Shielding design for NanoTerasu: gas-bremsstrahlung and induced radiations

Photo courtesy of PhoSIC

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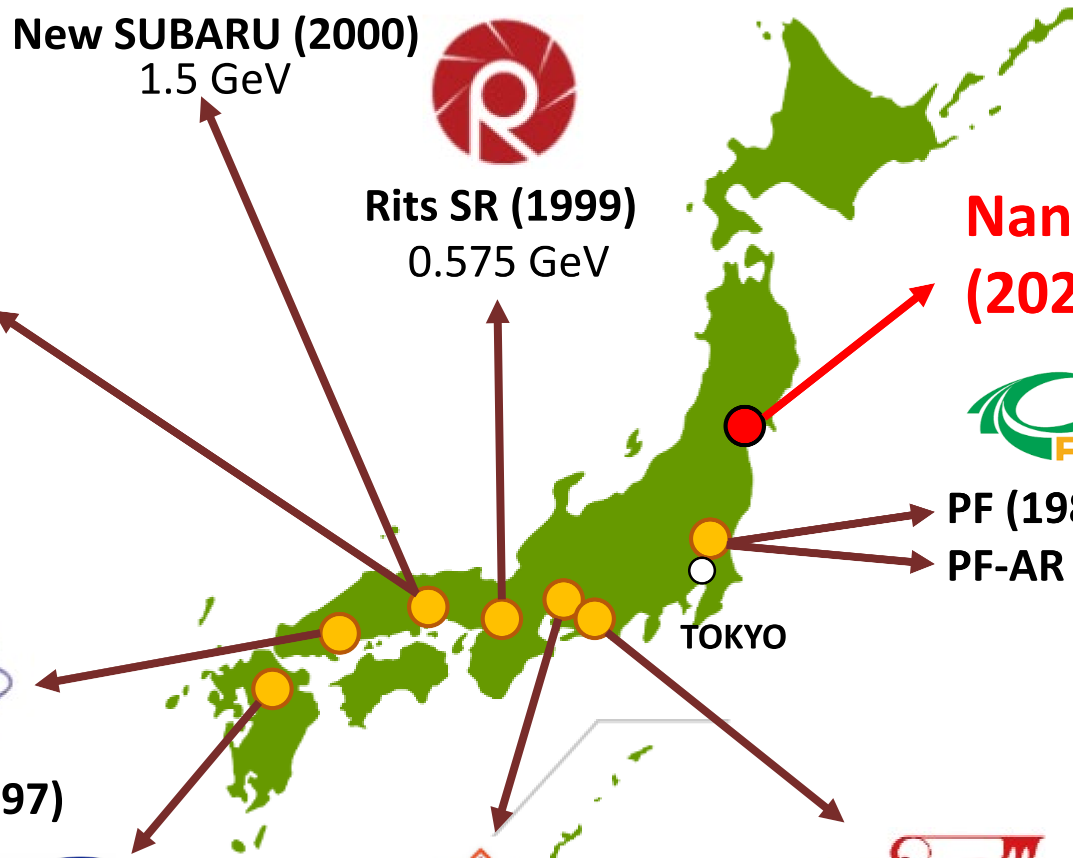
30/05/2023
Radsynch23

Contents

1-a : Synchrotron Radiation Facilities in Japan

(Operation start)



SACLA (2012)
8 GeV

SPring-8 (1997)
8 GeV

New SUBARU (2000)
1.5 GeV

Rits SR (1999)
0.575 GeV

NanoTerasu (2024) 3.0 GeV

PF (1983) 2.5 GeV
PF-AR (1987) 6.5 GeV

HiSOR (1997)
0.7 GeV

SAGA-LS (2006)
1.4 GeV

AichiSR (2013)
1.2 GeV

UVSOR (1984)
0.75 GeV

1-b: Introduction

Origin of the facility’s name NanoTerasu

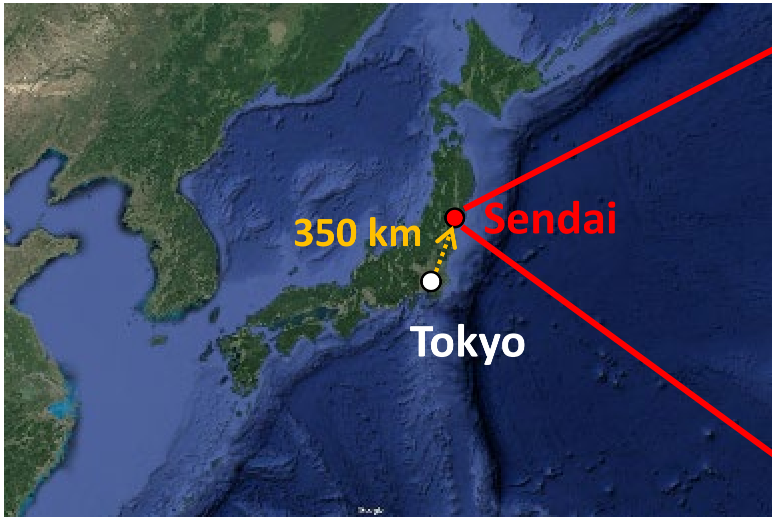
Nano	:	the scale of observation that will be conducted at the facility
Terasu	:	the Japanese word for shining a light on something
		the goddess of the sun in Japanese mythology “Ama<u>terasu</u>”

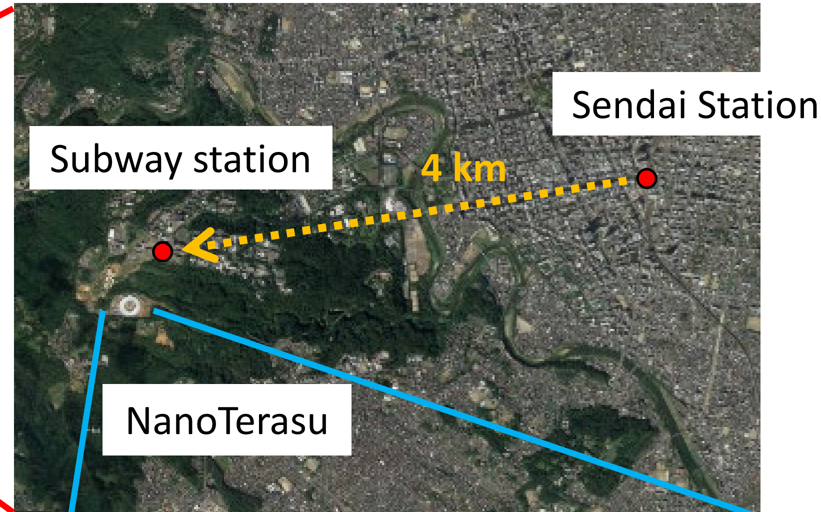
14/05/2023

The G7 Science and Technology Ministers' Meeting was held in the experimental hall of NanoTerasu.

https://www8.cao.go.jp/cstp/english/others/2023/g7_2023_en.html

1-c : Location and Access to NanoTerasu in Japan

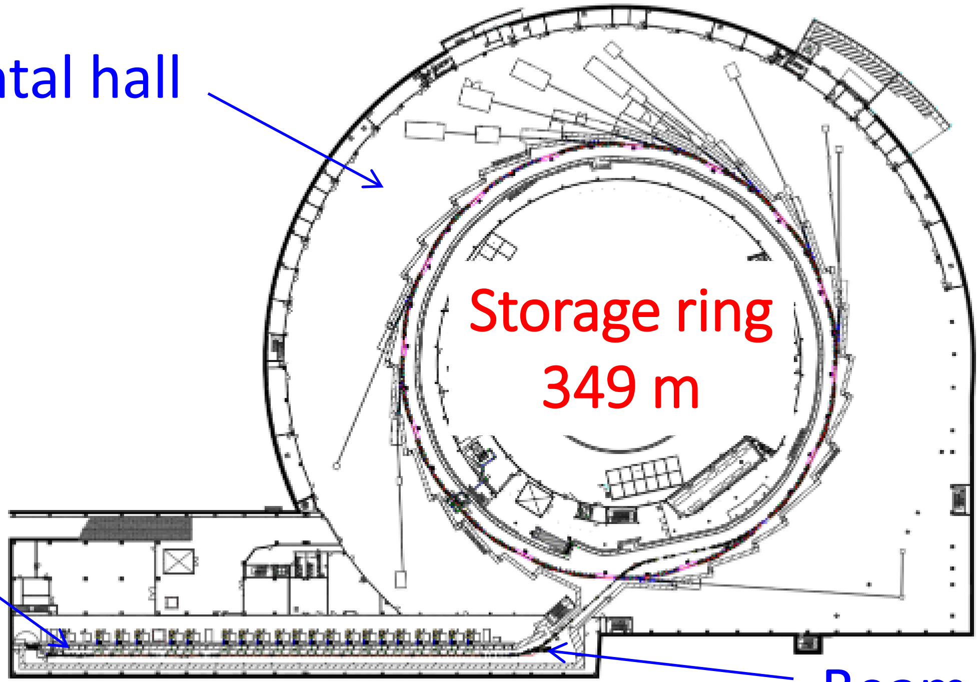




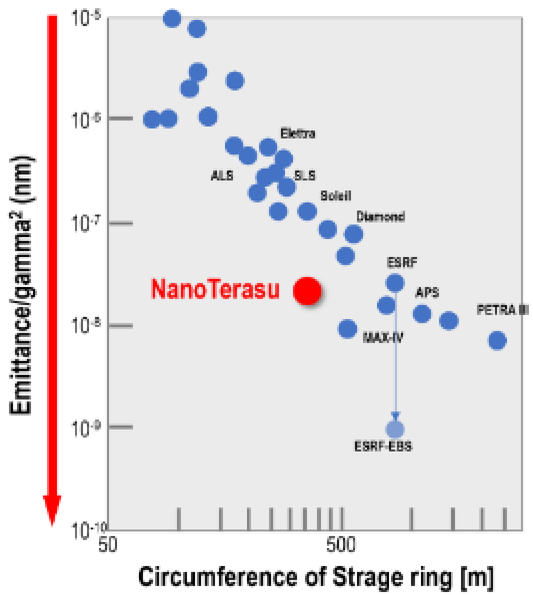
Sendai:

- Population: 1 million
- 90 minutes from Tokyo on the Bullet Train

1-d : Overview of NanoTerasu



Emittance of synchrotron light sources

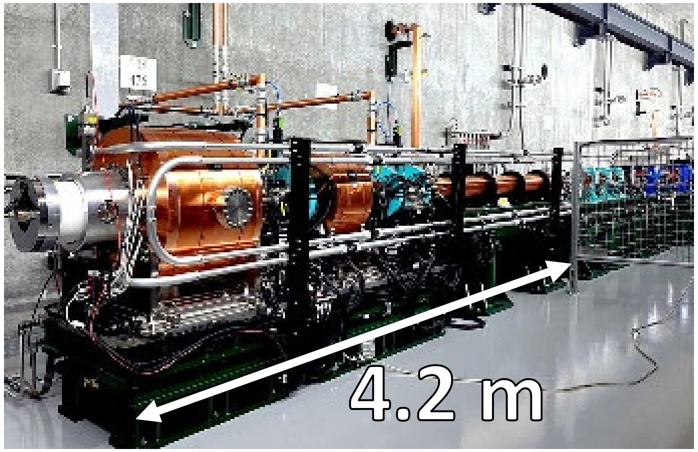


This project was started in 2019 and scheduled to operate in 2024. At the beginning 10 beamlines will be operating.

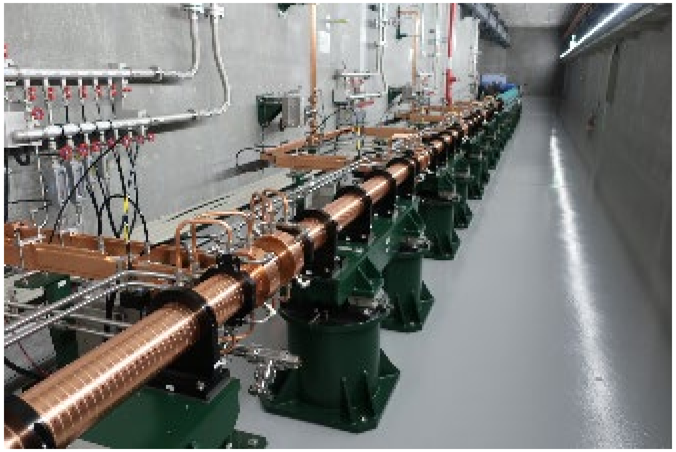
Parameters	
Electron energy	3 GeV
Natural emittance	1.14 nm.rad
Stored current	400 mA
Max (Beginning). number of undulators	14 (8)
Max (Beginning). number of multi-pole wigglers	14 (2)

1-d : Linac

Electron gun

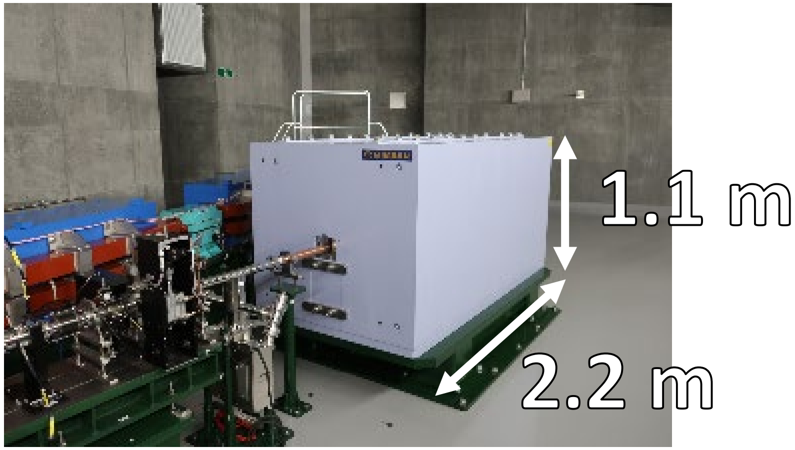


3 GeV C-band (5.7 GHz) accelerator (40 of 2m-long-cavities)

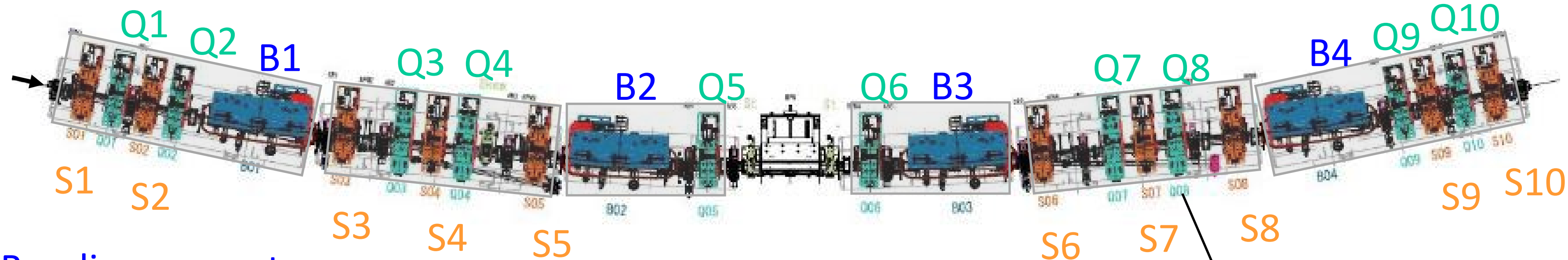


Parameters		Injector
Beam energy	E (GeV)	3
Normalized emittance	(μmrad)	<10
Emittance at 3 GeV	(nmrad)	<1.7
Bunch charge	(nC)	0.3
Repetition rate (Normal)	(Hz)	1

Beam dump (Steel)



1-d : Storage Ring: 4BA lattice

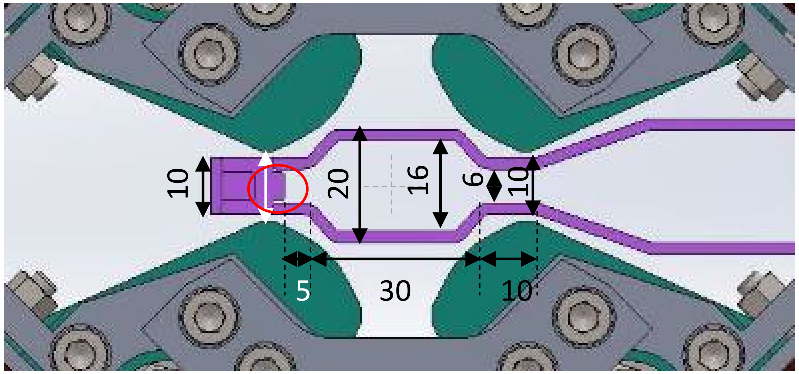


B: Bending magnet

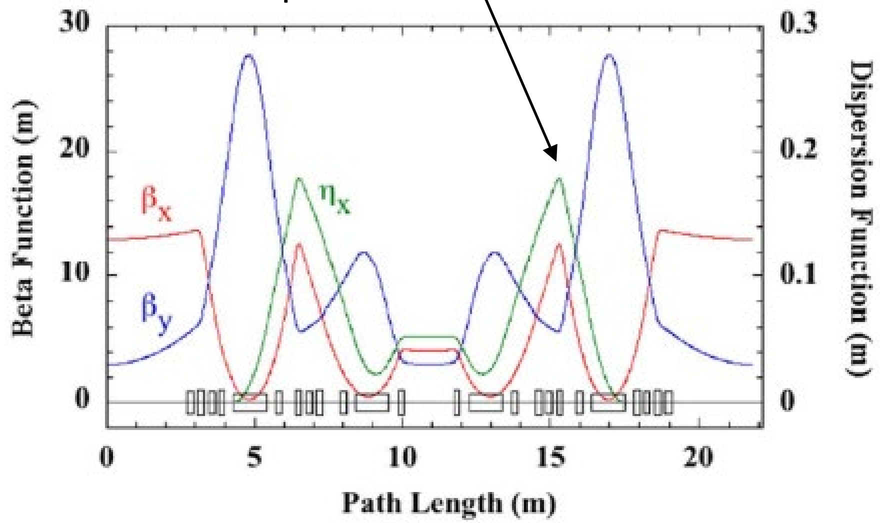
Q: Quadrupole magnet

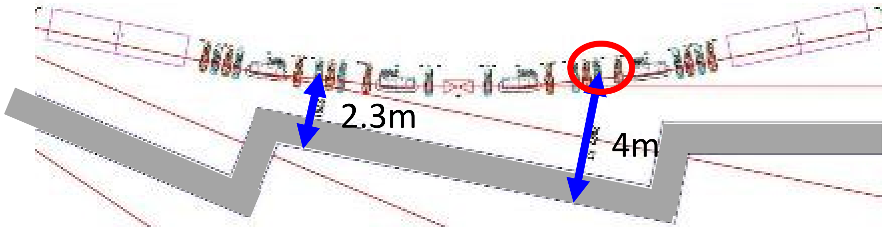
S: Sextupole magnet

Electron beam absorber (Graphite)



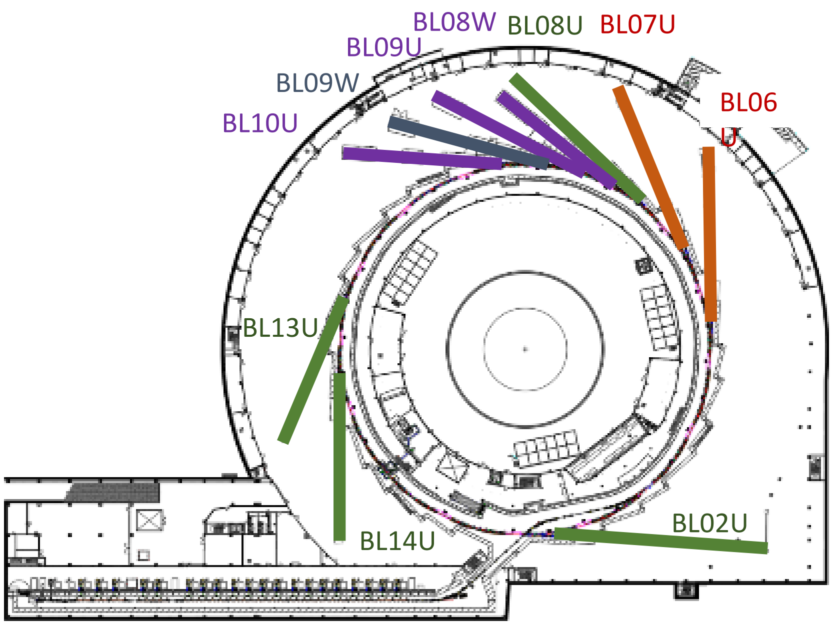
Optics of 4BA lattice

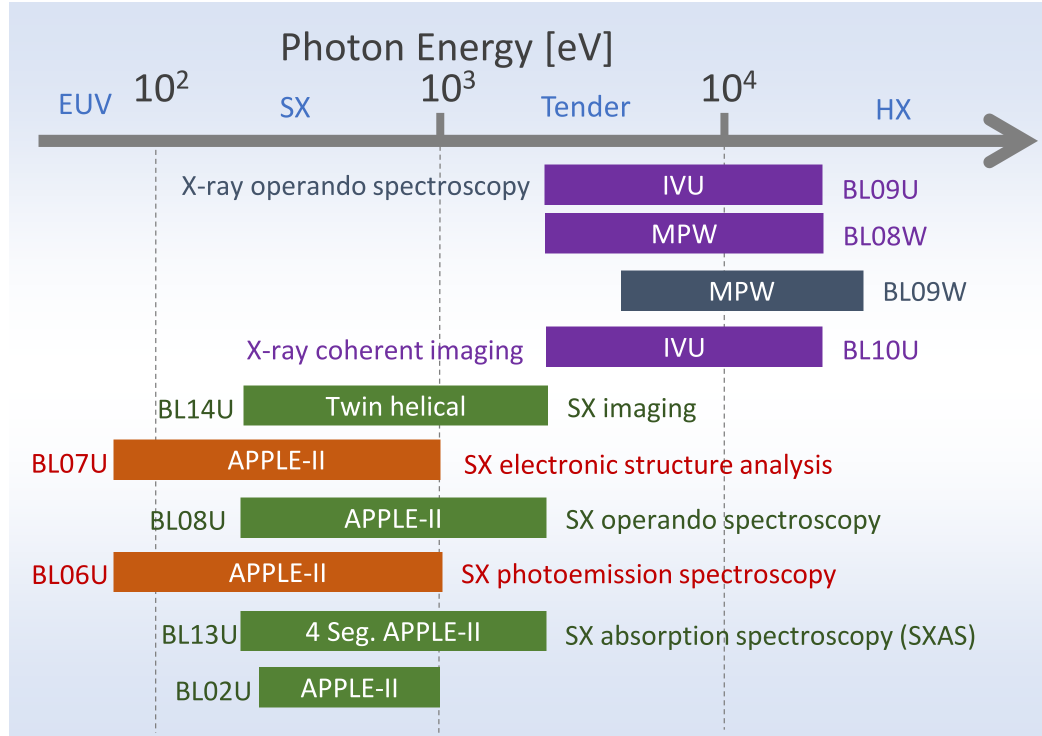




1-d : Beamlines

Undulators and MPWs in the first phase 10 beamlines





1-e : Project status

item	2019FY	2020FY	2021FY	2022FY	2023FY	2024FY
Building	Constructing →	→	→	→		
Linac				Installation →	Commissioning ··· →	User operation →
Storage Ring				Installation →	··· →	
Beam lines				Installation →	→ ··· →	
authorization			Submission of application documents ●	Passed (Document review) ★	Leakage dose inspection (Linac) ★ (SR, BL) ★	

today



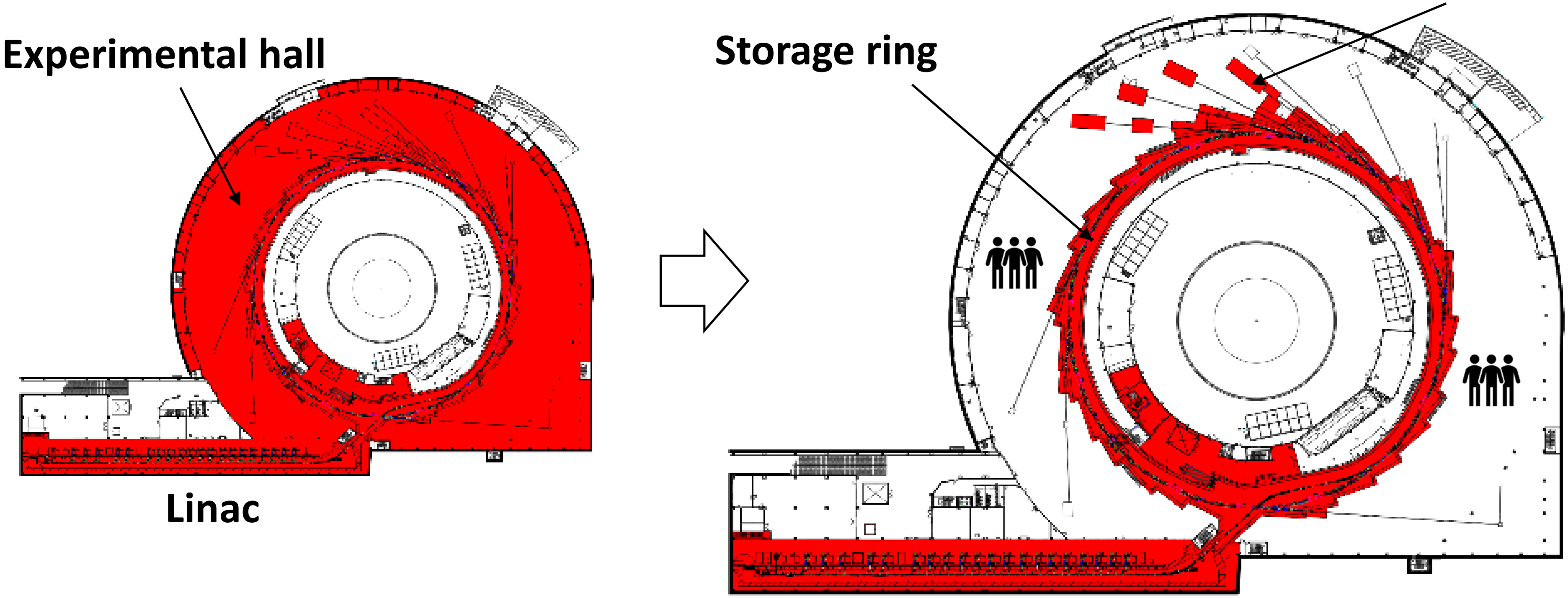

2-a : Designation of Radiation-controlled area

Japanese Law

General area: less than 1.3 mSv / 3 month → **520 hours of work per 3 month** → **2.5 μSv/h**

Conventional setting in Japan

NanoTerasu
Design goal < 1.25 μSv/h



Radiation-controlled area

3-b : Assumption of beam loss and point

1. Collimator
500 keV, 600 pC/s
(0.0003 W)

2. Collimator
3 MeV, 600 pC/s
(0.0018 W)

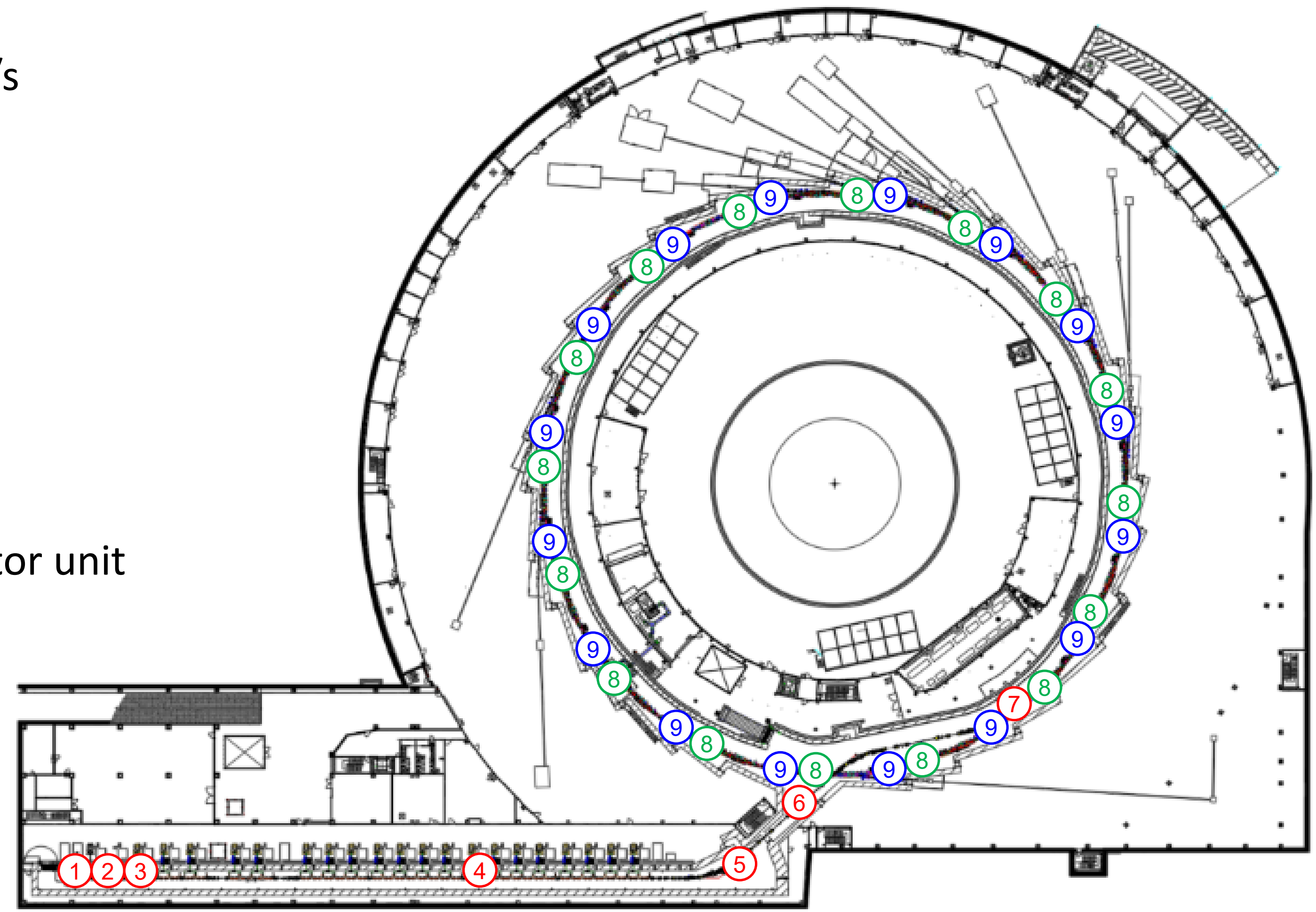
3. Slit
40 MeV, 60 pC/s
(0.0024 W)

4. C-band accelerator unit
3 GeV, 4 pC/s
(0.012 W)

5. Beam dump
3 GeV, 400 pC/s
(1.2 W)

6. Beam transport line
3 GeV, 4 pC/s
(0.012 W)

7. Beam injection
3 GeV, 5% of incident electrons (0.009 W)



3-b : Assumption of beam loss and point

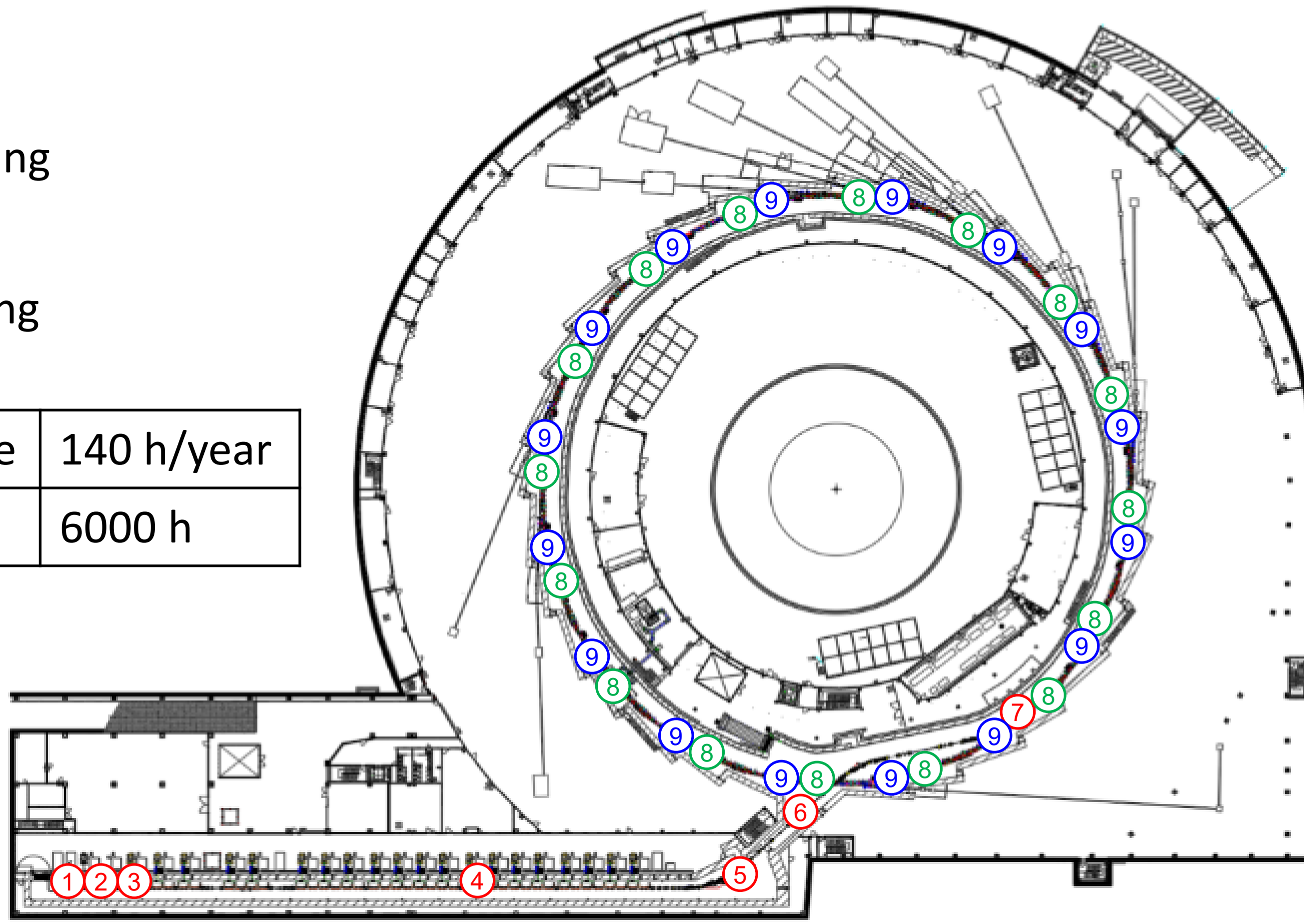
8 Straight section

- Gas scattering
- Gas bremsstrahlung

9 Absorber

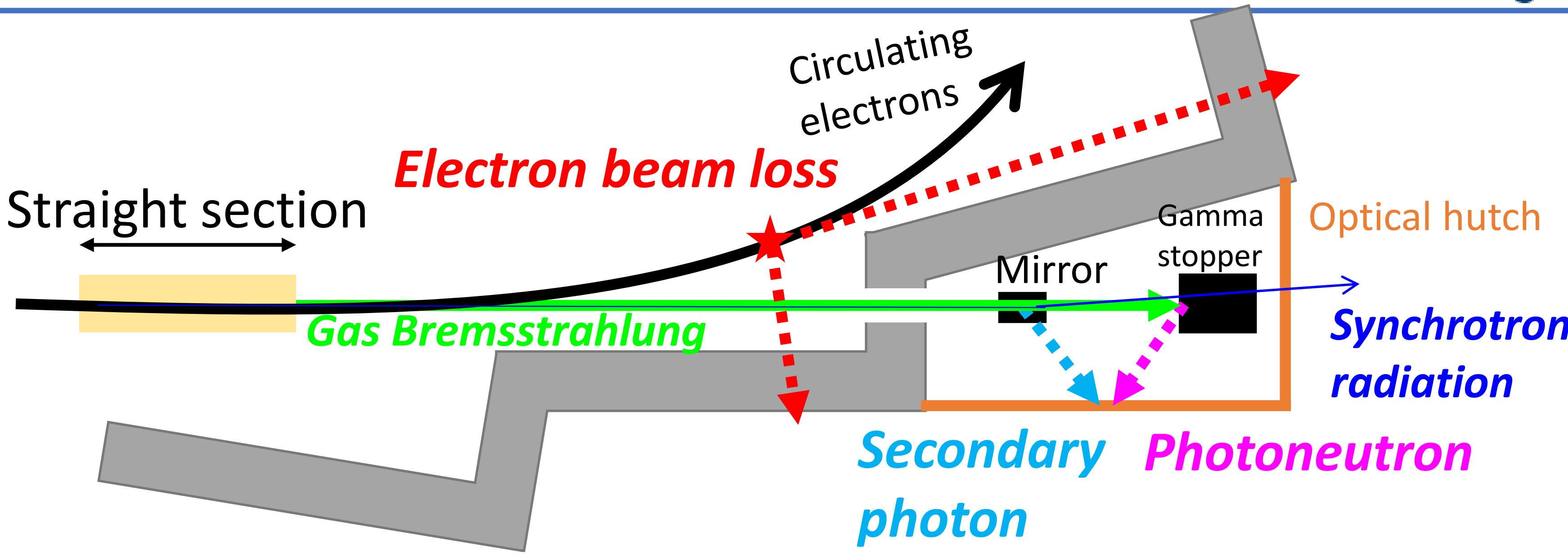
- Touschek scattering
- Beam abort

Mean Time Between Failure	140 h/year
Annual operation hours	6000 h



Vacuum pressure	10^{-7} Pa
Stored beam lifetime $\tau = (\tau_G^{-1} + \tau_T^{-1})^{-1}$	8.2 h
Gas scattering lifetime τ_G	18 h
Touschek lifetime τ_T	15 h (400 mA)

3-c : Shielding calculation method



Electron beam loss

- E. Braeuer, ESRF/SHIELD/88-04 Oct. (1988) (Revised).
- W. P. Swanson, Technical Report Series No.188, IAEA (1969).
- T. M. Jenkins, Nucl. Instrum. Meth. 159, 265 (1969).

Parameters : angle, beam loss power, distance,…

Gas Bremsstrahlung

- B. Rossi, Prentice-Hall, Englewoodcliffs, NJ, 1952.
- S. Ban et al., Health Phys. 57 (3), 407 (1989).

Parameters : residual gas pressure, composition, length of straight section,…

Secondary photon

- Liu et al., Health Phys. 68, 2, 205 (1995).

Parameters : angel, distance, …

Photoneutron

- Liu et al., Health Phys. 68, 2, 205 (1995).

Parameters : target material, distance, …

Synchrotron radiation

- SPECTRA: a synchrotron radiation calculation code

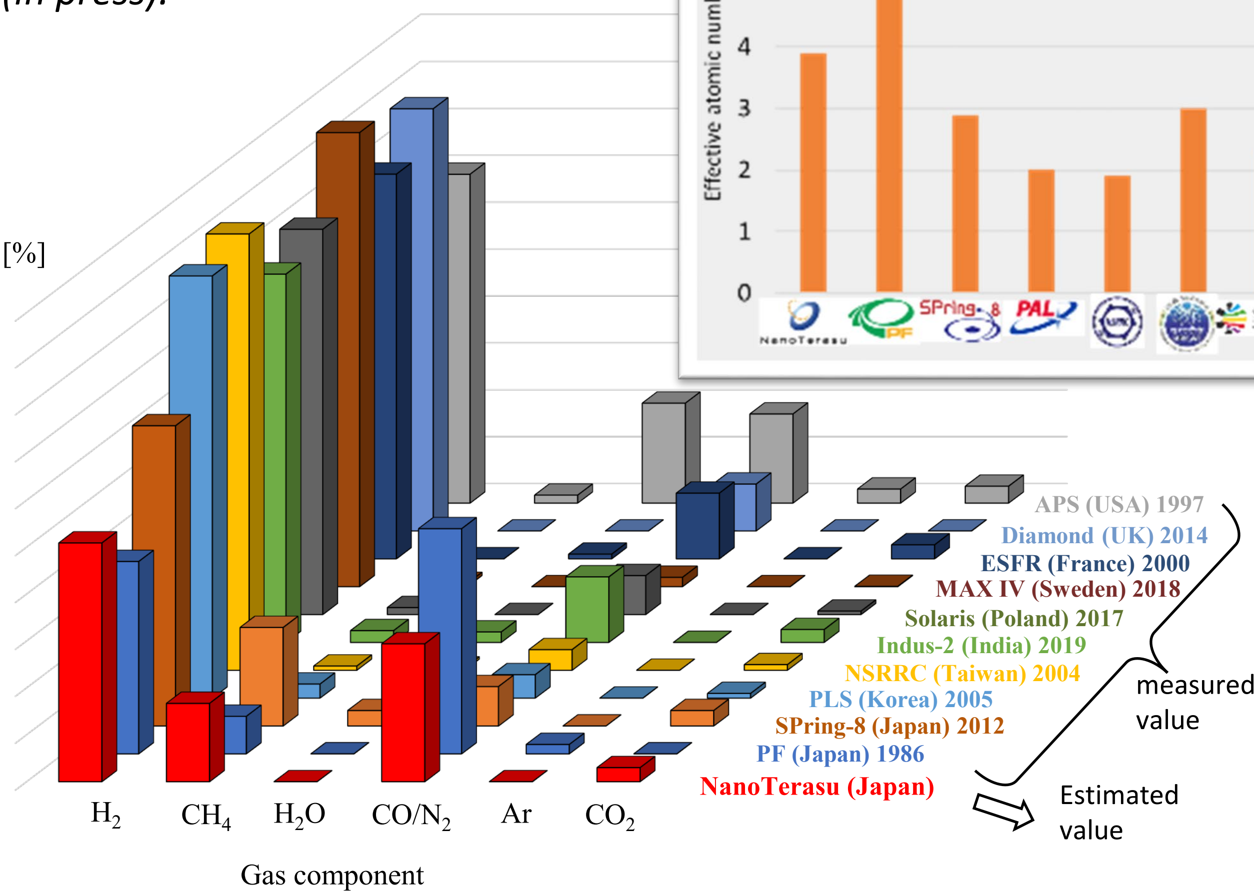
Parameters : magnetic field strength, Periodic length, Number of Regular periods,…

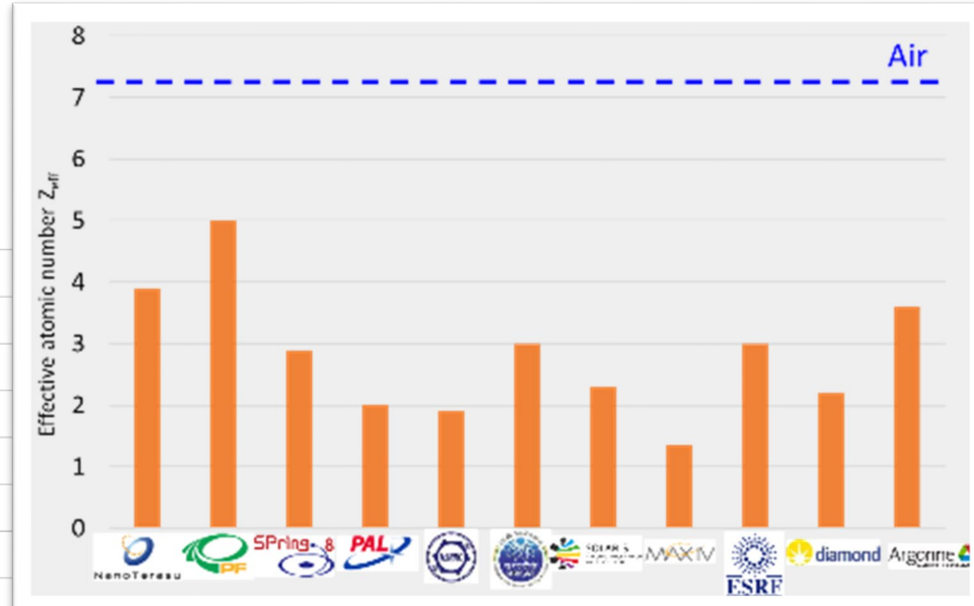
3-c : Residual gas composition for gas bremsstrahlung calculations

Most of the residual gas components in the storage ring are **H_2**

➡ Shielding design (Previous studies [Air] × gas correction)

A. Takeuchi et al., "Estimation of absorbed dose due to gas bremsstrahlung based on residual gas in electron storage rings", Nucl Sci Eng, 2023 (in press).





NanoTerasu

3-d : Shielding structure

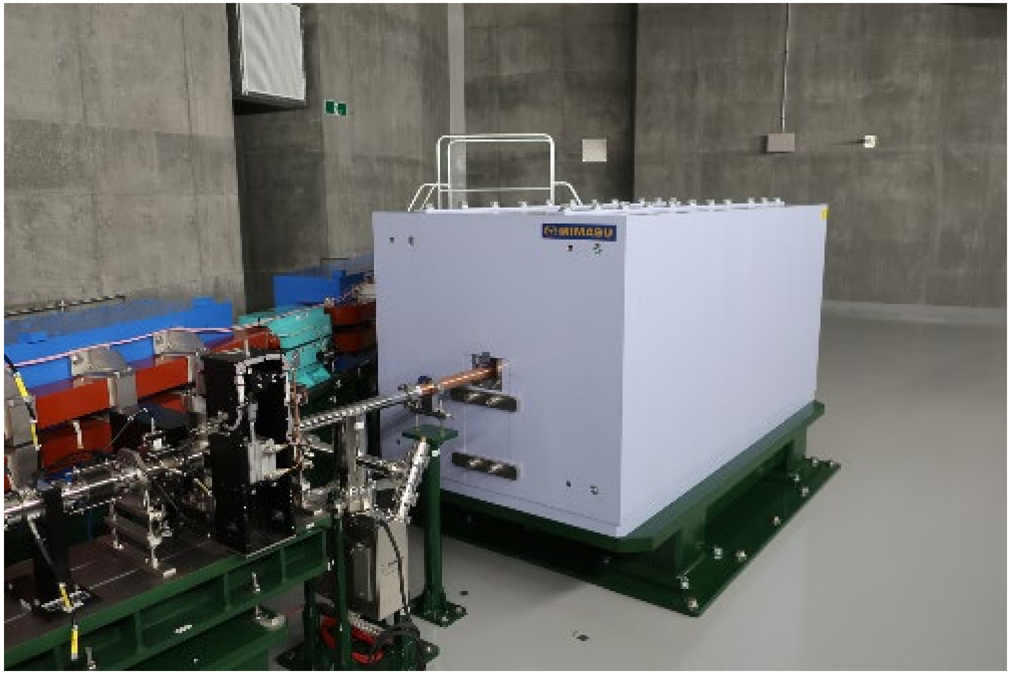
QST

Electron Beam loss

Shielding wall

Concrete : 1 m thick

Beam dump



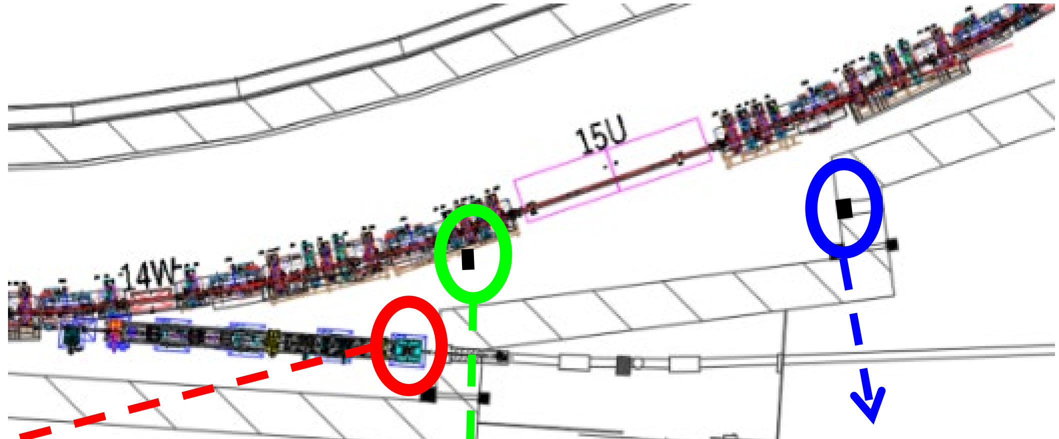
Steel : 0.5 m thick

3-d : Shielding structure

Gas Bremsstrahlung (inside tunnel)

Beam Shutter

Tungsten alloy : 30 cm thick



Local shielding

Lead : 10 cm thick

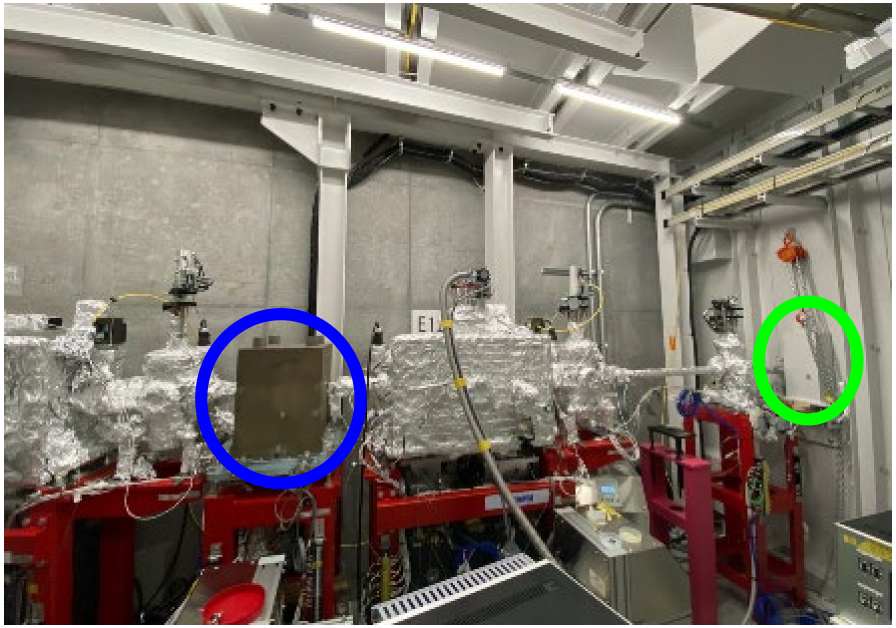
Local shielding

Lead : 30 cm thick

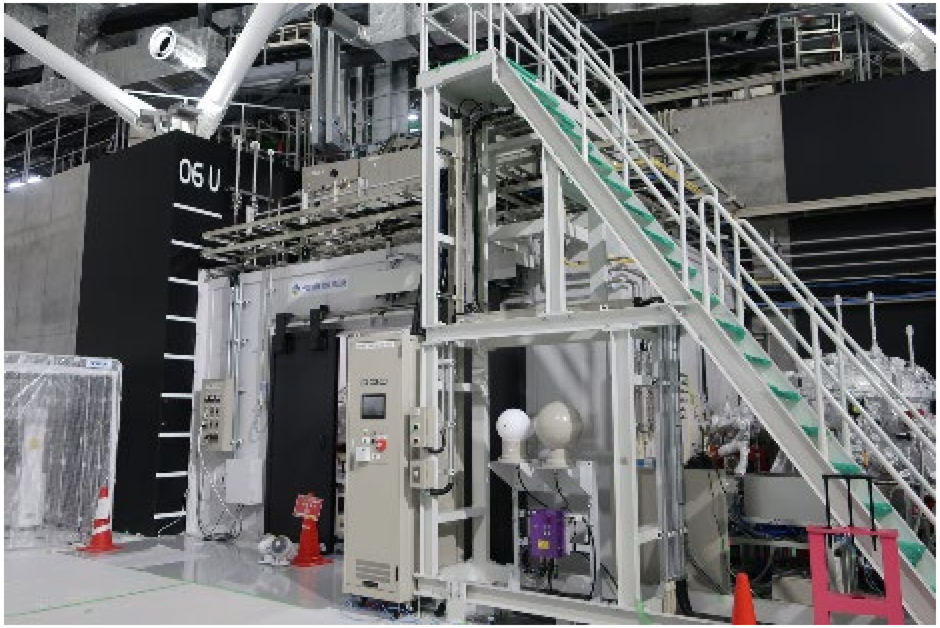
3-d : Shielding structure

Gas Bremsstrahlung (outside tunnel)

Local shielding



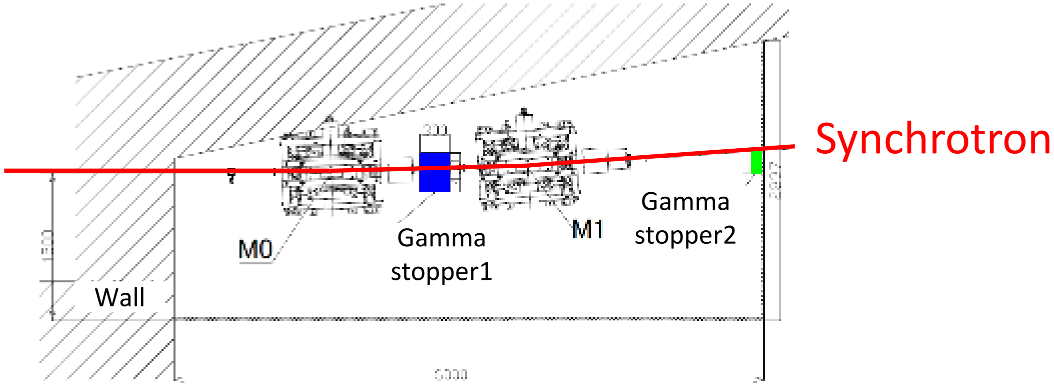
Enclosure



Lead: 30 cm thick

Lead: 10 cm thick

Lead : 1 cm thick

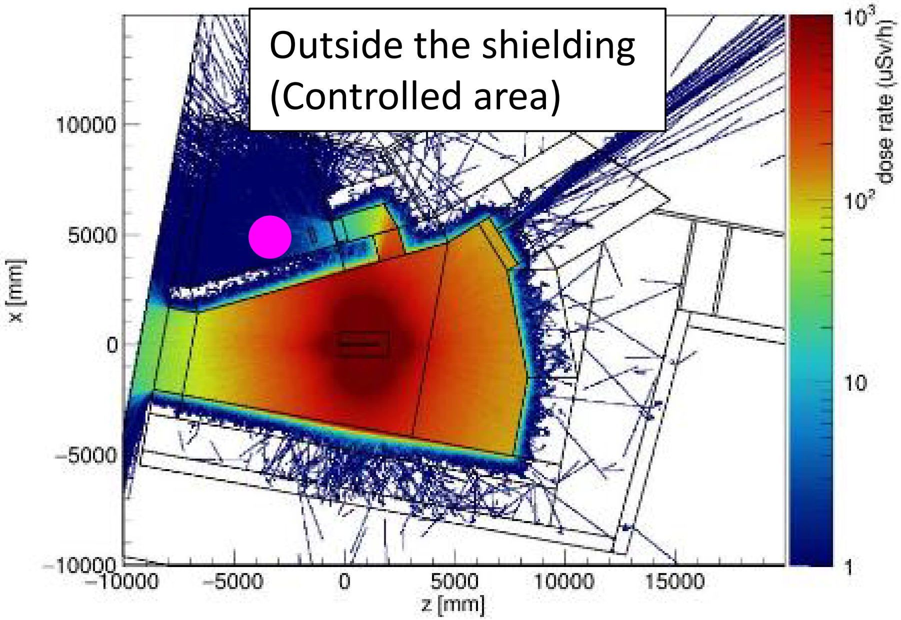


3-e : Dose calculation and measurements

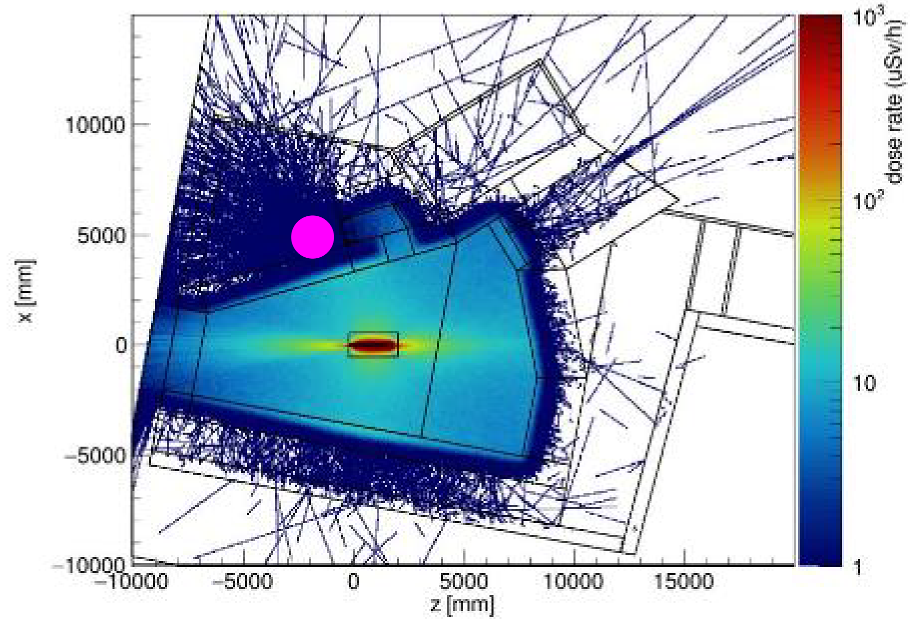
Beam dump

PHITS ver.3.24

Neutrons dose



Photons dose

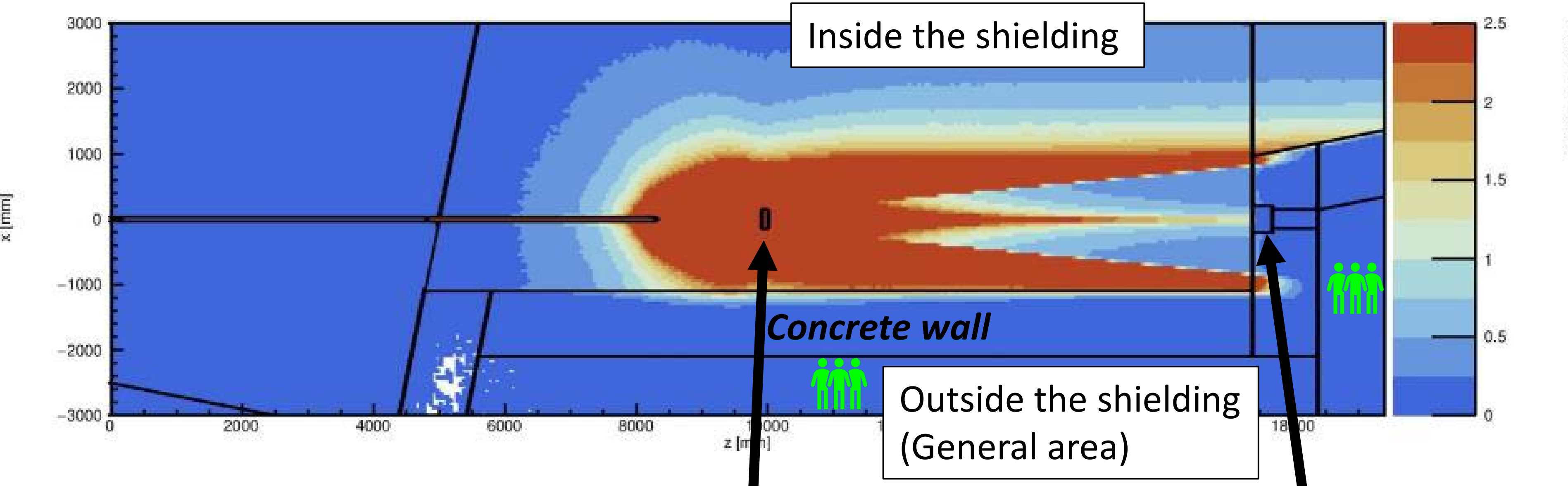


PHITS	7.5 uSv/h
Measurement	6.5 uSv/h

3-e : Dose calculation

Gas Bremsstrahlung (inside tunnel)

PHITS ver.3.24



PHITS < 0.5 uSv/h

Lead : 10 cm thick

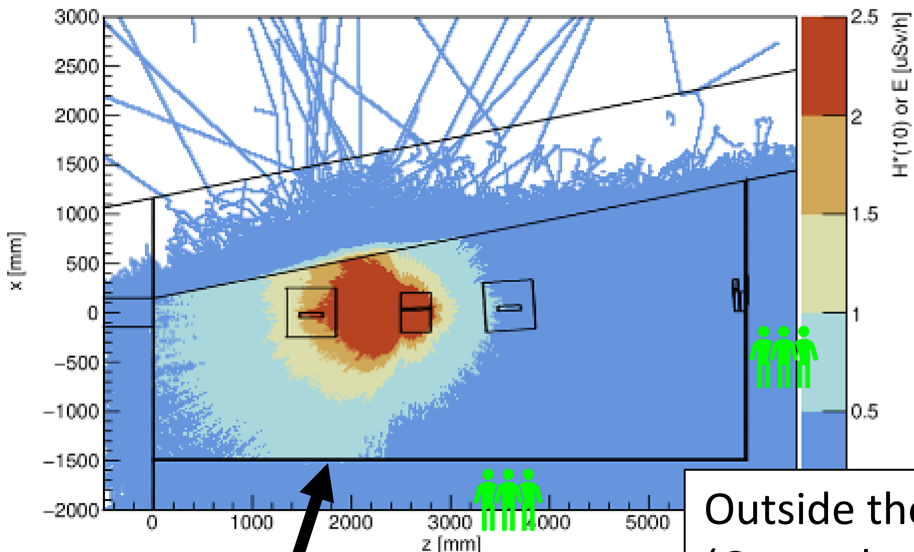
Lead : 30 cm thick

3-e : Dose calculation

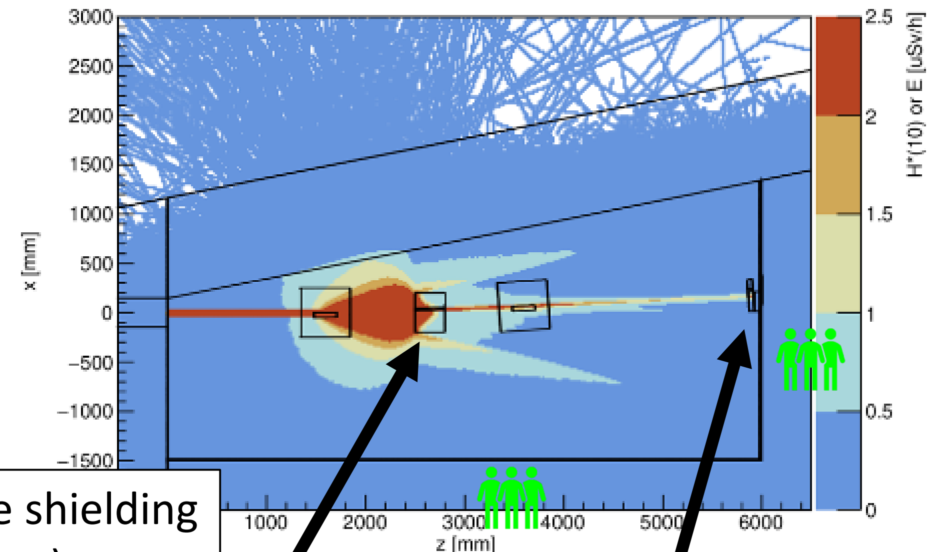
Gas Bremsstrahlung (outside tunnel)

PHITS ver.3.24

Neutrons dose



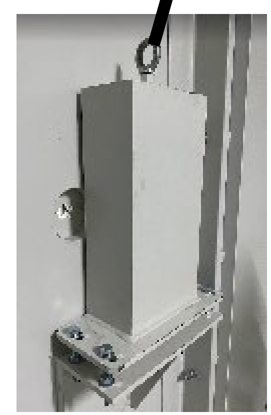
Photons dose



Outside the shielding
(General area)

Lead : 1 cm thick

Lead : 30 cm thick



Lead : 10 cm thick

PHITS < 0.5 uSv/h

4 : Summary

- NanoTerasu is the first facility in Japan designed to exclude most of the experimental hall from radiation-controlled areas.
- Shielding design is evaluated using empirical equations and monte-carlo simulation.
- The beam commissioning has been started in April 2023.
- User operation is scheduled to start in April 2024.

Thanks for your attention!

NanoTerasu

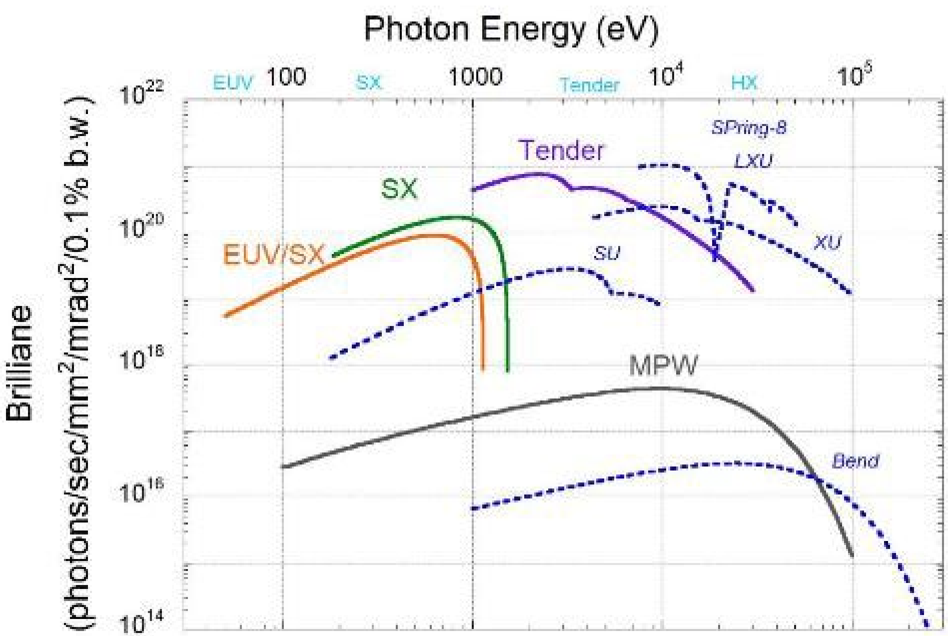
Photo courtesy of PhoSIC

To Boldly Look Where No One Has Looked Before

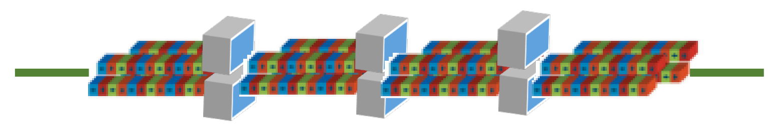
Set a Course for the New Nano Word. Engage!

Light source overview

APPLE-II is the workhorse of the SX sources.



BL	ID	λ_w (mm)	N_w
02U 07U	APPLE-II	56	71
06U 08U	APPLE-II	75	53
13U	4 Seg. APPLE-II	56	11 x 4

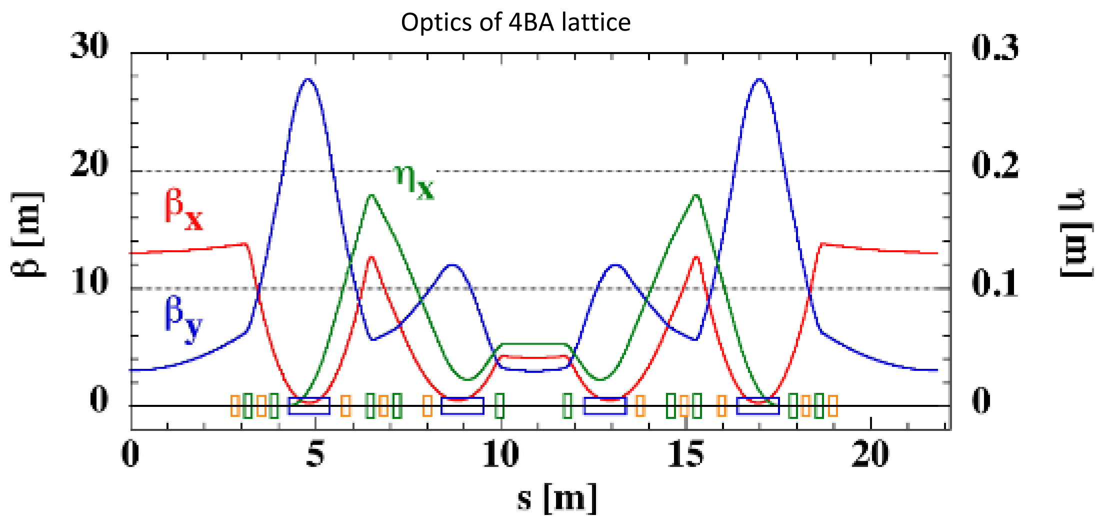


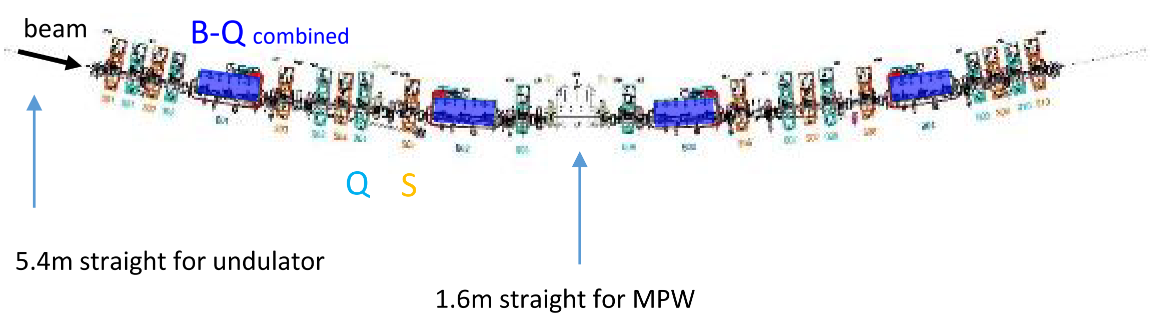
- Brilliance ~10^{21} photons/sec/mm²/mrad²/0.1% b.w. for 1-3 keV
- MPW Hard X-ray (HX) sources


as of Dec. 22, 2021

by courtesy of Hitachi Metals, Ltd.

Storage ring (SR): 4BA lattice





Ring parameters	
Natural emittance	1.14 nm.rad
Energy spread	0.084 %
Betatron tune (ν_x,ν_y)	(28.17, 9.23)
Natural chromaticity (ξ_x,ξ_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)

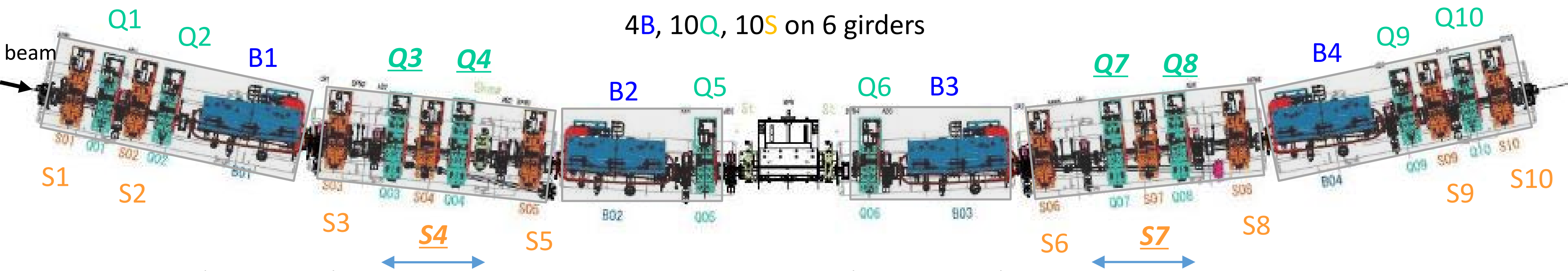
Magnet	Max. fields	#/cell	#/ring
B-Q combined	0.87 T -7.1 T/m	4	64
Quadrupole	49 T/m	10	160
Sextupole	1540 T/m^2	10	160

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

SR: Magnet

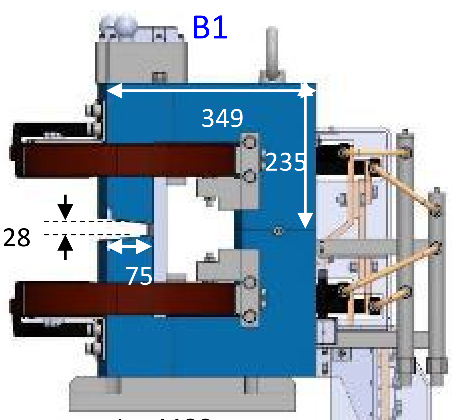
Concept

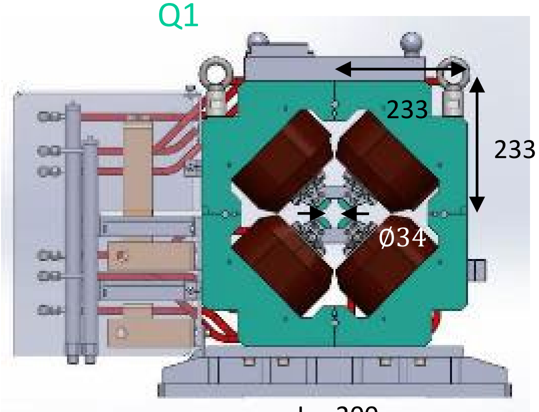
Magnet system with small number of types and power supplies for low cost and easy maintenance

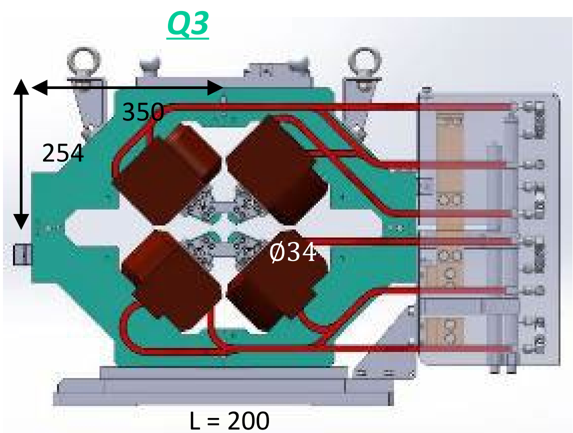


B-Q combined (massive steel)

Quadrupoles (laminated steel)







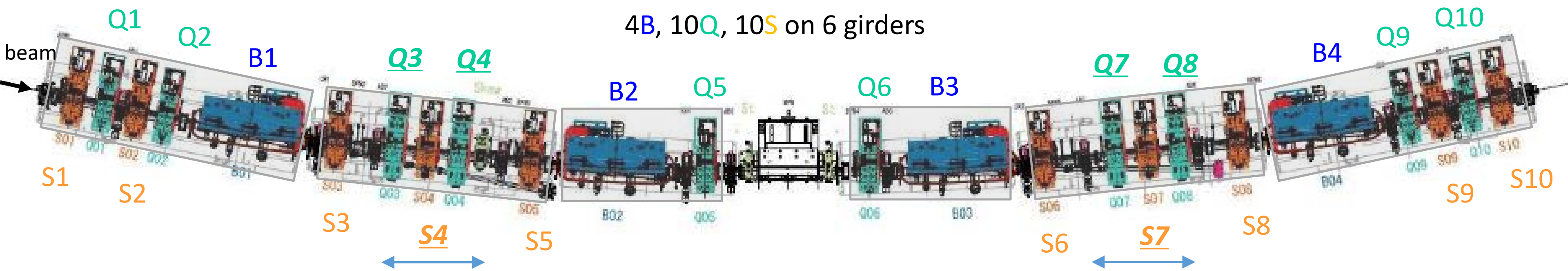
SR: Magnet

- Aux. power supply to an individual Q for mag. field adjustment
- Aux. coils for SX as steering magnets and fine tuning of mag. field

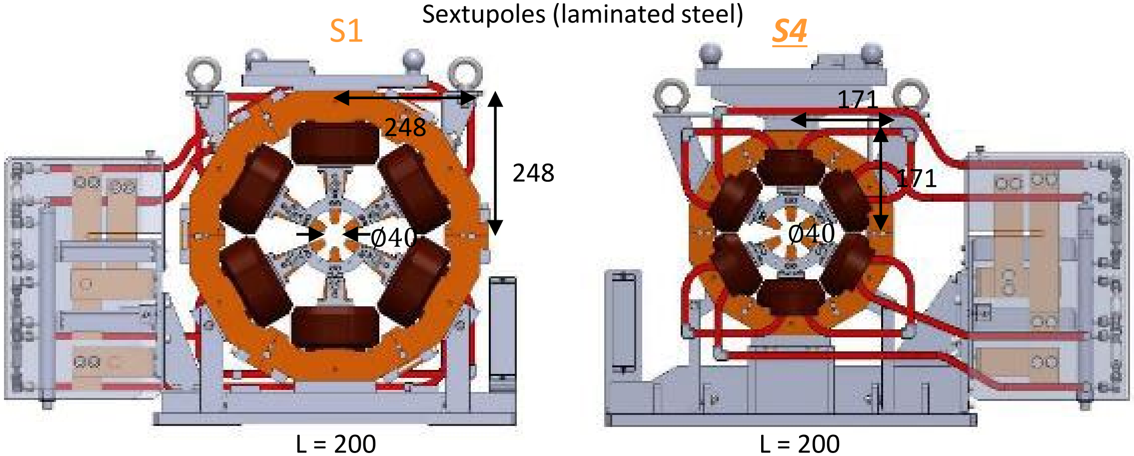
Concept

Magnet system with small number of types and power supplies for low cost and easy maintenance

4B, 10Q, 10S on 6 girders



Sextupoles (laminated steel)



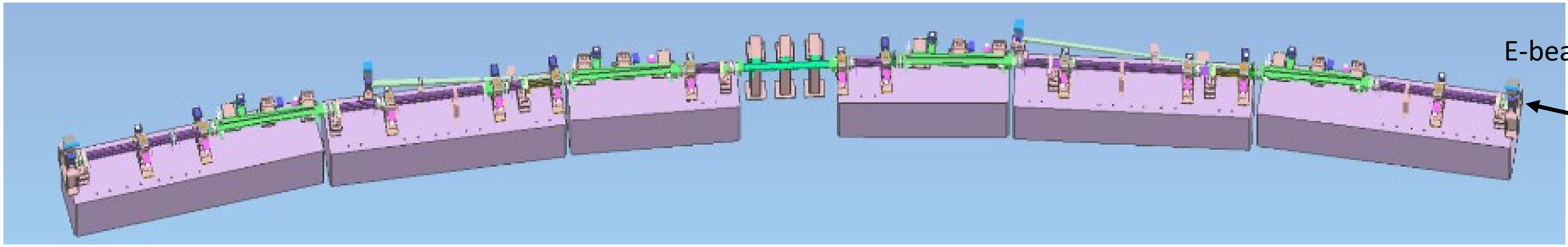
- 11 sets of family magnets: B, 5Q, 5S
- Common power supply for each family
- 11 power supplies: B, 5Q (2 types), 5S

Requirement

Field deviation of magnets:
$< \pm 0.2$ % (B)
$< \pm 0.4$ % (Q, S)

2-1. SR: Vacuum

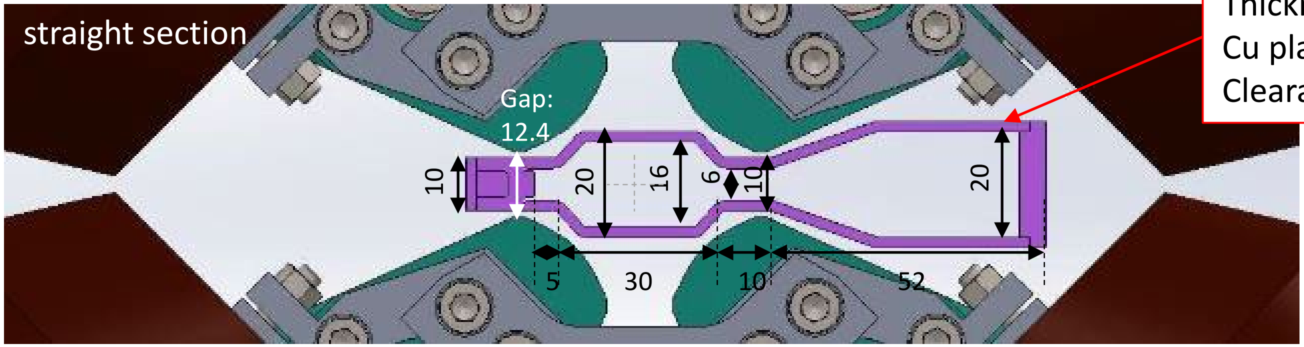
Goal: 20h of gas scattering lifetime for 400 mA current requiring 1×10^{-7} Pa CO equivalent



Features

- Stainless steel (316) chamber with 2 mm thickness and Cu plating inside to meet short gap and to reduce impedance

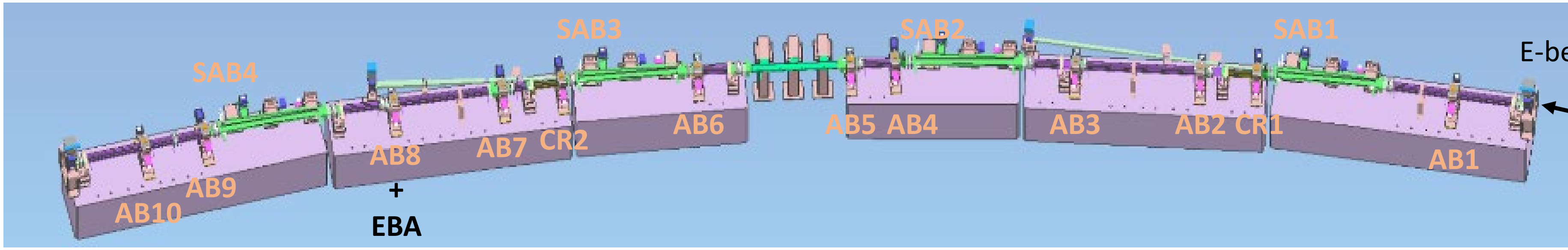
Cross section of vacuum chamber



Stainkess steel (316)
Thickness: 2mm
Cu plating: 0.1mm
Clearance: 1.2mm

2-1. SR: Vacuum

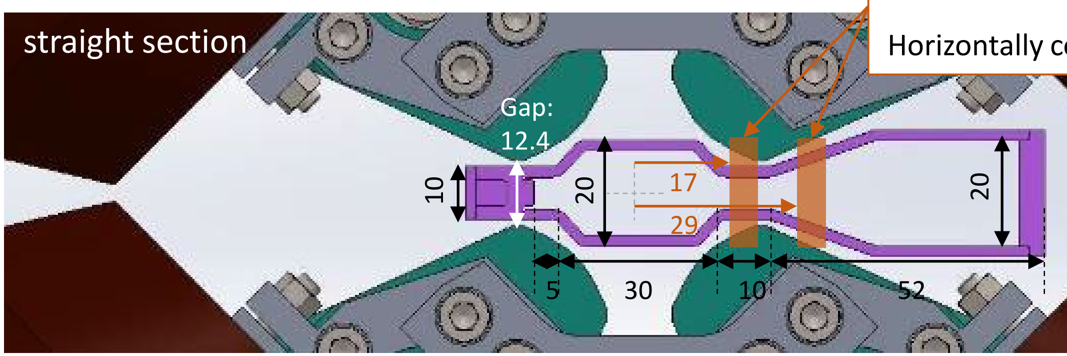
Goal: 20h of gas scattering lifetime for 400 mA current requiring 1×10^{-7} Pa CO equivalent



Features

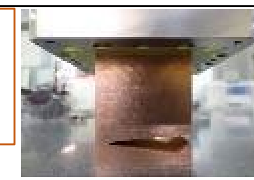
- Stainless steel (316) chamber with 2 mm thickness and Cu plating inside to meet short gap and to reduce impedance
- Discretely arranged 10 photon absorbers (AB), 2 crotch ABs (CR), 4 supplemental ABs (SAB) and pumps
- Electron beam absorber for the high intensity beam to be spread out during beam abort

Cross section of vacuum chamber



AB/CR placed at 17 or 29 mm from beam trajectory.

Horizontally compact vacuum chambers.



- Only 4 types (1 AB, 2 CR, 1 SAB) for low cost and easy maintenance
- Max. SR peak power density of ~200 W/mm^2
- Average pressure is 6×10^{-8} Pa (CO) at 400 mA after 1500 Ah dose → 22hrs. lifetime

Public-Private Regional Partnerships promoting NanoTerasu.

The next-generation synchrotron radiation facility satisfies **many of the needs in academia and industry**. It will **strengthen research capabilities and improve productivity in our industry, academia, and national research sectors**. This project will be a leading case of a large-scale state-of-the-art research facility based on **public-private regional partnerships**.

(December 17, 2018 Press conference by the Minister of Education, Culture, Sports, Science, and Technology.)

[National Agent]

- National Institute of Quantum Science and Technology (QST)

[Partners]

- Photon Science Innovation Center (PhoSIC/General Incorporated Foundation)
- Miyagi prefecture
- Sendai City
- Tohoku University
- Tohoku Economic Federation

Operational in FY 2024

Task	Constructor
Electron Accelerator	Government
Beam Lines	Government: 3 BLs Partners: 7 BLs
Building	Partners
Land forming	Partners

Total budget
270 million USD

Limitations of Japanese Law

public dose limit

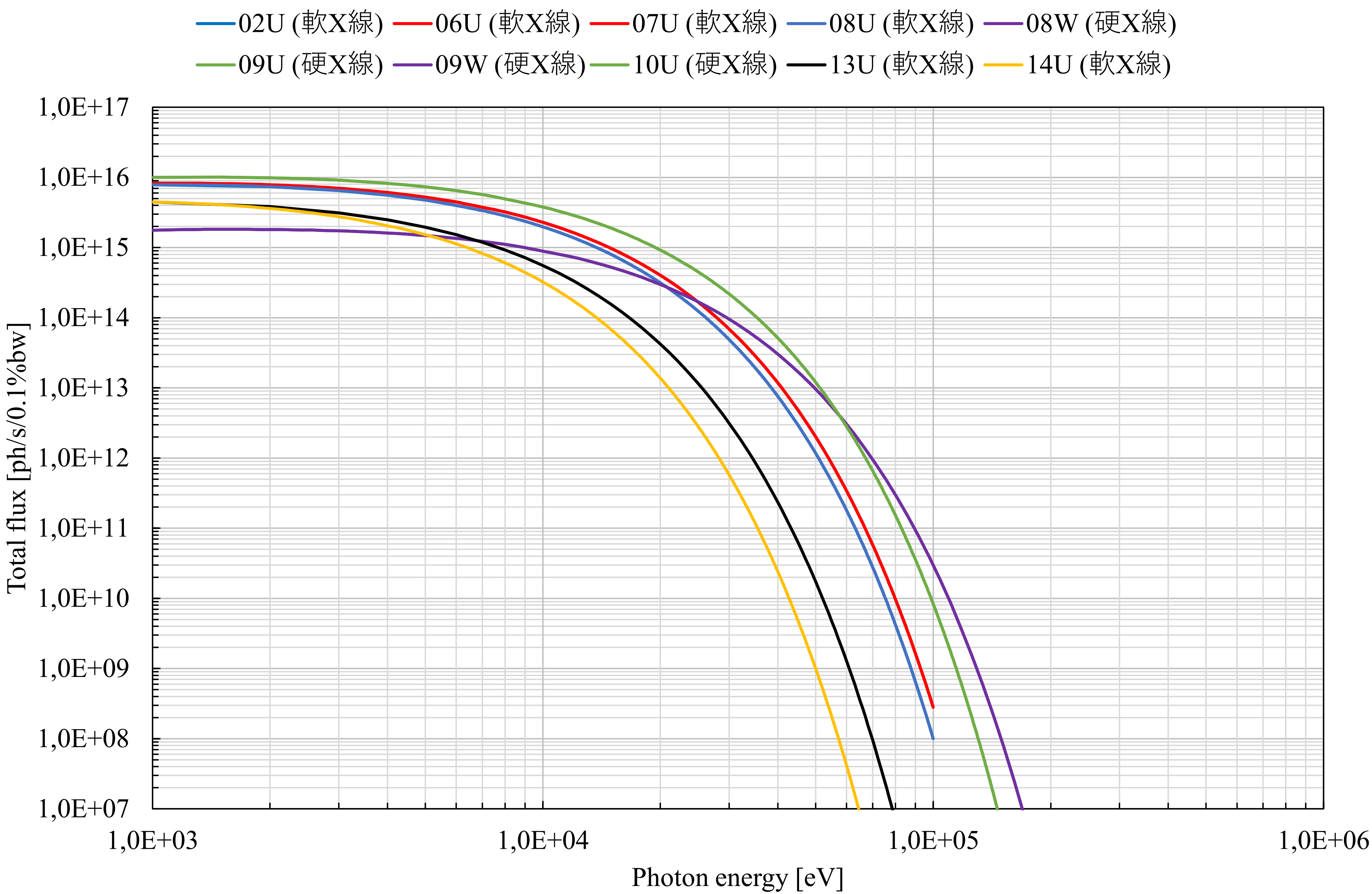
1.3 mSv/3M

Evaluation Time

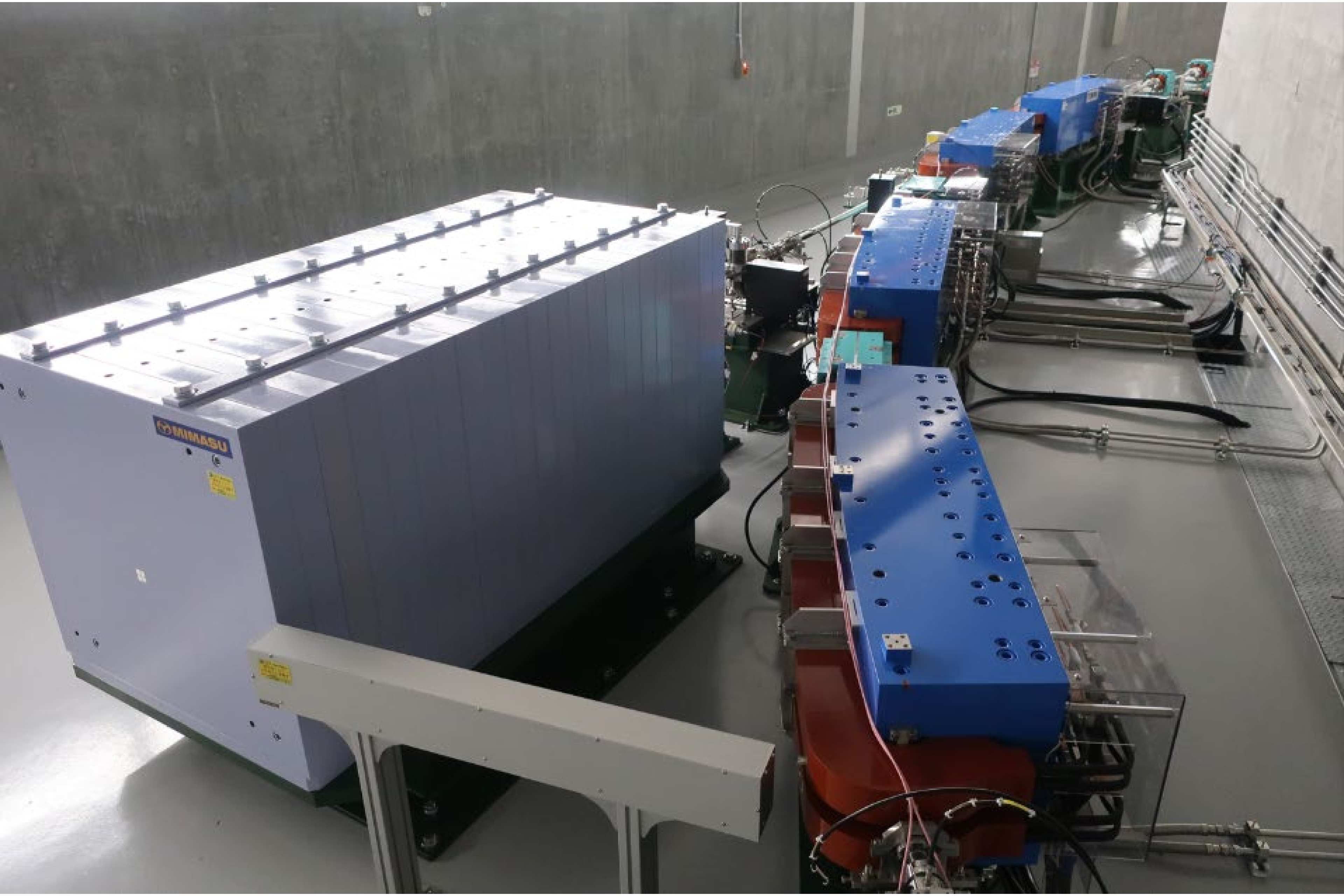
$$8\ \text{h/d} \times 5\text{d/w} \times 13\text{w/3M} = 520\ \text{h/3M}$$

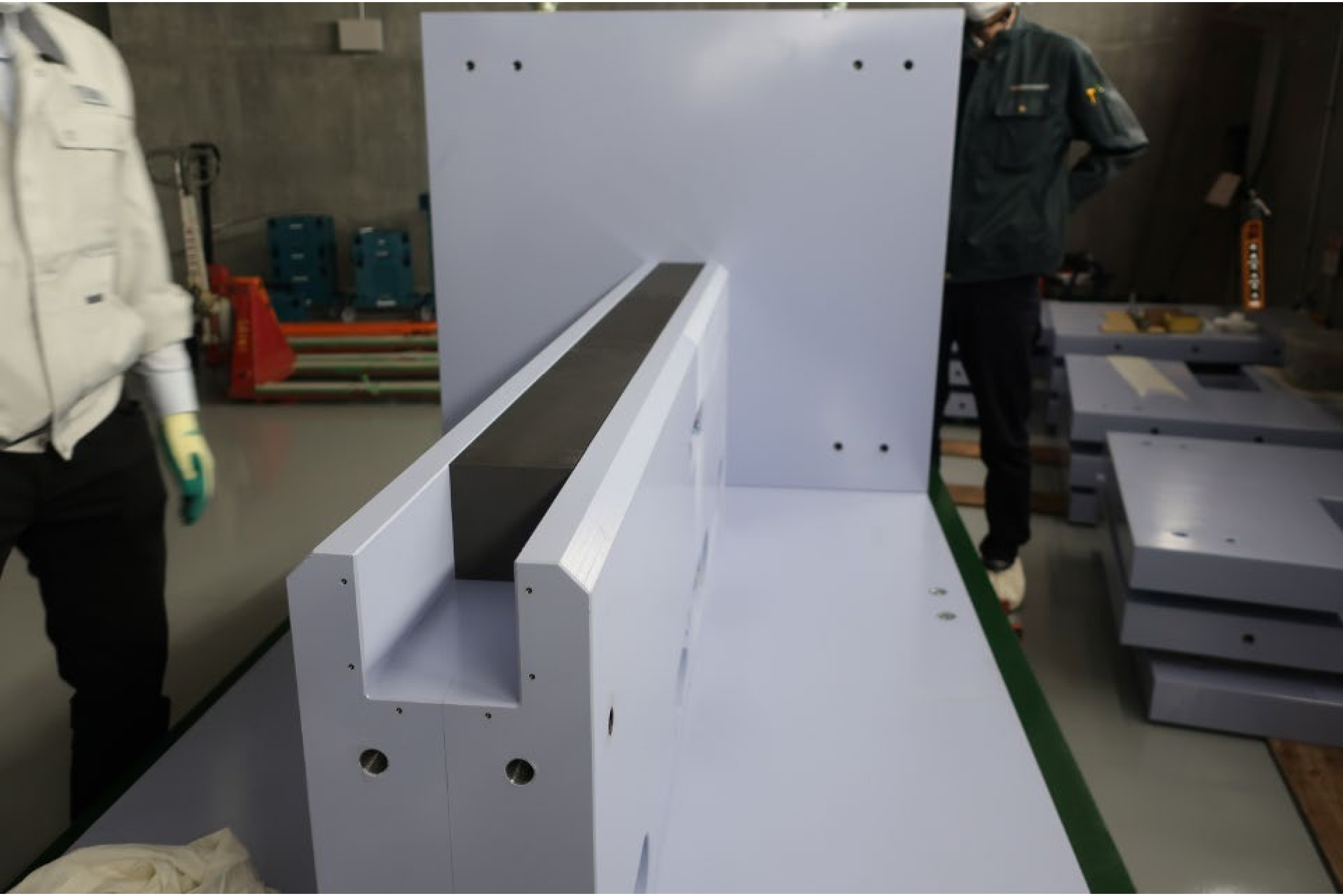
⬇

$$\frac{1.3\ \text{mSv/3M}}{520\ \text{h/3M}} = 2.5\ \mu\text{Sv/h}$$



02U (軟X線)
06U (軟X線)
07U (軟X線)
08U (軟X線)
08W (硬X線)
09U (硬X線)
09W (硬X線)
10U (硬X線)
13U (軟X線)
14U (軟X線)
Total flux [ph/s/0.1%bw]
1,0E+17
1,0E+16
1,0E+15
1,0E+14
1,0E+13
1,0E+12
1,0E+11
1,0E+10
1,0E+09
1,0E+08
1,0E+07
1,0E+03
1,0E+04
1,0E+05
1,0E+06
Photon energy [eV]


MIMASU

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