Shielding design for NanoTerasu: gas-bremsstrahlung and induced radiations

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30/05/2023
Radsynch23
1. NanoTerasu
   a. Synchrotron Radiation Facilities in Japan
   b. Introduction
   c. Location and Access
   d. Overview
   e. Project status

2. Shielding design
   a. Radiation-controlled area
   b. Beam loss
   c. Calculation method
   d. Shielding structure
   e. Dose calculation and measurements

3. Summary
1-a : Synchrotron Radiation Facilities in Japan

SACLA (2012) 8 GeV
SPring-8 (1997) 8 GeV
New SUBARU (2000) 1.5 GeV
Rits SR (1999) 0.575 GeV
HiSOR (1997) 0.7 GeV
SAGA-LS (2006) 1.4 GeV
AichiSR (2013) 1.2 GeV
UVSOR (1984) 0.75 GeV
PF (1983) 2.5 GeV
PF-AR (1987) 6.5 GeV
NanoTerasu (2024) 3.0 GeV

(Operation start)
1-b: Introduction

Origin of the facility’s name

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 “Amaterasu”

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

Maps Data: Google, ©2020 CNES / Airbus, Maxar Technologies, Planet.com
This project was started in 2019 and scheduled to operate in 2024. At the beginning 10 beamlines will be operating.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>1.14 nm.rad</td>
</tr>
<tr>
<td>Stored current</td>
<td>400 mA</td>
</tr>
<tr>
<td>Max (Beginning). number of undulators</td>
<td>14 (8)</td>
</tr>
<tr>
<td>Max (Beginning). number of multi-pole wigglers</td>
<td>14 (2)</td>
</tr>
</tbody>
</table>

https://www.nanoterasu.jp/nanoterasu_online_poster4/index-eng.html
1-d : Linac

Electron gun

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

Beam dump (Steel)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Injector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy E (GeV)</td>
<td>3</td>
</tr>
<tr>
<td>Normalized emittance (µmrad)</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Emittance at 3 GeV (nmrad)</td>
<td>&lt;1.7</td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
<td>0.3</td>
</tr>
<tr>
<td>Repetition rate (Normal) (Hz)</td>
<td>1</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>item</th>
<th>2019&lt;sub&gt;FY&lt;/sub&gt;</th>
<th>2020&lt;sub&gt;FY&lt;/sub&gt;</th>
<th>2021&lt;sub&gt;FY&lt;/sub&gt;</th>
<th>2022&lt;sub&gt;FY&lt;/sub&gt;</th>
<th>2023&lt;sub&gt;FY&lt;/sub&gt;</th>
<th>2024&lt;sub&gt;FY&lt;/sub&gt;</th>
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<tbody>
<tr>
<td>Building</td>
<td>Constructing</td>
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<td></td>
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<tr>
<td>Linac</td>
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<tr>
<td>Storage Ring</td>
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<tr>
<td>Beam lines</td>
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<tr>
<td>authorization</td>
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<td>Submission of</td>
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<td>application</td>
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<td>(Document review)</td>
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<td>Leakage dose</td>
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<td>inspection</td>
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<tr>
<td></td>
<td>(Linac) (SR, BL)</td>
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</tbody>
</table>

- **2019<sup>FY</sup>**: Construction of Building
- **2020<sup>FY</sup>**: Installation of Linac
- **2021<sup>FY</sup>**: Installation of Storage Ring
- **2022<sup>FY</sup>**: Installation of Beam lines
- **2023<sup>FY</sup>**: Commissioning
- **2024<sup>FY</sup>**: User operation

**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

Experimental hall
Linac

Storage ring
Beamline

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

<table>
<thead>
<tr>
<th>Mean Time Between Failure</th>
<th>140 h/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual operation hours</td>
<td>6000 h</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Vacuum pressure</th>
<th>$10^{-7}$ Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored beam lifetime $\tau = (\tau_G^{-1} + \tau_T^{-1})^{-1}$</td>
<td>8.2 h</td>
</tr>
<tr>
<td>Gas scattering lifetime $\tau_G$</td>
<td>18 h</td>
</tr>
<tr>
<td>Touschek lifetime $\tau_T$</td>
<td>15 h (400 mA)</td>
</tr>
</tbody>
</table>
3-c : Shielding calculation method

Electron beam loss
Parameters: angle, beam loss power, distance, ...

Gas Bremsstrahlung
Parameters: residual gas pressure, composition, length of straight section, ...

Secondary photon
Parameters: angle, distance, ...

Photoneutron
Parameters: target material, distance, ...

Synchrotron radiation
Parameters: magnetic field strength, Periodic length, Number of Regular periods, ...

Most of the residual gas components in the storage ring are $\text{H}_2$

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

3-d : Shielding structure

Electron Beam loss

Shielding wall

Beam dump

Concrete : 1 m thick

Steel : 0.5 m thick
3-d : Shielding structure

**Gas Bremsstrahlung (inside tunnel)**

Beam Shutter

- Tungsten alloy : 30 cm thick
- Lead : 10 cm thick
- 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

Synchrotron

Wall

Gamma stopper1

Gamma stopper2
3-e: Dose calculation and measurements

**Beam dump**

PHITS ver.3.24

**Neutrons dose**

- Outside the shielding (Controlled area)

**Photons dose**

- PHITS: 7.5 uSv/h
- Measurement: 6.5 uSv/h
3-e: Dose calculation

Gas Bremsstrahlung (inside tunnel)

PHITS ver.3.24

Inside the shielding

Concrete wall

Outside the shielding
(General area)

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

<table>
<thead>
<tr>
<th>Neutrons dose</th>
<th>Photons dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside the shielding (General area)</td>
<td></td>
</tr>
</tbody>
</table>

Lead : 1 cm thick

**PHITS**  

< 0.5 uSv/h

Lead : 30 cm thick  
Lead : 10 cm thick
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!

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.

<table>
<thead>
<tr>
<th>BL</th>
<th>ID</th>
<th>( \lambda_w ) (mm)</th>
<th>( N_w )</th>
</tr>
</thead>
<tbody>
<tr>
<td>02U</td>
<td>APPLE-II</td>
<td>56</td>
<td>71</td>
</tr>
<tr>
<td>07U</td>
<td>APPLE-II</td>
<td>75</td>
<td>53</td>
</tr>
<tr>
<td>06U</td>
<td>APPLE-II</td>
<td>56</td>
<td>11 x 4</td>
</tr>
<tr>
<td>08U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13U</td>
<td>4 Seg. APPLE-II</td>
<td>56</td>
<td>11 x 4</td>
</tr>
</tbody>
</table>

- Brilliance \( \sim 10^{21} \) 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

Optics of 4BA lattice

<table>
<thead>
<tr>
<th>Ring parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural emittance</td>
<td>1.14 nm.rad</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.084 %</td>
</tr>
<tr>
<td>Betatron tune $(ν_x, ν_y)$</td>
<td>(28.17, 9.23)</td>
</tr>
<tr>
<td>Natural chromaticity $(ξ_x, ξ_y)$</td>
<td>(-60.50, -40.99)</td>
</tr>
<tr>
<td>Damping partition number $(J_x, J_y, J_z)$</td>
<td>(1.389, 1.0, 1.611)</td>
</tr>
<tr>
<td>RF accelerating frequency</td>
<td>508.759 MHz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>592</td>
</tr>
<tr>
<td>Natural bunch length</td>
<td>2.92 mm (9.74 ps)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Max. fields</th>
<th>#/cell</th>
<th>#/ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Q combined</td>
<td>0.87 T -7.1 T/m</td>
<td>4</td>
<td>64</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>49 T/m</td>
<td>10</td>
<td>160</td>
</tr>
<tr>
<td>Sextupole</td>
<td>1540 T/m²</td>
<td>10</td>
<td>160</td>
</tr>
</tbody>
</table>

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

- 4B, 10Q, 10S on 6 girders
- B-Q combined (massive steel)
- Quadrupoles (laminated steel)
- L = 1130
- L = 200
- L = 200
- L = 254
- L = 350
SR: Magnet

Concept

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

- 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:
< ±0.2 % (B)
< ±0.4 % (Q, S)
2-1. SR: Vacuum

Goal: 20h of gas scattering lifetime for 400 mA current requiring \(1 \times 10^{-7}\) 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

- Stainless 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 $1 \times 10^{-7}$ 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

- Only 4 types (1 AB, 2 CR, 1 SAB) for low cost and easy maintenance
- Max. SR peak power density of ~200 W/mm²
- Average pressure is $6 \times 10^{-8}$ 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

<table>
<thead>
<tr>
<th>Task</th>
<th>Constructor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Accelerator</td>
<td>Government</td>
</tr>
<tr>
<td>Beam Lines</td>
<td>Government: 3 BLs</td>
</tr>
<tr>
<td></td>
<td>Partners: 7 BLs</td>
</tr>
<tr>
<td>Building</td>
<td>Partners</td>
</tr>
<tr>
<td>Land forming</td>
<td></td>
</tr>
</tbody>
</table>

Total budget
270 million USD
Limitations of Japanese Law

public dose limit

1.3 mSv/3M

Evaluation Time

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

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