Spallation Neutron Source

Japan Atomic Energy Agency (JAEA)

J-PARC

Shin-ichiro Meigo

Outlook of talk

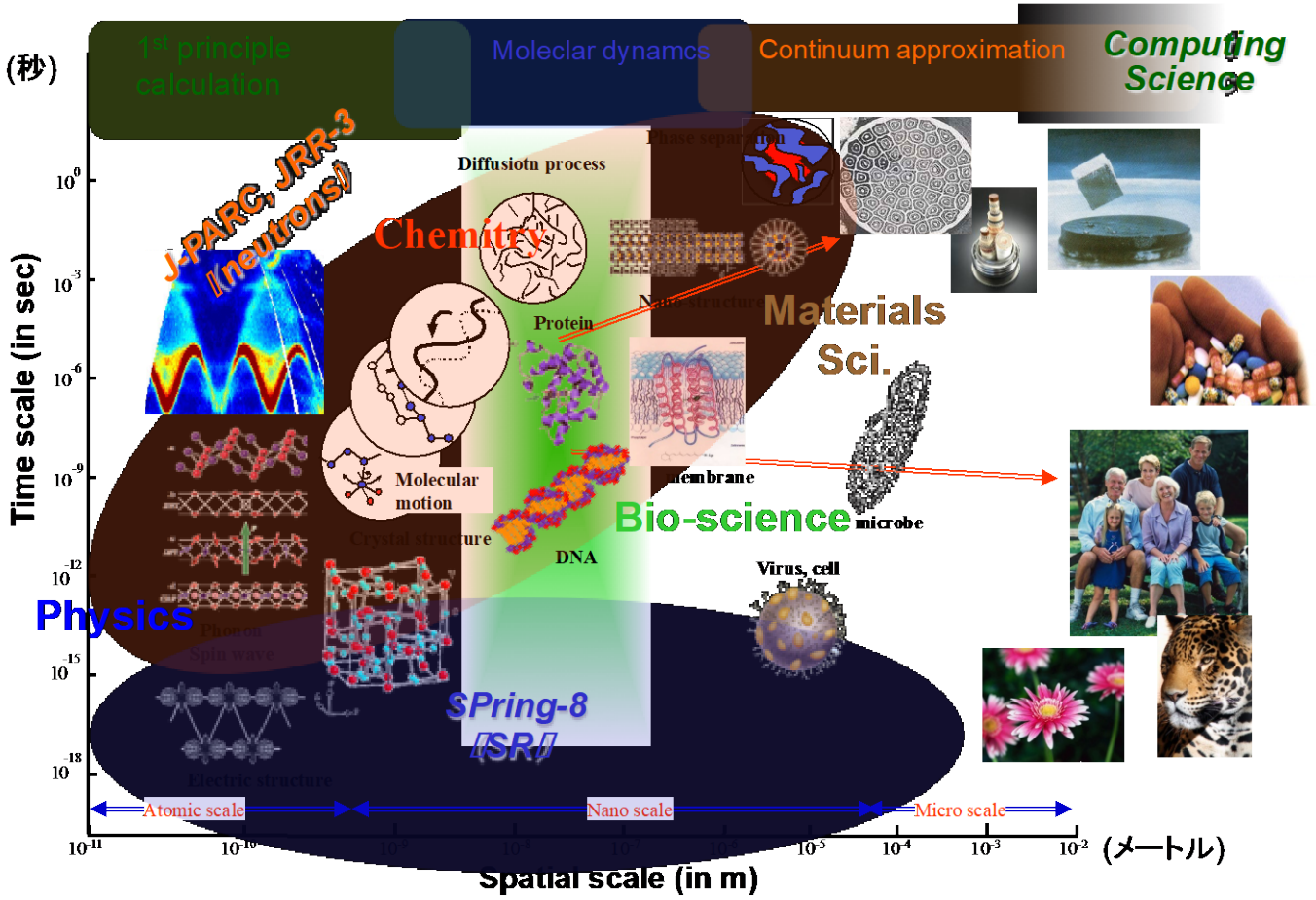
- Introduction
  - J-PARC
  - Spallation reaction
- Spallation neutron source
  - Present and issues
- Beam delivery to target
  - Beam flattening using non-linear beam optics
- Future plan at J-PARC as neutron source
- Accelerator Driven System (ADS)
- Summary



J-PARC = Japan Proton Accelerator Research Complex

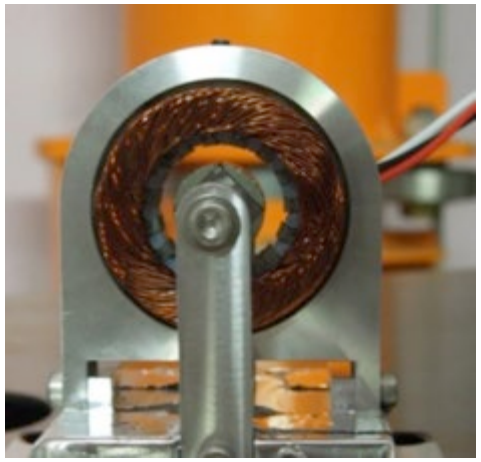
Neutron and muon

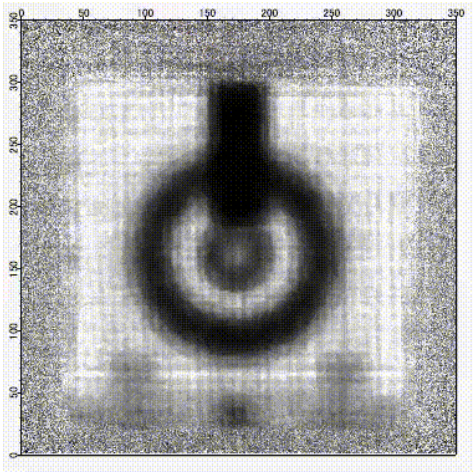
- Neutron and muon
  - Good probe, especially for materials and life sciences
- Neutron
  - Best probe for hydrogen and magnetic fields.
- Muon
  - Similar but slightly different characteristics from electrons
- High requirements of science using high-intensity neutrons
  - Using time-of-flight, wavelength, or energy can be chosen.
  - Pulsed neutron source is better choice.

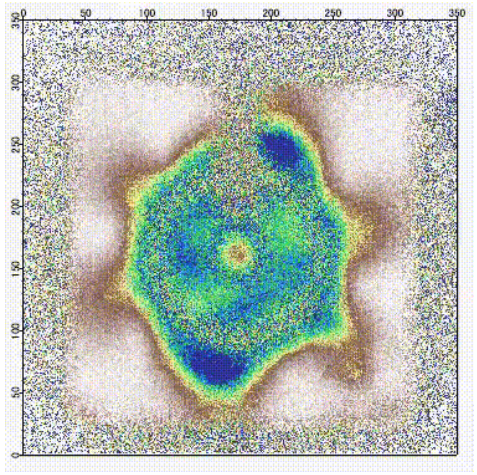


Magnetic Imaging at J-PARC

- **Not only DC Field but also AC Field can be observed.**





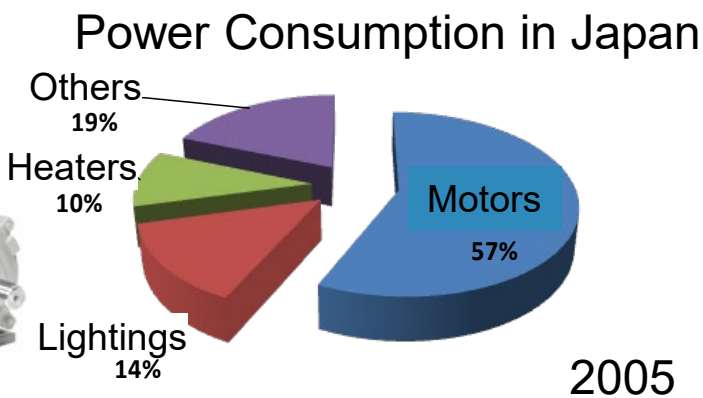


The world's 1st demonstration of visualizing magnetic field of a working motor.

Collaboration with Hitachi Ltd. HITACHI Inspire the Next

Results are used to improve simulation technology to design higher performance motors.





Motors consume more than 50% of total electric power in Japan

Supported by Photon and Quantum Basic Research Coordinated Development Program by MEXT (2013-2018)

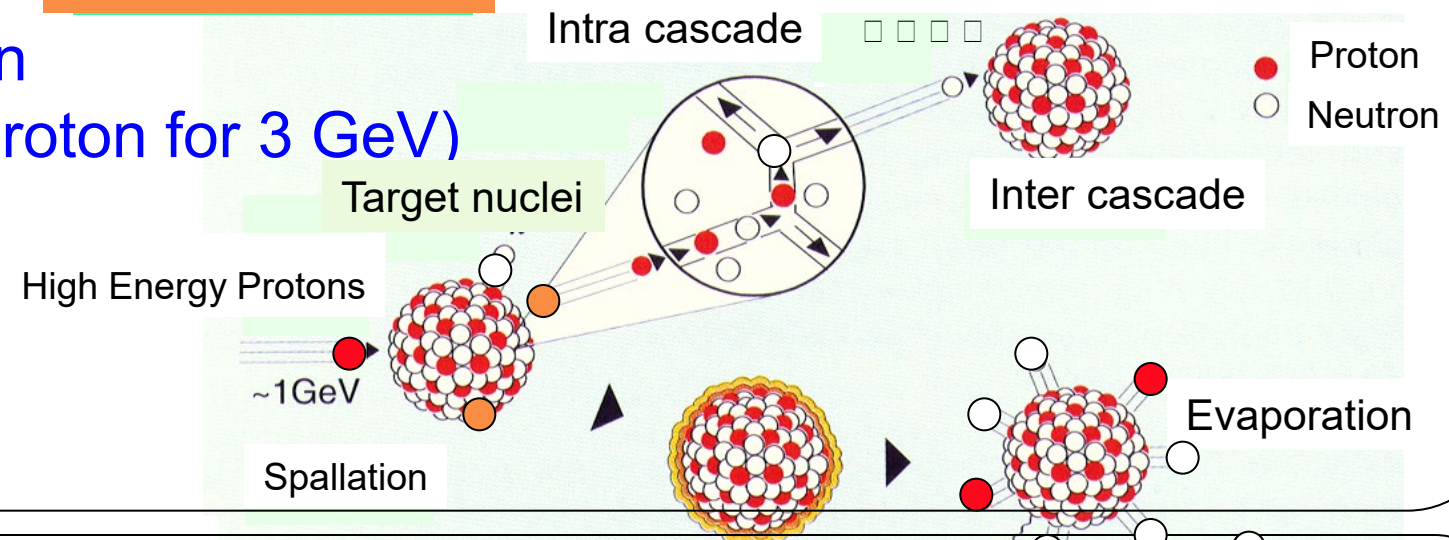
Neutron production

Spallation: Very effective for neutron production (Neutrons ∝ Proton beam power)

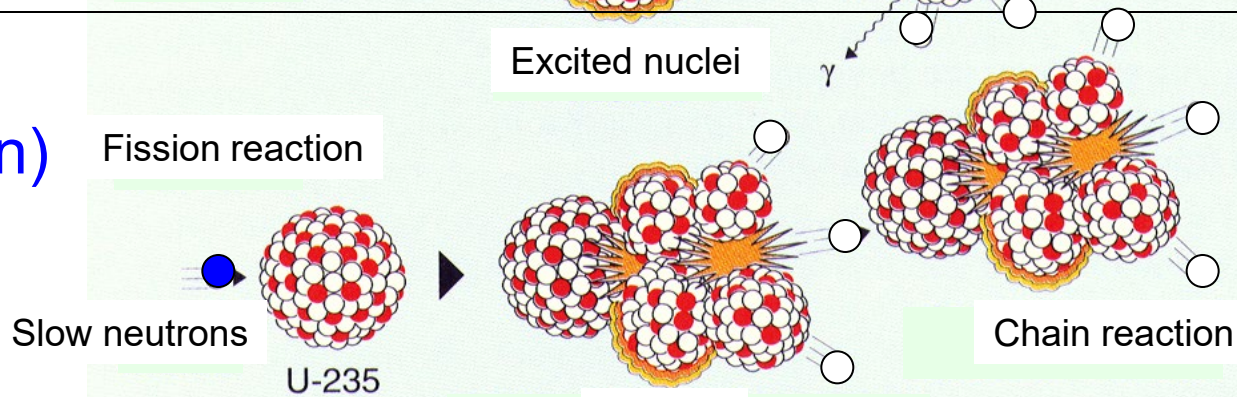
- Number of neutron productions: Spallation source1 MW ~ Reactor 15 MW
- Less heat production than fission

Neutron Production

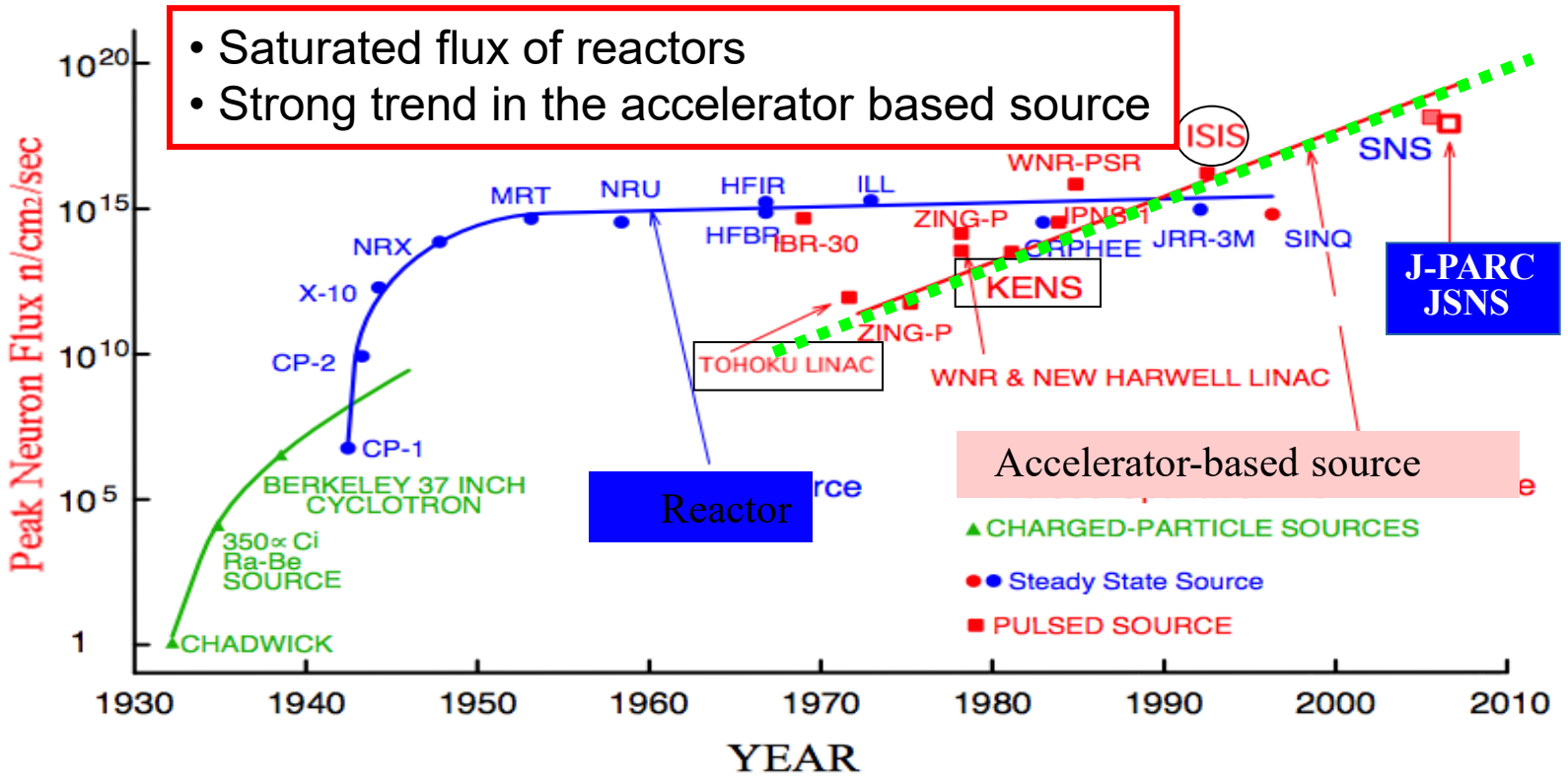
Spallation (~40 n/proton for 3 GeV)



Fission (~2n/reaction)



Historical neutron intensity





Since 1984, 2nd Target Station in 2008



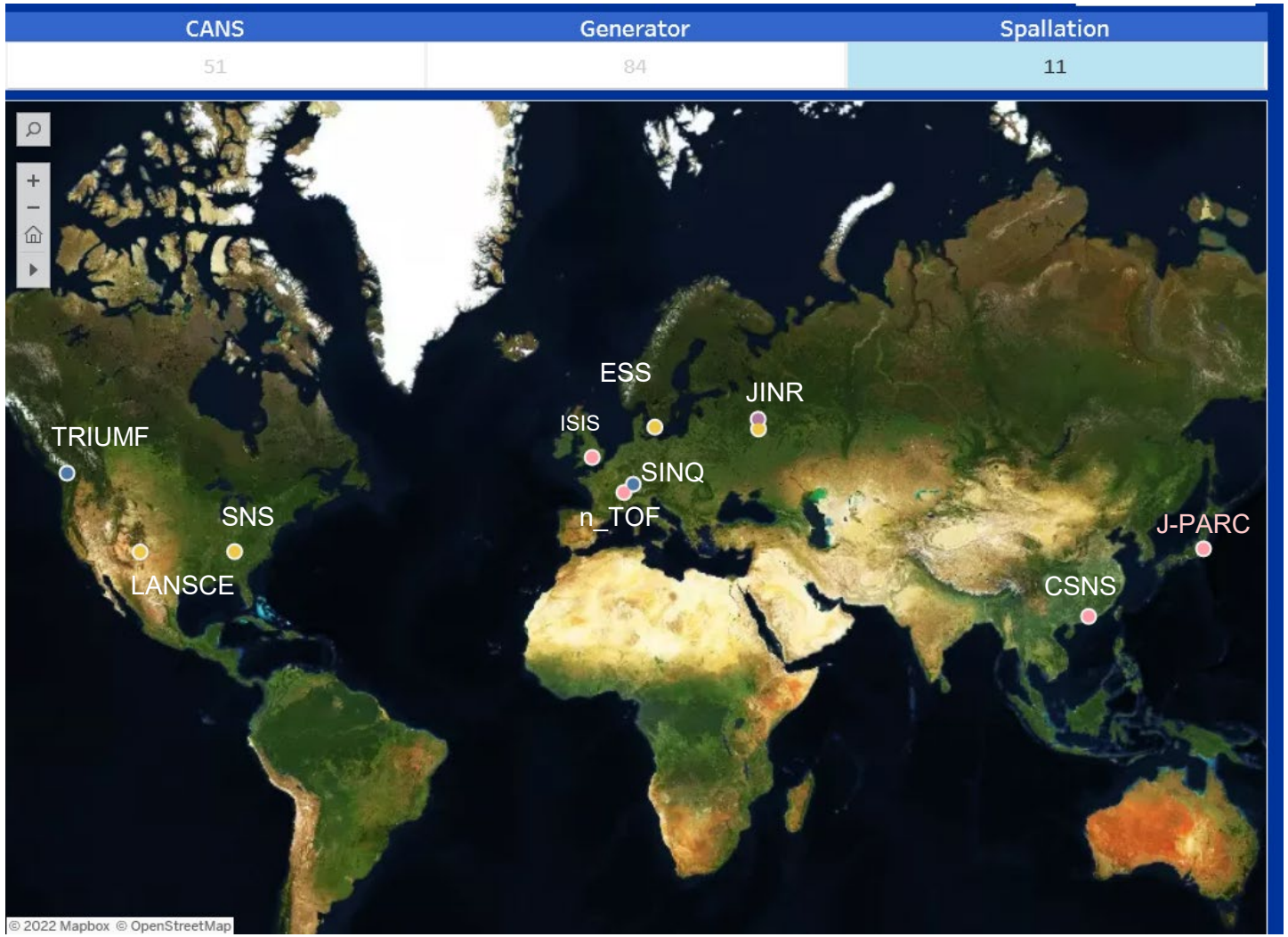
Operation since April, 2006

- CSNS 2017
  0.1MW, near Honkong
- ESS 2023
  5MW, Sweden

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Spallation neutron sources

11 facilities exist in the world

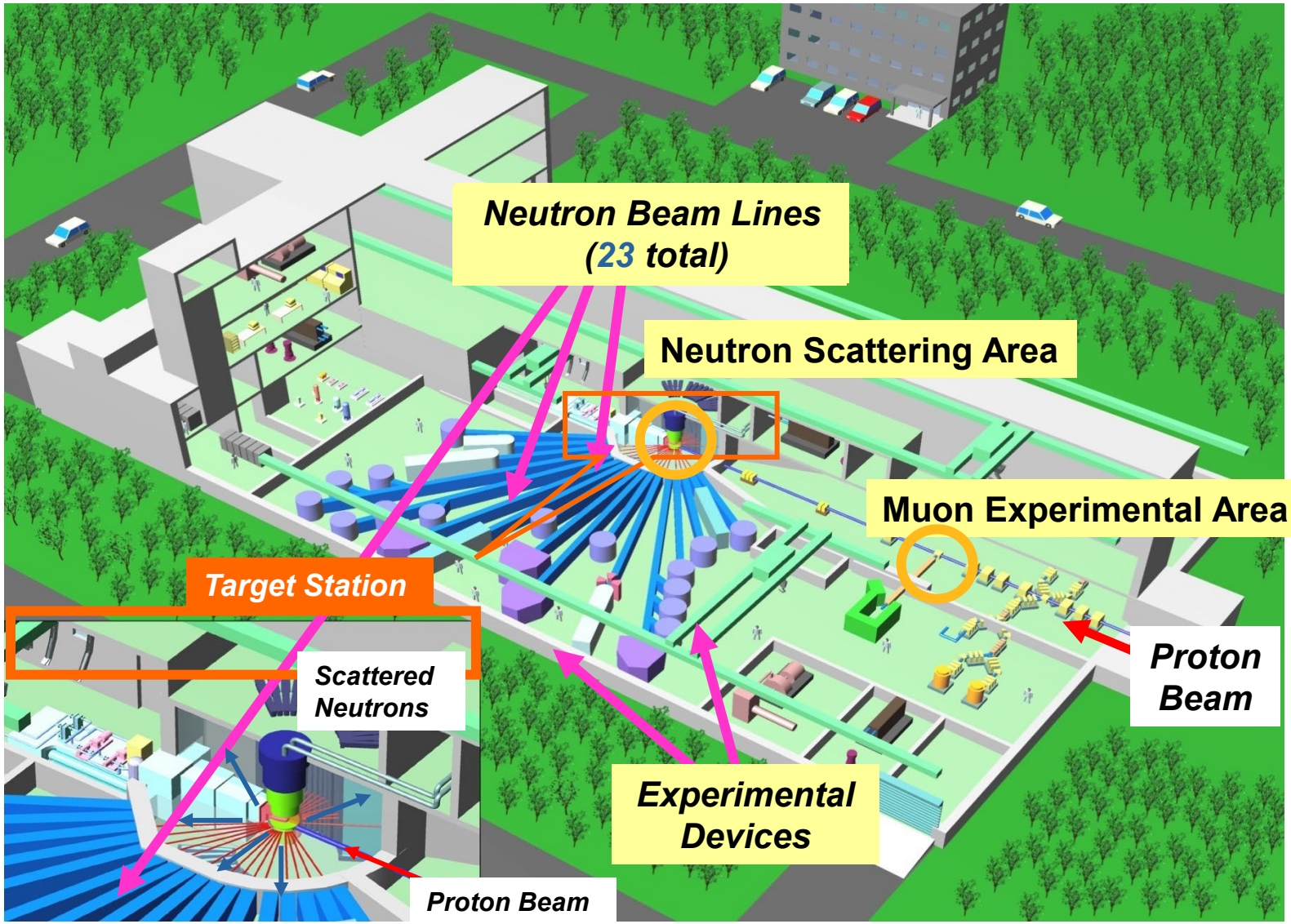


IAEA : https://nucleus.iaea.org/sites/accelerators/Pages/default.aspx

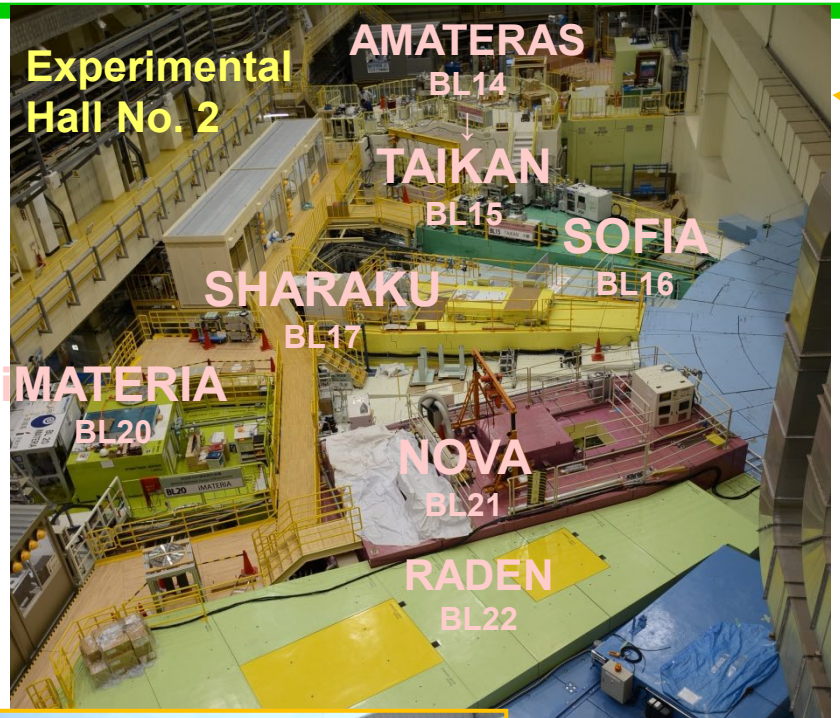
Categorized the spallation neutron source

Pulse width	Facilities	Accel.	Target	Ep [GeV]
Short pulse (< 1 us)	n_TOF at CERN LANSCE ISIS CSNS SNS MLF at J-PARC	LINAC LINAC+SR RCS RCS LINAC+SR RCS	Pb W W W Hg Hg	20 0.8 0.8 1.6 1 3
Long pulse	ESS	LINAC	W rotating	2
CW	RCNP at Osaka univ. TRIUMF SINQ at PSI	Cyclotron Cyclotron Cyclotron	W W Pb	0.4 0.5 0.6

Material and Life Science Experimental Facility (MLF)



Neutron instruments at MLF





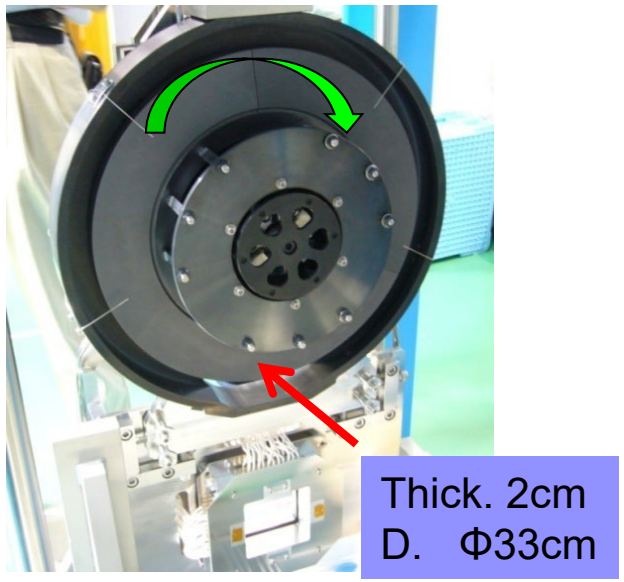


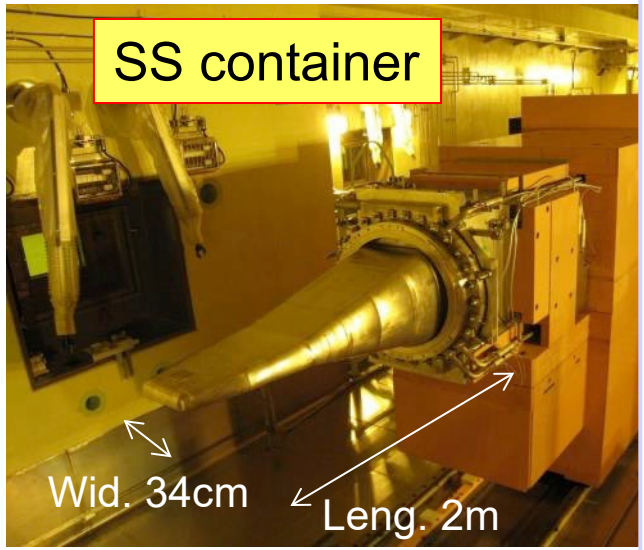




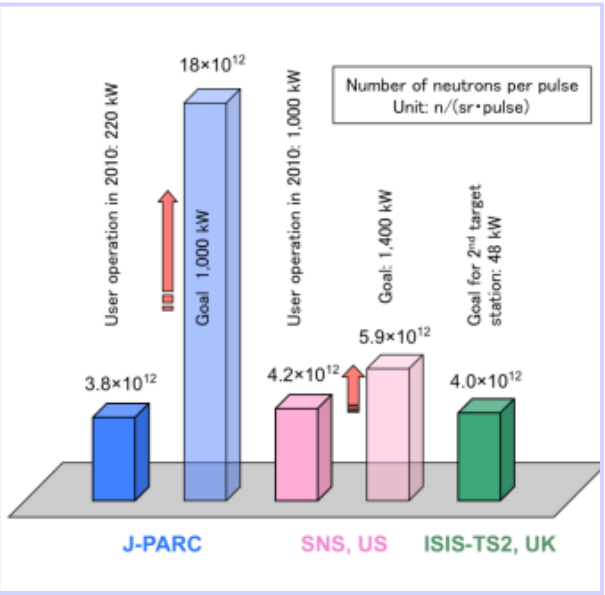
Production targets at MLF

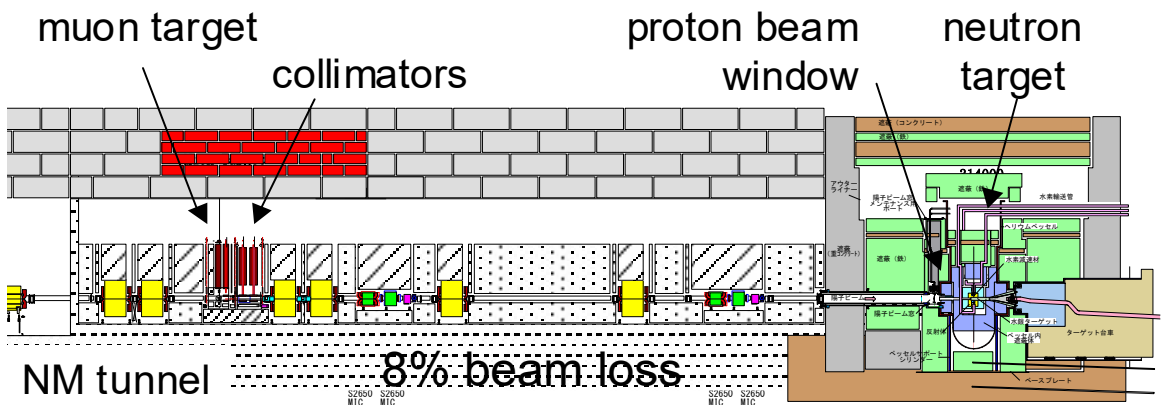
- Muon production target
  - Carbon graphite
  - Rotating (15 rpm)
- Neutron prod. target
  - Mercury

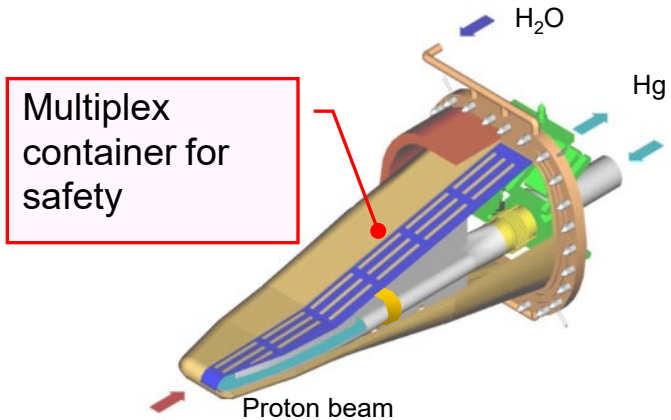




Highest-intensity pulse neutron







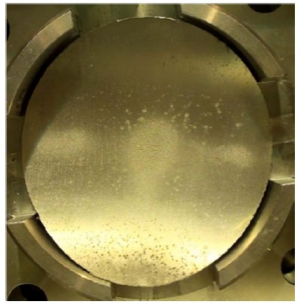
Mercury target for neutron production

- Why mercury is used as target？
  - Large neutron production due to the large mass number of the target nuclide
  - No cooling issues
    - Decay heat issue on tungsten target
    - Pb-Bi will be challengingly used at ADS.
  - Radioactive waste minimization
  - Discussion at the start of building of J-PARC
    - Hg or W
    - For future multi MW beam, we concluded to use Hg as target.
  - Hopefully, no issues. But we actually have minor issues, as explained later.

Issue on target

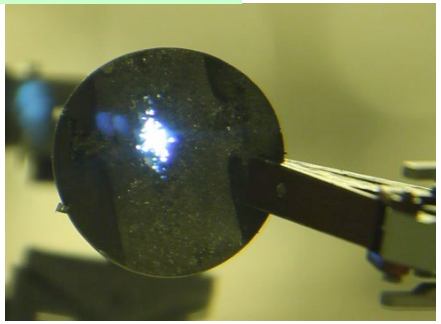
- Handling of high-intensity proton beam
  - Pitting damage proportional to 4th power of the peak current density at target (P4 Law)
    - Beam scanning and rastering do not help mitigation.
- J-PARC more challenging than SNS
  - SNS: 60Hz (23 kJ/shot), Storage ring without muon production target
  - MLF: 25Hz (40 kJ/shot), RCS with muon production target
- Reduce of peak current density at the target is essential.
- Beam flattening by the non-linear beam optics was developed.

Vessel window



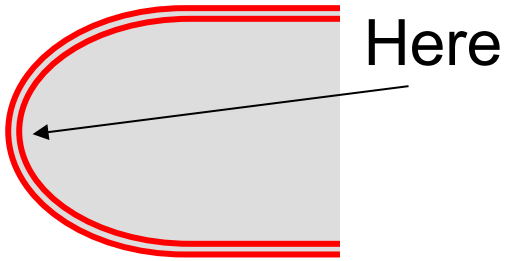
5 cm

Damage at JSNS target



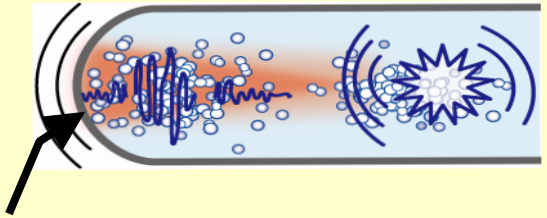
Completely holes appeared at SNS

After use of the target, the sample place where the hole saw made the inner wall.



Cavity erosion at target vessel

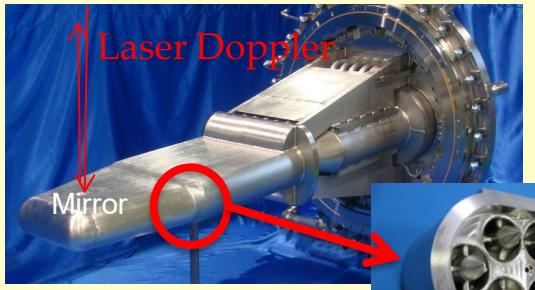
Mercury vessel

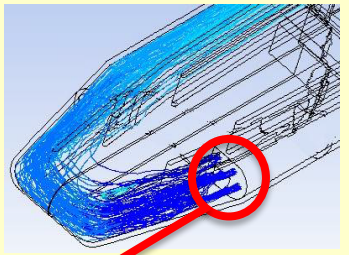


Beam window (2.5 mm-t)
Most vulnerable to cavitation damage

Damage∝ P^4

Vibration measurement with a
Laser Doppler Vibrometer(LDV)





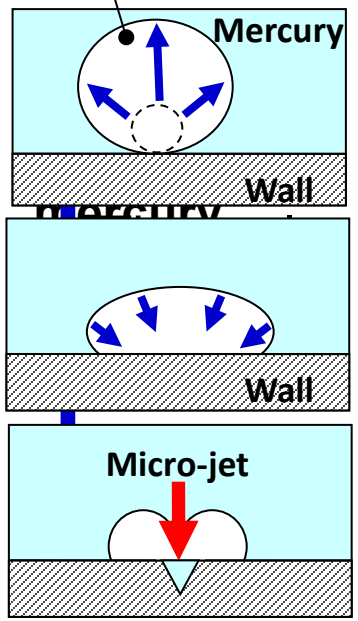


He-gas micro-bubbles
injecting into Hg target

Bubbling
distribution

Swirl type bubbler

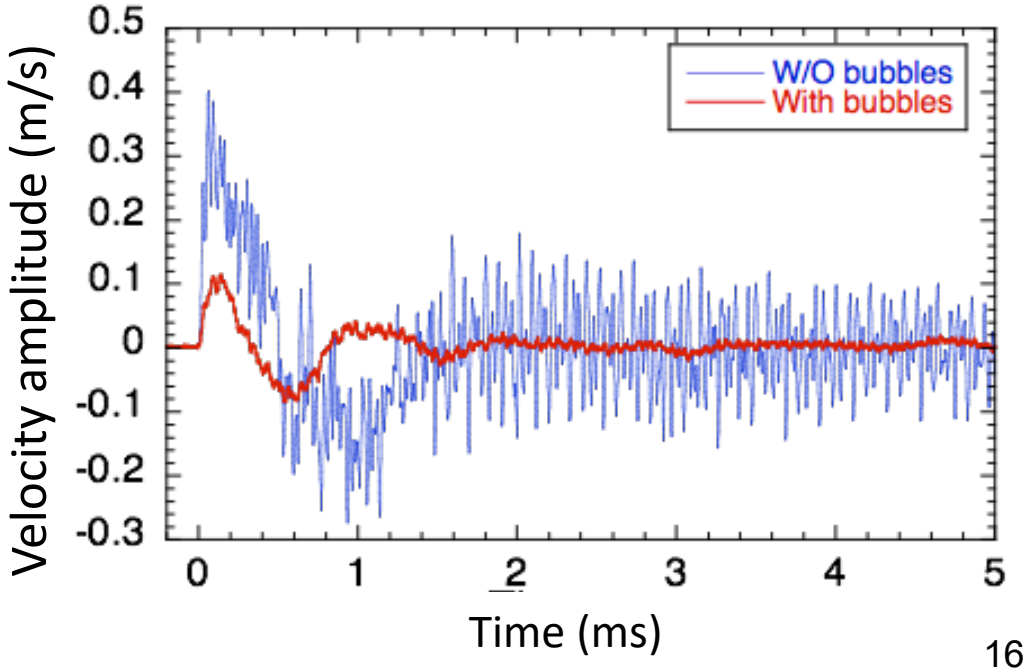
Cavitation bubble



Bubble inflates by the mercury negative pressure.

Cavitation bubble shrinks rapidly.

Shrink energy concentrates to one point



Target management

Operation Plan of Neutron Source

※R&D required target for 2 years use with 1 MW

FY	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Power (kW)	600	600	700	700~800	700~1000	700~1000	700~1000	700~1000		700~1000
Target #	#11	#10		#14	#13	#15	#16	#18		#19
Target Fabrication	#14	#15		#16	#17	#18				
Disassembl-able Target	Development and basic design									
	Design and Mockup tests for Remote handling devices and procedures									
Number of used targets	8	9	10	11	12	12	13	13	14	14

Fabrication period was extended to 3 years.

- Power will be decided based on the measured damage depth data and its prediction.
- Planning to extend the target lifetime to 2 years after getting prospect of stable and long-term operation with 1 MW.

Volume reduction of used target vessels is indispensable.

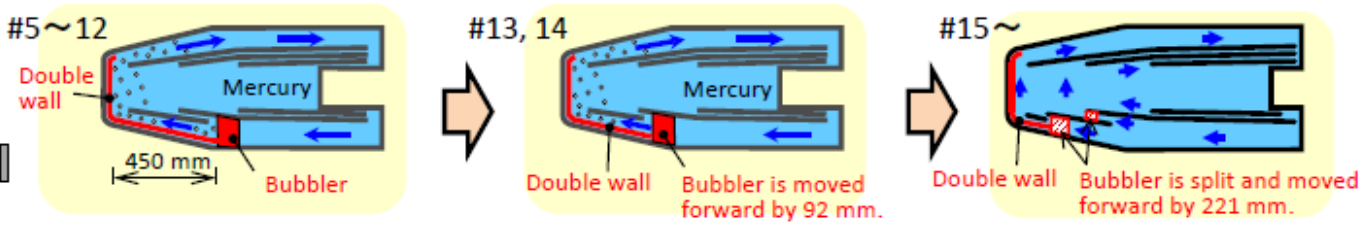
The total storage capacity in MLF & RAM is around 22 with present target design.

- RAM building will be full in 2034 if no measures are taken.
- Storage space should be saved by volume reduction and lifetime extension of the target vessels.
- The date of RAM building to be full can be extended more than 20 years if both of those two measures are taken.

Target improvement for pitting damage mitigation



#10 ~ : Constraint-free type

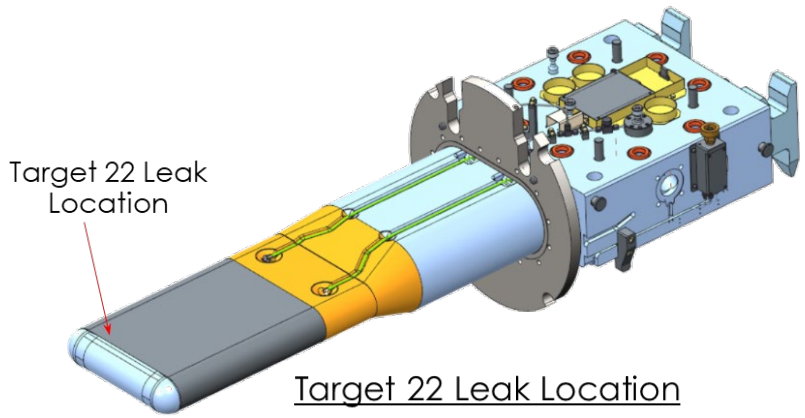


Other issues on the target

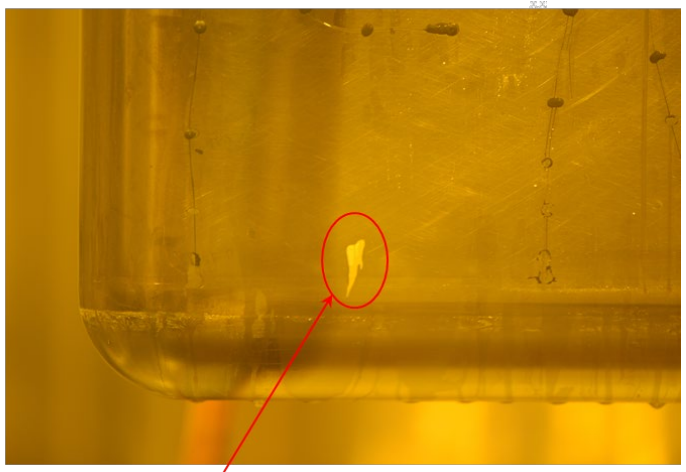
SNS (ORNL):

- Leak of mercury (N.B., Not happened at J-PARC, but water leakage occurred a lot.)

Target 22 Leak Location

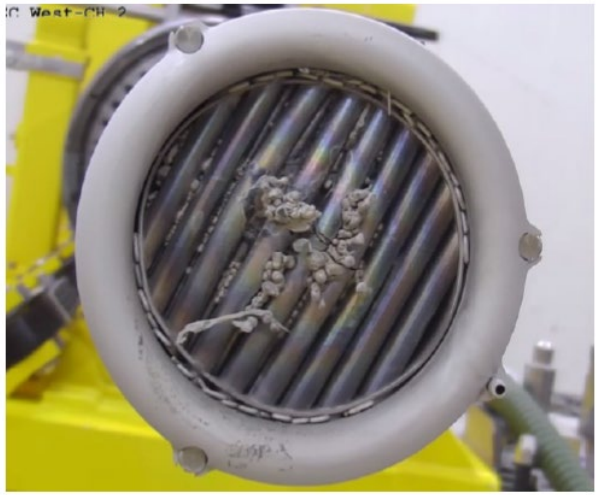


Target 22 Leak Location



SINQ (PSI):

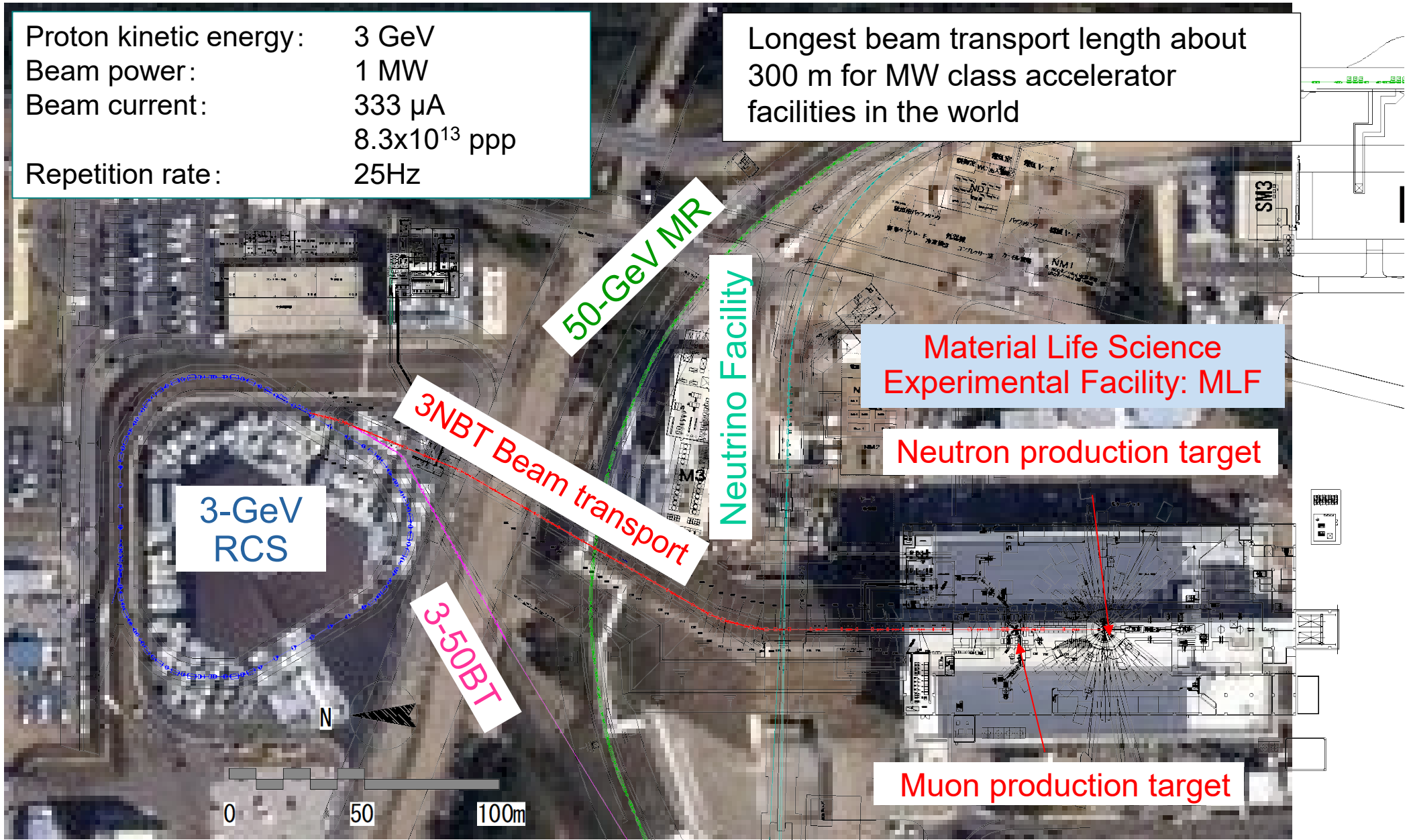
- Target blocks were melted due to over focused beam.





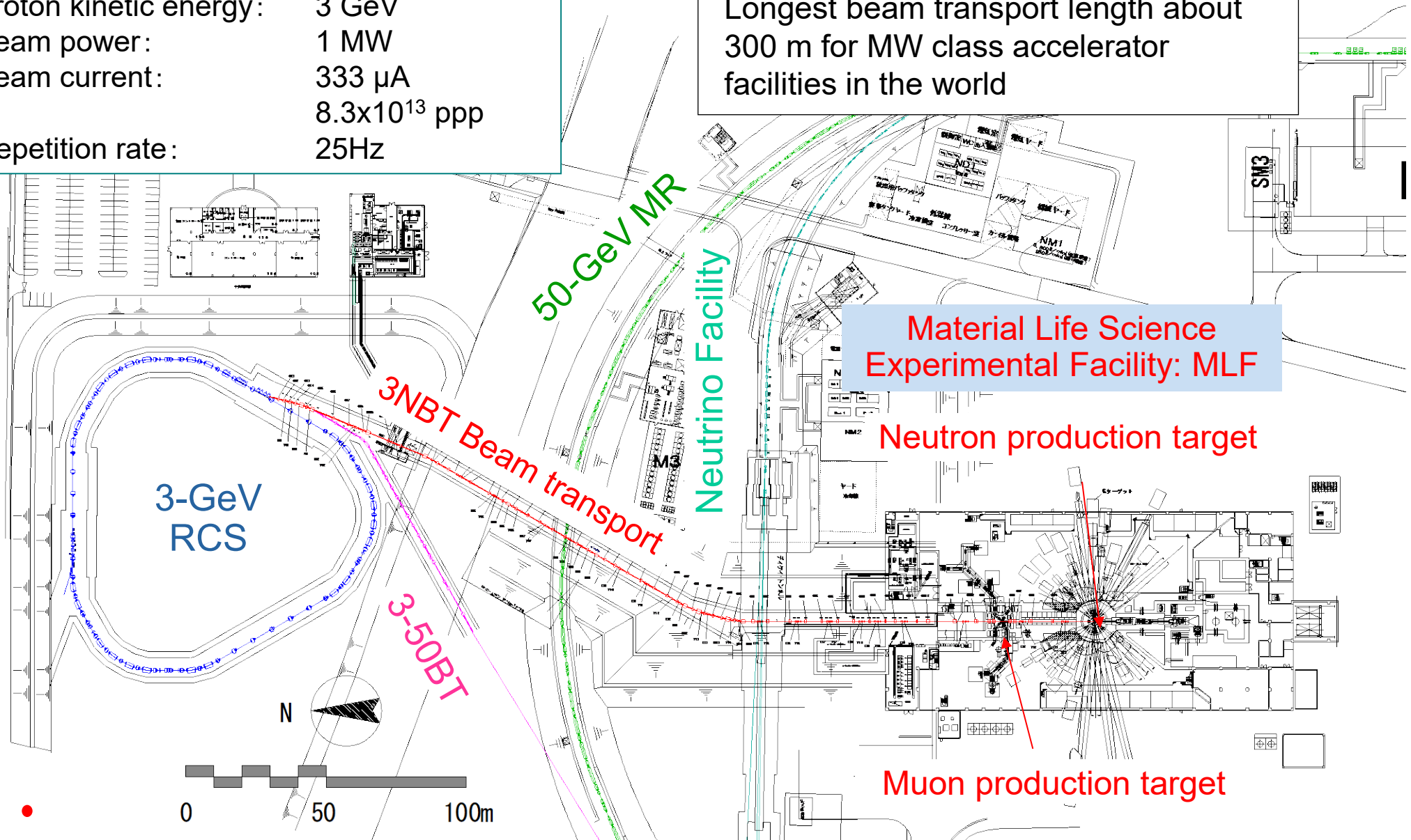
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Beam transport to MLF target



Proton kinetic energy:	3 GeV
Beam power:	1 MW
Beam current:	333 μA
	8.3×10^{13} ppp
Repetition rate:	25Hz

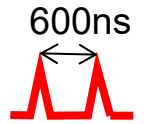
Longest beam transport length about 300 m for MW class accelerator facilities in the world

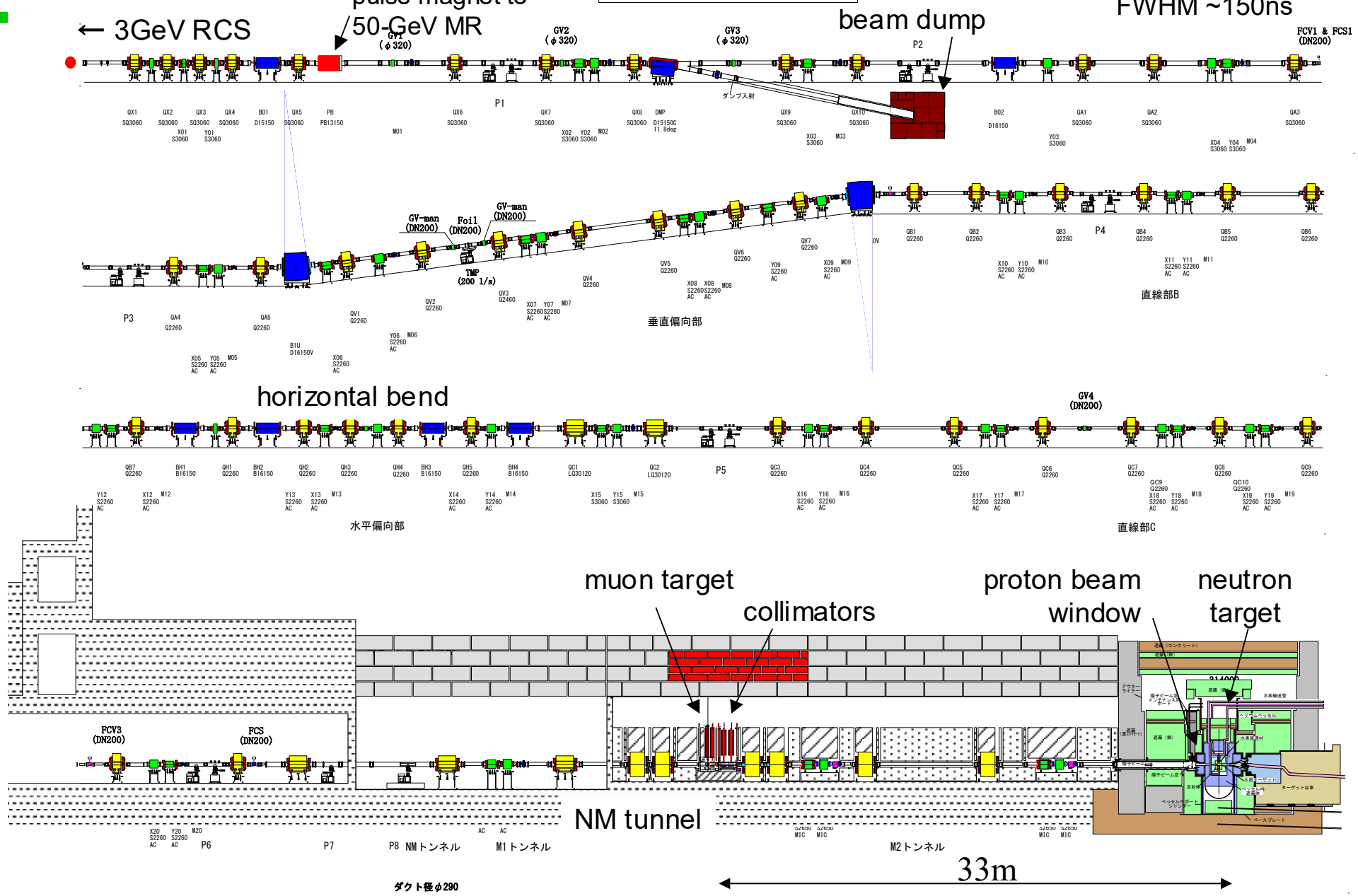


Length 314m

Bending: 9 p.
Quad: 54 p.
Ster. : 45 p.

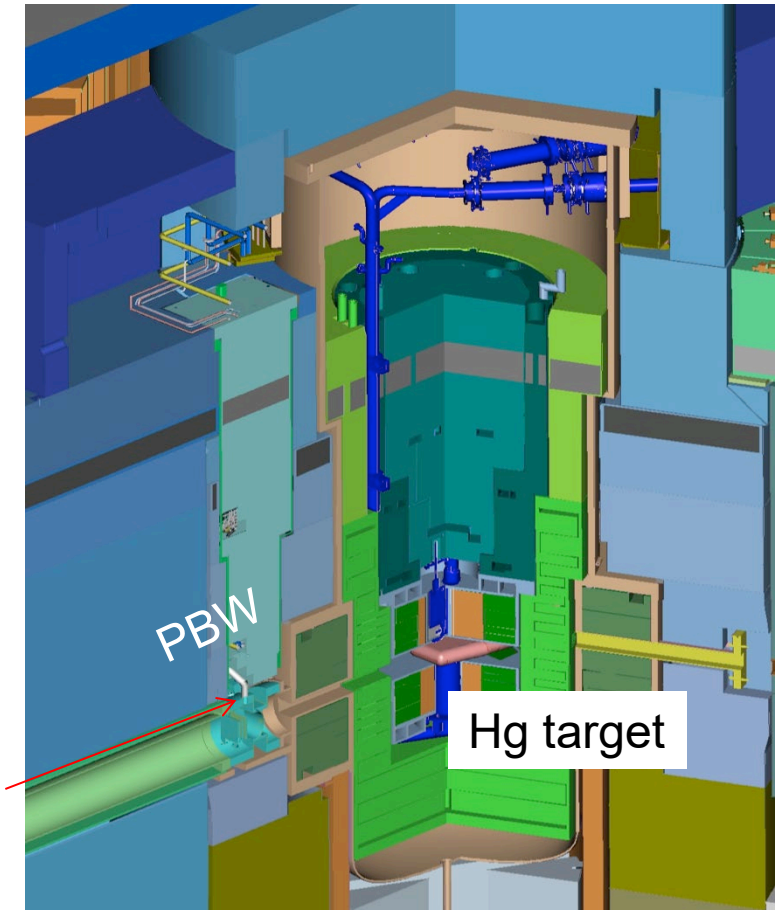
Pulse structure

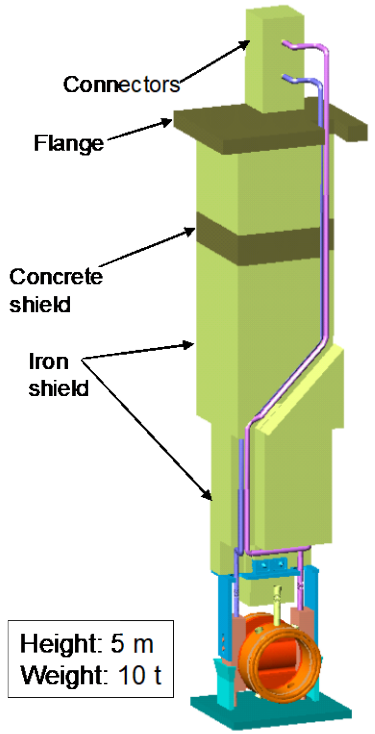


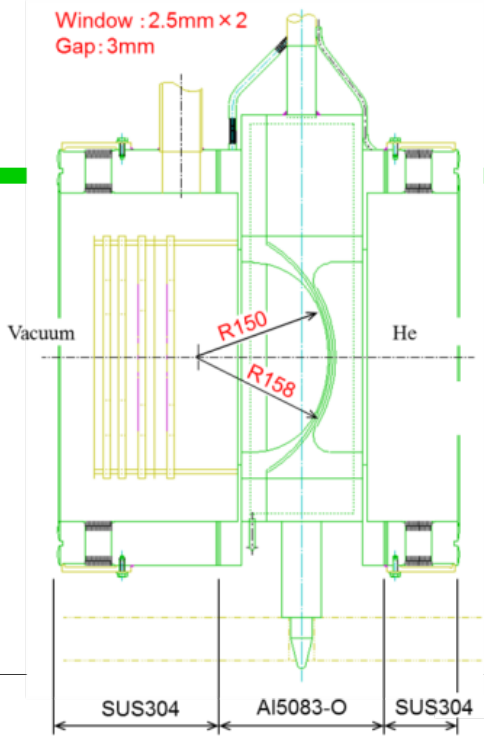


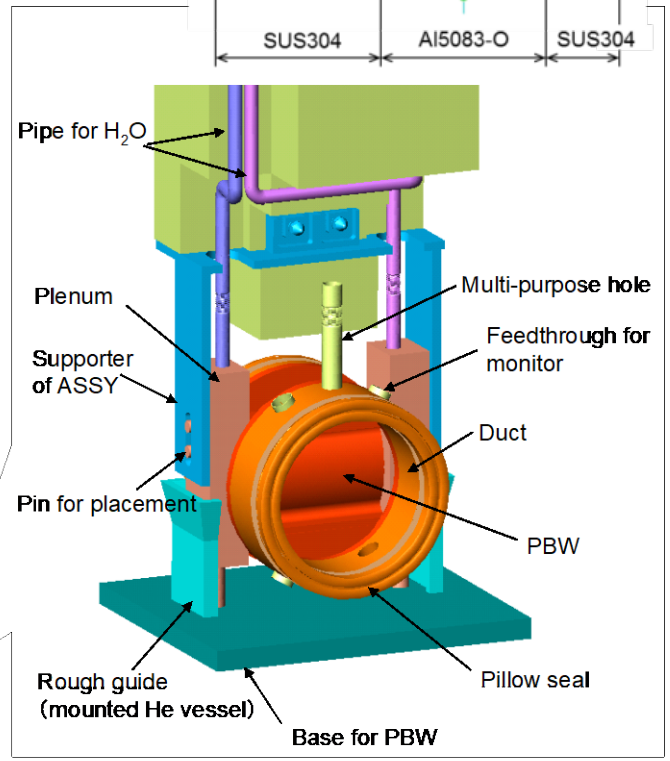
Proton beam window (PBW)

- Separation wall between vacuum and He filled area
  - Al alloy (A5083)　2.5 mm x 2 pieces
- Deploying beam monitors (Beam profile and halo)
- Lifetime：2 years (Estimated by SINQ)

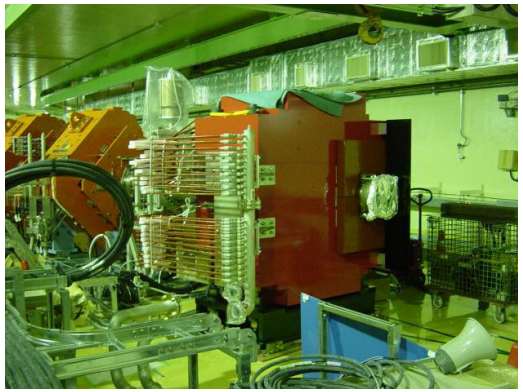








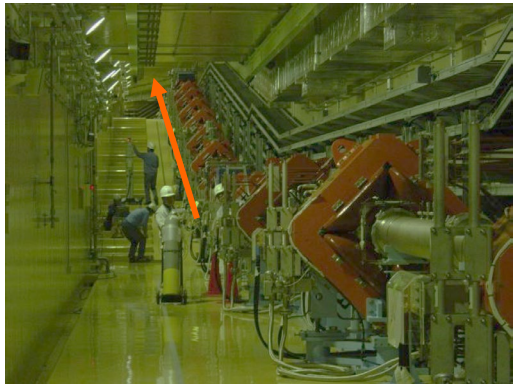
Inside beam tunnel



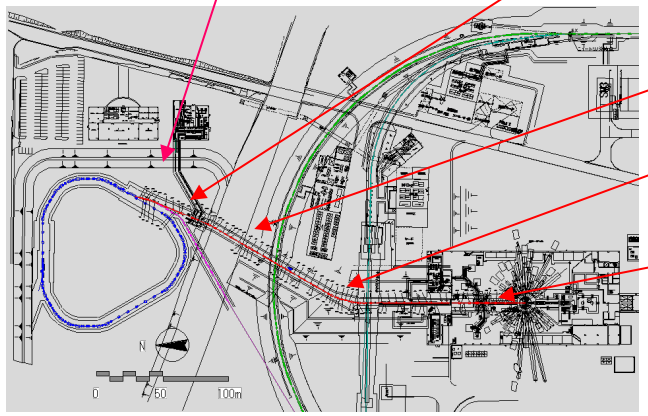
Ext-septum

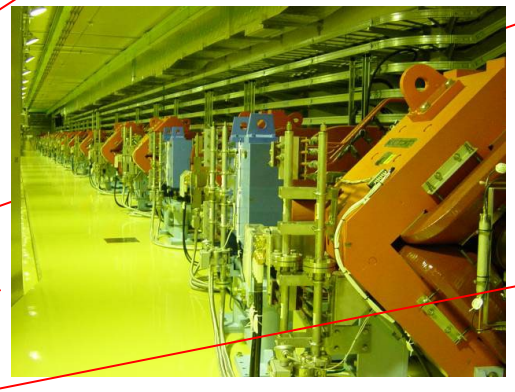


Ext and BT for MR

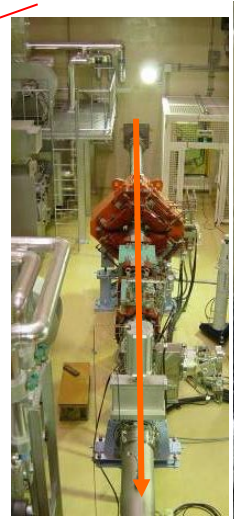


Vertical bend section

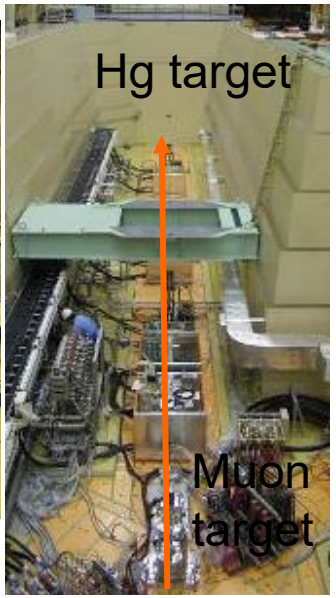




Horizontal bend section



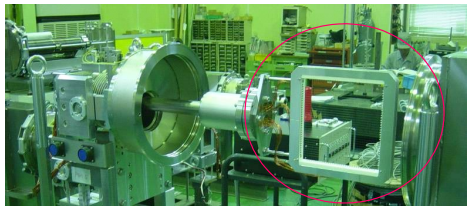
M1 section

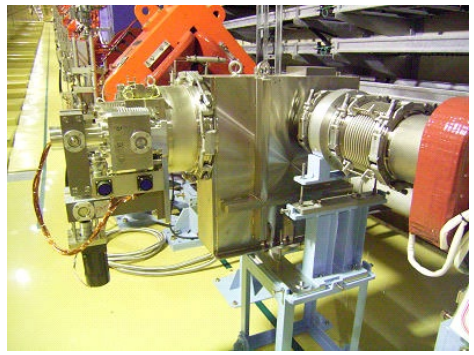


M2 section

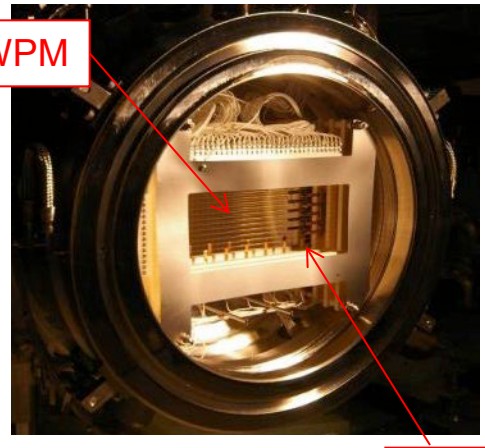
Beam diagnostic

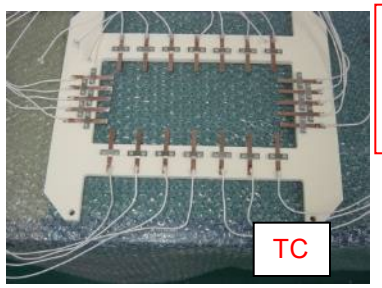
- Beam monitoring is essential for high-intensity beam operation.
- Beam profile and halo monitors (on-line)
  - Multi-Wire Profile Monitors (MWPMs) with Silicon Carbide (SiC) wires
- 2D image： Image of radiation activity observation in front of the target vessel by imaging plate (IP) after beam operation (off-line)





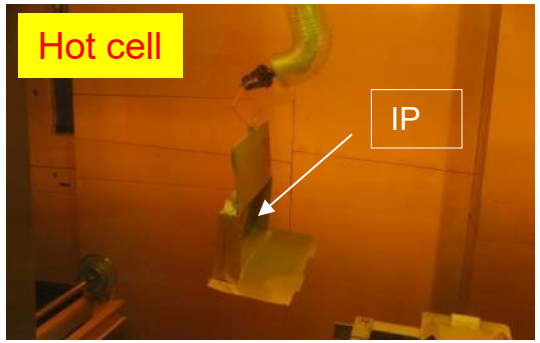
MWPM

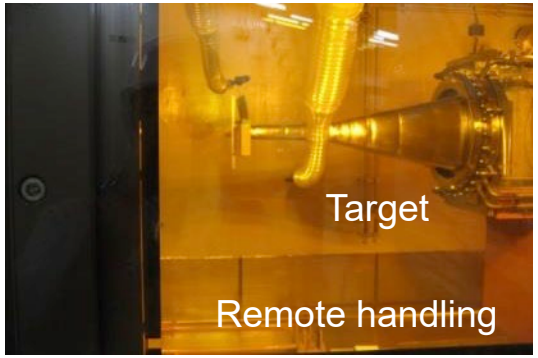




Halo monitor
- SEC
- TC

Monitor at PBW





Imaging plate (IP)

25

Beam shaping with non-linear optics

- To be relax the target embarkment under irradiation, non-linear optics using octupole magnet has been developed.

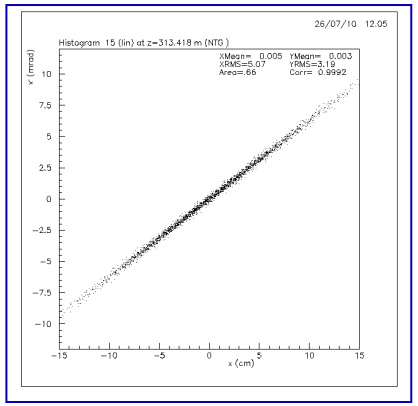
S. Meigo+, "Two-parameter model for optimizing target beam distribution with an octupole magnet", PRAB 23. 062802 (2020).

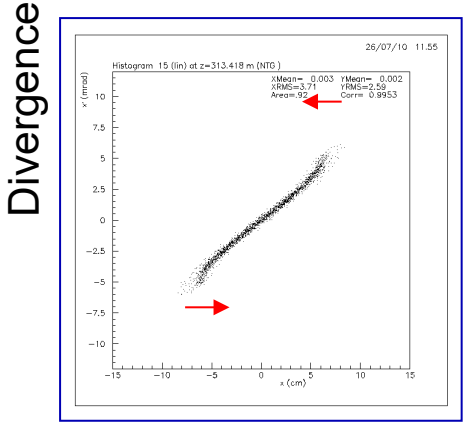
Linear

Non-linear

Octupole magnet

Phase space distribution



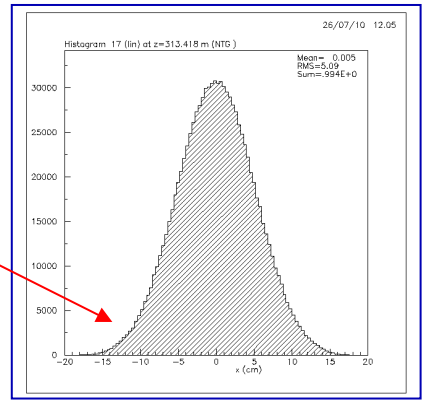


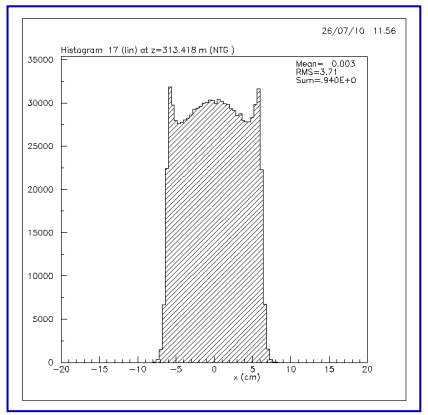


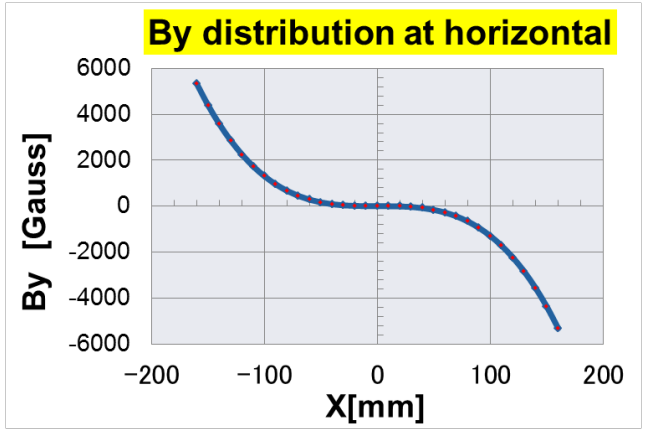
800 T/m^3

Spatial distribution

Heat load at tail giving the limit of peak

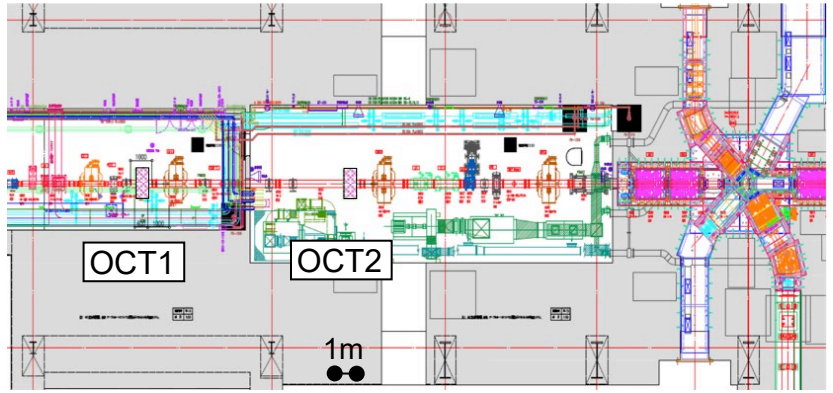






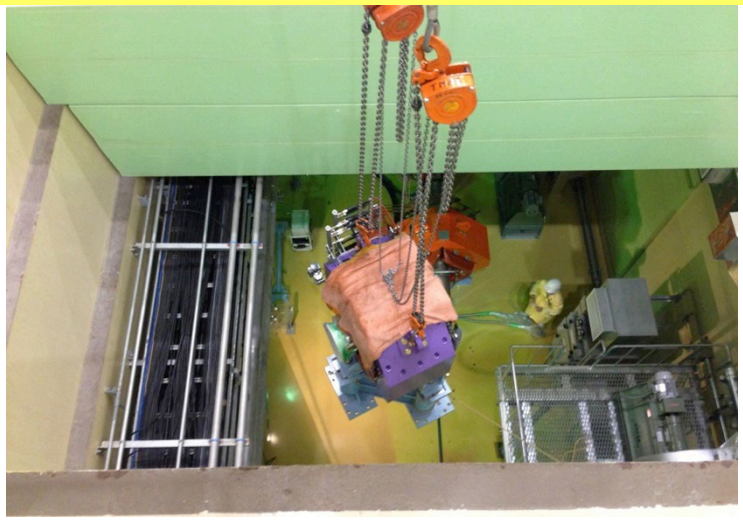
Installation of octupole magnets

- For peak reduction, octupole magnets were installed on 2013.
  - OCT1 and OCT2 installed at downstream 3NBTand M1 tunnels
  - Beam Position Monitor (BPM) placed at OCT1 and 2 for beam centering at octupoles.

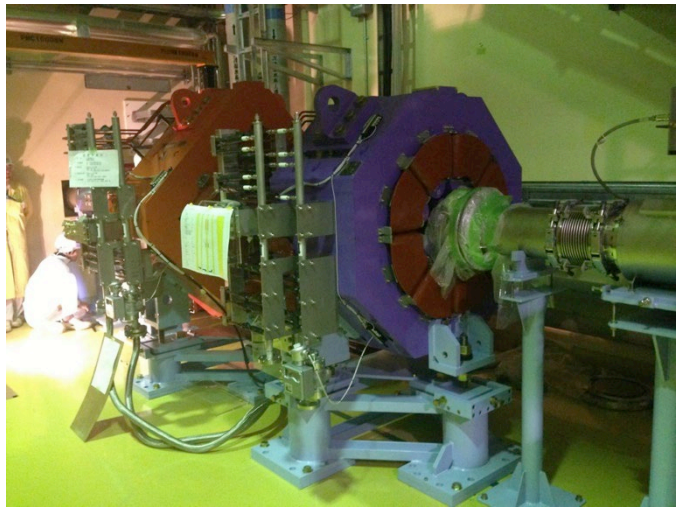


Horizontal view

Shields above M1 tunnel opened for transport OCT2 to tunnel

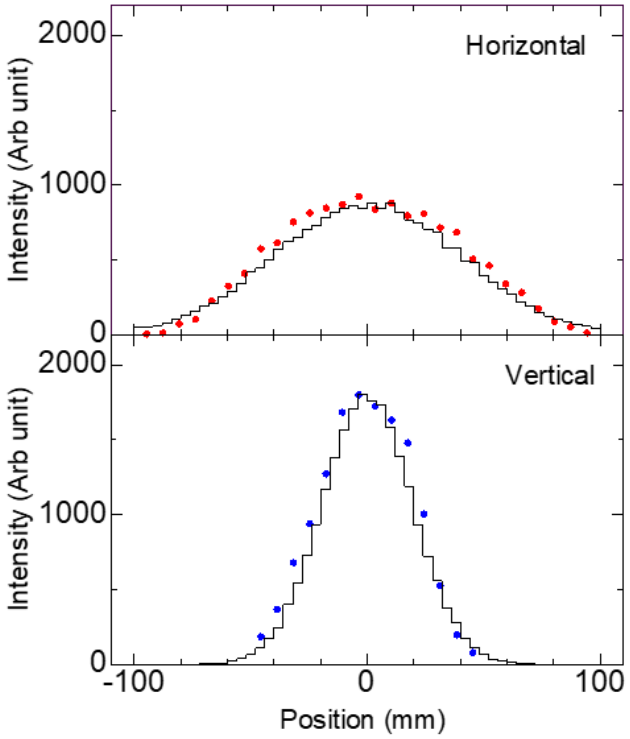


Completed installation of OCT1 at downstream of 3NBT tunnel

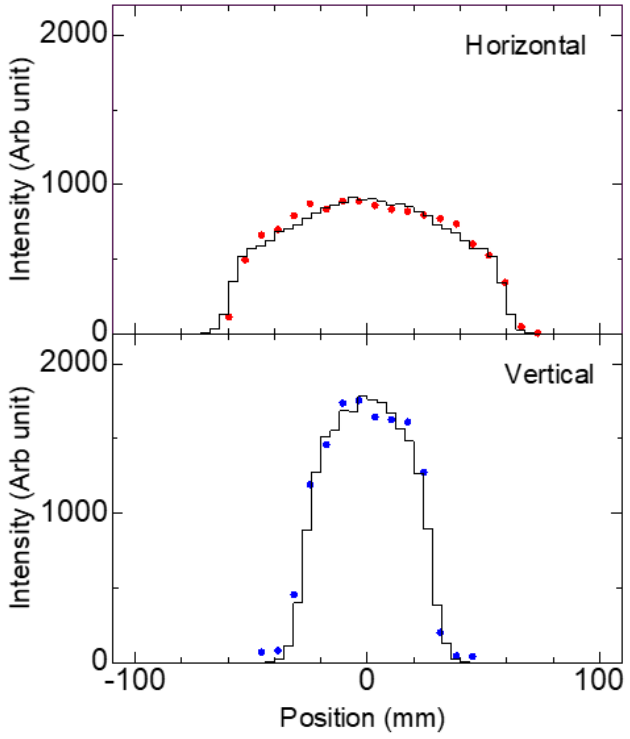


Result of beam shaping by non-linear optics

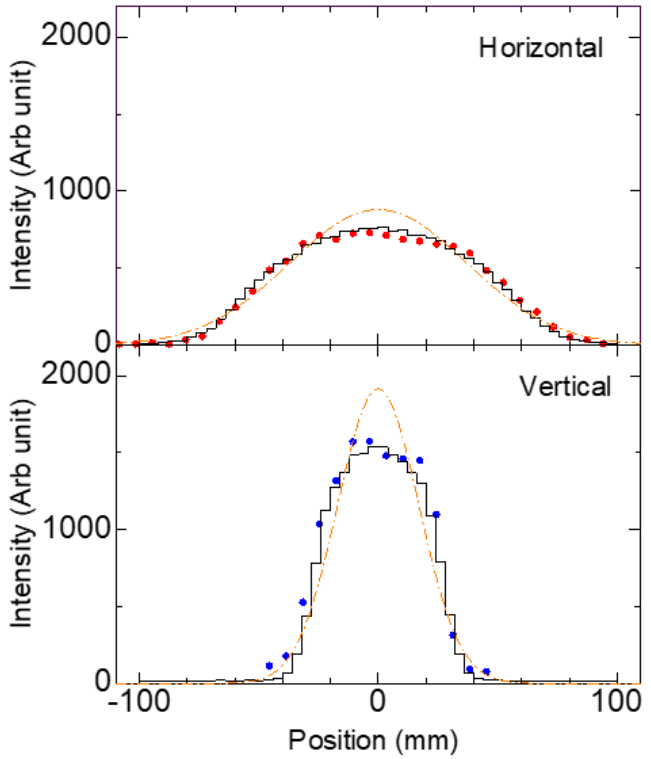
OCT 0A



OCT 698A

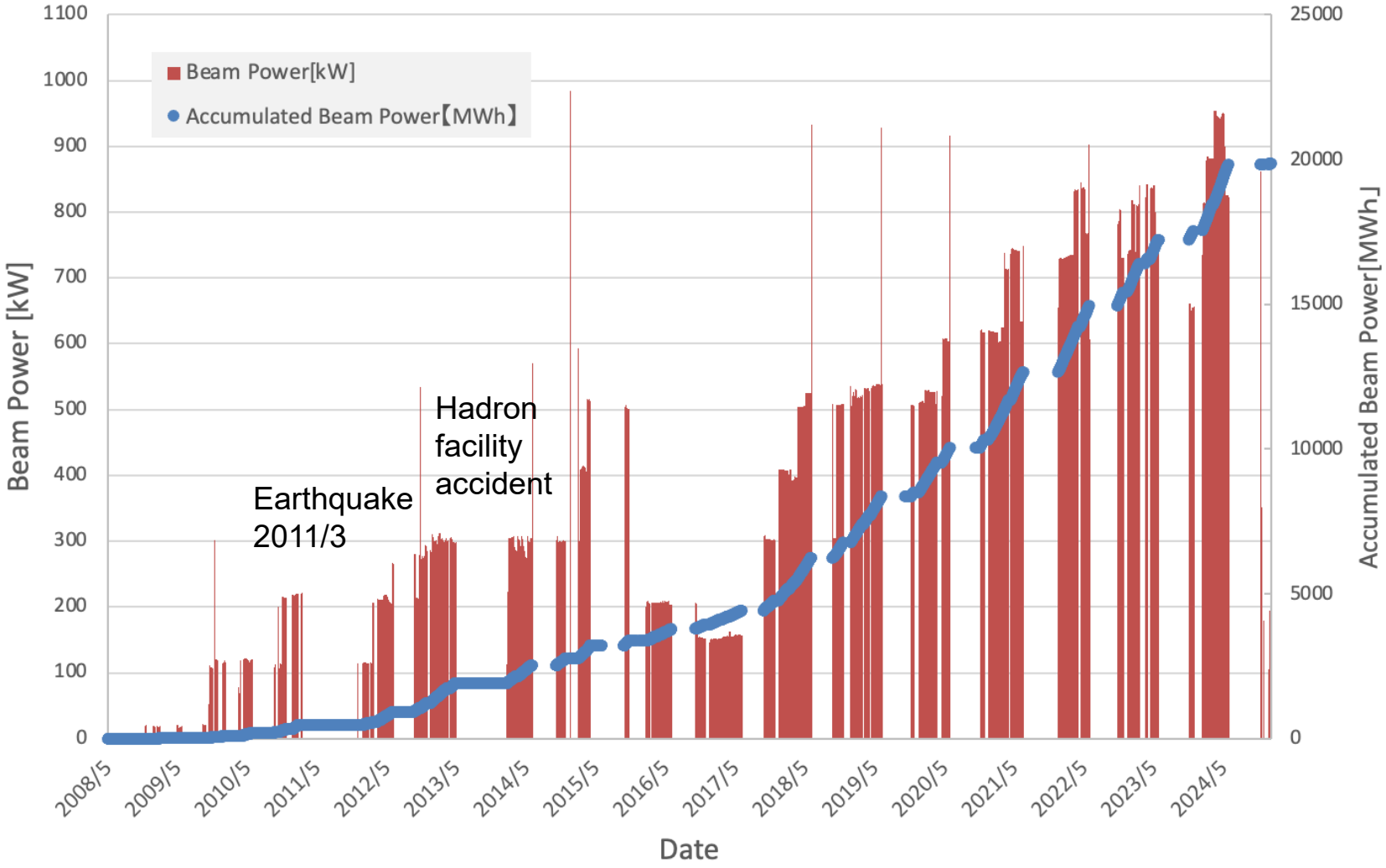


OCT 698A
with muon target



- Peak intensity can be decreed ~40%.
- Side effect of beam loss can minimized by tuning the phase advance between octupole and target.

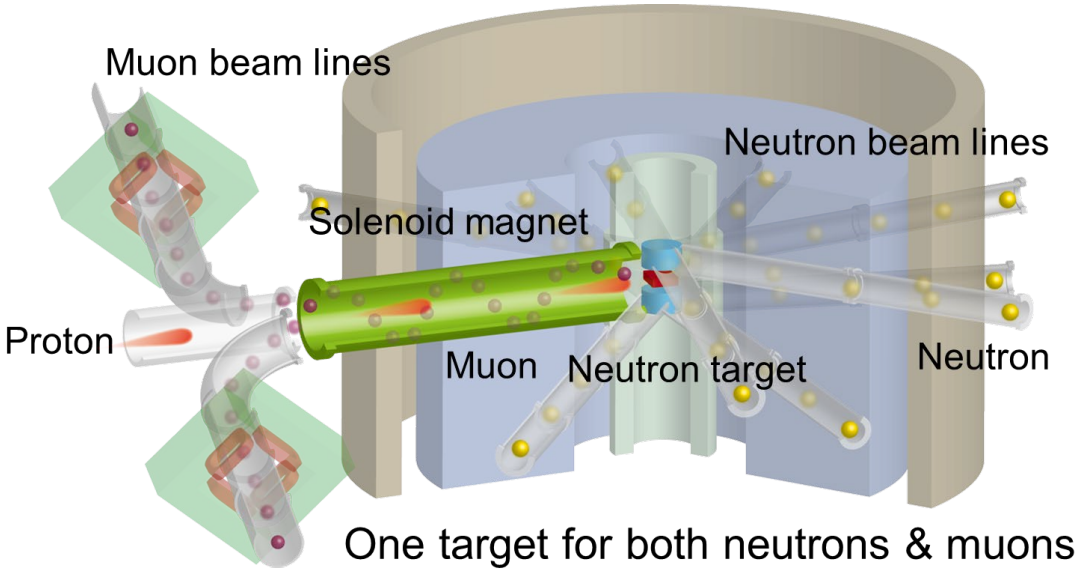
Beam operation status



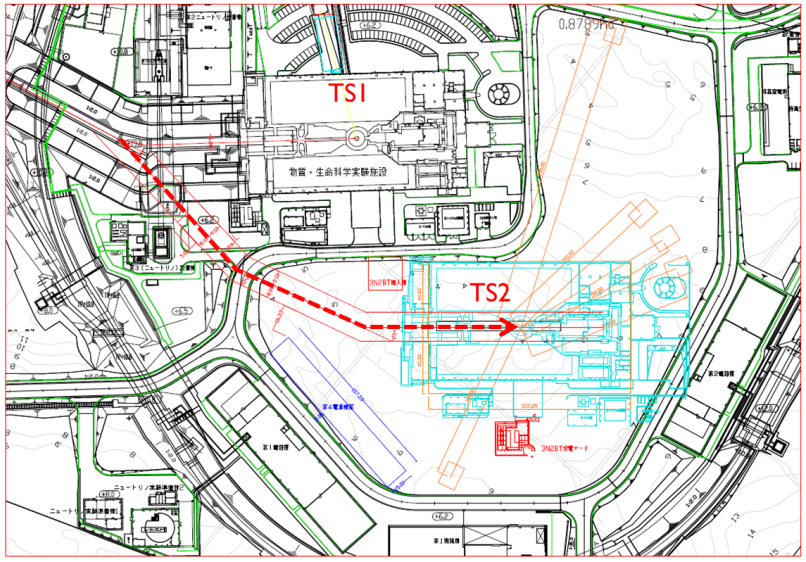
- Steady ~0.8-MW beam operation with availability ~95%.

- Introduction
  - J-PARC
  - Spallation reaction
- Spallation neutron source
  - Present and issues
- Beam delivery to target
  - Beam flattening using non-linear beam optics
- Future plan at J-PARC as neutron source
- Accelerator Driven System (ADS)
- Summary

Future plan of 2nd target station of MLF (TS2)

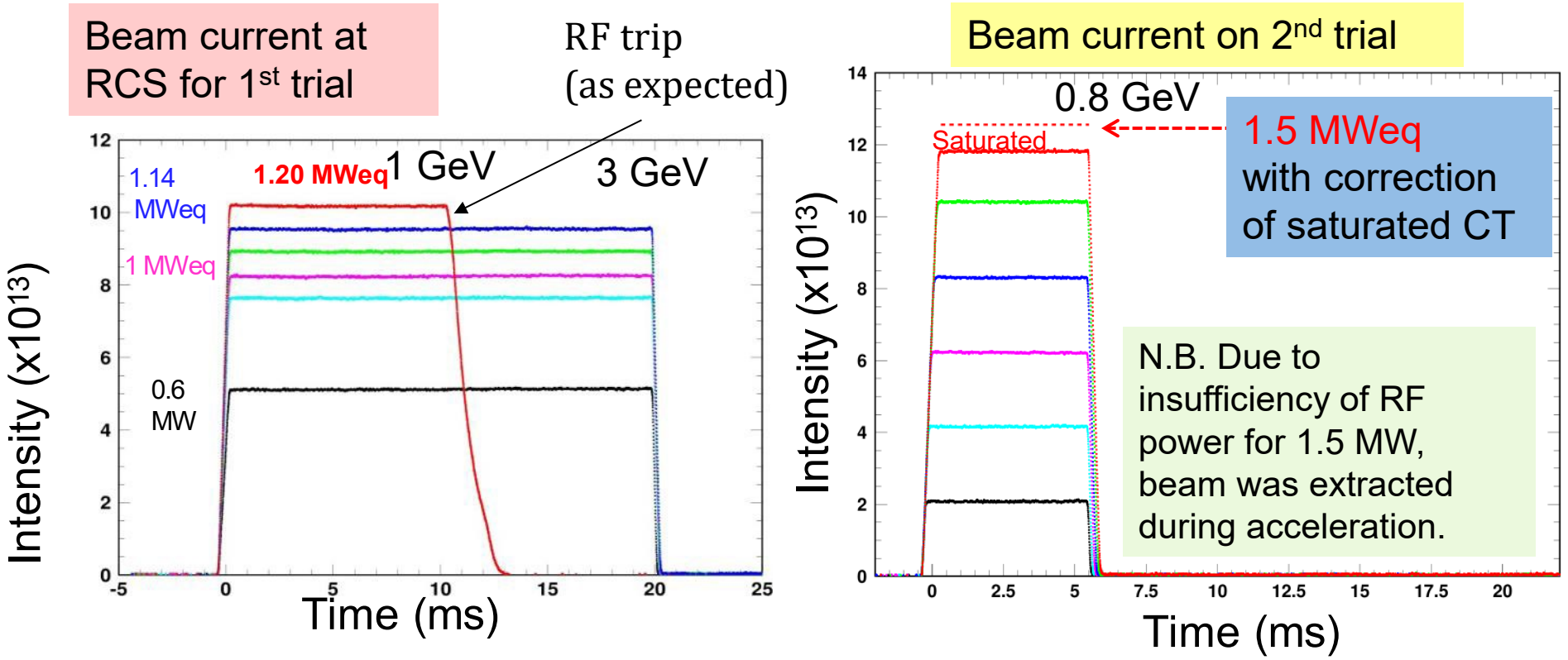


- Beam will be split to deliver with low rep. rate (< 5 Hz) to TS2.
- Rotating tungsten target
- Neutron and muon productions
- Budget not approved yet



Beam power beyond 1 MW

- RCS has started beam test toward multi-MW using beam dump.
- 1.1 MWeq of 3 GeV successfully demonstrated using beam dump. But the MLF target cannot accept now.
- After RF power upgrade, multi-MW seems to be promising.

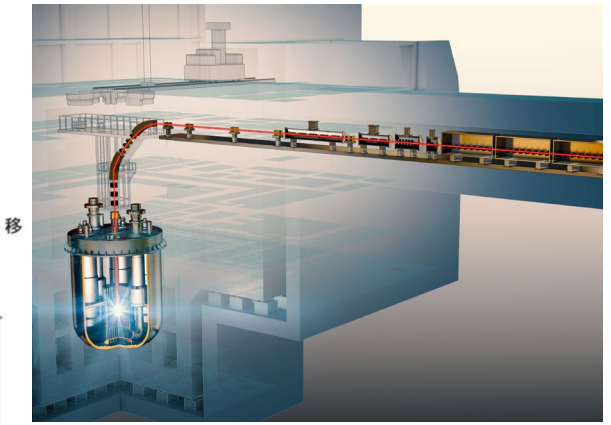


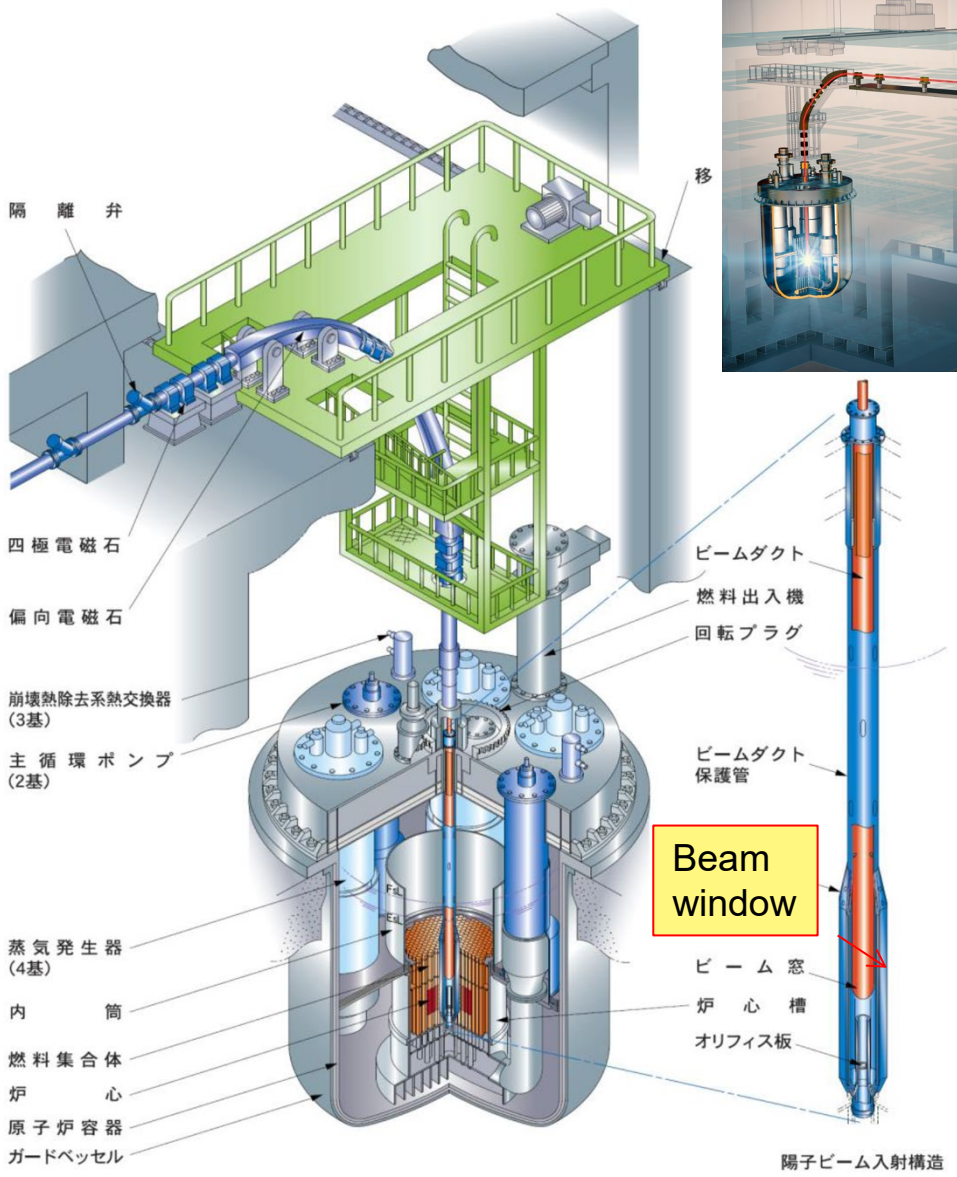
- Introduction
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Accelerator Driven System (ADS)

- JAEA ADS (since 1980)
  - Transmutation (mainly fission) in the subcritical reactor (K_{eff}<1) of minor actinide (Np, Am, Cm) from spent nuclear fuel
- Belgium (MYRHHA) and China (CiADS) have developed this as well.

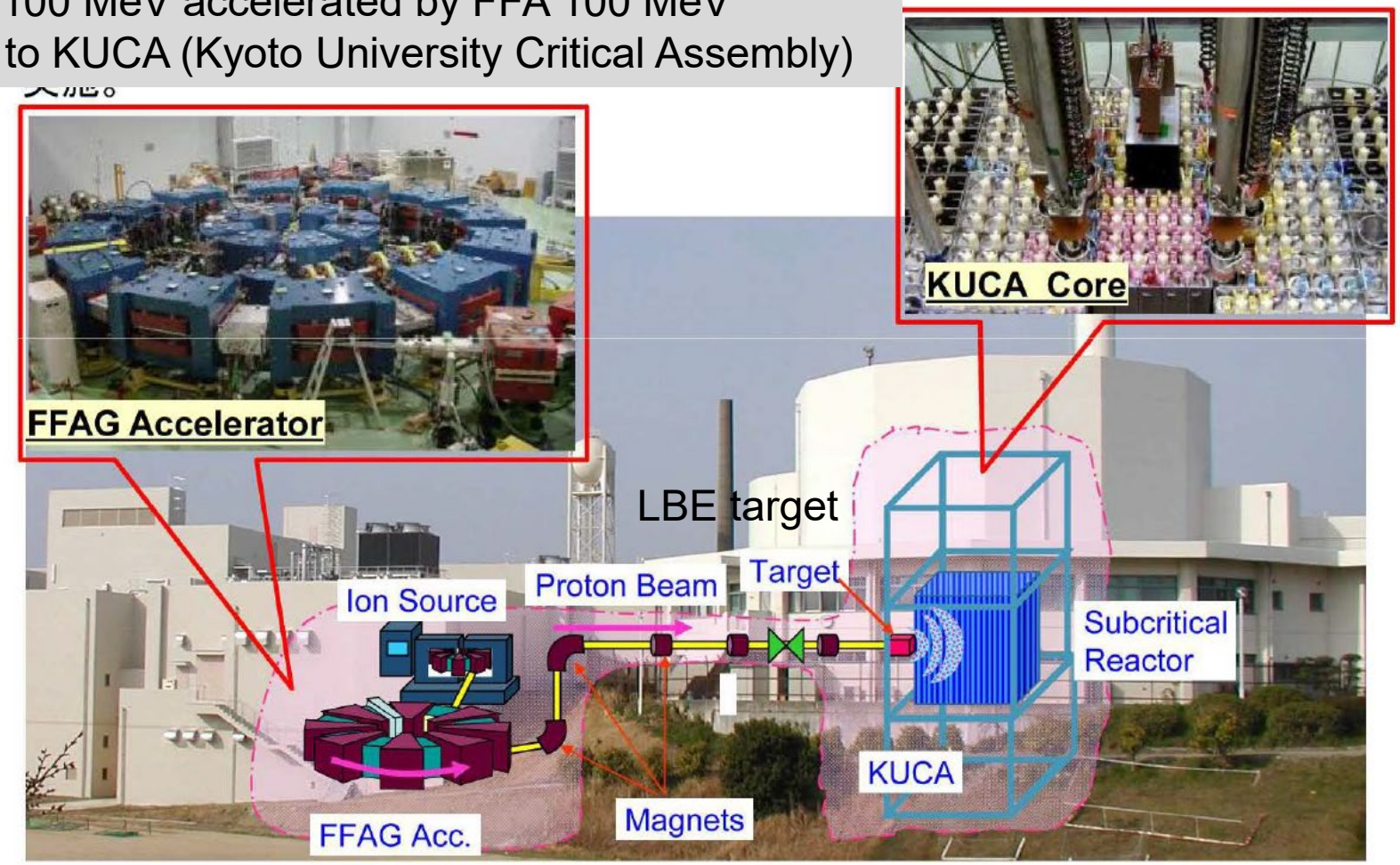
Proton energy	1.5 GeV
Max. proton power	30 MW
Reactor thermal power	800 MWt
Target and coolant	Pb Bi
Effective neutron multiplication factor (Keff)	0.97
Transmutation rate	10%/year





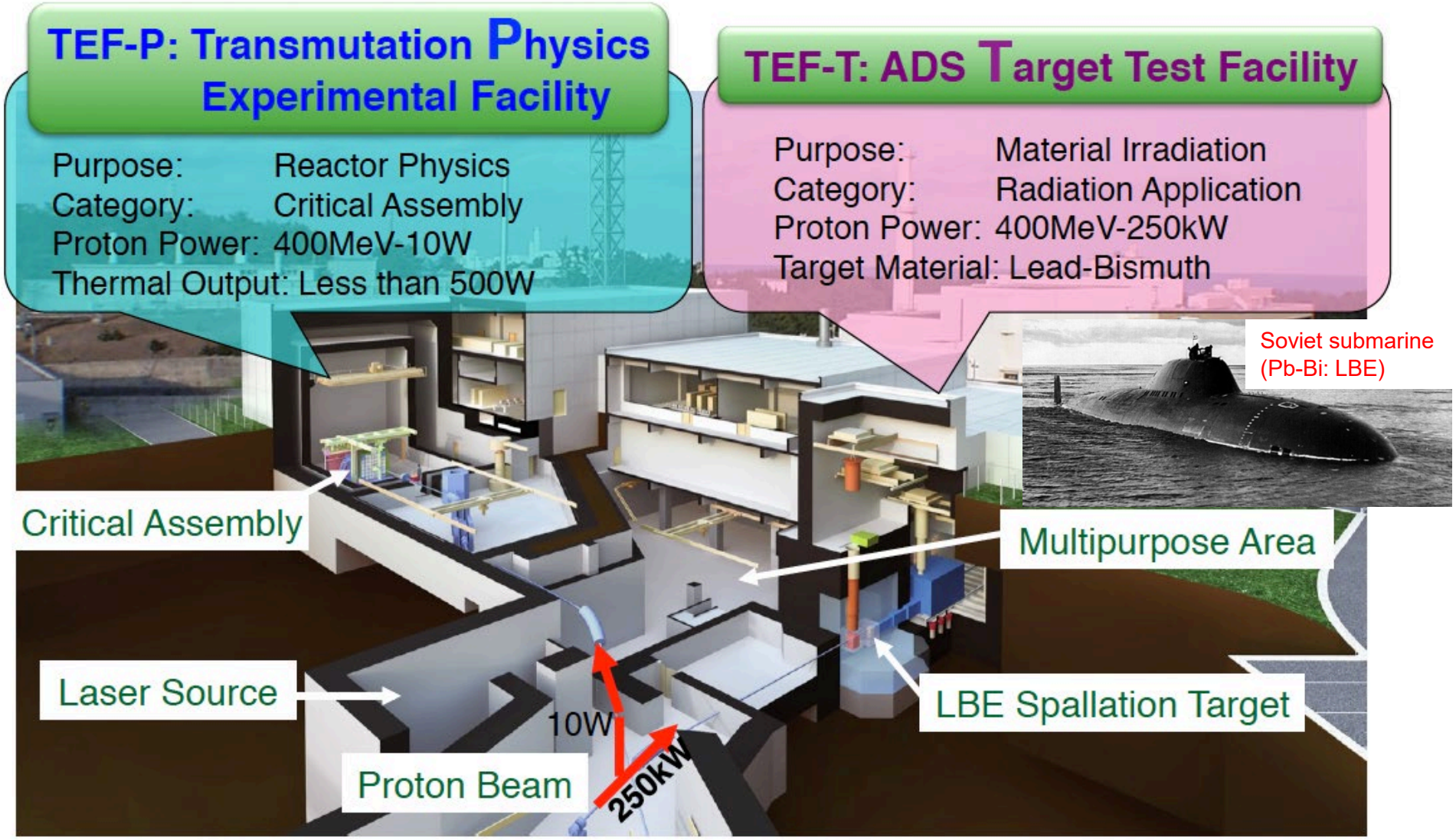
ADS at Kyoto University at KUCA

Protons of 100 MeV accelerated by FFA 100 MeV introduced to KUCA (Kyoto University Critical Assembly)

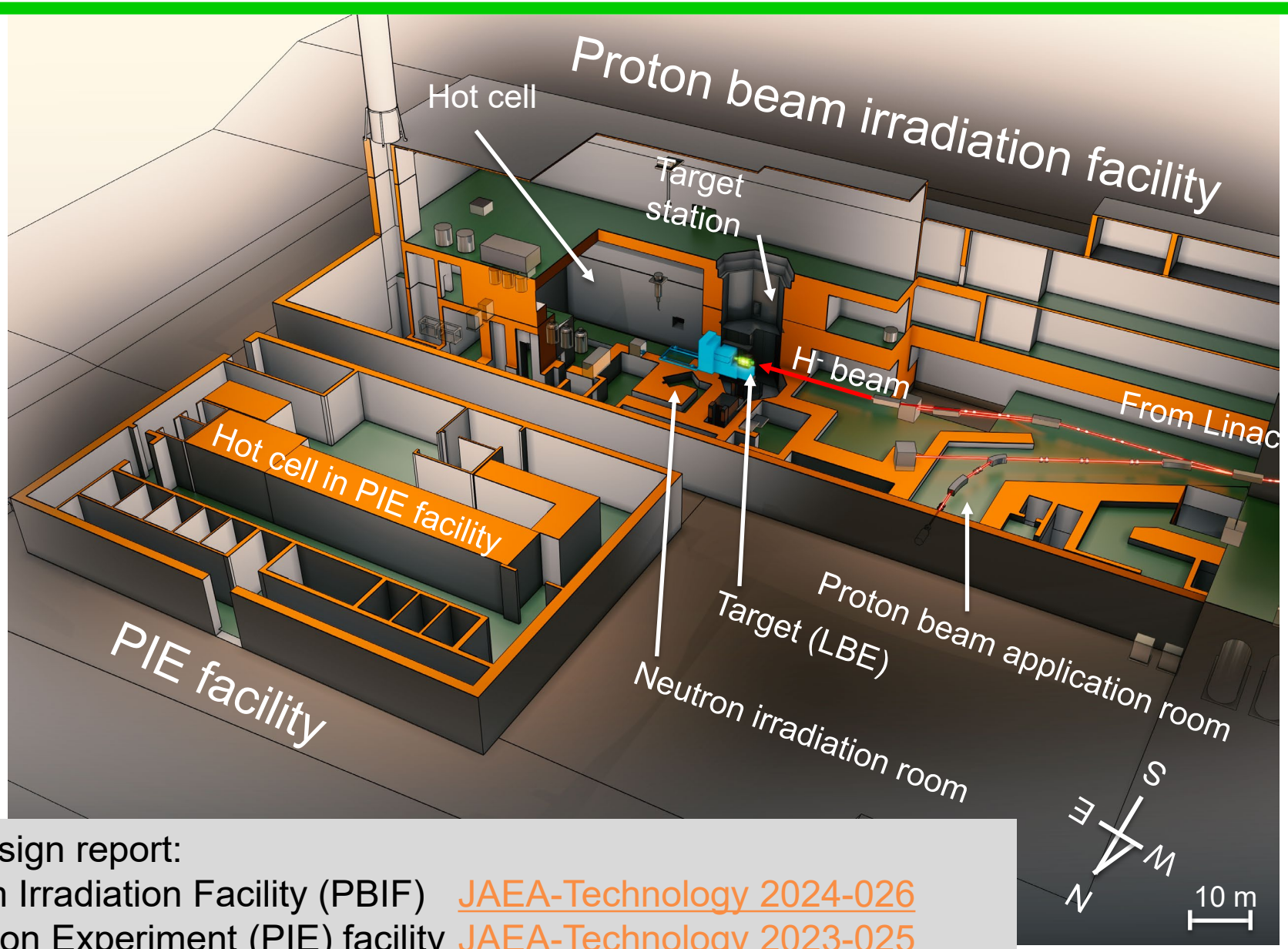


- Even though the power is extremely low, this is the first demonstration of ADS using spallation

Transmutation Experimental Facility (TEF)



Proton Beam Irradiation Facility



Technical design report:
Proton Beam Irradiation Facility (PBIF) JAEA-Technology 2024-026
Post Irradiation Experiment (PIE) facility JAEA-Technology 2023-025

Soft errors and semiconductor

TRIUMF

TRIUMF High Intensity Proton Beams
Operating Experience with Radiation Effects

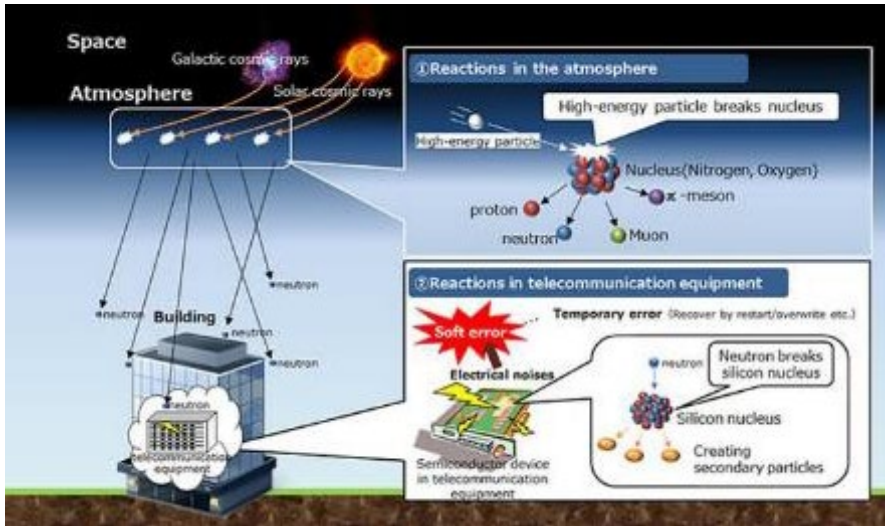
Ewart Blackmore TRIUMF



500 MeV H^- Cyclotron
Extraction by Stripping
3-4 Proton Beam Lines
Different Energy & Intensity
DC beam with microstructure
Operating since 1974
ISAC RIB Facility since 1998
Muon Physics CMMS
Isotope Production
PIF&NIF Facilities

E. Blackmore RADIATE 2019 Page 1

Hitachi web page



TRIUMF

Proton/Neutron Beam Test Area

Energies 500 MeV – 5 MeV

Cable lengths – 65 ft, 20 m

Fairly low radiation levels in area so PCs, testing units etc can stay in area.

Access to area in < 1 min.

TV monitoring and remote X-Y table for device positioning.

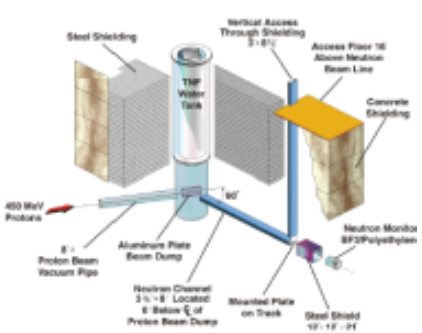
User control of beam on/off.

Intensity changes in seconds.

Energy changes by degrader in seconds, by extraction 15-30 minutes.



BL2C/1B Proton Beams



TNF Neutron Beam

E. Blackmore RADIATE 2019 Page 16

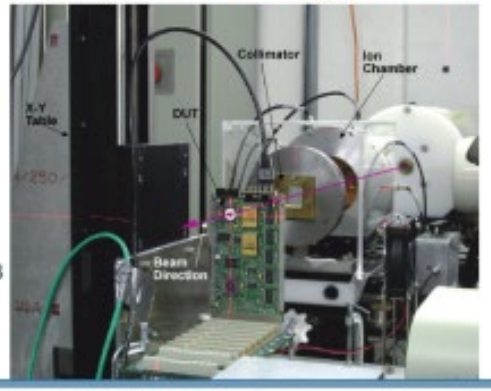
TRIUMF

Proton Testing at TRIUMF

Proton Test Setup – BL2C Test energy: 5-105 MeV

Features

- Collimator for beam size
- X-Y table for moving DUT
- Laser alignment
- Range shifter for energy changes
- Ion chamber for dosimetry
- Similar setup on BL1B but higher energy



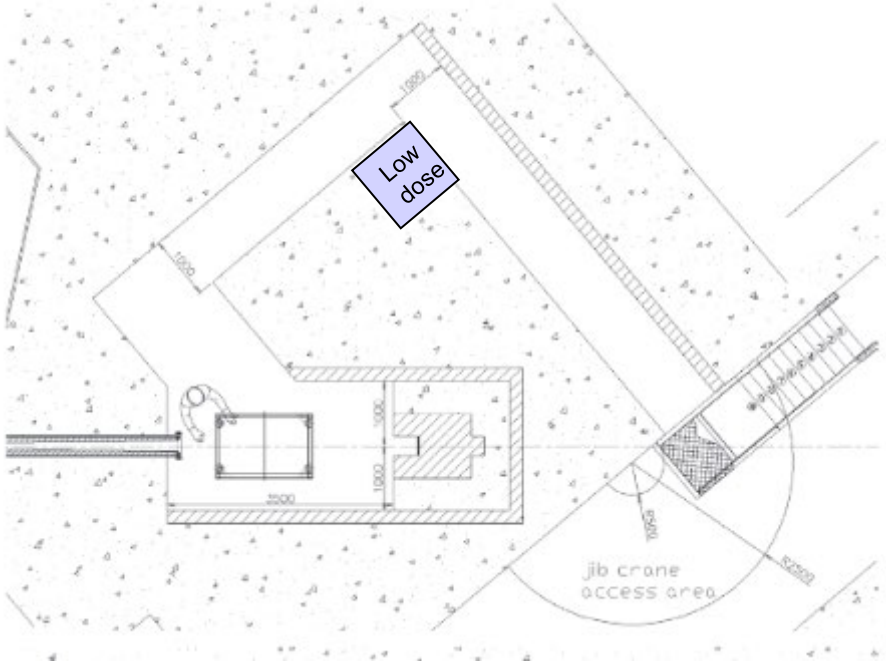
E. Blackmore KOMAC Workshop 2017 Page 18

For soft error and semiconductor

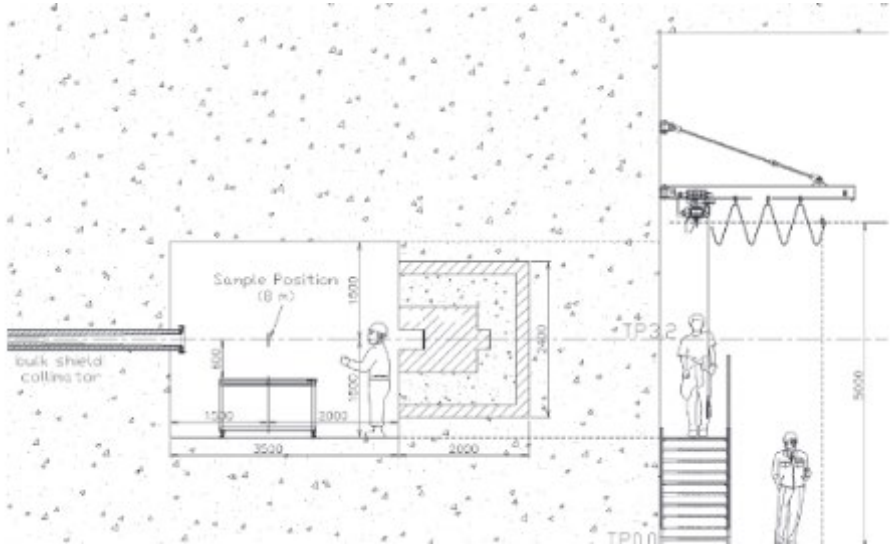
For application of space environment

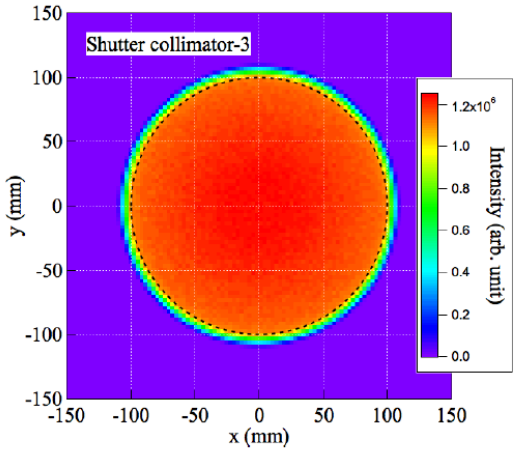
Neutron beam line at new facility

Horizontal view



Vertical view JAEA Tech. 2017-003





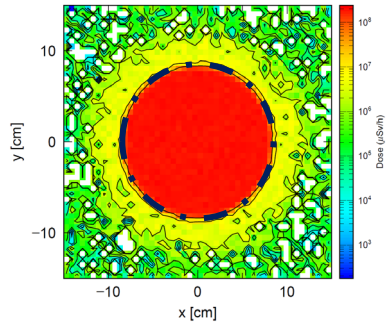
Calculation result of neutron beam profile

Low-dose area is required to prevent soft-error of users' instruments

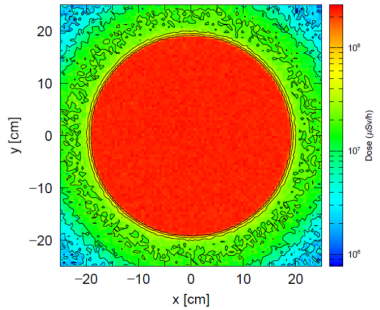
Improvement of neutron beam

Expansion of neutron beam area was required.

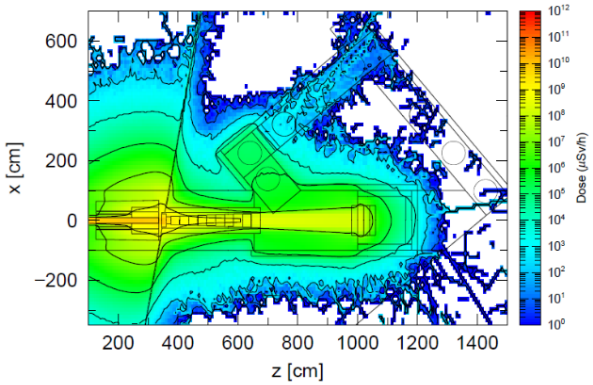
Φ 171 mm

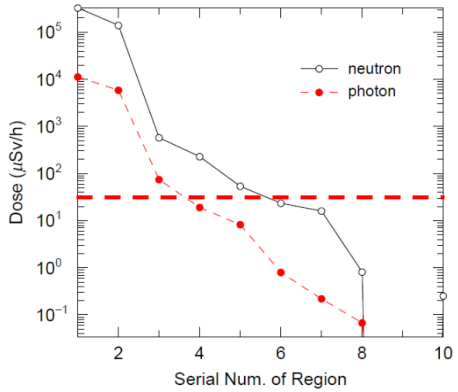


Φ 400 mm



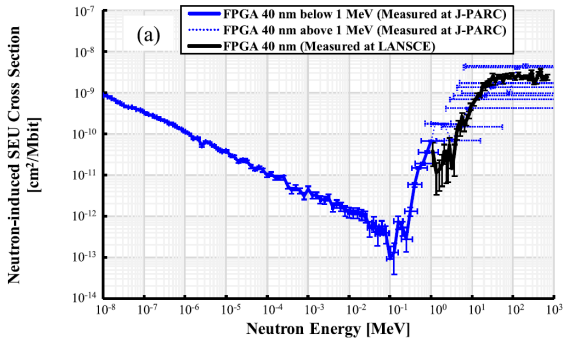
Dose rate calculation

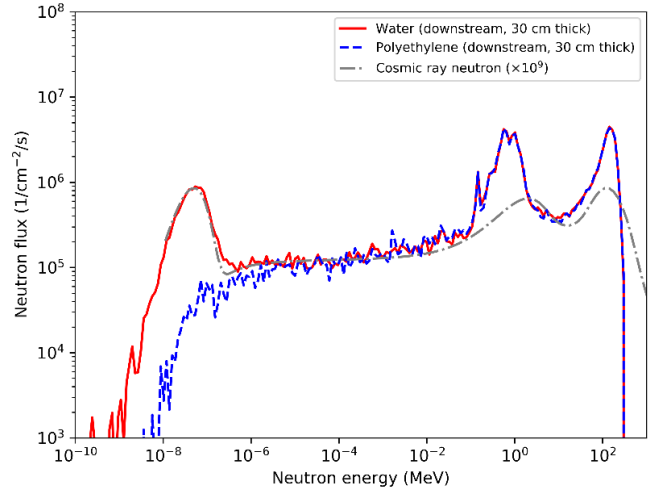




H. Iwashita+, IEEE 70, 216 (2023)

Large SEU (Single Event Upset) cross section in the thermal region

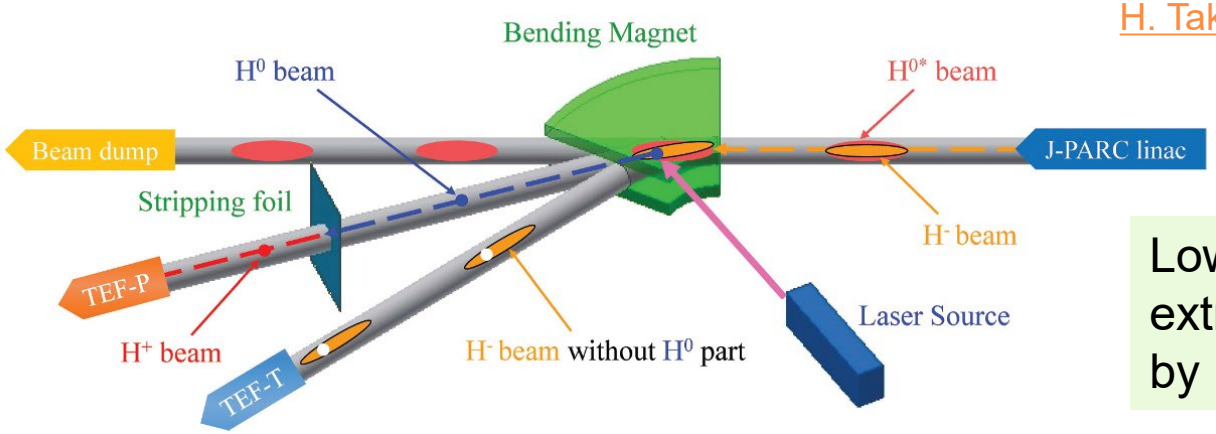




Similar terrestrial neutron spectrum

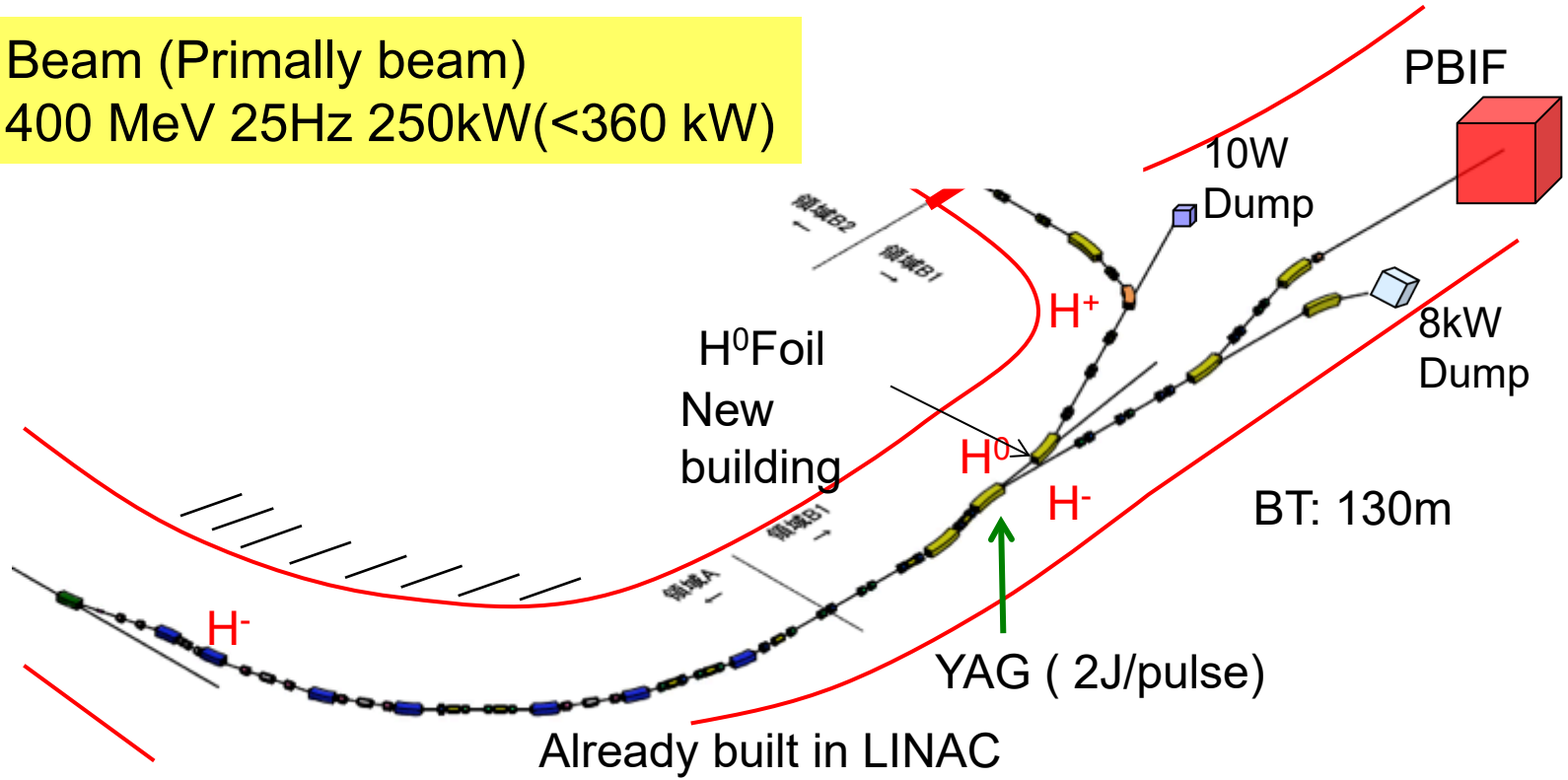
Low-intensity proton beam extraction

H. Takei, et al., J. Nucl Sci Tech. 58 588 (2020)



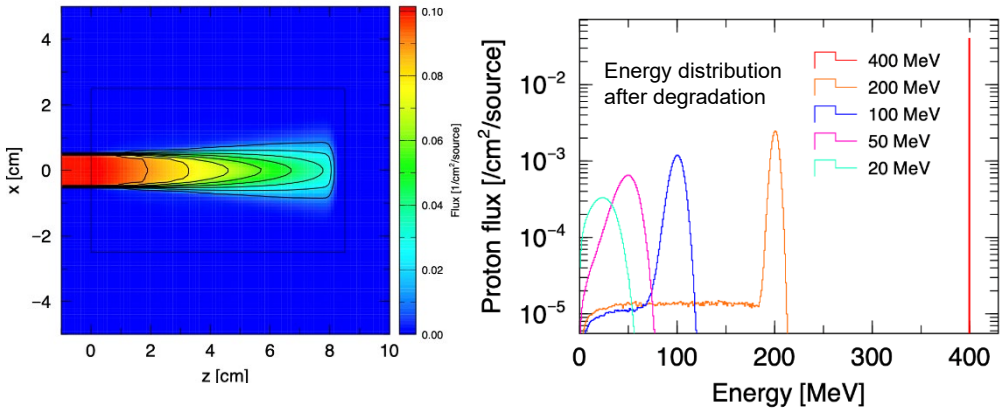
Low intensity H+ beam (<10 W) extracted from H⁻ primary beam by Laser charge exchange

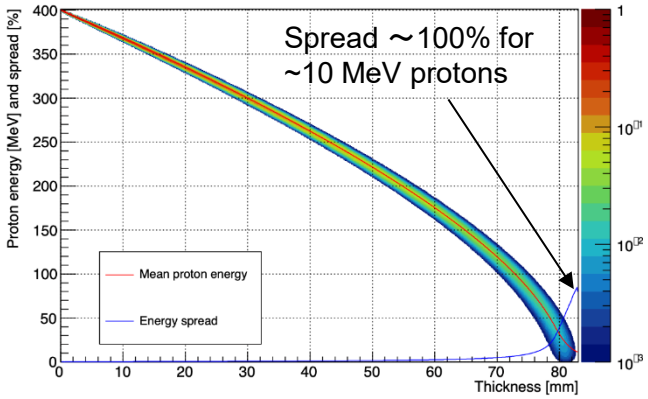
H⁻ Beam (Primally beam)
- 400 MeV 25Hz 250kW(<360 kW)



Proton beam energy degrader

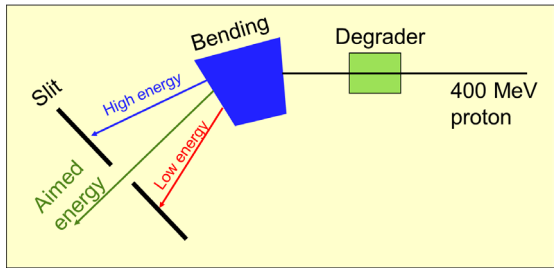
Beam behavior at tungsten degrader



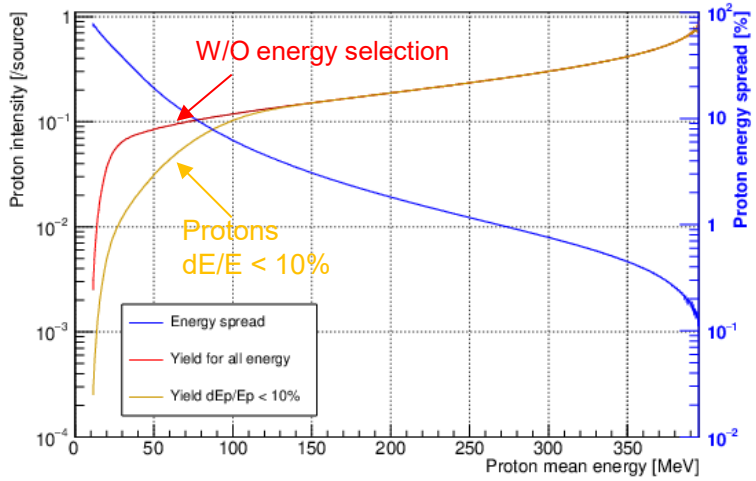


Energy straggling spreads the distribution

Available mono-energy proton by bending and slit



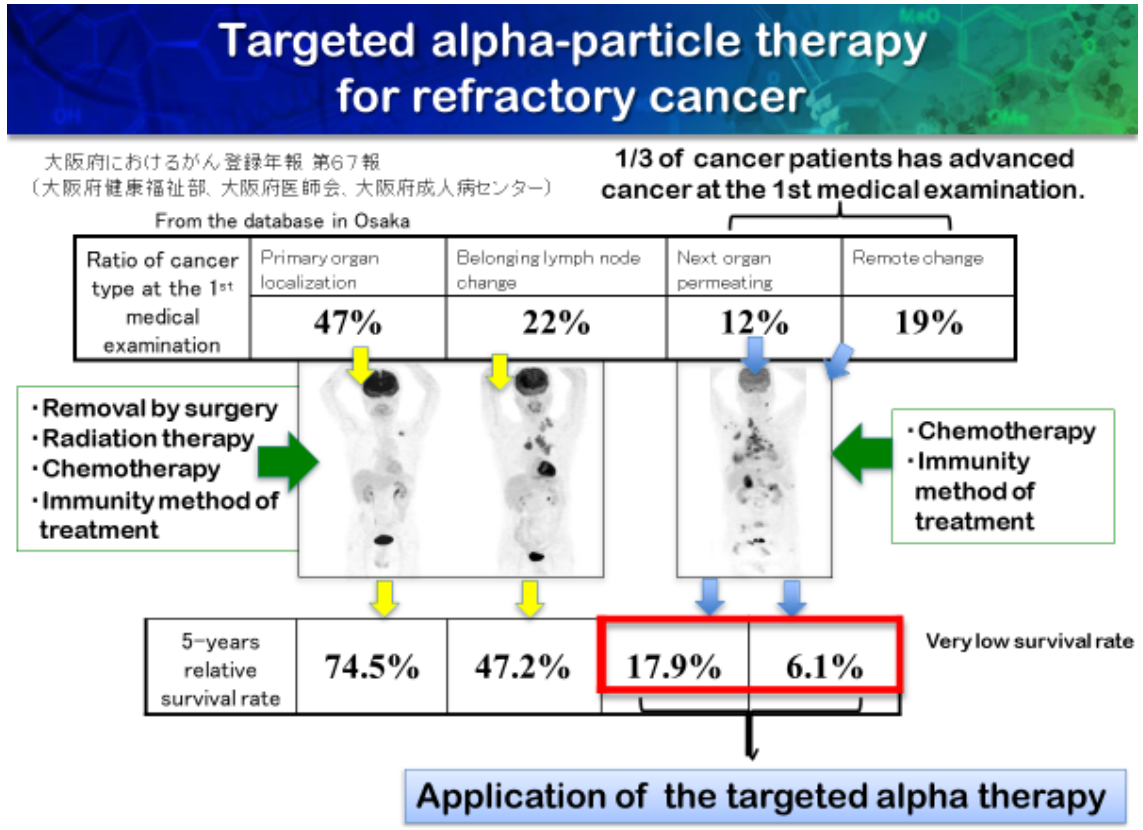
Intensity of proton with and without choosing energy of dE/E < 10%



- Although the yield is low <10^{-3}, of primary protons showing availability protons ～10 MeV
- Might be available several MeV protons, but must consider the energy spread due to the air between the window and samples

RI medicine

- Production of RI for medicine was considered in TEF-T using a rapid transfer tube.
- Those nuclides are important.
  - α-emitting nuclides such as ^{225}Ac ($T_{1/2}$ 10 d)
  - SPECT for ^{99}Mo ($T_{1/2}$ 66 h) are important.
- NB: Invited to the Medical RI consortium organized by the Nuclear Safety Technology Center, commissioned by the Japanese Cabinet Office



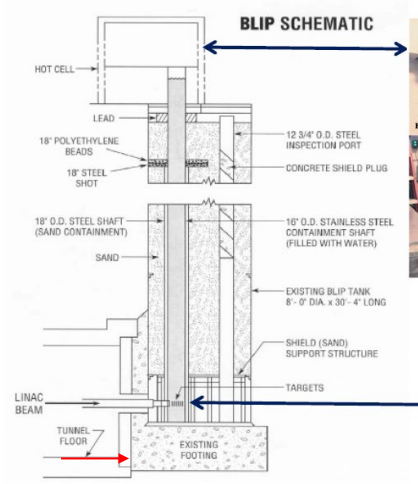
SPECT:
Single Photon Emission Computed Tomography

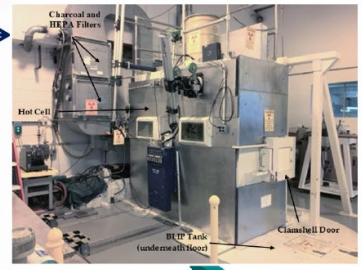
Dose :
24 MBq/person for 60 kg

RI production

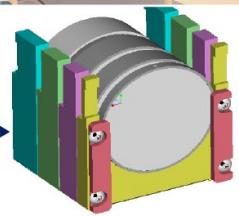
- US/Canada proton accelerators (BNL, LANL, TRIUMF) are vigorously producing medical ^{225}Ac ($T_{1/2}$ 10 days) by spallation reaction using ^{232}Th
- Already procedure established to reduce ^{227}Ac (< 8 x 10^{-7}) with a relative long half-life (22 years)

Brookhaven Linear Isotope Producer

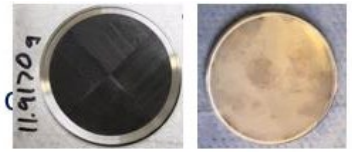




Target box. is taken out to the above cell and targets are transported by the cask.



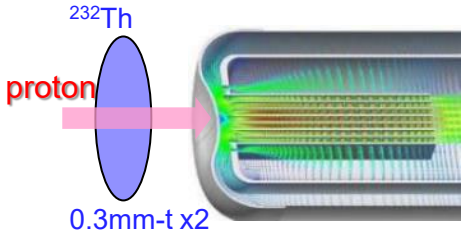
Target box



Th-232 targets used in BLIP
Diameter 60 mm, 0.3 mm-t
*Sealed in Inconel container

BNL (BLIP) Proton beam 0.2 GeV, 165 μA, 33 kW
Irradiation period 12 days, ^{225}Ac production 2 GBq/batch
NB: Since containment of ^{227}Ac is low, its separation is not done in the U.S. and Canada

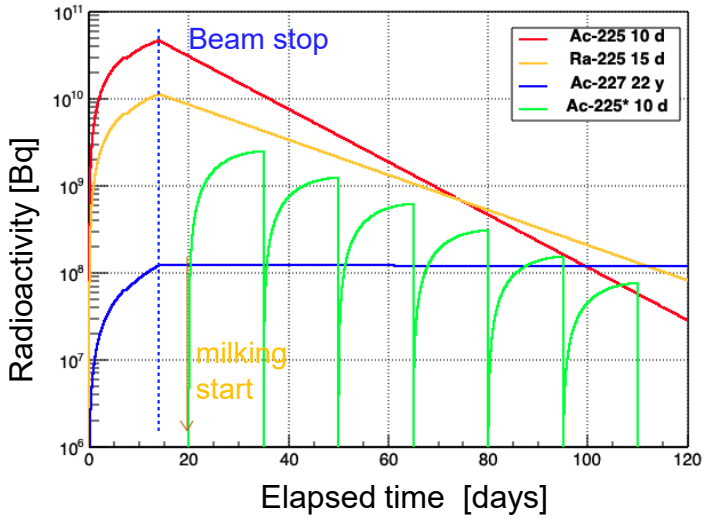
Same as BLIP, Th targets (0.3 mm-t, Φ60 mm, 10 g) irradiated by protons (400 MeV 250 kW) with approval small amount of fuel



LBE target (φ15 cm x 1 m)

- Peak current density and irradiation period are similar to BLIP (< 20 μA/cm^2 for 10 days)
- Not ignorable but small effect on downstream beams

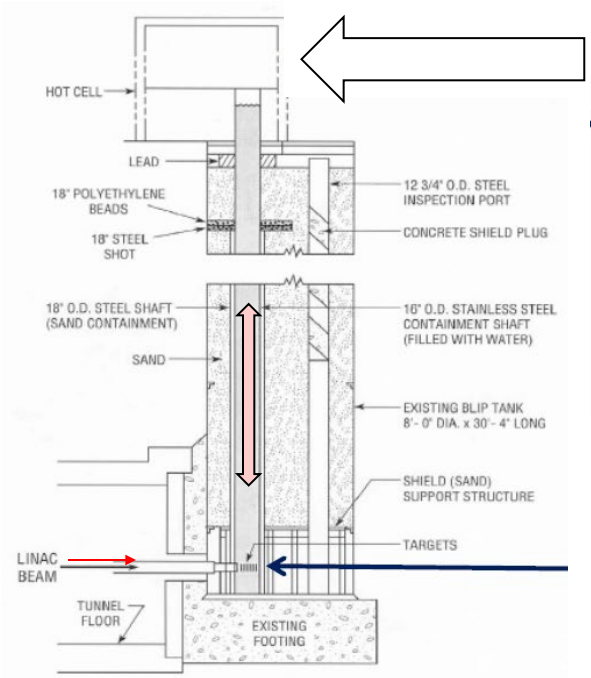
^{225}Ac production by Th target



- Ac-225 (including^{227} Ac ~1%) production :
  47 GBq/batch ⇒ 8 batches/year 376 GBq/year
- Ac-225* (^{227}Ac < 8 x 10^{-7}) production :
  4.9 GBq/batch ⇒ 39 GBq/year for 8 batches/year
- ^{225}Ac generator of ^{229}Th 0.3 GBq for 40 years

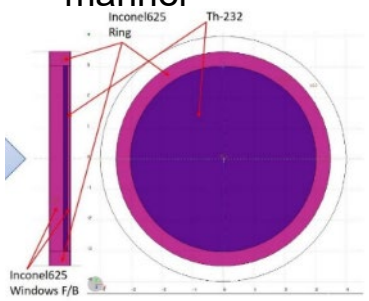
Reference: Reactor (Joyo) ^{226}Ra with 2 g ⇒ 24 GBq/60d

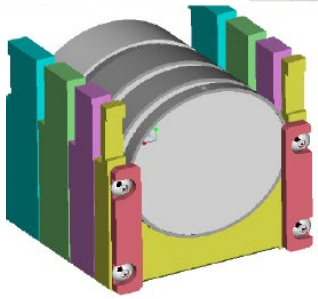
RI production and Material beam irradiation test



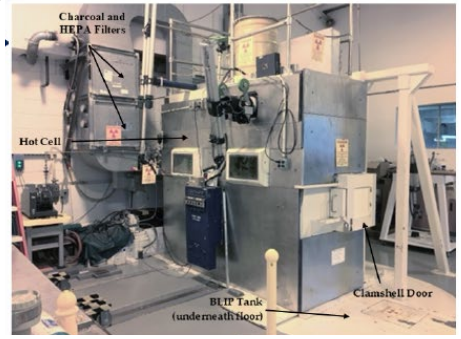
Th-232 target and material test

- Inconel alloy capsule (Φ60 mm, total thickness ~3 mm)
- Material test applied similar manner





Upper cell (BNL)



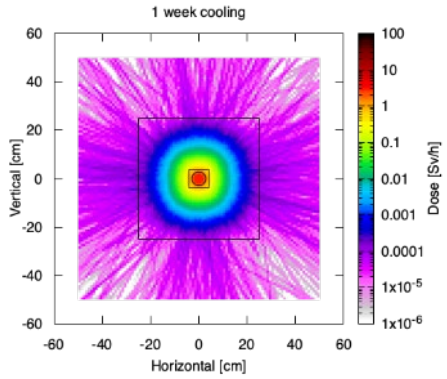
Hot cell for Ac process (BNL)



- RI production and material irradiation tests may be applied similar manner at BLIP (Shielding design underway)
- Possibility of chemical processing in the upper cell
  - Challenging
    - Remote chemical process to product Ac
    - Th target fabrication in Japan
    - Frequent target exchange

Dose rate distribution in transfer casks after 1-week decay (FLUKA)

- Surrounding area << 1 mSv/h

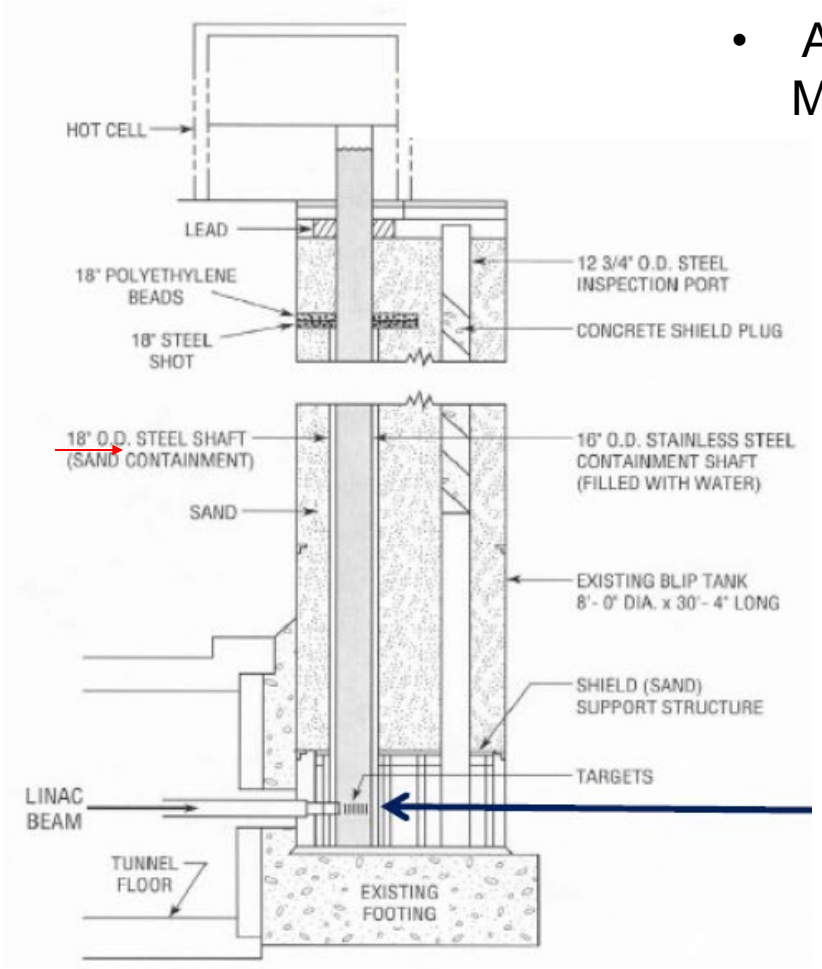


Annual plan at the facility

[Month]	7	8	9	10	11	12	1	2	3	4	5	6
Beam					→	→	→	→	→	→	→	→
Outage	→	→	→	→								
Ac prod.					●	●	●	●	●	●	●	●

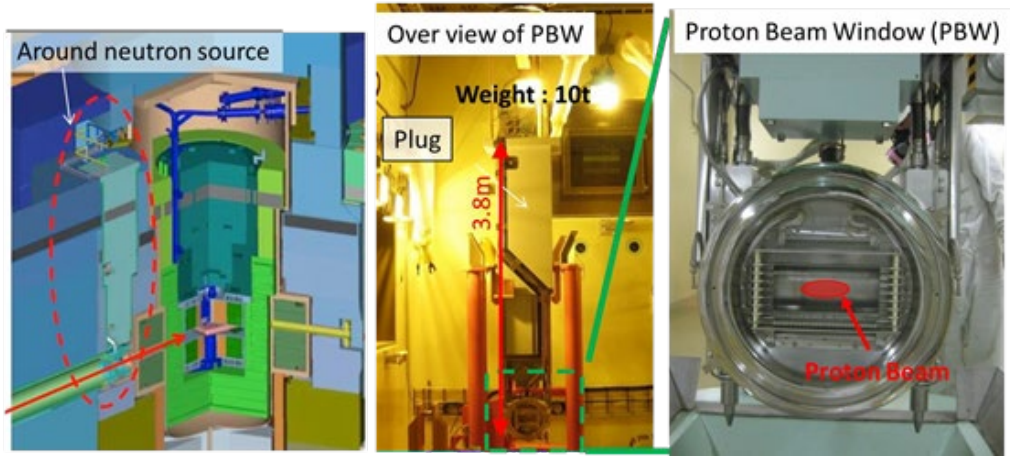
Targetry for RI production

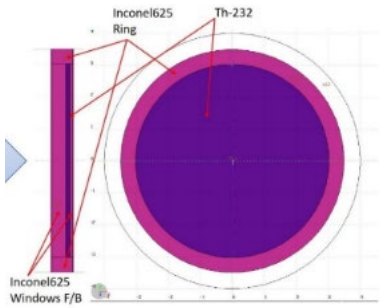
BLIP vertical view



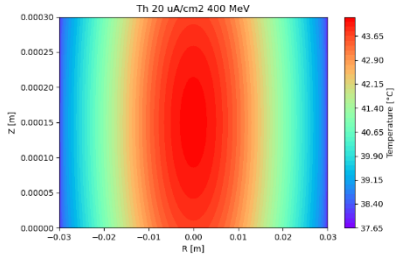
- To avoid tritium contamination, a similar scheme of BLIP might be difficult at J-PARC.
- A similar structure of the proton beam window at MLF will be a candidate for RI production target.

MLF Proton Beam Window (PBW)





Heat analysis on Th target

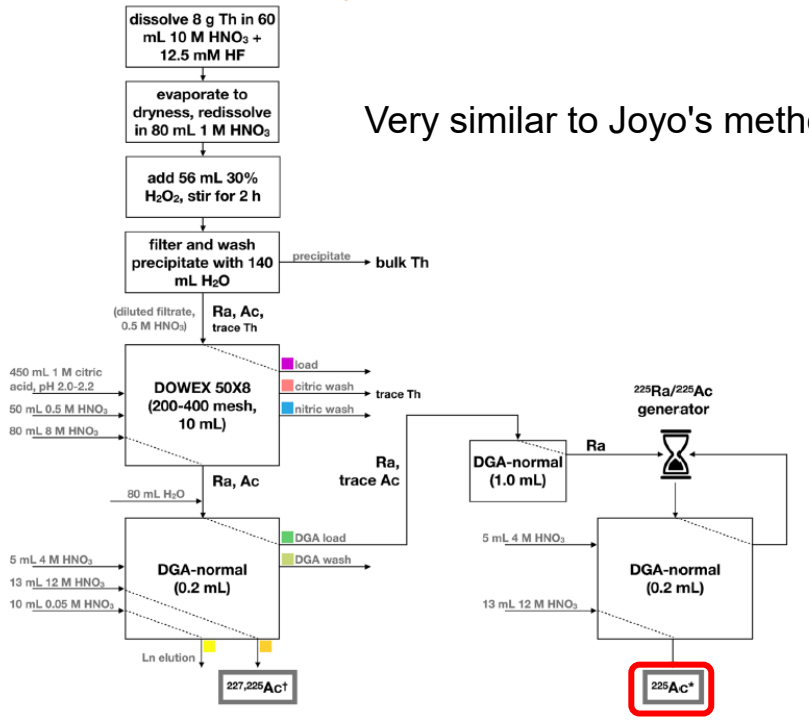


T < 50 C for 250 kW

Chemical process (Actinium extraction)

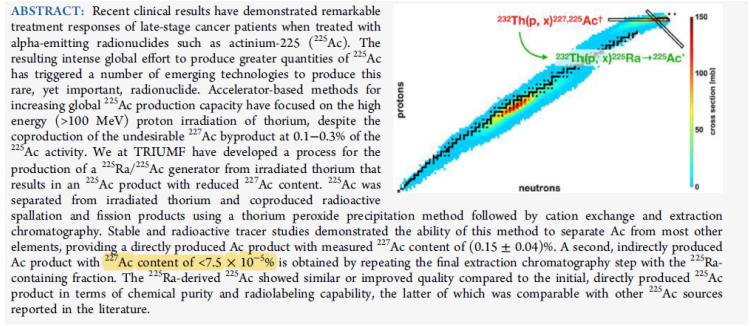
Chemical process proposed by TRIUMF

^{232}Th-Spallation-Produced^{225} Ac with Reduced^{227} Ac Content



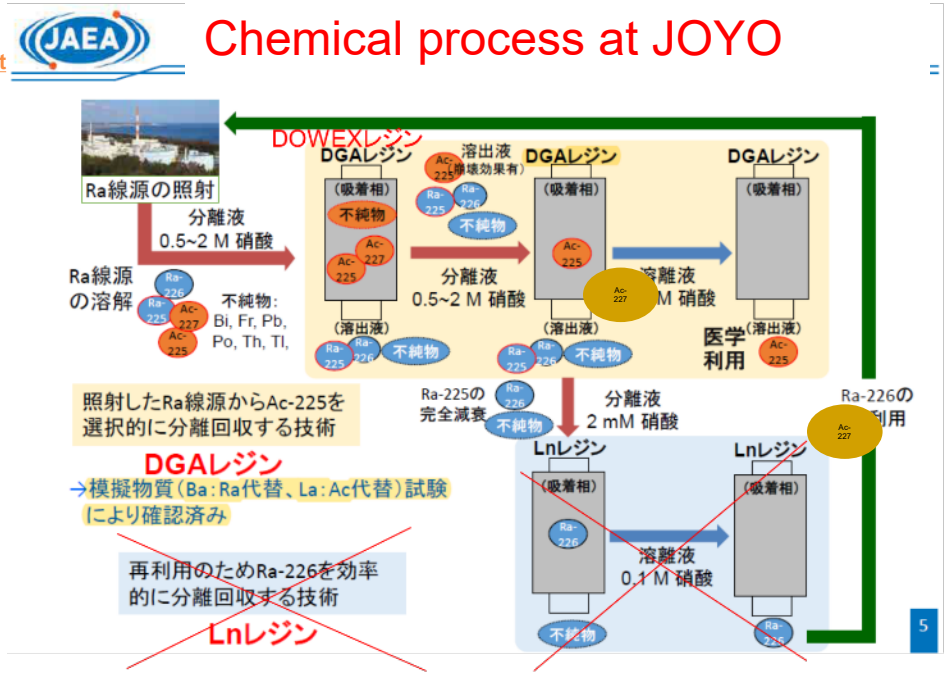
Very similar to Joyo's method

Figure 2. Flowchart describing the process used to produce ^{227,225}Ac† and ^{225}Ac* from thorium metal irradiated with high energy (>100 MeV) protons. Colored squares correspond to the fractions shown in the Figure 4 legend.


ABSTRACT: Recent clinical results have demonstrated remarkable treatment responses of late-stage cancer patients when treated with alpha-emitting radionuclides such as actinium-225 (^{225}Ac). The resulting intense global effort to produce greater quantities of ^{225}Ac has triggered a number of emerging technologies to produce this rare, yet important, radionuclide. Accelerator-based methods for increasing global ^{225}Ac production capacity have focused on the high energy (>100 MeV) proton irradiation of thorium, despite the coproduction of the undesirable ^{227}Ac byproduct at 0.1−0.3% of the ^{225}Ac activity. We at TRIUMF have developed a process for the production of a ^{225}Ra/^{225}Ac generator from irradiated thorium that results in an ^{225}Ac product with reduced ^{227}Ac content. ^{225}Ac was separated from irradiated thorium and coproduced radioactive spallation and fission products using a thorium peroxide precipitation method followed by cation exchange and extraction chromatography. Stable and radioactive tracer studies demonstrated the ability of this method to separate Ac from most other elements, providing a directly produced Ac product with measured ^{227}Ac content of (0.15 ± 0.04)%. A second, indirectly produced Ac product with ^{227}Ac content of <7.5 × 10^{-5}% is obtained by repeating the final extraction chromatography step with the ^{225}Ra-containing fraction. The ^{225}Ra-derived ^{225}Ac showed similar or improved quality compared to the initial, directly produced ^{225}Ac product in terms of chemical purity and radiolabeling capability, the latter of which was comparable with other ^{225}Ac sources reported in the literature.

Extremely low amount of Ac-227 < 7.5 x 10^{-7}

Chemical process at JOYO



Planned collaboration with Chemistry Division at JAEA (developing JOYO's process)

- Other challenging
  - Approval of nuclear fuel (Th) use at the facility (under discussion)

Summary

- Spallation neutron source has been progressed and has the capability to achieve at a level of multi MW.
- Still many issues remain at the target.
- J-PARC accelerator has demonstrated with 1 MW operation, which shows the possibility of multi-MW at the accelerator.
- ADS as an extreme high-intensity spallation neutron source will realize in the future.
  - Challenging accelerator and target systems
  - J-PARC will build a new facility for including ADS and material studies.

Thank you for attention

Memorial shot after completed beam test of 1MW for 1 h

