Operational Status of NanoTerasu storage ring

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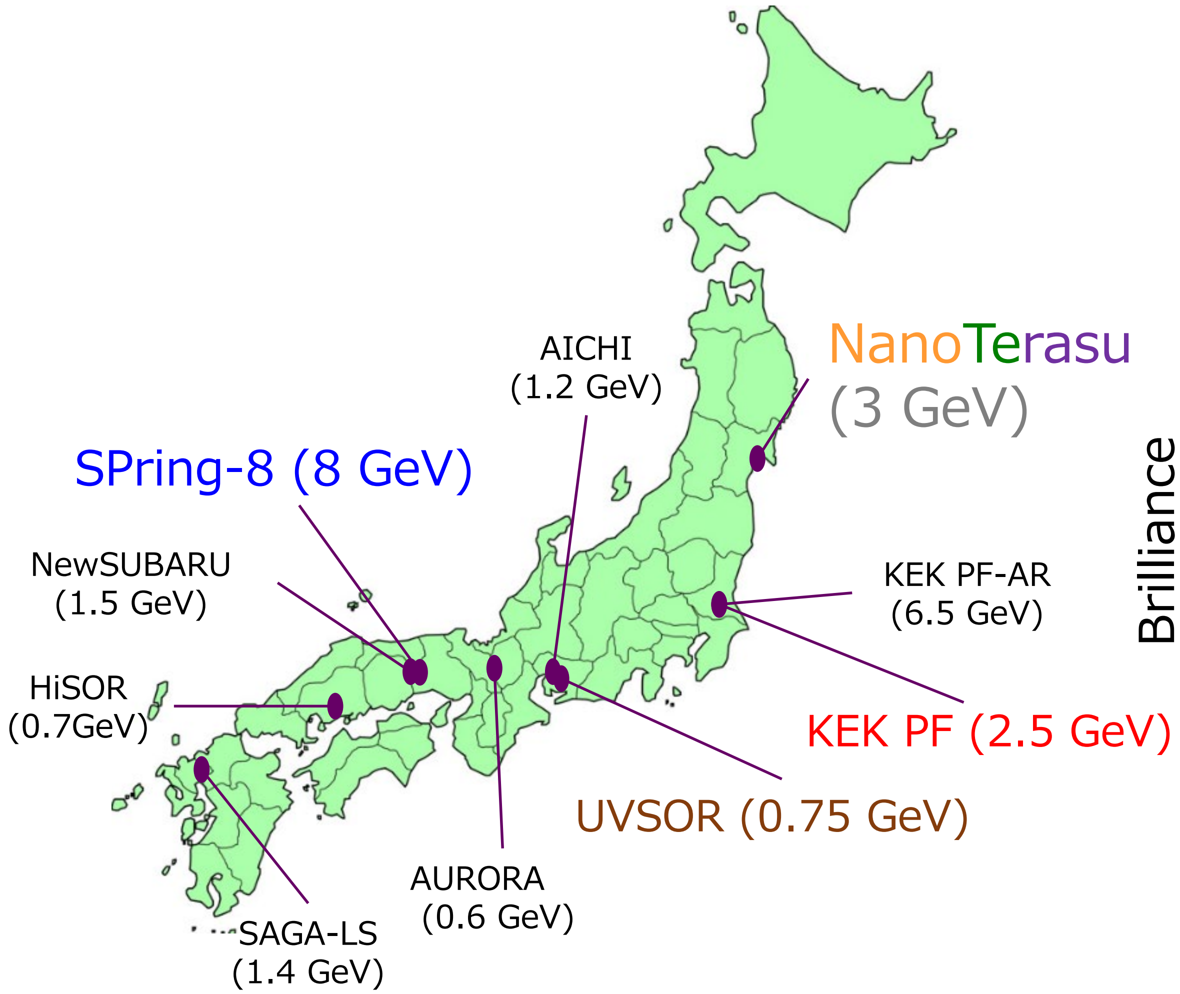
NanoTerasu, QST

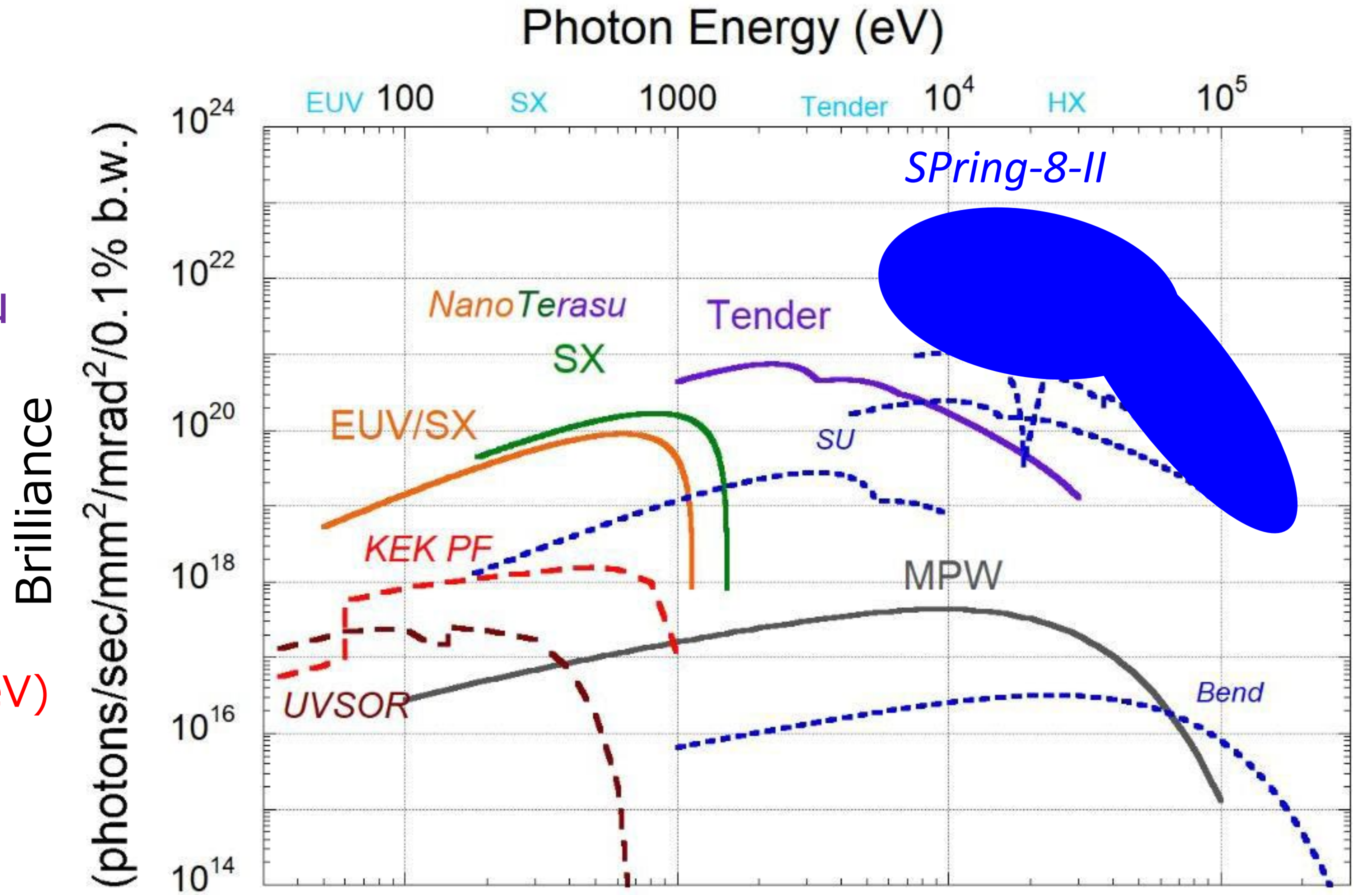
LER2025, Hamburg, Germany, 8 October 2025

Outline

1. Role in Japanese photon science platform
2. NanoTerasu: a new 3GeV MBA light source
    2-1. Overview
    2-2. Commissioning
    2-3. The 1st year user operation at 200 mA
3. High current operation: the most important issue to be resolved
    3-1. HOM-damped TM020 cavity
    3-2. Longitudinal BBF system to suppress instability for 400 mA operation
4. Summary

1. Japanese photon science platform since FY2024





NanoTerasu accelerator system was designed and constructed together with SPring-8 members at RIKEN and JASRI for Japanese photon science platform.

2-1. NanoTerasu overivew

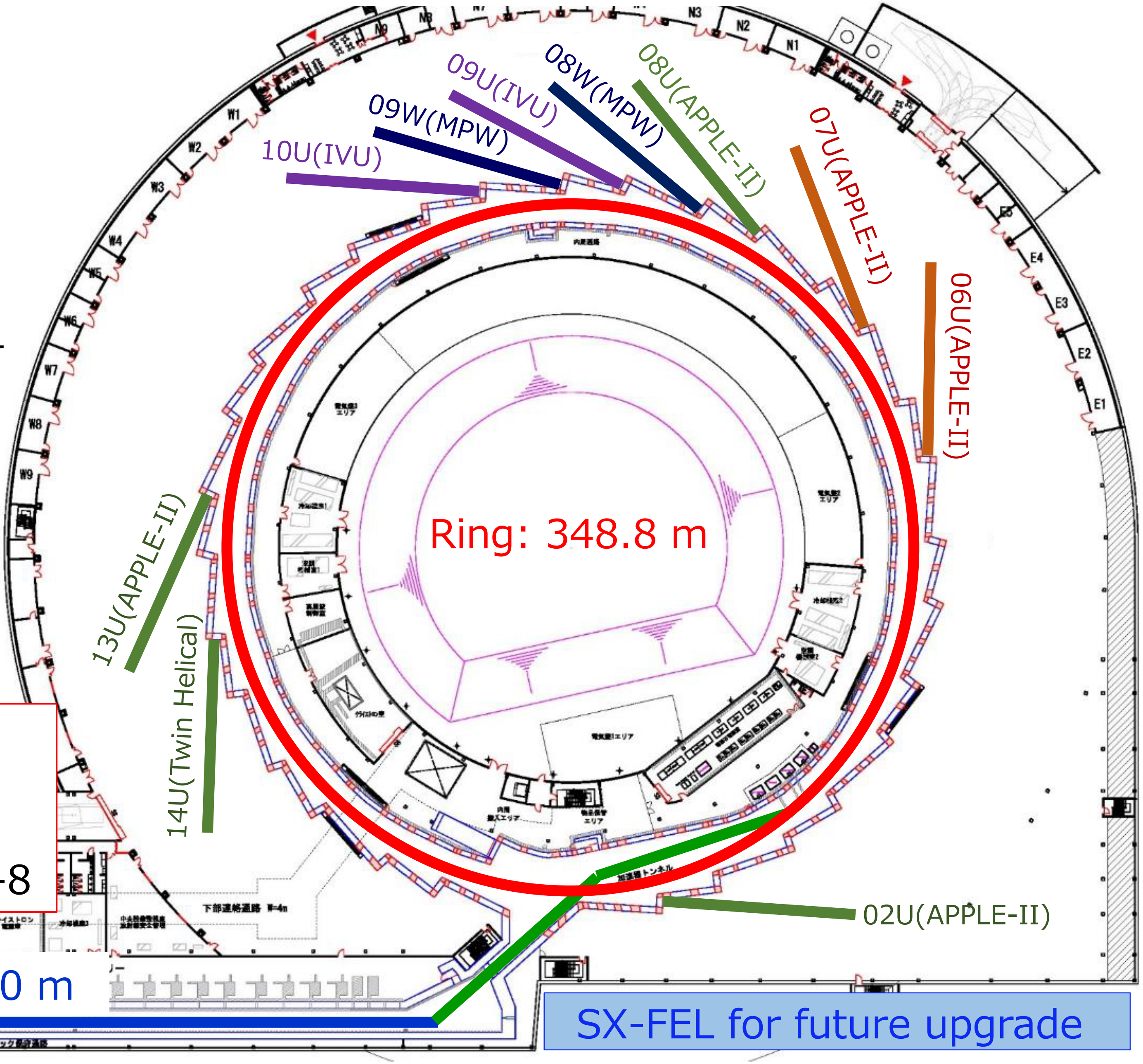
Medium-sized 3GeV MBA light source

Linear accelerator (Linac)	Length
NanoTerasu	110 m
MAX IV	250 m

- Minimal design by C-band acc. / Future soft XFEL

Storage ring	Circumference
NanoTerasu	348.8 m
MAX IV, SIRIUS	528, 518 m
SLS 2.0	288 m

- 4BA lattice / A new TM020 cavity



Features:
- Significant cost reduction
- Utilization of R&Ds for SPring-8-II
- Feedback of operation experience of SPring-8

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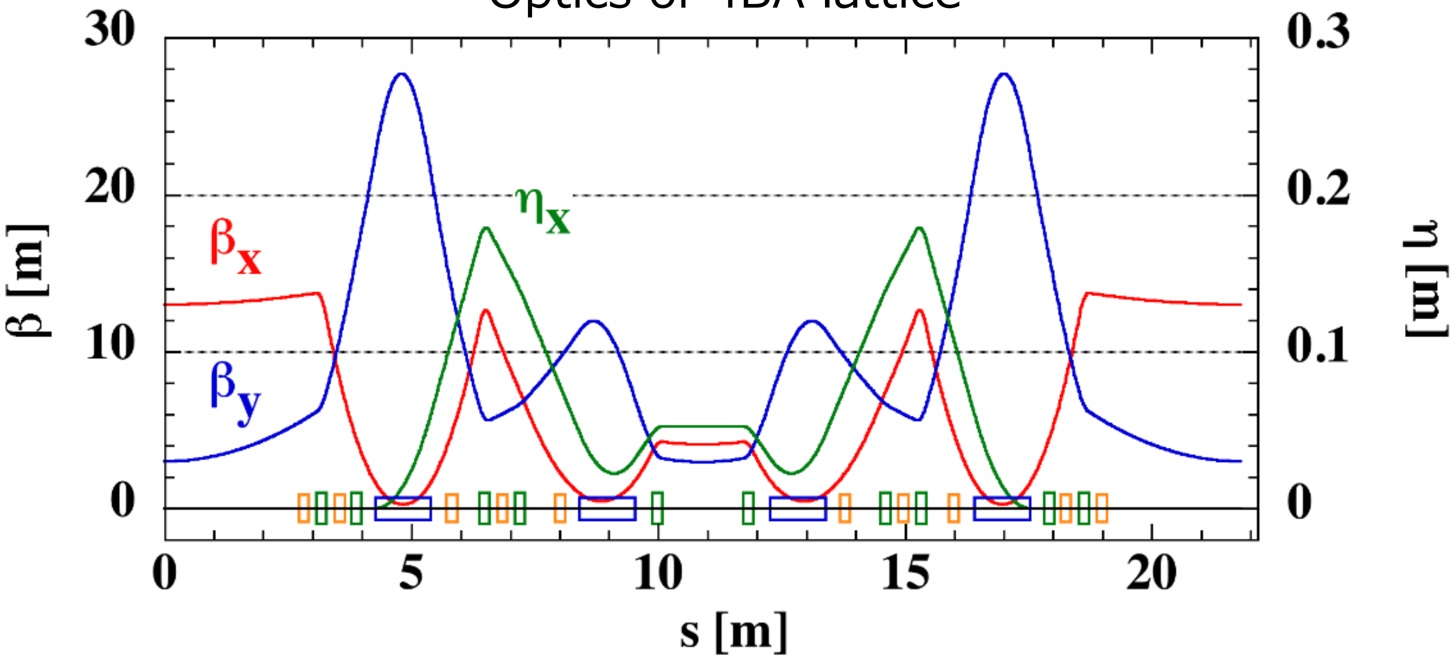
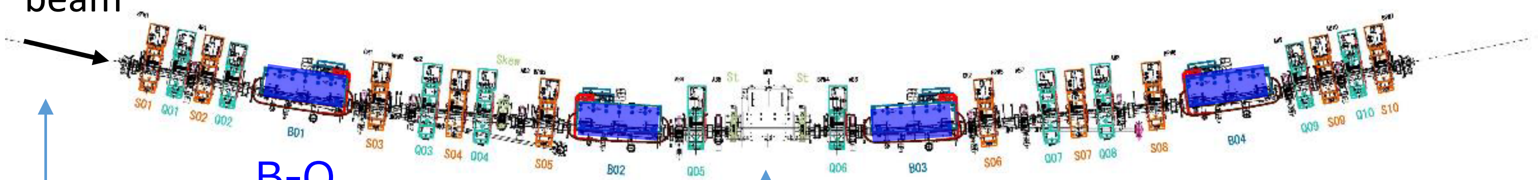
2-1. 4BA Lattice for NanoTerasu

Optics of 4BA lattice



beam



B-Q Q S

5.4m straight for undulator

1.6m straight for MPW

Ring parameters	
Natural horizontal emittance	1.14 nm.rad
Nominal stored current	400 mA
Energy spread	0.084 %
Betatron tune (n_x,n_y)	(28.17, 9.23)
Natural chromaticity (x_x,x_y)	(-60.50, -40.99)
Damping partition number (J_x,J_y,J_z)	(1.389, 1.0, 1.611)
RF accelerating frequency	508.759 MHz
Harmonic number	592
Natural bunch length	2.92 mm (9.74 ps)
The number of cells	16

Magnet	Max. fields	#/cell	Gap Bore rad. (mm)
B-Q combined	0.87 T -7.1 T/m	4	28
Quadrupole	49 T/m	10	34
Sextupole	1540 T/m^2	10	40

H-focusing: 8 quads.
V-focusing: 4 B-Q combined bends + 2 quads.

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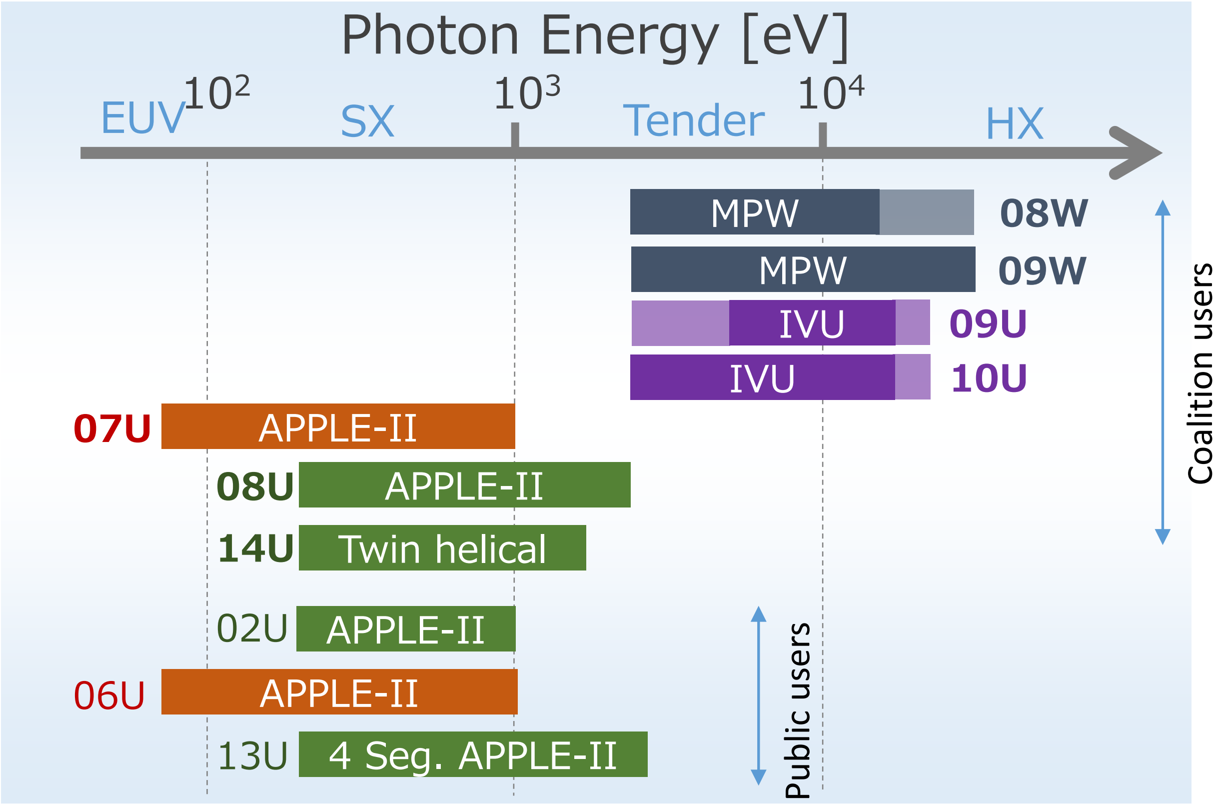
no reverse bends
no longitudinal gradient bends
no damping wigglers

2-1. IDs for NanoTerasu

Maximum number of IDs are 14 undulators and 14 multi-pole wigglers (MPW)
7 BLs for coalition users based on a collaboration scheme between academia and industry.
3 BLs for public use based on proposal applications.



BL	ID	λ_w(mm)	N_w	K_max
08W **09W**	MPW	120	5	20.7
09U **10U**	In-Vacuum Undulator	22	166	2.37
06U **07U**	APPLE-II（EUV）	75	53	7.78
02U **08U**	APPLE-II（SX）	56	71	4.76
13U	4 Seg. APPLE-II（SX）	56	10 x 4	4.76
14U	Twin helical	56	33×2	2.91

Typical beamline length is 60m from ID center

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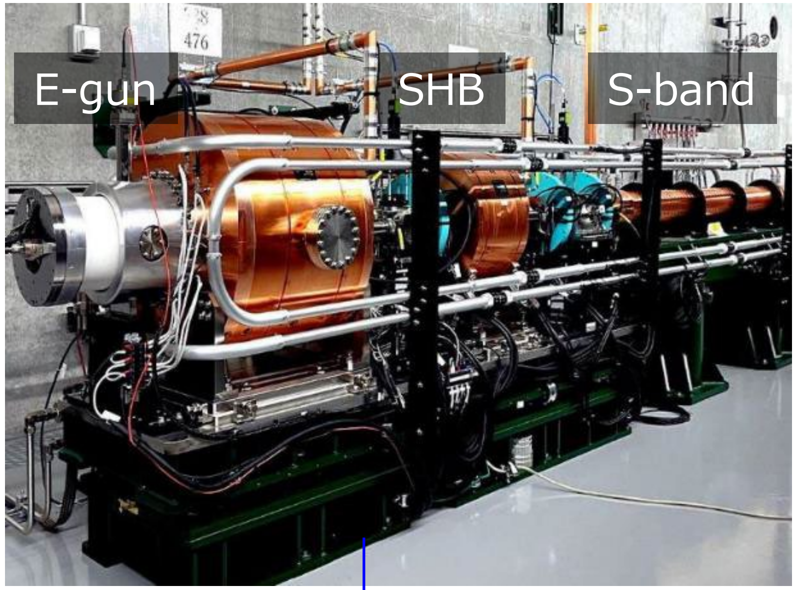
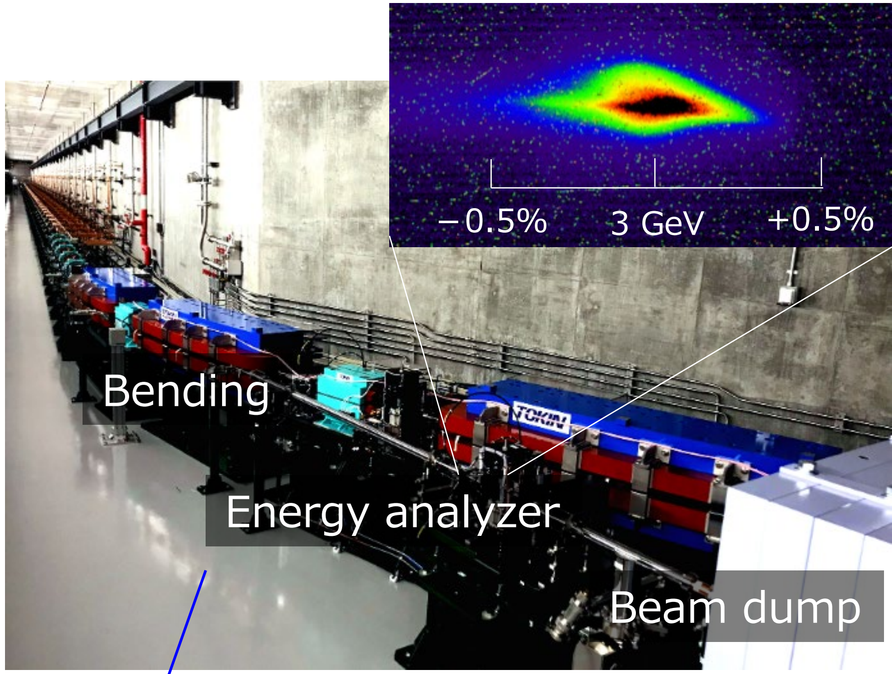
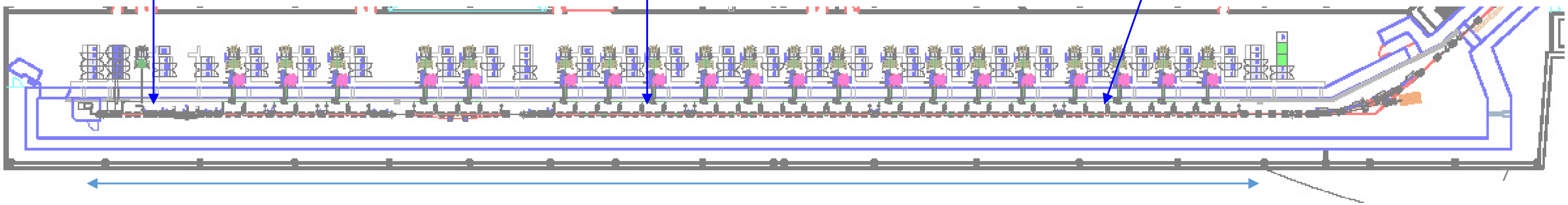
2-2. Linac commissioning

- A 40 MeV injector composed of a transparent grid thermionic cathode gun and S-band linac.
- 40 of 2m long C-band cavities with an accelerator gradient of 40MV/m
- E-beam generation from gun in Apr. 2023 and 3GeV acceleration after 10 days



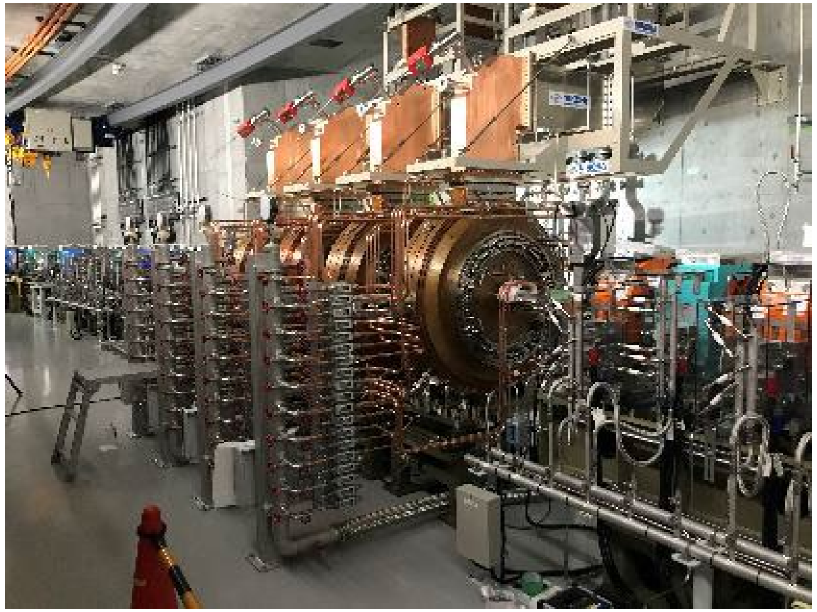


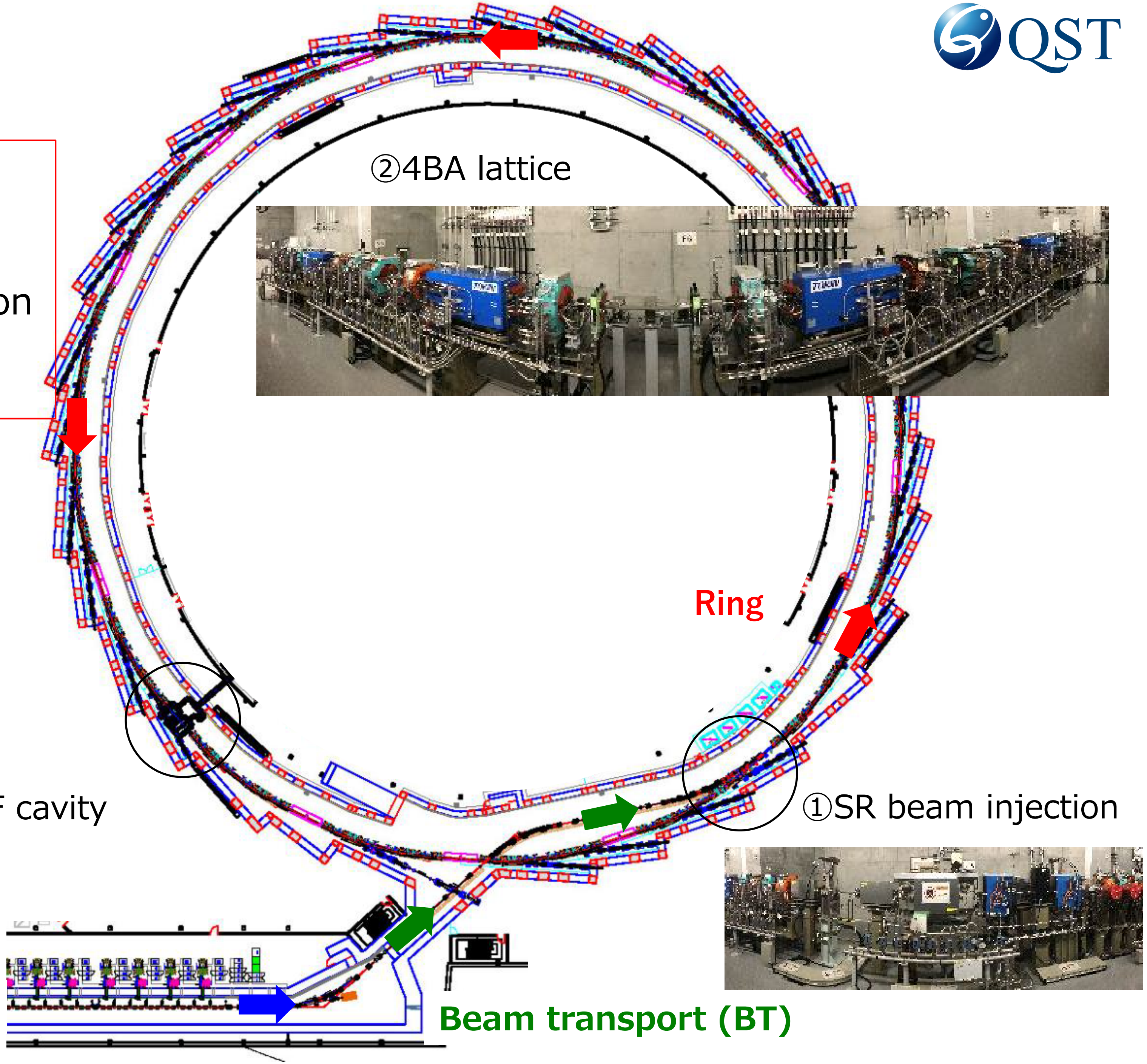


2-2. Storage ring

The 1st MBA ring in Japan

Features:
① In-vacuum transparent off-axis injection
② 4BA lattice
③ HOM-damped TM020 cavities





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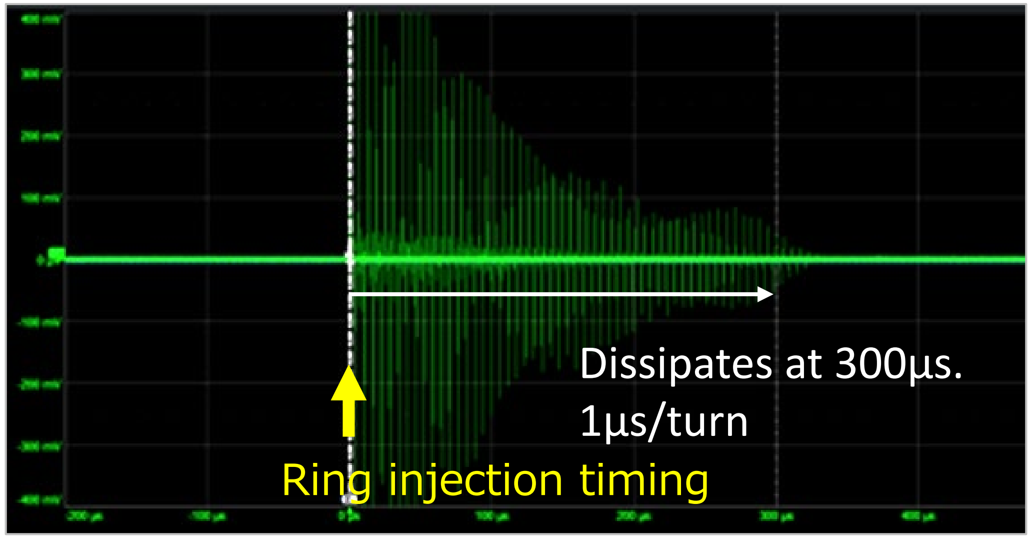
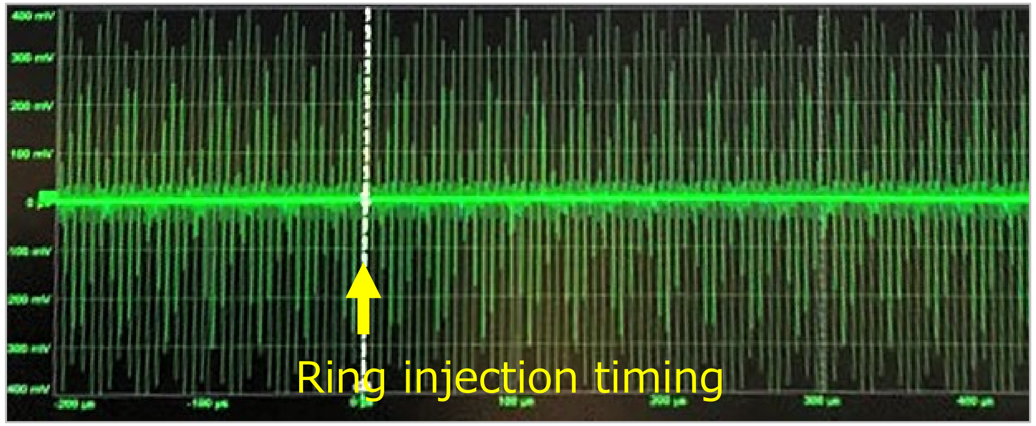
2-2. Ring commissioning

Date	Event
Jun. 8th, 2023	Start of ring beam injection 300 turns with RF cavity off
Jun. 16th, 2023	First e-beam store with RF cavity on First light

BPM signal during 300 turns with RF cavity off



BPM signal during beam store with RF cavity on



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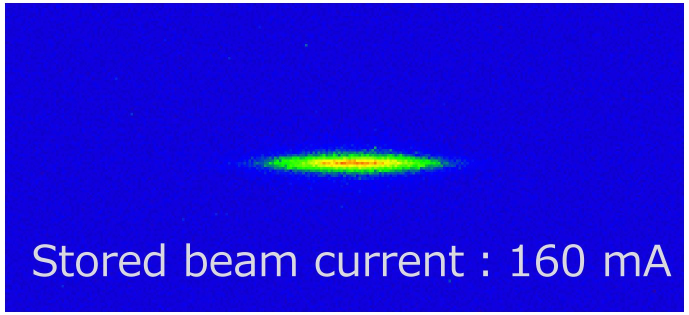
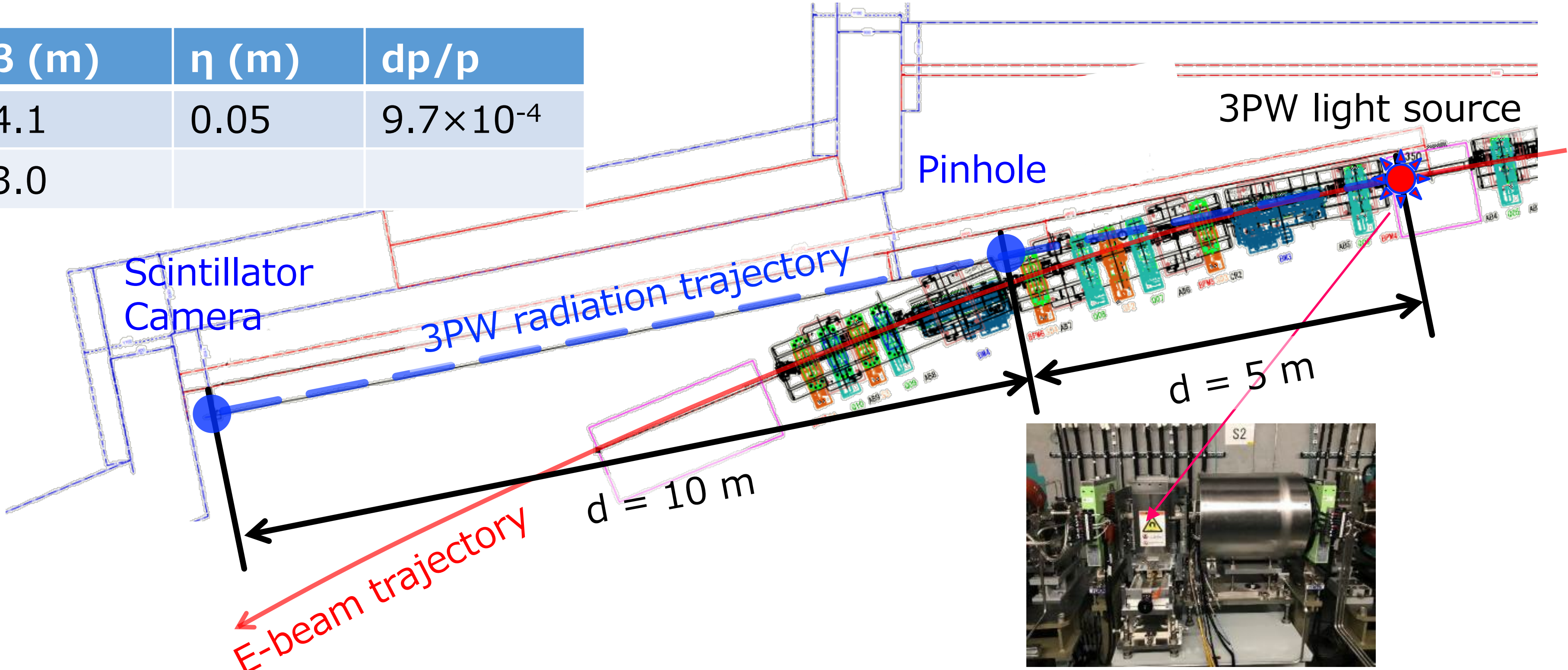
2-2. Ring commissioning

- Fine tuning of stored beam trajectory for corrections of COD, tune, dispersion, chromaticity and so on.
- 200 mA in Sep. 2023, but HOM induced coupled bunch instability > 200 mA.
- Beam size at short straight center is measured with 3PW and an X-ray pinhole camera system.
- Measured horizontal emittance is close to designed value.
- Energy spread is enlarged to 0.097% from 0.084% under assumption of emittance of 1.14 nm.rad.
- Commissioning details can be found in a paper by S. Obara et al., https://doi.org/10.1103/physrevaccelbeams.28.020701

	σ (μm)	ε (nm·rad)	β (m)	η (m)	dp/p
x	84	~1.1	4.1	0.05	9.7×10^{-4}
y	9	0.02	3.0		





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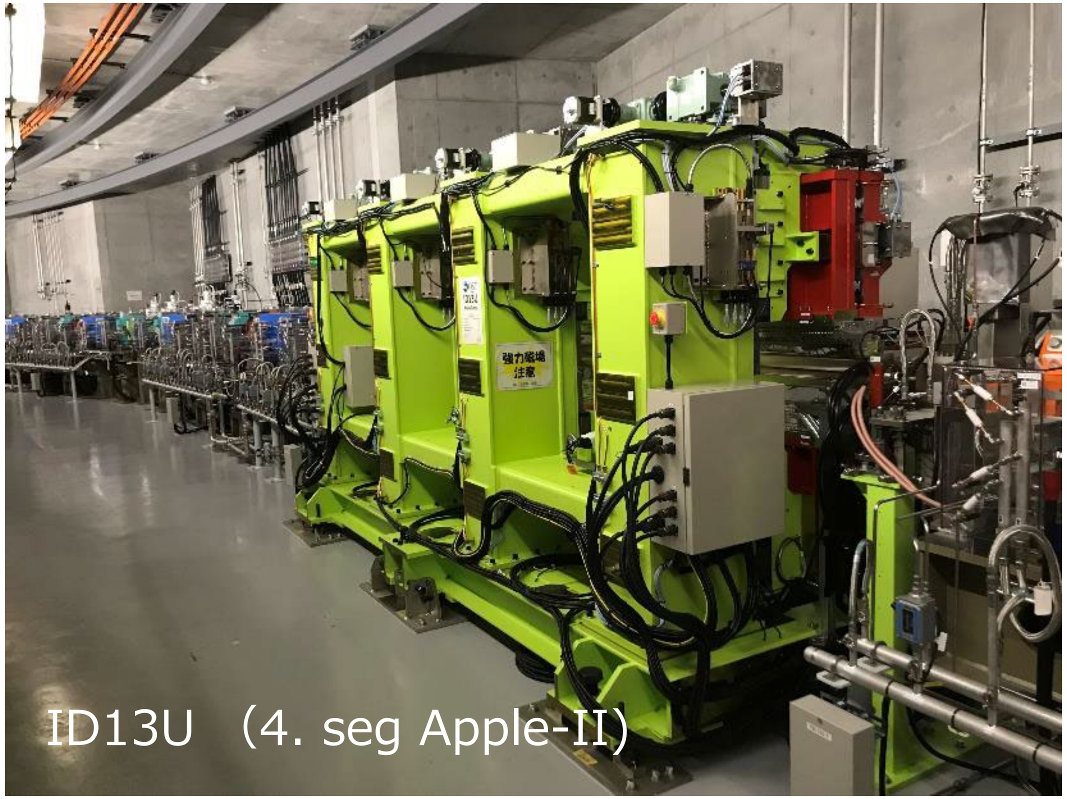
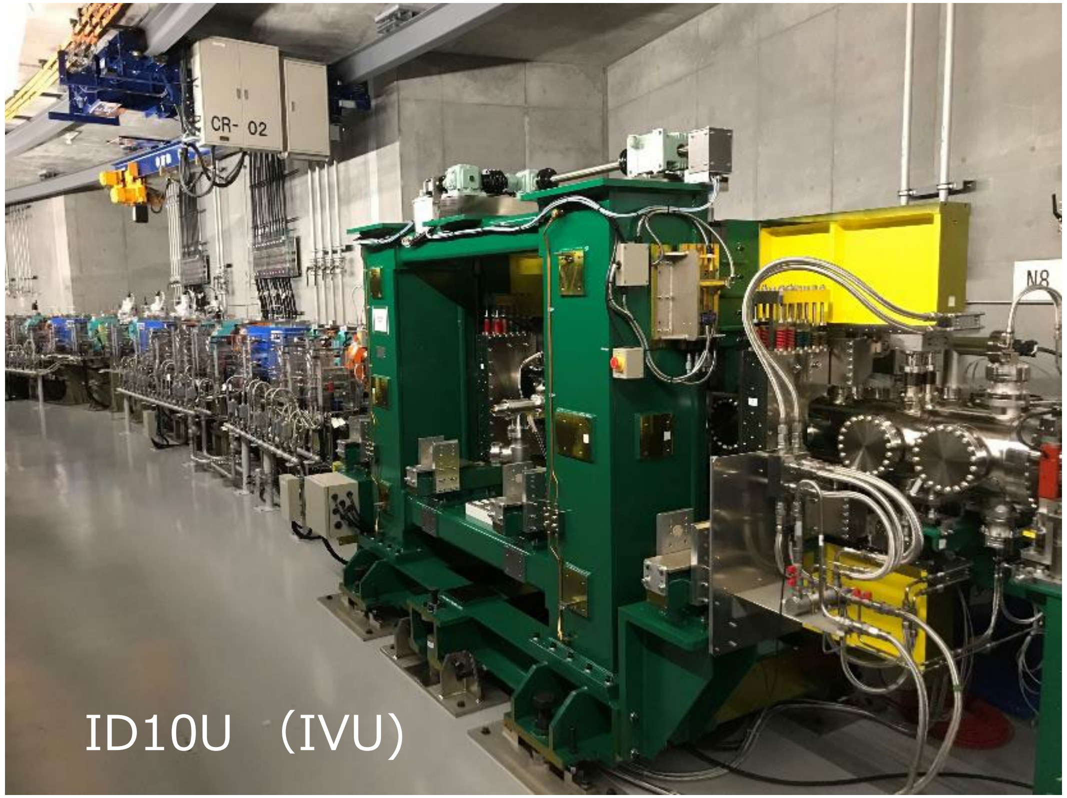
2-2. ID commissioning

- ID commissioning started in Sep. 2023
- Steerers up and downstream of each undulator to correct beam trajectory as functions of gap and phase
- Beamline commissioning started in Feb. 2024 after preparing all the correction tables.



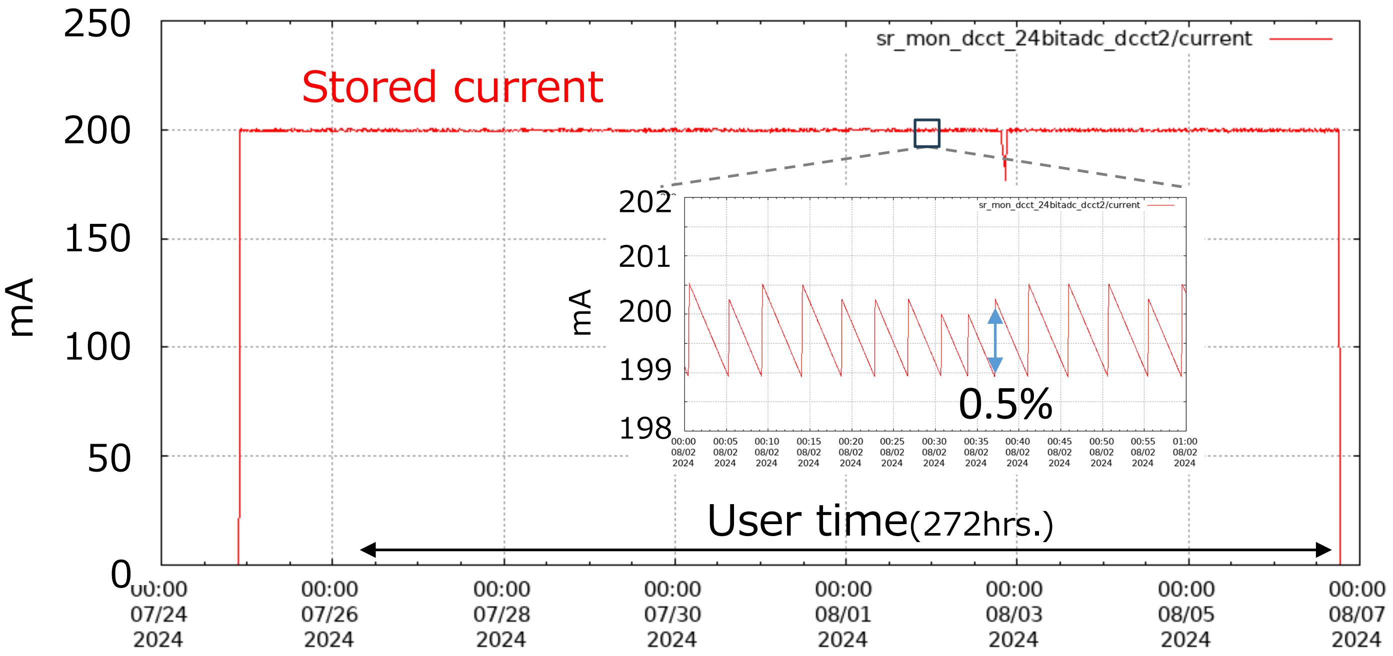
ID13U （4. seg Apple-II)



ID10U （IVU)

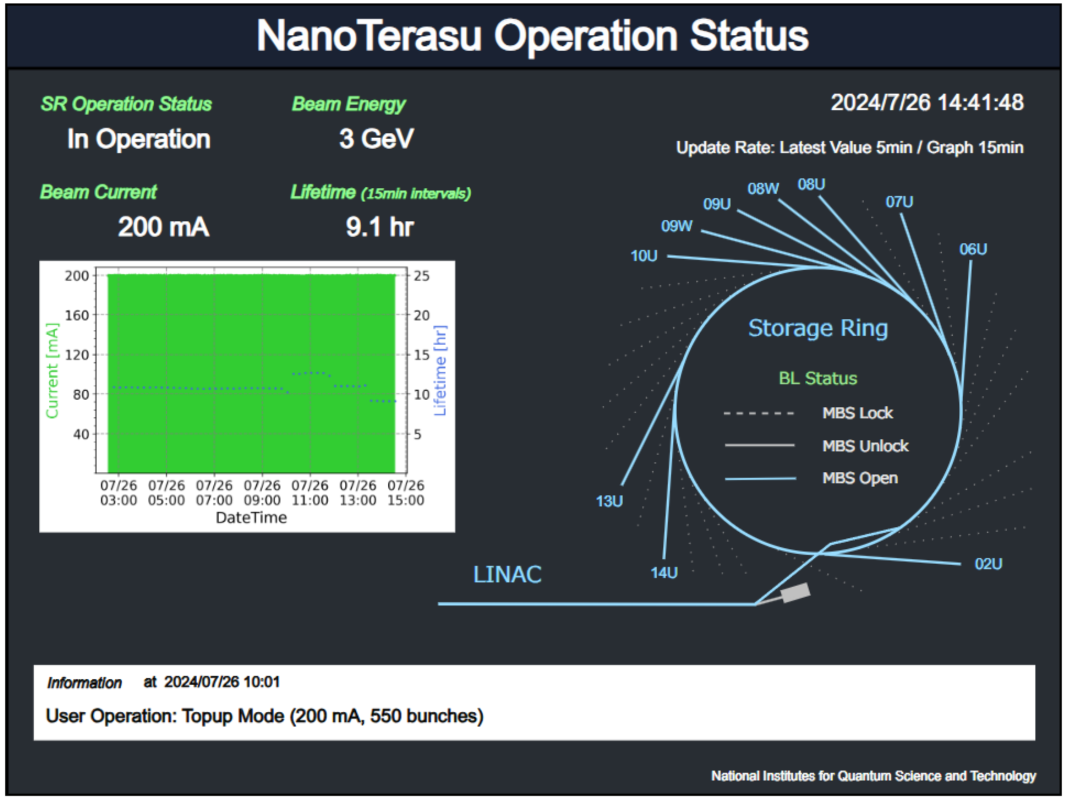
2-3. User Operation

- The first user time started in Apr. 2024 with stored current of 160mA at top-up mode.
- The stored current was increased to 200 mA with 550 bunches with fluctuation of 0.5% from Jul. 2024.
- Typical lifetime is 10 hours with 10 IDs under operation and linac beam is injected every 4,5 minutes.
- SX and tender X-rays are roughly 50 times brighter than existing sources in Japan.



N. Nishimori et al., https://doi.org/10.1088/1742-6596/3010/1/012011

https://nanoterasu.jp/users/operation_status/



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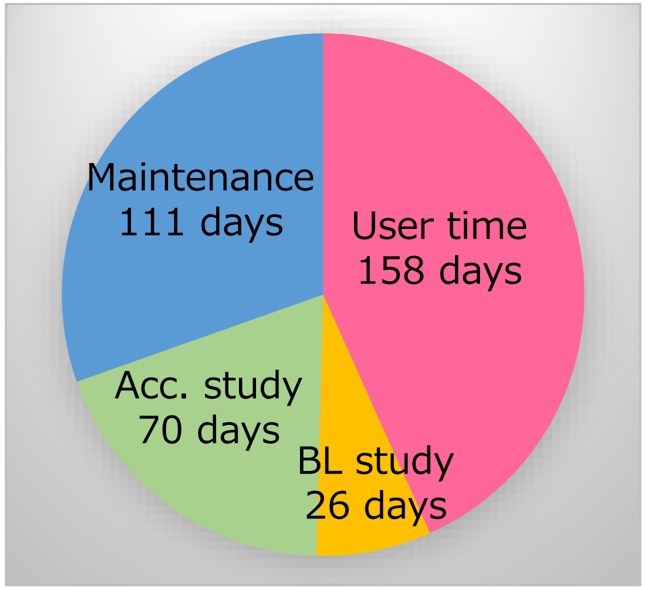
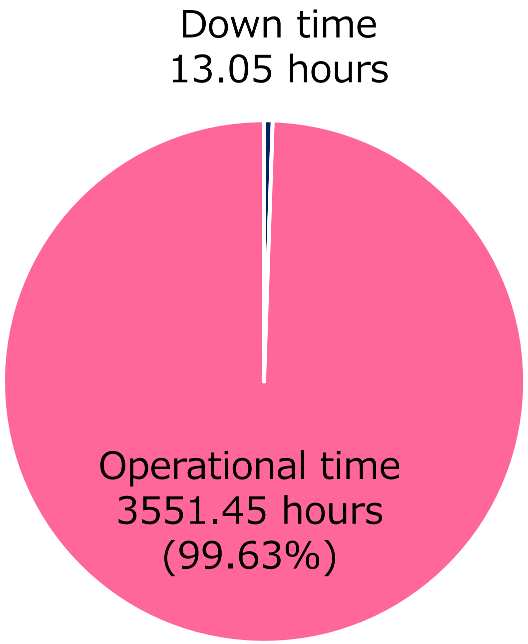
2-3. FY2024 Operational statistics

- Scheduled user time in FY2024 was >3500 hrs.
- X-ray availability was 99.63 %, MTBF (Mean Time between Faults) was 323 hrs.
- Most of faults were due to ring RF discharges.





Item	Statistics
Scheduled user time (h)	3568.5
Total down time (h)	13.05
Fault rate (%)	0.37
No. of faults	11
MTBF (h)	323.2
Mean down time (h)	1.2

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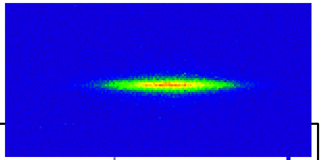
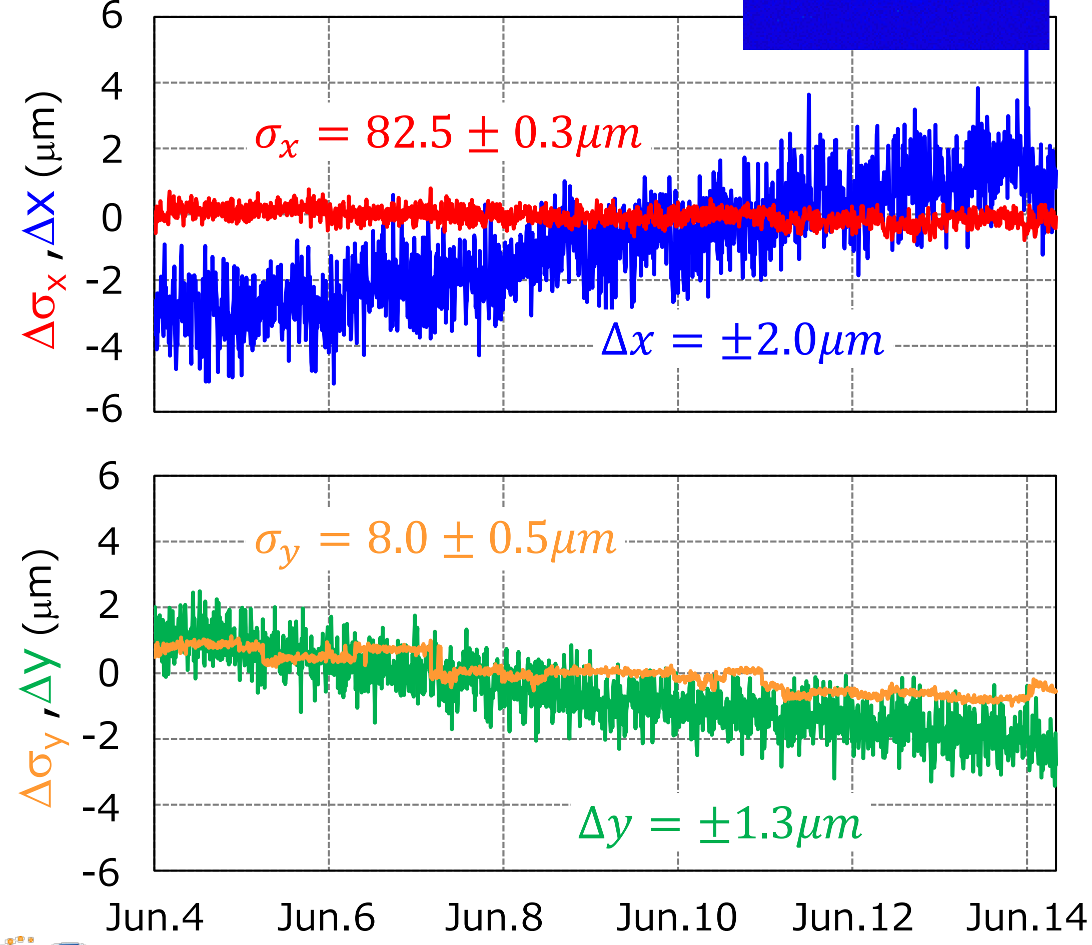
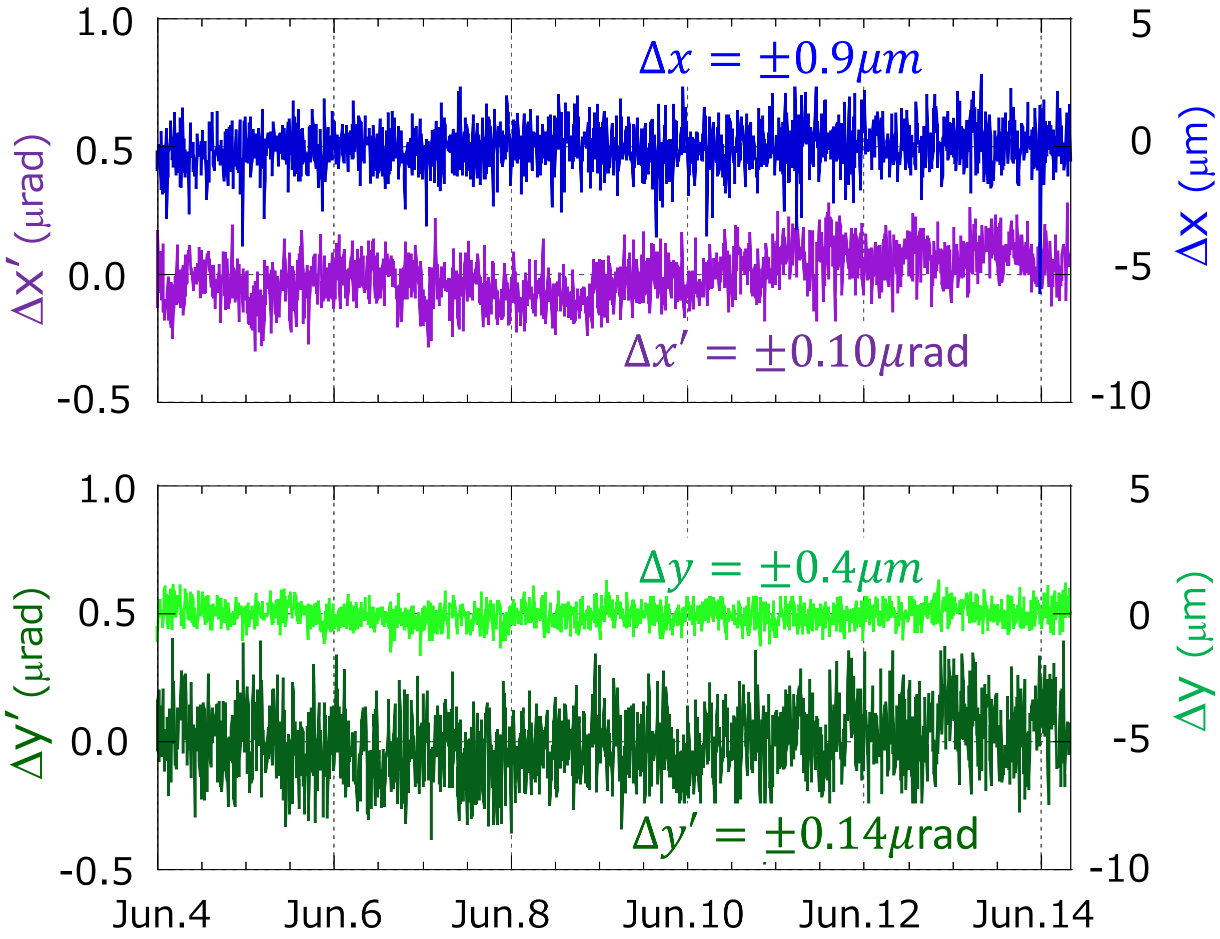
2-3. Stability of X-ray size and position

X-ray pinhole camera profile from a 3-pole wiggler





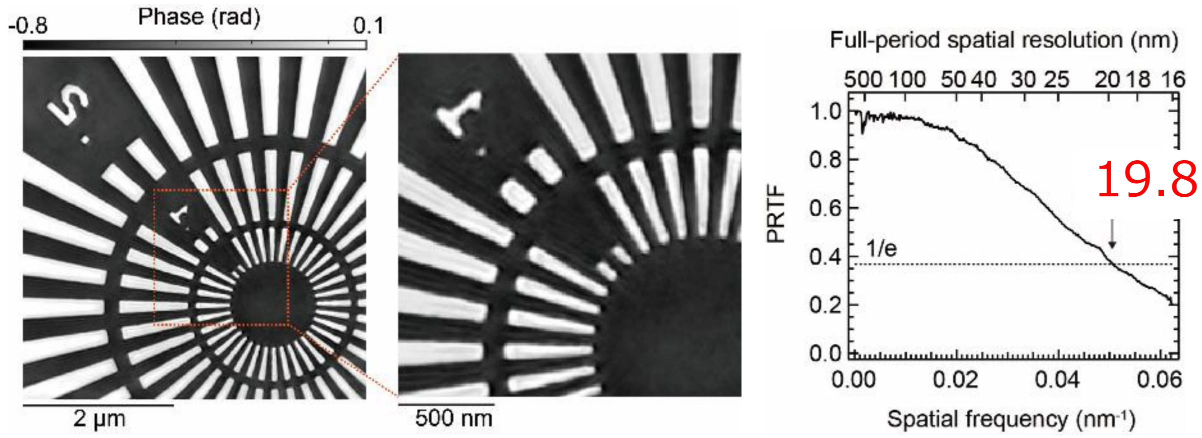
X-ray angle and position estimated from two BPMs located at both ends of ID06 undulator

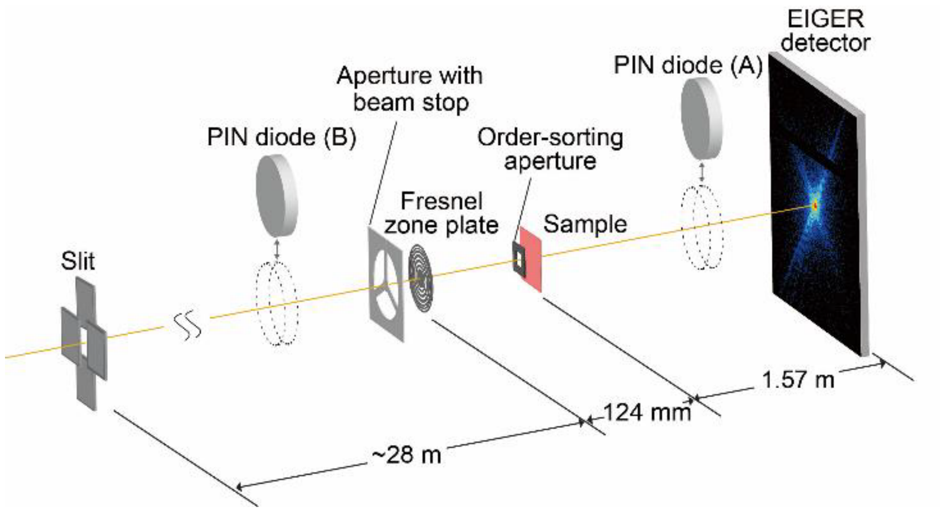


2-3. The First Exp. Result at NanoTerasu BL10U

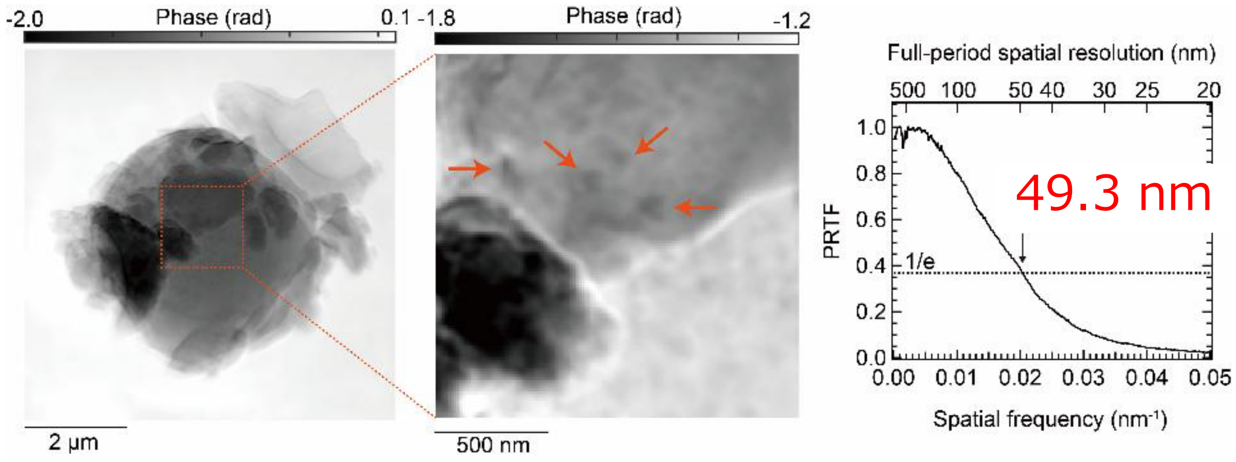
Applied Physics Express **17**, 052006 (2024) https://doi.org/10.35848/1882-0786/ad4846
"Towards a Sub-10 nm Spatial Resolution by Tender X-ray Ptychographic Coherent Diffraction Imaging"
N. Ishiguro, Y. Takahashi et al. (Tohoku Univ.)

A 200 nm-thick Ta test chart at 3.5 keV





Sulfurized polymer particle at 3.5 keV

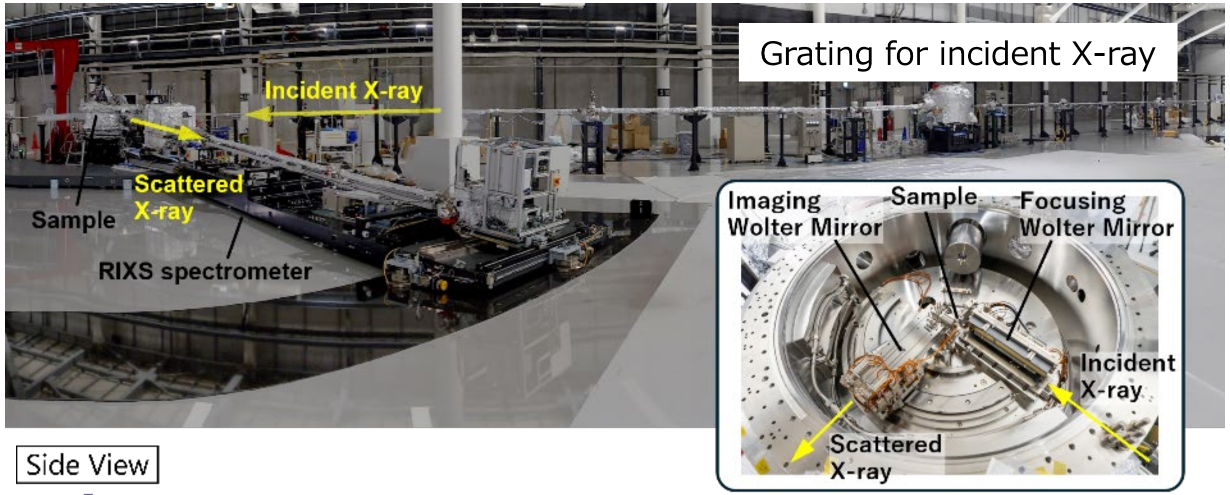


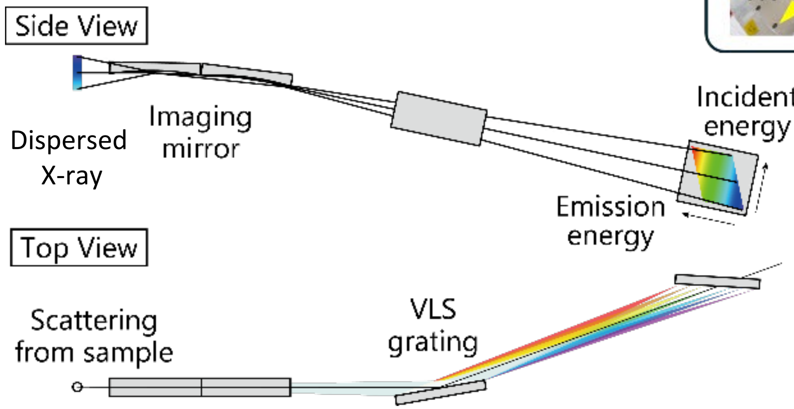
Compared with SPring-8,
spatial resolution ~2.5x
brightness ~40x @ 160mA
= 2.5^4 (Porod's law)

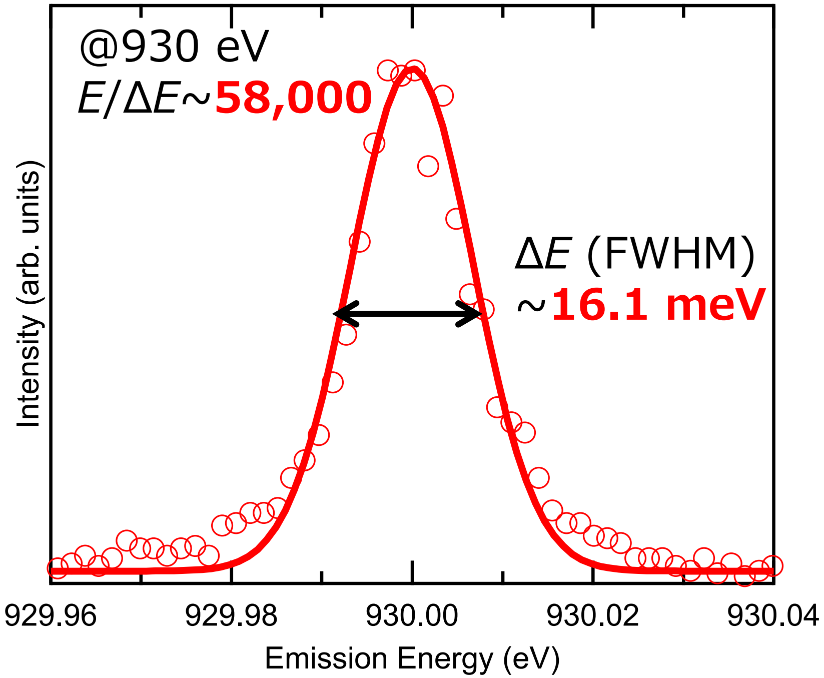
2-3. RIXS (Resonant inelastic X-ray scattering) BL02U

J. Miyawaki, K. Yamamoto et al., SRN **38**, 4 (2025) https://doi.org/10.1080/08940886.2025.2501509

- Target resolution: <10 meV at 250–1000 eV, $E/\Delta E$>100,000 with 2D-RIXS technique
- Ultrahigh resolution: 16.1 meV at 930eV ($E/\Delta E$=58,000) was achieved!
- High throughput: Only 3–4 hours to acquire an ultrahigh-resolution RIXS spectrum at 400 mA beam current







Facility	E/ΔE
AERHA @SOLEIL	6,000
IXS @DLS	35,000
€RIXS @ESRF	33,000
ADRESS @SLS	11,000
SIX @NSLS-II	42,000
HORNET @NanoTerasu	20,000
2D-RIXS @NanoTerasu	58,000

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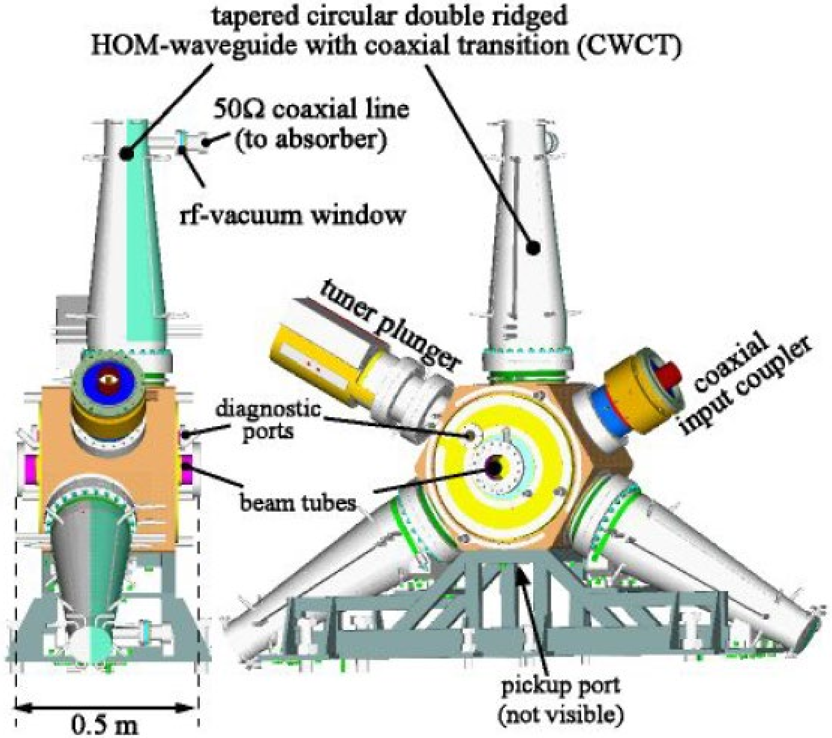
3-1. HOM-damped TM020 cavity

EU HOM-damped cavity

- Widely used at: ALBA, BESSY, Diamond, ESRF-EBS, SLS 2.0, etc.
- Low HOM impedances <5 kΩ (long.), <220kΩ/m (trans.)
- Operated without coupled-bunch instability (CBI)

E. Weihreter, EPAC08, THXM03 (2008)



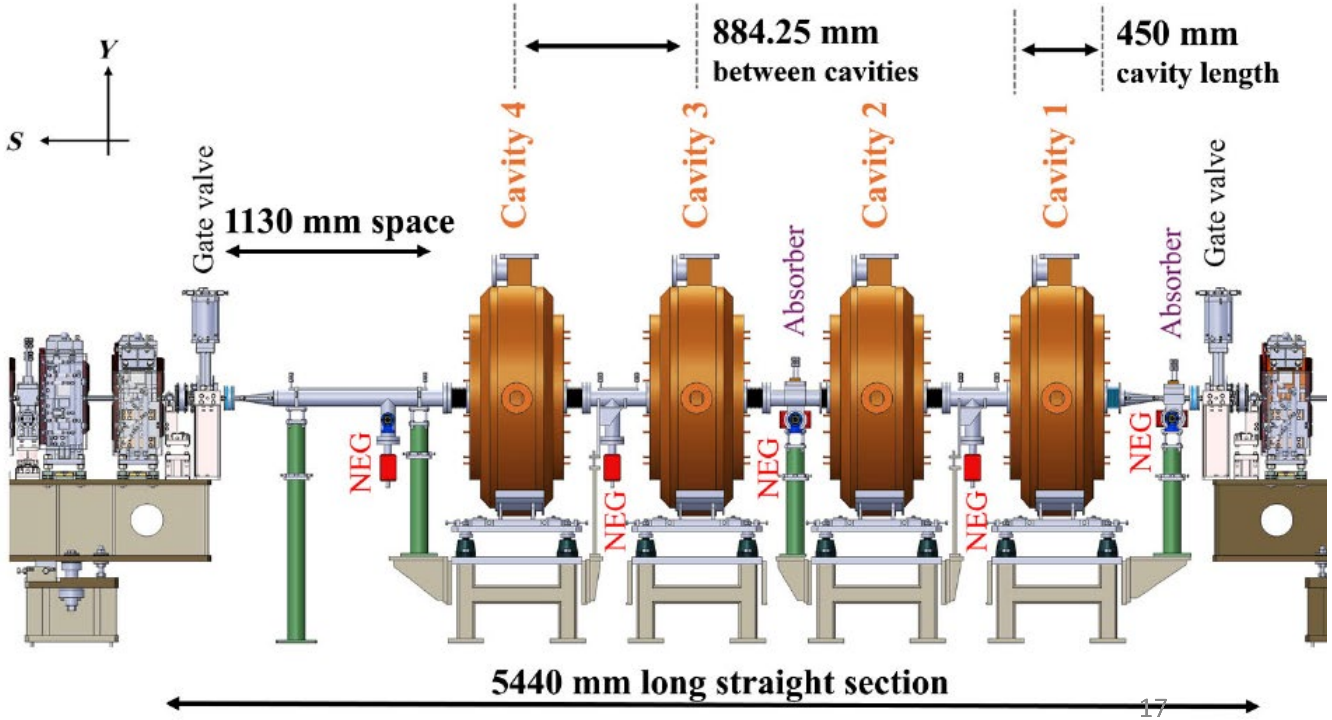
HOM-damped TM020 cavity

- Developed at SPring-8 by H. Ego
- 4 cavities used at NanoTerasu
- HOM impedances <100 kΩ (long.), <500kΩ/m (trans.)

※ definition of shunt impedance is twice grater than that of EU

- Operated without CBI up to 200 mA

H. Ego, NIMA **1064**, 169418 (2024)



S. Obara, PRAB **28**, 020701 (2025)

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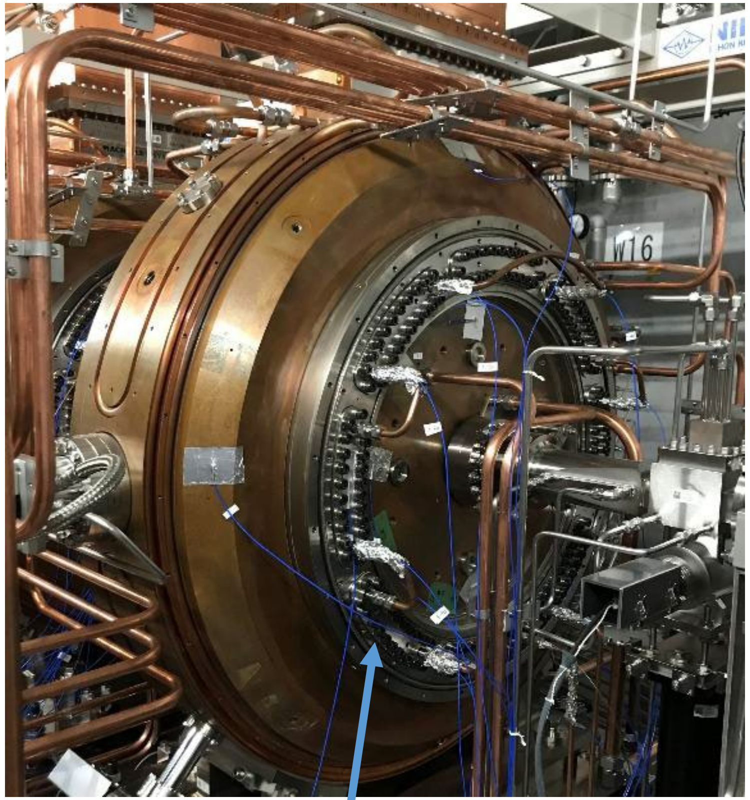
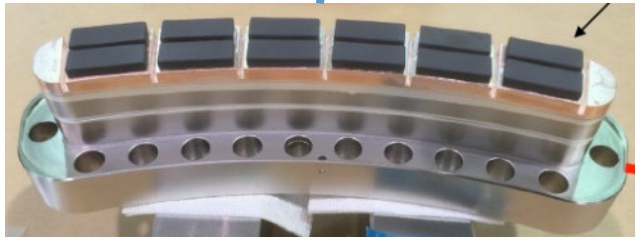
3-1. HOM-damped TM020 cavity

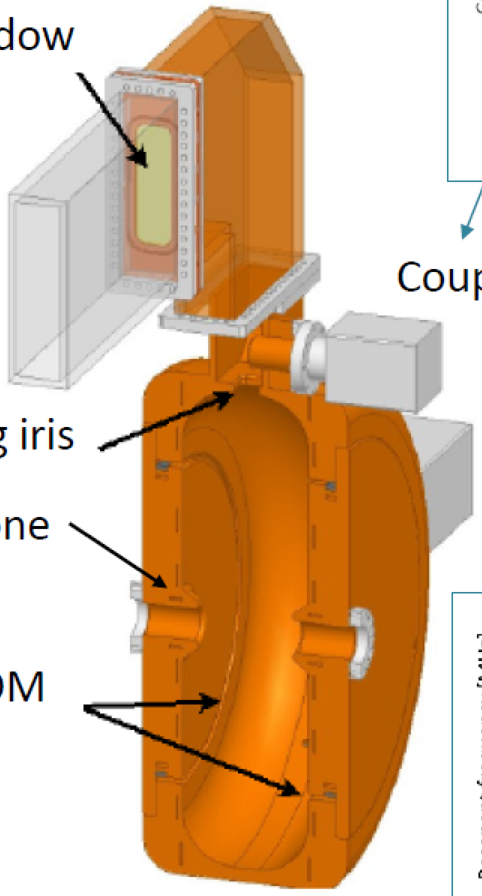


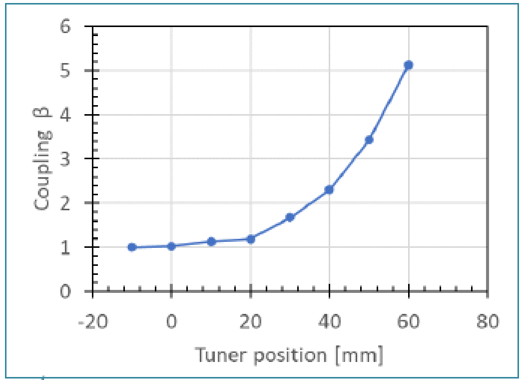


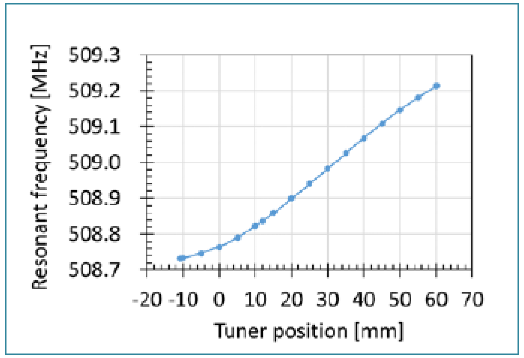
- HOM dampers along slots in the cavity
- Variable coupling to reduce reflection power
- Fine tuning with 0.3MHz/40 mm tuner stroke

Parameters	Values
Mode	TM020
Unloaded Q_0	60000
R/Q_0 (Ω)	113
R ($M\Omega$) *	6.8
Variable Coupling	1-5
Cavity Voltage V	750 kV
Input Power P	84.5 kW
Number of cavities	4
Total Voltage nominal	3000 kV
Radiation loss/turn wo ID	621 keV

$* \ R = V^2/P$







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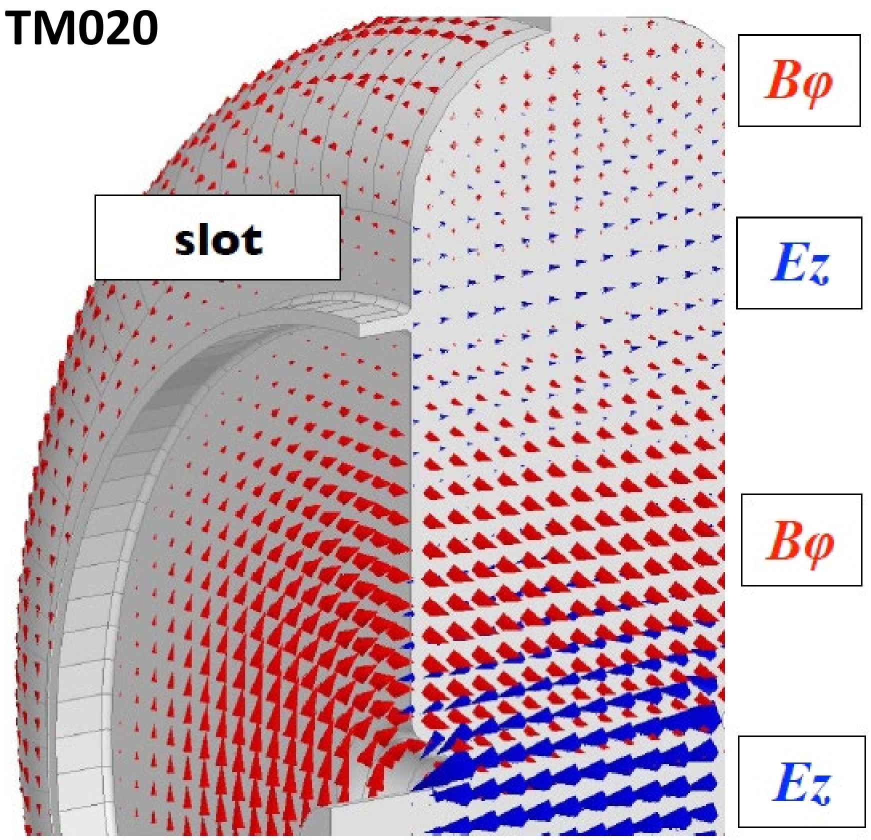
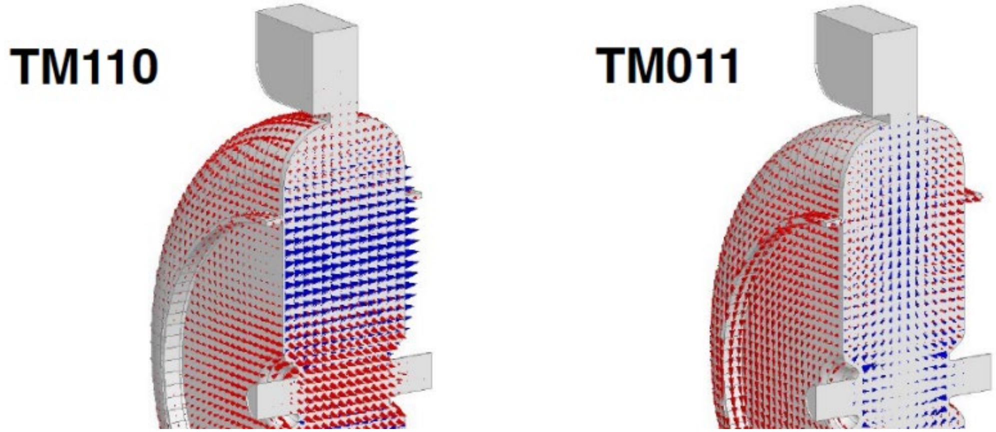
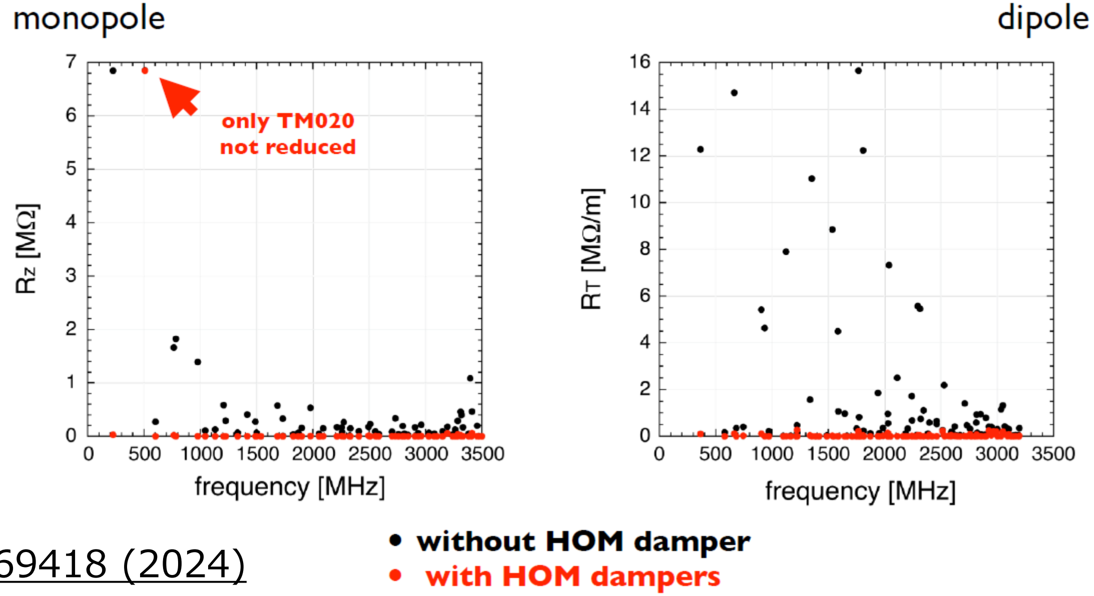
H. Ego, NIMA **1064**, 169418 (2024)

3-1. HOM damped TM020 cavity

- TM020 mode is not absorbed by dampers located at slots along nodes of magnetic fields of TM020 mode.
- Field distributions of HOM and LOM differ from TM020 mode.
- Monopole and dipole mode impedances are estimated to be less than 100 kΩ and 500 kΩ/m, respectively.







H. Ego, NIMA **1064**, 169418 (2024)

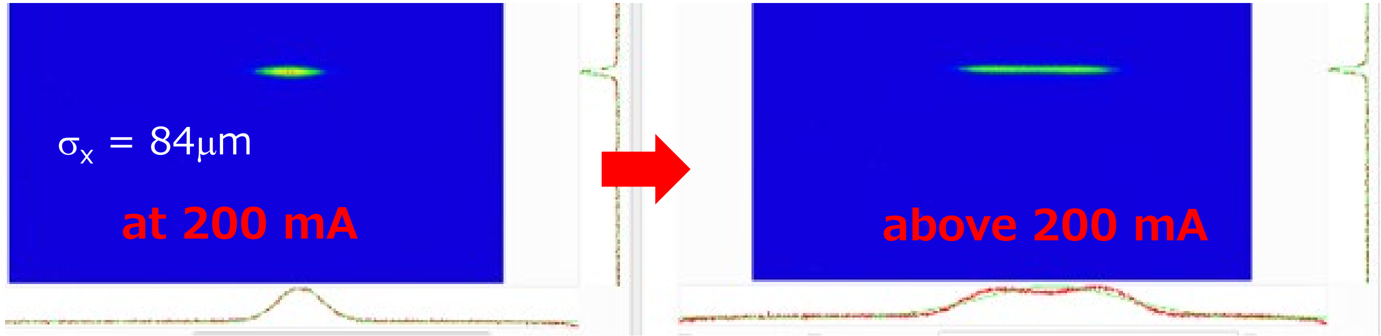
3-2. Coupled bunch instability (CBI)

- Horizontal size at a dispersive section increases above 200 mA due to CBI.
- HOM at 1.9 GHz measured in a cavity pickup signal increases by 40 dB when CBI was observed.
- Measured CBI growth time at 1.9 GHz is 35 ms.

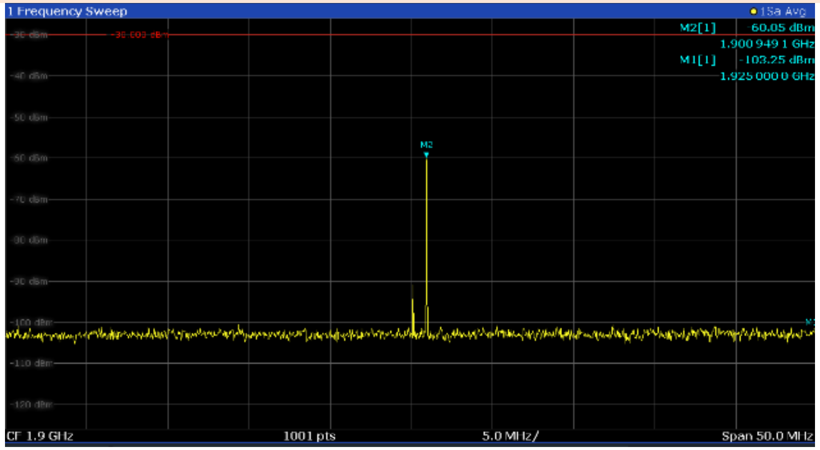
K. Ueshima, IBIC2025, TUPCO08 (2025)

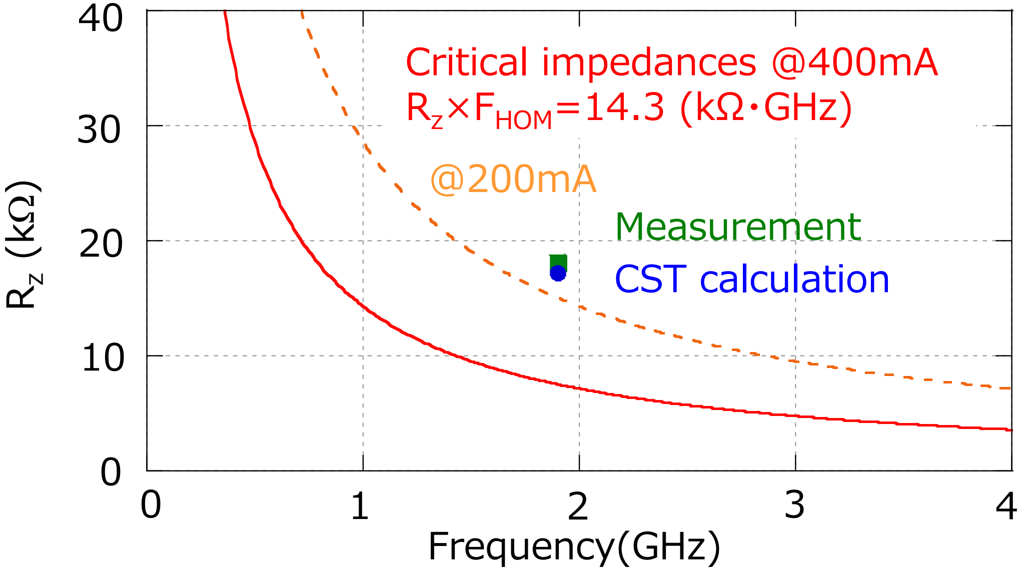
$$\frac{1}{\tau_{meas}} = \frac{1}{\tau_{CBI}} - \frac{1}{\tau_{rad}}$$

Time	1.9 GHz HOM at 200 mA	
τ_{meas}	Measured CBI growth time	35 ms
τ_{rad}	Radiation damping time	7.0 ms
τ_{CBI}	Net CBI growth time	5.8 ms



HOM at 1.9GHz measured in a cavity pickup signal





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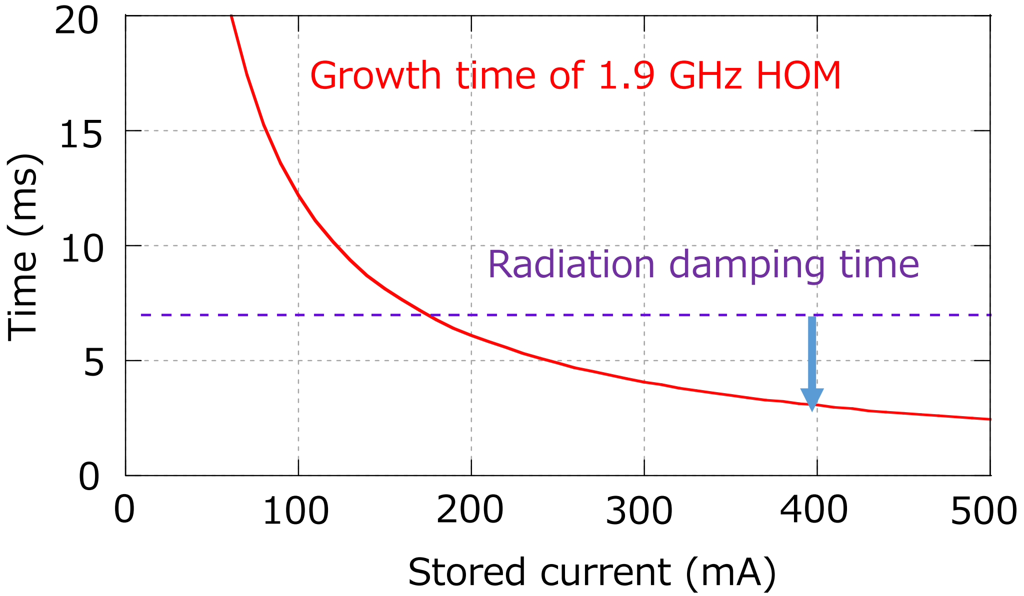
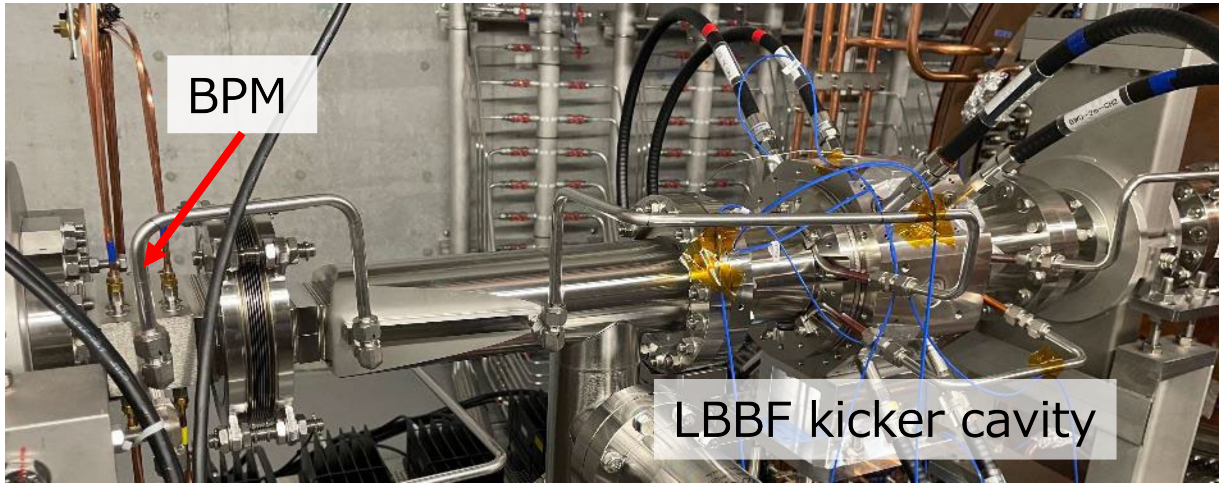
3-2. Bunch-by-bunch feedback (BBF) cavity

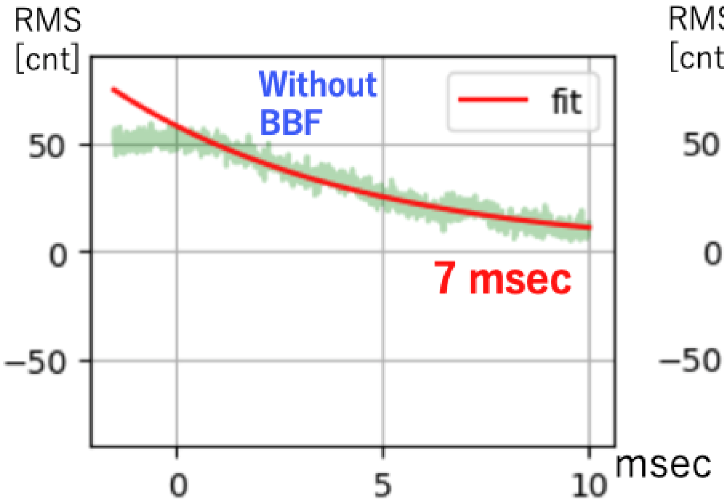
K. Ueshima, IBIC2025, TUPCO08 (2025)

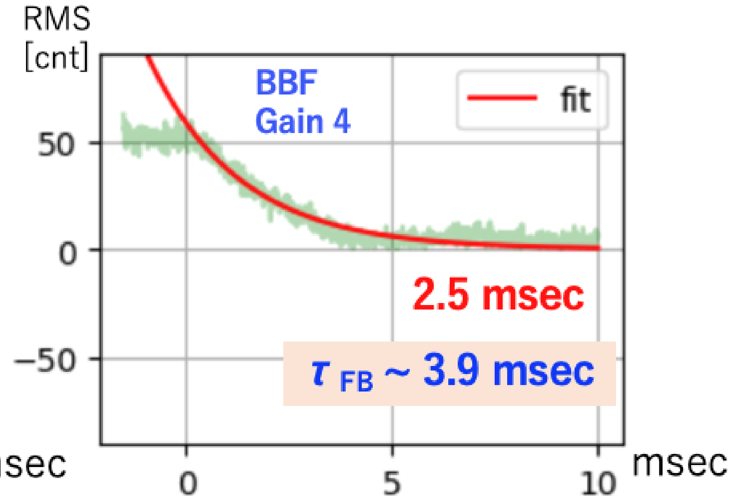
- Growth time of 1.9 GHz HOM at 400 mA is estimated to be 3 ms.
- A waveguide-overloaded kicker cavity and longitudinal BBF system for making damping faster.
- Grow/damp measurement with LBBF cavity shows damping time of 2.5 ms, which is faster than growth time





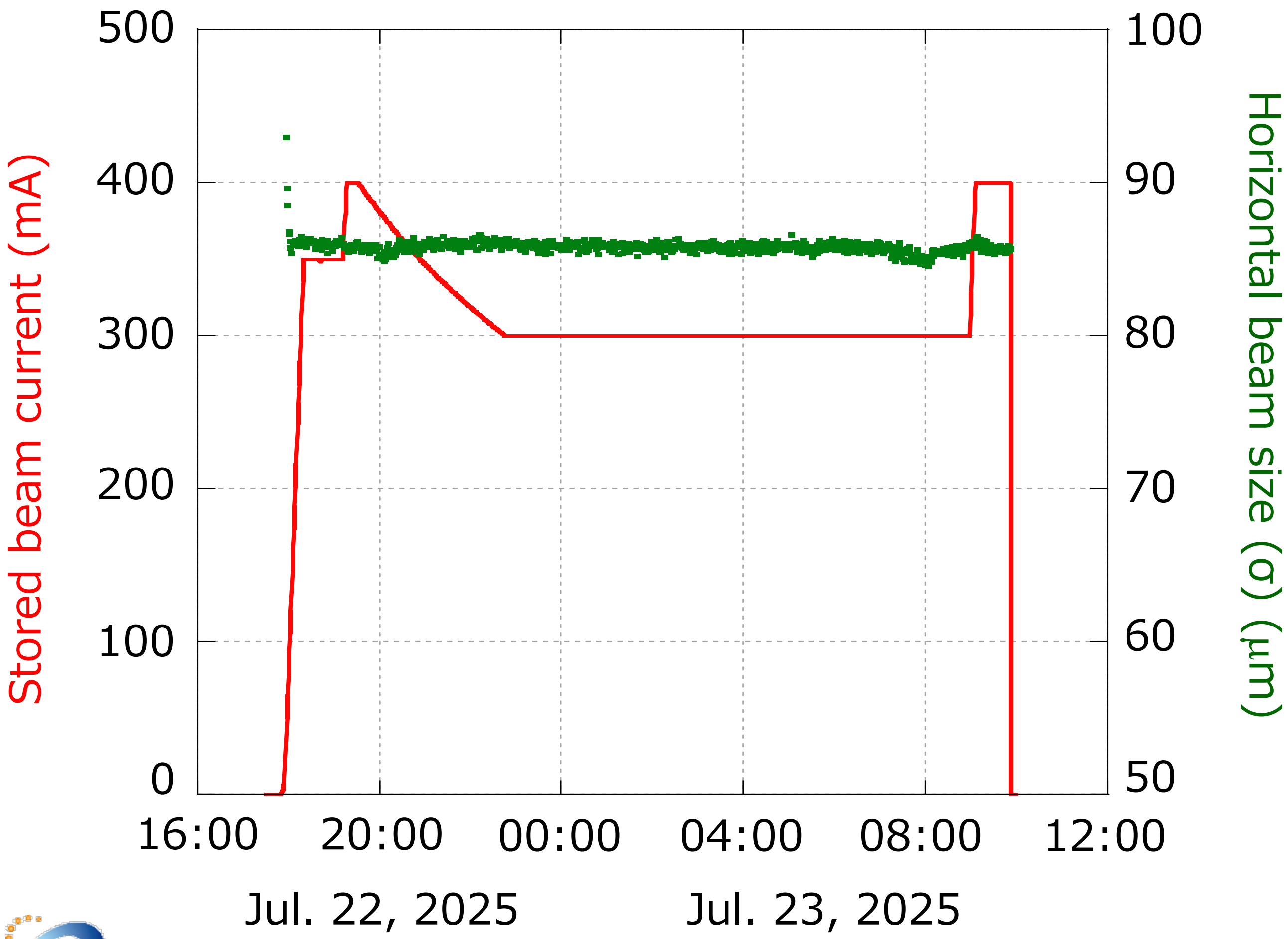
Time	1.9 GHz HOM at 400 mA	
τ_{CBI}	Estimated CBI growth time	3.1 ms
τ_{rad}	Radiation damping time	7.0 ms
τ_{BBF}	Required BBF damping time	<5.0 ms

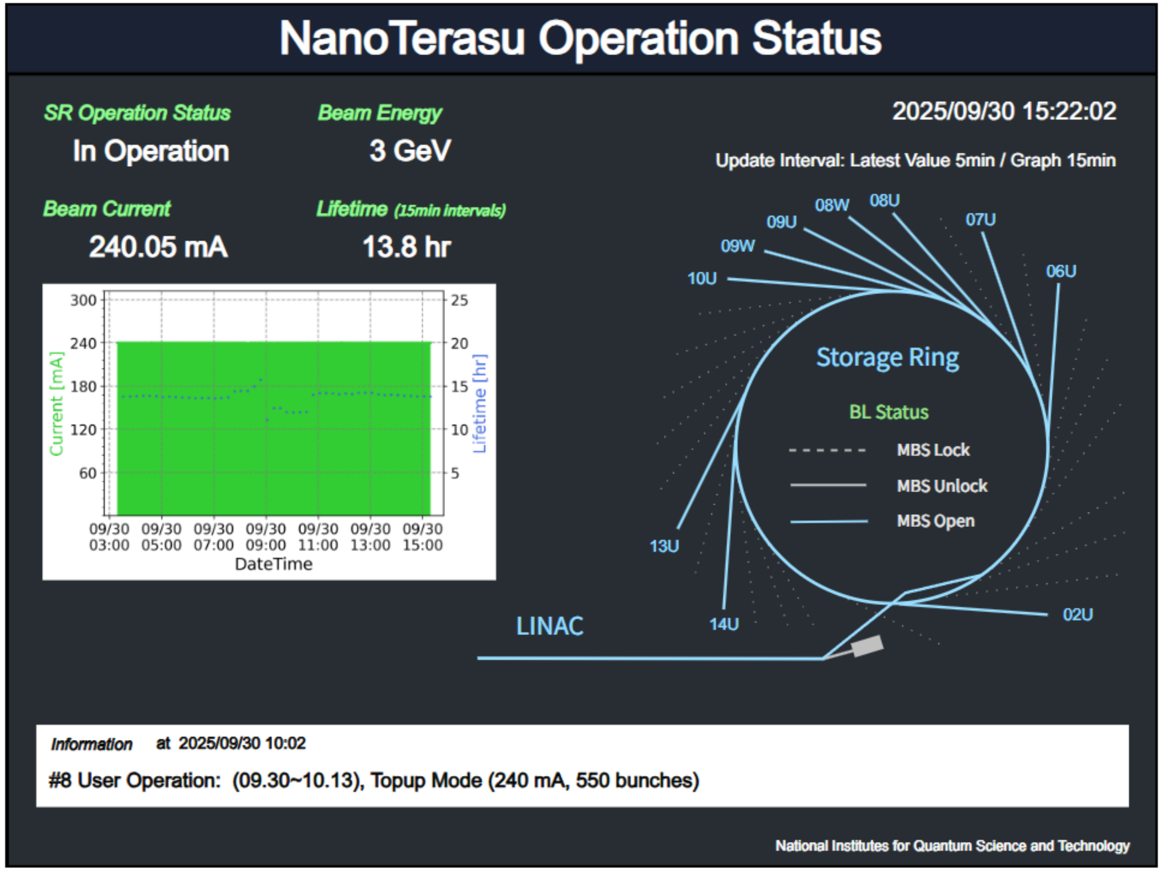




3-2. High current operation

- 400 mA operation without instability was demonstrated with LBBF cavity. **K. Ueshima, IBIC2025, TUPCO08 (2025)**
- 350 mA operation for 8 hours was also demonstrated.
- We plan to increase stored beam current by 40 mA every two weeks user operation.





NanoTerasu

3-2. NanoTerasu commissioning timeline

Date	Item
Apr. 17th, 2023	Electron beam generation from gun
Apr. 27th, 2023	3 GeV electron beam acceleration
Jun. 8th, 2023	SR beam injection 300 turns with RF cavity off
Jun. 16th, 2023	Beam stored with RF cavity on
Sep. 11th, 2023	200 mA
Sep. 14th ,2023	ID commissioning
Nov. 15th ,2023	300 mA with longitudinal coupled bunch instability (LCBI)
Dec. 7th ,2023	Beamline commissioning at exp. Hall
Apr. 1st ,2024	User operation at 160 mA without LCBI
Jul. 26th ,2024	User operation at 200 mA without LCBI
Jul. 22th ,2025	400 mA without LCBI with longitudinal bunch-by-bunch feedback (LBBF)

Parameters	Spec.	Achieved.
Energy	3 GeV	3 GeV
H. Emittance	1.14 nm.rad	~1.1nm.rad*
V. Emittance	0.01 nm.rad	0.02 nm.rad
Energy spread	0.0843%	0.097%*
Stored current	400 mA	400mA
Beam lifetime		10 hours@200mA

* Energy spread is enlarged to 0.097% from design value of 0.084% under assumption of emittance of 1.14 nm.rad.

NanoTerasu

Summary

- NanoTerasu started user operation in April 2024 as the 1st MBA light source in Japan especially for SX and Tender X-ray users.
- Highly stable beam with ~1.1 nm.rad emittance and 200 mA
- High resolution demonstrated in BL experiments
- User operation at 400 mA is coming.

Acknowledgement

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- All the members of QST NanoTerasu center and PhoSIC for their assistance.