

- During top-up operation, beam injection is performed every 20 s
- Stable top-up operation was achieved with injection beam charge of 0.3 nC while keeping a constant stored beam current

Top-up Operation and Energy Stability

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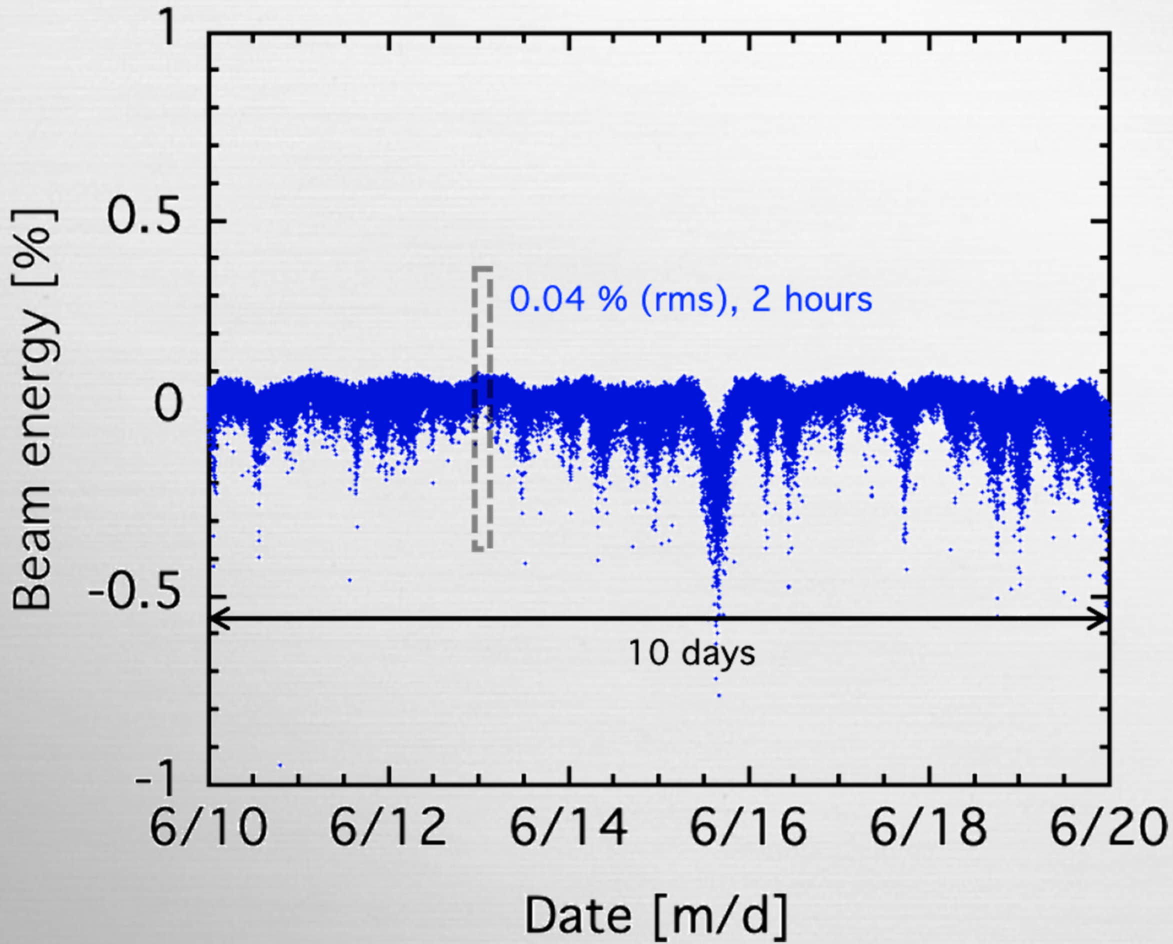

Beam energy stability:

- The 3 GeV beam energy remained stable within ±0.3 % over period of more than 10 days.
- This stability was maintained without any beam tuning or energy feedback system.

These results demonstrate the excellent operational stability of the NanoTerasu linear accelerator.

Summary

» A simple and stable 3 GeV linear accelerator was developed for NanoTerasu.

» Beam commissioning was completed rapidly, achieving the design beam performance within 10 days.

» TOF-based beam tuning provided an effective and optimization method for the 40 MeV pre-injector.

» Stable top-up operation has been maintained since 2024 without any accelerator retuning.

» The successful operation validates the effectiveness of minimal and compact design philosophy for achieving high beam quality, stability, and availability.

» The accelerator is designed to support future extension to an SX-FEL facility.

Summary

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Nuclear Instruments and Methods in Physics Research A 1090 (2026) 171670

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

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Check for updates

Design and performance of a compact 3-GeV injector for the low-emittance storage ring in NanoTerasu

Koichi Kan *, Takao Asaka, Kota Ueshima, Shuhei Obara, Yuji Hosaka, Nobuyuki Nishimori

NanoTerasu Center, National Institutes for Quantum Science and Technology (QST), 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi, 980-8572, Japan

A B S T R A C T

A 3-GeV linear accelerator was constructed as a full-energy injector, enabling high-efficiency and high-stability injection into NanoTerasu, a storage-ring light source with a multi-bend achromat lattice. The linear accelerator consists of a 40-MeV pre-injector and a C-band accelerator with a total length of 110 m. We developed a beam-based phase tuning method for RF cavities in the pre-injector. After this tuning, Twiss parameters and normalized emittance of less than 10 mm mrad measured at the pre-injector exit are consistent with a beam tracking simulation. The 3-GeV linear accelerator has greatly contributed to stable top-up operation, since operation began in 2024. The energy stability of the injected beam from the linear accelerator was achieved as 0.04% (rms) during 11 days of X-ray user experiment with top-up mode. The stored beam current in the storage ring is maintained at 200 mA by top-up operation. The variation of the stored beam current is kept within 0.04% (rms) by the stable injected beam.

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 063401 (2020)

Low-emittance radio-frequency electron gun using a gridded thermionic cathode

Takao Asaka,[1,2,3,*] Takahiro Inagaki,[1,2] Tamotsu Magome,[1,2,3] Nobuyuki Nishimori,[3] Yuji Otake,[2] Tsutomu Taniuchi,[2] Kenich Yanagida,[2] and Hitoshi Tanaka[1,3]

[1]*RIKEN SPring-8 Center, 1-1-1 Kouto, Sayo, Hyogo 679-5148, Japan*
[2]*Japan Synchrotron Radiation Research Institute (JASRI), 1-1-1 Kouto, Sayo, Hyogo 679-5198, Japan*
[3]*National Institutes for Quantum and Radiological Science and Technology (QST), 1-1-1 Kouto, Sayo, Hyogo 679-5148, Japan*

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REGULAR PAPER

https://doi.org/10.35848/1347-4065/abd0c9

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Transparent-grid scheme for generating cathode-emittance-dominated beams in a gridded thermionic gun

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Summary

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