Investigation of High-power 4K Nb_3Sn Superconducting RF Electron Linac for Production of Medical Radioisotopes (WG3)

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The Asian Forum for Accelerators and Detectors in 2024 (AFAD2024)
National Synchrotron Radiation Research Center (NSRRC), in Hsinchu, Taiwan,
17-19 April 2024

Collaborator

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- **KEK**

  K. Umemori, H. Sakai, H. Ito, T. Yamada, H. Hayano,
  S. Shanab

- **NIMS (National Institute for Materials Science)**

  A. Kikuchi, S. Ooi, M. Tachiki, S. Arisawa

- **Kyushu University**

  F. Honda

東北大学

Center for Applied Superconducting Accelerator
応用超伝導加速器センター

NIMS

KYUSHU UNIVERSITY

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  - Electron source for SRF linac
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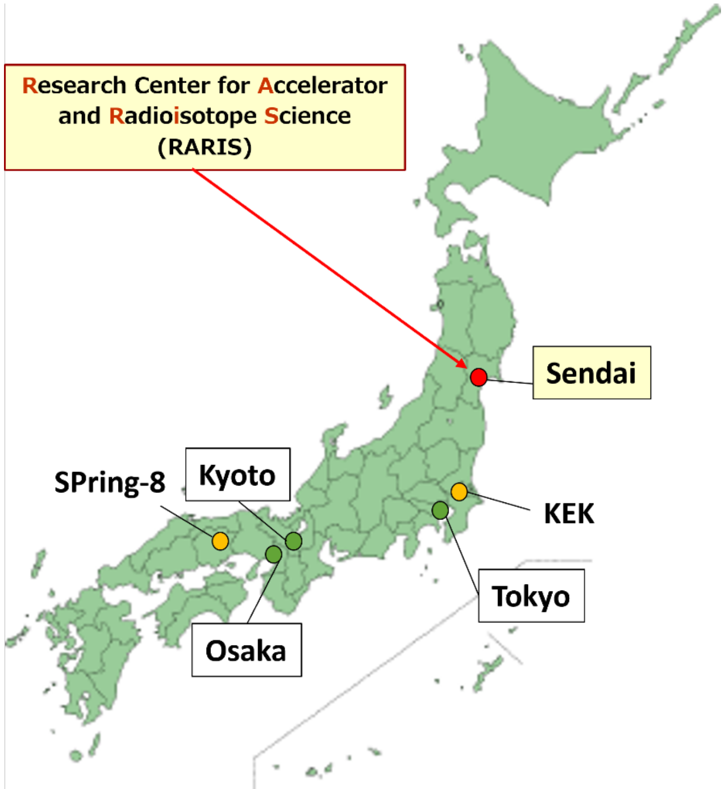
Research Center for Accelerator and Radioisotope Science (RARIS)

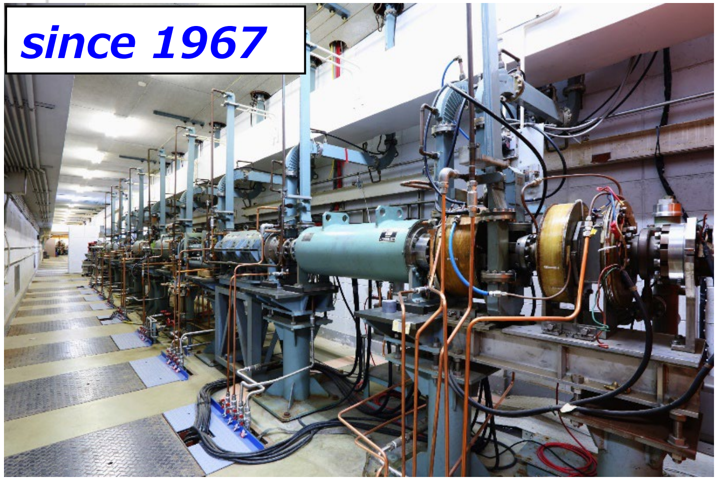


Apr. 2024

ELPH (Research Center for Electron Photon Science)

CYRIC (Cyclotron and Radioisotope Center)

RARIS



@Mikamine blanch (ELPH)

>> Basic studies of medical RI production using electron linac.

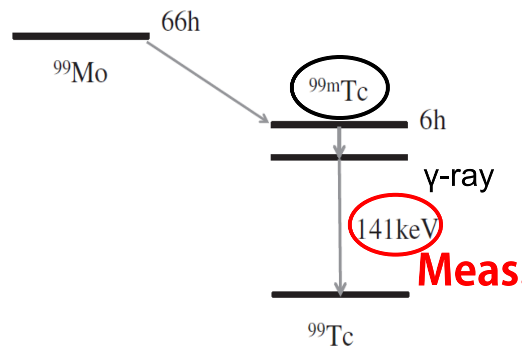
Beam energy: 10~60 MeV
Repetition: 300 pps
Ave. beam curr.: ~230 uA
=> Beam power ~10kW

Collaborative research

- **Basic studies of medical RI production using Electron Linac for Nuclear Medicine (diagnostics & Therapy).**

1) Production of ^{99}Mo/^{99m}Tc for SPECT.

SPECT (Single Photon Emission Computed Tomography)



2) Production of ^{225}Ac for Targeted Radionuclide/Alpha Therapy.

nihon medi+physics

HITACHI Inspire the Next

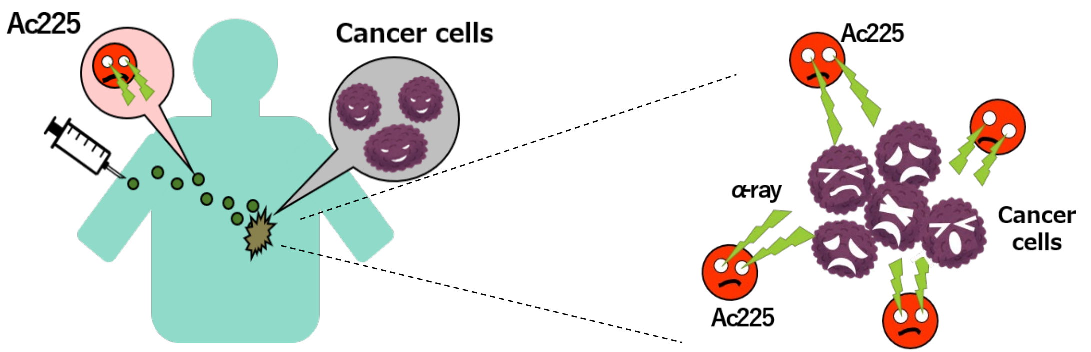
JFE

東京大学 THE UNIVERSITY OF TOKYO

KURNS

Targeted Radionuclide Therapy

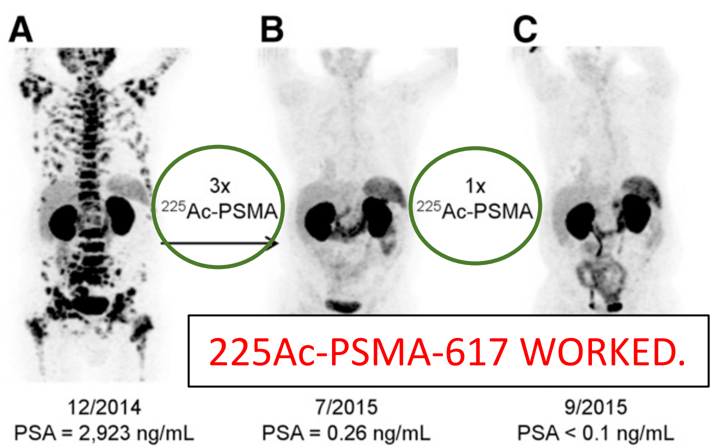
- **Targeted Radionuclide Therapy (TRT) using alpha-emitter is attracting attention as nuclear medicine.**



Administered Ac225 collects in active cancer cells.

α-rays with a short-range attack only cancer cells.

✓ **Heidelberg Univ., Germany (prostate cancer)**



Kratochwil, C. et al., J Nucl. Med., 2016, 57:1941-1944.

✓ ***The most promising alpha-emitter RIs***

^{211}At $T_{1/2}$ = 7 h

✓ ^{209}Bi(α, 2n)^{211}At *α-beam (30MeV)

^{225}Ac $T_{1/2}$ = 10 days

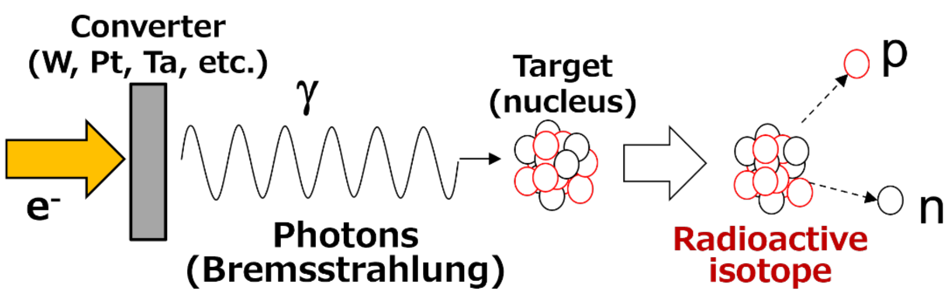
✓ **^{229}Th generator** ← "present"

JRC Karlsruhe：Germany
ONL（Oak Ridge National Lab）：USA
IPPE（Institute of Phys. and Power Eng.）：Russia
Total（3 institutes） <100GBq/year

RI production using electron linac

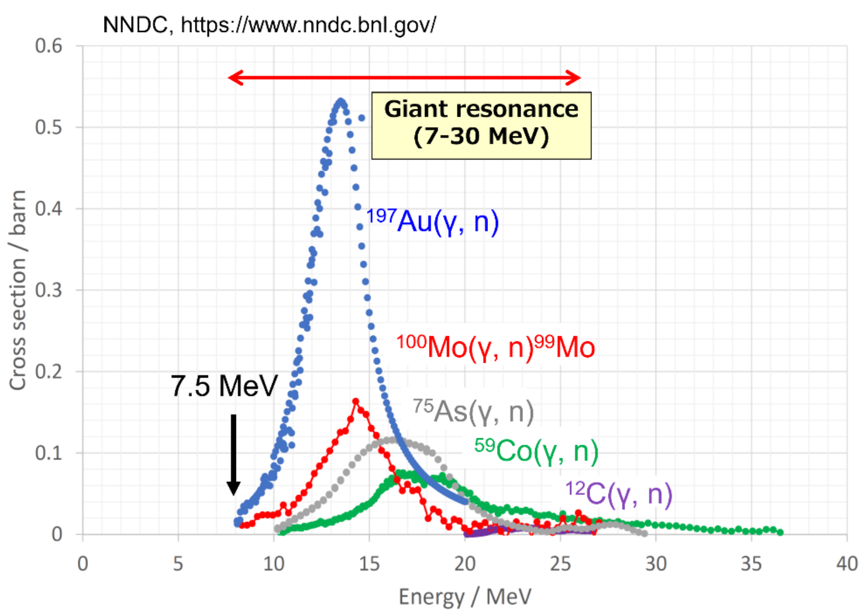
- **Radioactive isotopes** can be produced using nuclear reactor or accelerator.
- Bremsstrahlung is used in electron accelerator.

Photonuclear reaction

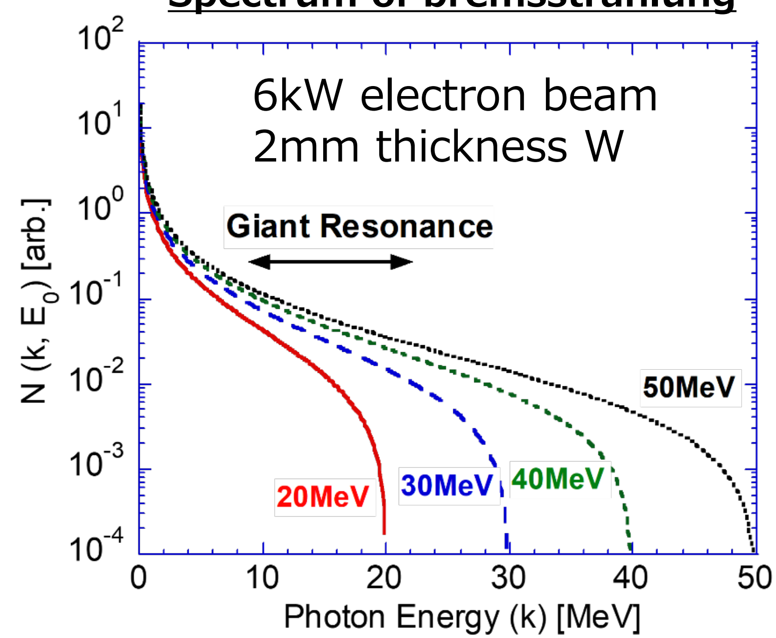


Target	Reaction	RI
Mo-100	$^{100}Mo(\gamma, n)^{99}Mo$ $^{99}Mo \rightarrow ^{99m}Tc + e$	Tc-99m
Zn-68	$^{68}Zn(\gamma, p)^{67}Cu$	Cu-67
Ge-70	$^{70}Ge(\gamma, 2n)^{68}Ge$ $^{68}Ge \rightarrow ^{68}Ga + e$	Ga-68
Ra-226	$^{226}Ra(\gamma, n)^{225}Ra$ $^{225}Ra \rightarrow ^{225}Ac + e$	Ac-225

Photonuclear reaction

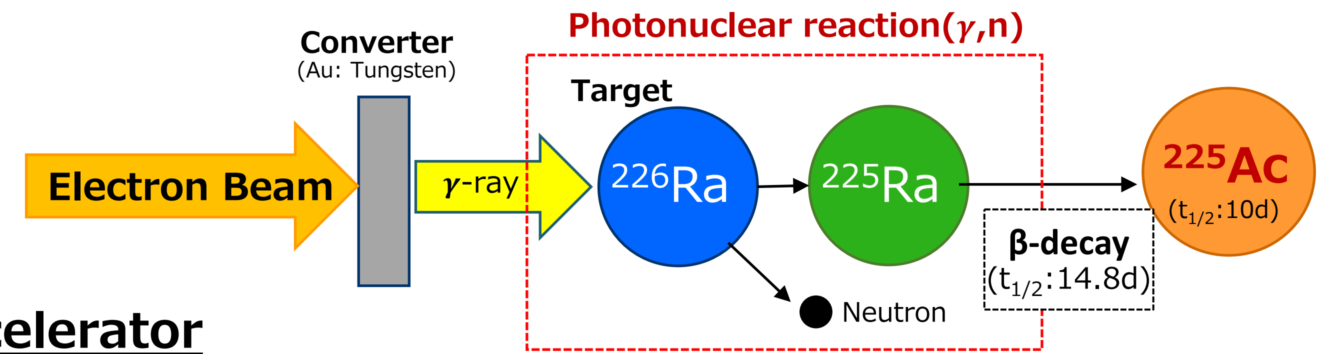


Spectrum of bremsstrahlung



Production of ^{225}Ac

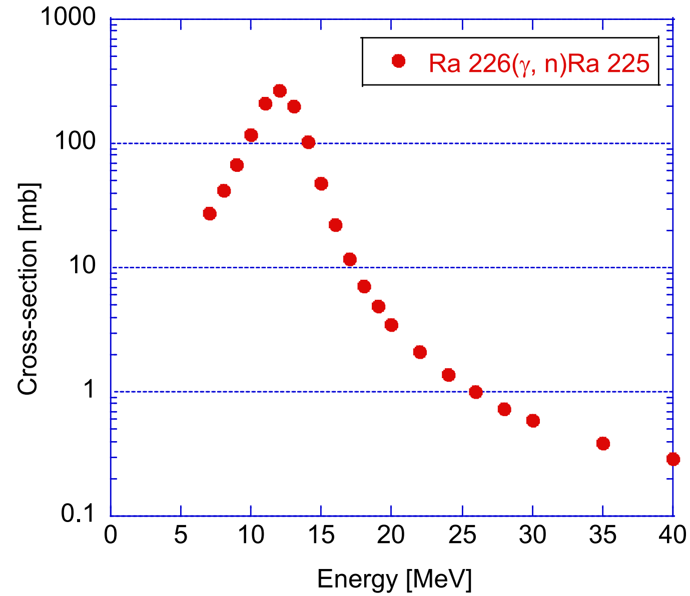
- **We are focusing on Ac225 production.**



Electron accelerator

- **The reaction cross section is relatively large, several hundred mb.**
- **Ac-225 (produced nuclide) is produced by the beta-decay of Ra-225 (half-life 14.8 days).**
- **Beam energy of about 35 MeV is acceptable. => compact**
- **Can be scaled up by the electron beam power & amount of 226Ra.**
- **No impurity nuclide(^{226}Ac or ^{227}Ac) are produced by photonuclear reaction.**

Theoretical cal. (No exp. data)



*https://tendl.web.psi.ch/tendl_2017/gamma_html/ Ra/GammaRa226xs.html

Other accelerator-based production

Large cyclotron

- **^{232}Th(p, spall) ^{225}Ac *Cyclotron(>100MeV)**
- **^{226}Ra(p, 2n) ^{225}Ac *Cyclotron(<25MeV)**

Impurity nuclides are produced
Protons have a short range in the target.

High power electron linac

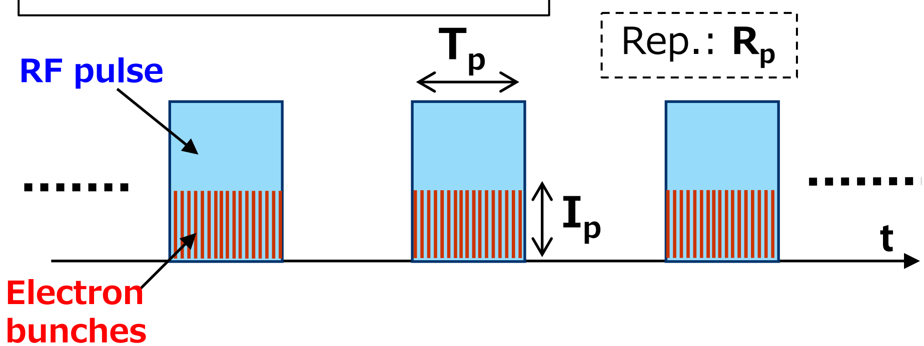
■ <u>High average currents</u> are effective for mass production of RI.

Beam power: $P[\mathrm{W}] = V_a[\mathrm{V}] \times \boldsymbol{I_{ave}}[\mathbf{A}]$

Average current: $\boldsymbol{I_{ave}}[\mathbf{A}] = I_P[\mathrm{A}] \times T_P[\mathrm{s}] \times R_P[\mathrm{Hz}]$

- Peak current in pulse (I_p)
- Pulse width (T_p), Pulse repetition (R_p)

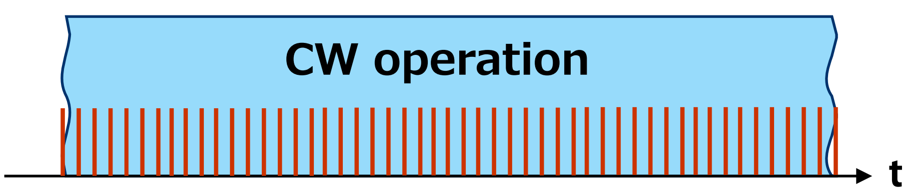
Normal-conducting



- ☐ Average beam current is limited by the duty of RF source. (**~a few mA**)
- ☐ Easy operation and maintenance

Super-conducting

$$T_P[s] \times R_P[Hz] \Rightarrow 1$$



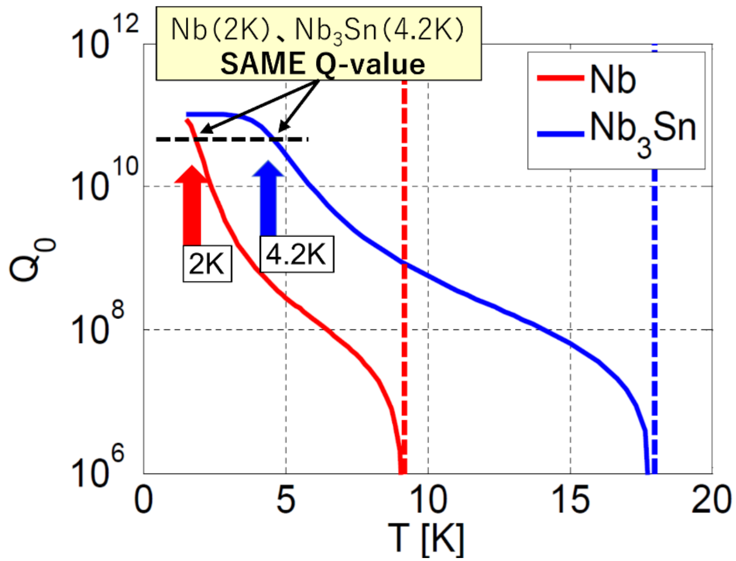
- ☐ SRF linac can be operated in **CW mode**.
- ☐ Issues: Cavity cooling and maintenance
  Startup and shutdown takes time
- ☐ Still difficult for commercial use.

The most significant obstacle to operating the 2K SRF cavities is the large amount of liquid helium required.

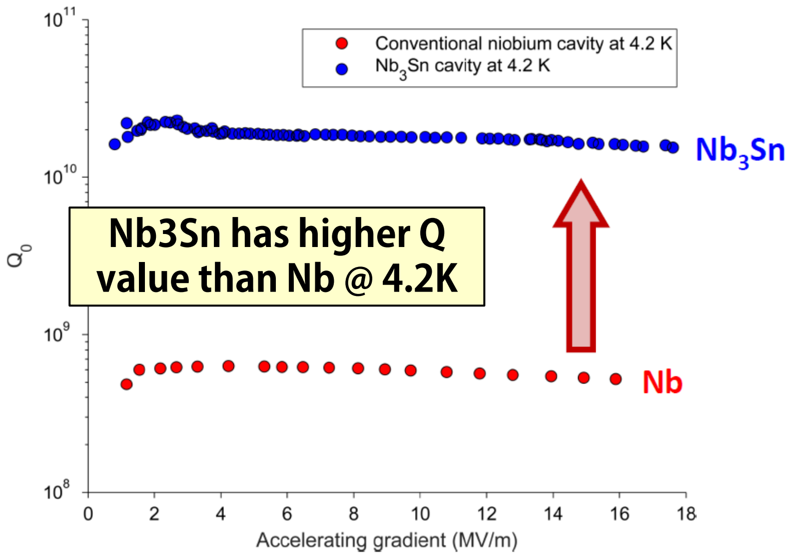
Nb_3Sn Superconducting

Nb_3Sn

- Higher critical temperature (Tc=18K) .
- 4K operation available.
  - No liquid helium required.
    - ➔ No need for large scale cooling facilities.
    - ➔ Can be used in small facility such as University.
  - GM cryocooler can be used.
    - ➔ Easy operation
- Higher Q-value (lower surface resistance) compared to Nb.



S. Posen, M. Liepe, and D. L. Hall, Appl. Phys. Lett. **106**, 082601 (2015); https://doi.org/10.1063/1.4913247

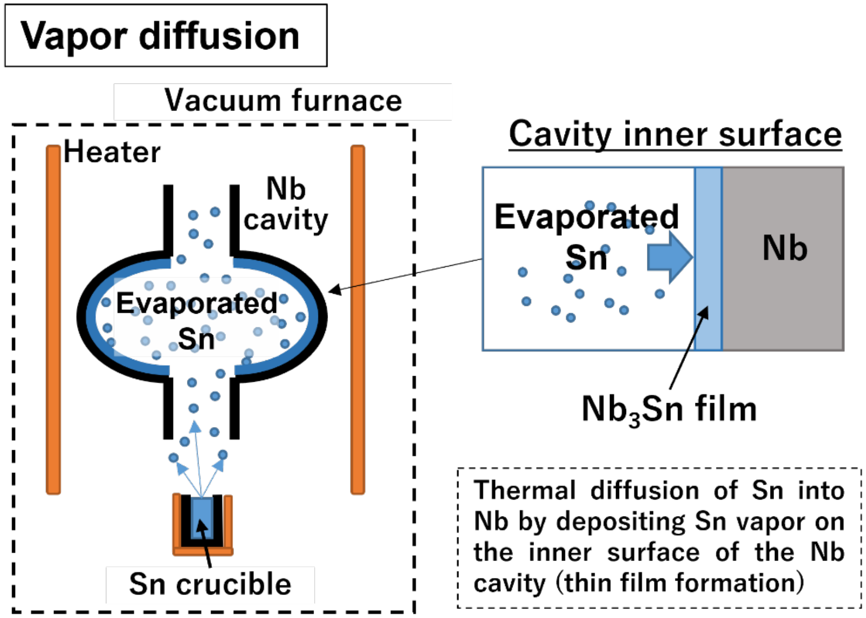


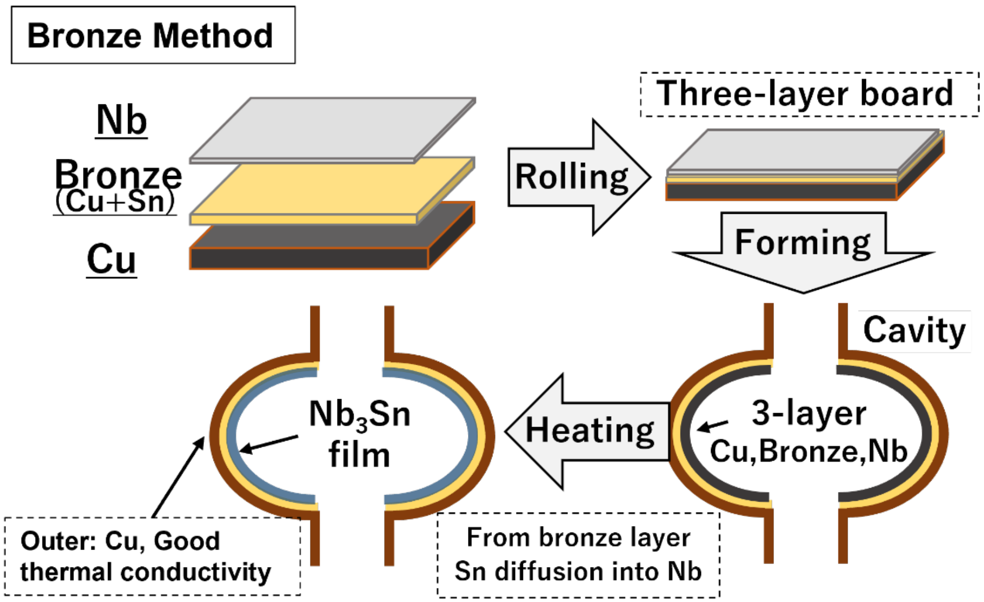
S. Posen et al., Applied Physics Letters 106, Issue 8 (2015).

Development of Nb_3Sn RF cavity

- **Nb3Sn cavities are being developed worldwide.**

- **The two methods are being studied in our collaboration.**
  - **Vapor-diffusion (KEK: H. Ito)**
  - **Bronze process: Roll-Processed (NIMS: A. Kikuchi)**
    Electroplating (KEK: H. Ito, H. Hayano)





Studies of Nb_3Sn thin film

- **Research and development on Nb3Sn thin film formation is being conducted by the collaborators.**

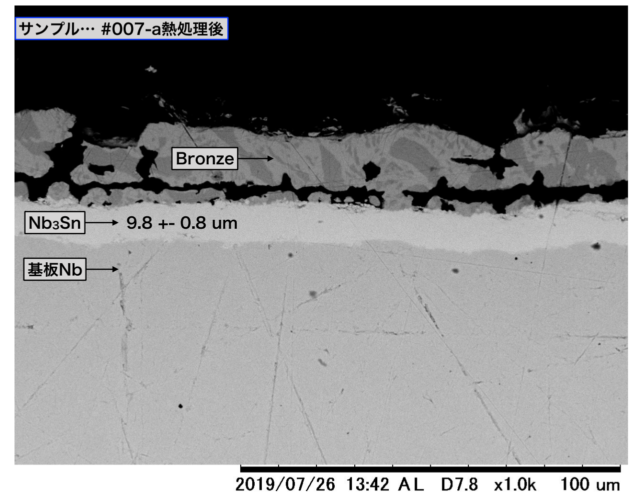
✓ **Inside of 1.3GHz cavity after coating by the Sn vapor diffusion method @KEK.**

✓ **Measured Q_0 value achieved 1.0×10^{10}.**

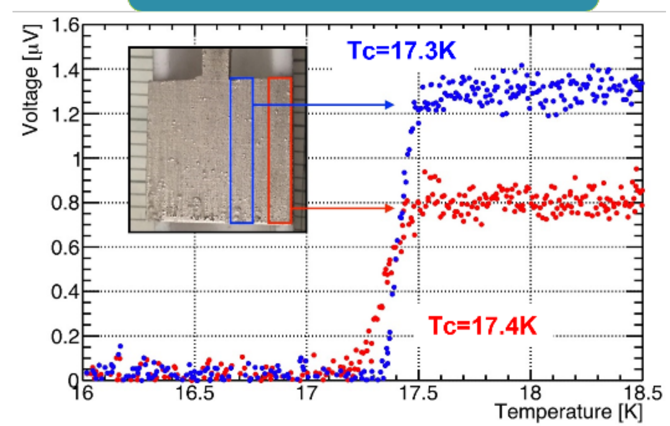
H. Ito et al., Proc of 21th Int. Conf. RF Supercond. (SRF2023), TUPTB014, pp414-418

✓ **Dr. Kikuchi (NIMS) succeeded in developing a multi-layer plate (Cu-Bronze-Nb). The plates will be used to make a cavity in 2024.**

✓ **Nb3Sn sample produced by the electroplating method.**



KEK sample T_c measured

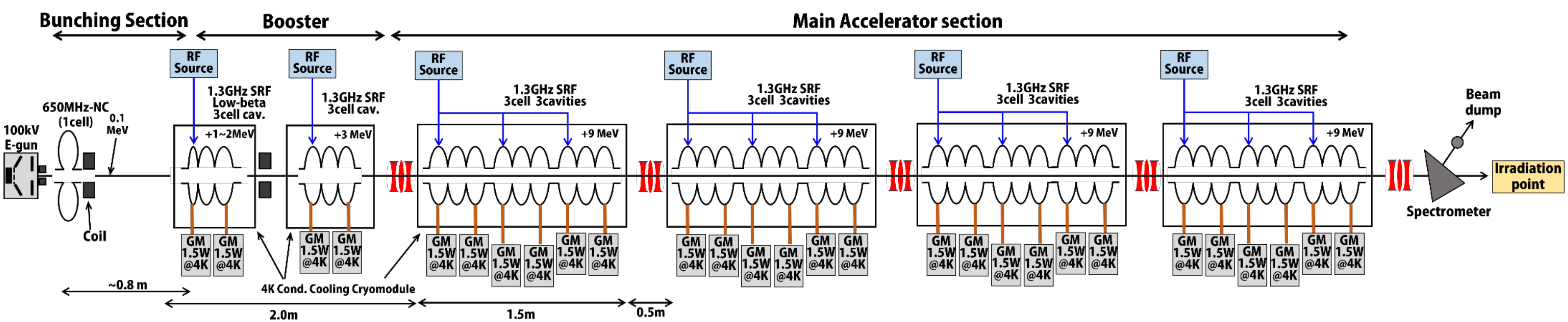


Configuration of 4K SRF Linac

- **Design study of a high-power electron linac using 4K superconducting technology has been started.**

  - **DC thermionic gun** (100keV) with fast grid pulser
  - Normal RF single cell buncher (650 MHz)
  - **Nb3Sn SRF cavity** (1300GHz)
    - 3cell low-beta cavity x (1~2MeV)
    - 3cell buncher cavity x (~3MeV)
    - 4 module (3cell x 3cavities) 9MeV x 4)

Beam power : 400 kW
Beam energy= 40 MeV
Average current = 10 mA
Bunch charge = 100pC
Rep. =100 MHz



Key issues:

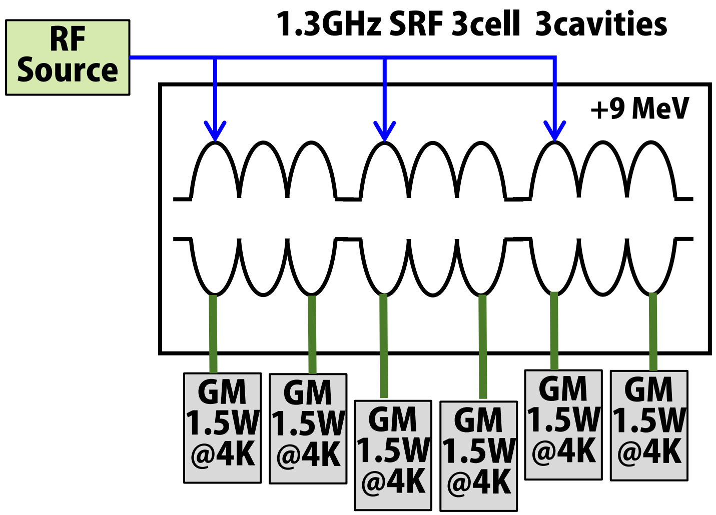
1. **Nb3Sn superconducting cavities , conduction cooling system.**
2. **Electron gun capable of producing a continuous series of electron bunches with high repetition rates.**

Cryomodule of 4K SRF linac

- Energy gain: 1MeV/cell (cell length=0.115m, Ea ~8.7MV/m)
- Dynamic loss (3cell, 1cavity) $P_c = \frac{V_c{}^2}{(r/Q)\cdot Q_0} = 2.7\ [\mathrm{W}]$

$$\left(V_c = 3\ MV, r/Q = 333,\ Q_0 = 1 \times 10^{10}\right)$$

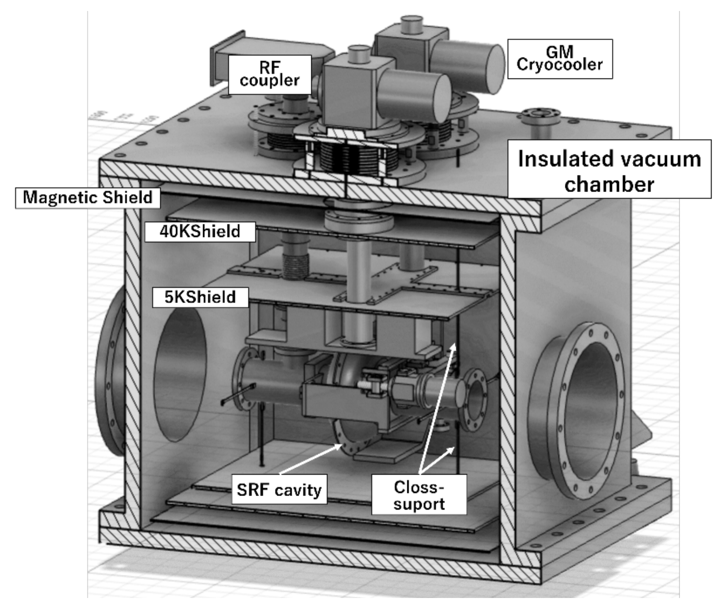
- Required two GM cryocoolers (1.5W@4.2K) for 3cell cavity
- Input power for 3cell cavity: ~30kW (Required development)



- ✓ Cryocooler: 7kW/unit x (2x3x4+4) =196W
- ✓ 1.3GHz RF source =400/0.5 = 800kW
- ✓ Total power = 196+800 ~ 1000 kW

Power efficiency ~ 40 %

Cryomodule for 1.3 GHz single-cell cavity



Design by T. Yamada (KEK)

Electron gun for SRF linac

Requirements for electron guns for SRF linac

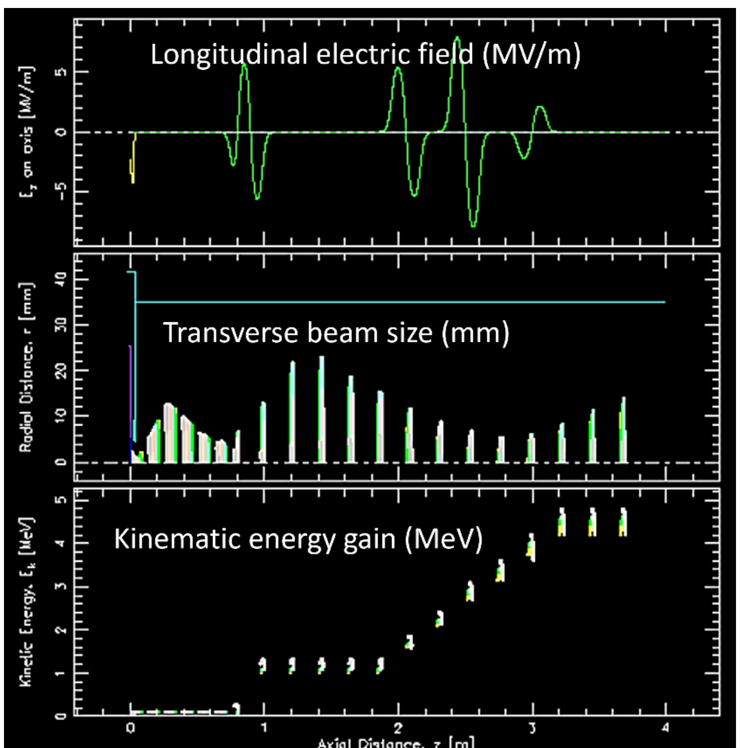
- **Continuous-pulsed beam (High repetition & short bunch)**
- **Robustness and reliability**

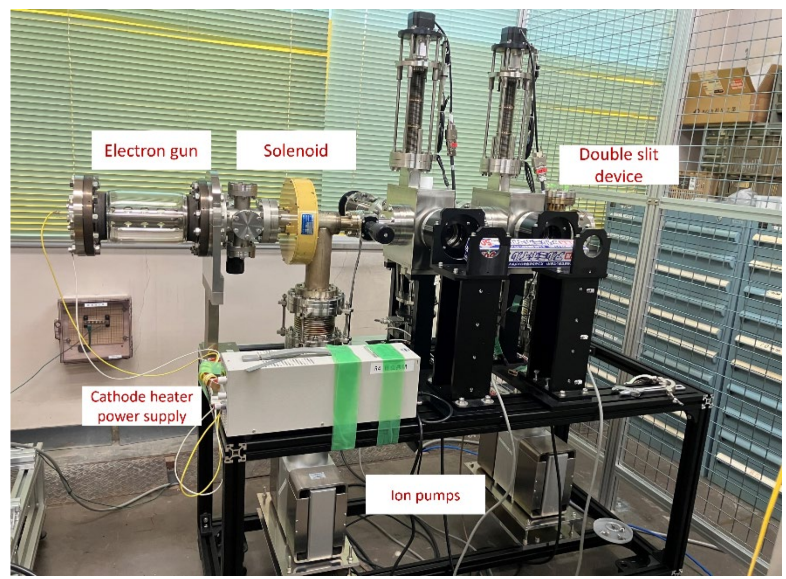
Cathode (Y646B , CPI)

Commercially available

- ***DC high-voltage***
- ***Gridded thermionic cathode***
- ***Fast grid pulser for cathode grid***

HV = 100kV, Initial pulse length = 170 ps (rms)





A test bench for electron guns is being constructed for the beam characteristic measurement.

Summary

- We are conducting the basic research for RI production using electron linac (normal conducting S-band). Suitable beam energy for RI production via photo nuclear reaction is about **30~40MeV.**
- To realize large-scale RI production, we have started development of a **Nb_3Sn SRF linac that can be operate at 4K** with high average beam current.
- 400kW, R226(4.3g). 20 h irradiation: ~1TBq (20MBq/person)
- The basic design of a 400 kW **Nb_3Sn SRF linac** is under development.
  - DC thermionic gridded electron gun (robust and reliable)
  - Nb_3Sn SRF and its conduction cooling system
- **S-band (2856 MHz) Nb_3Sn SRF cavity (single cell) with conduction cooling** is constructed by vapor diffusion process. The Nb_3Sn cavity will be installed in a beamline (t-ACTS) at Tohoku University, where beam acceleration will be demonstrated in 2025.

Acknowledgement

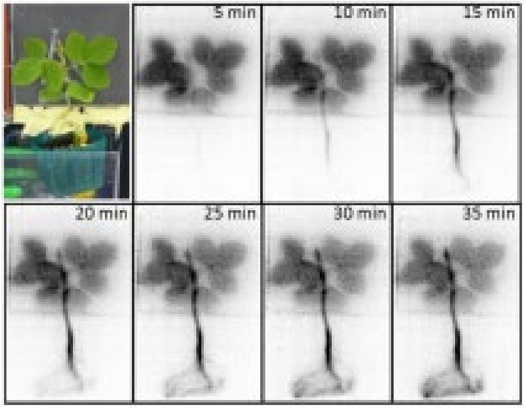
We would like to thank all the collaborators. This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research(A), Grant Number 23H00101.

Backup slides

Applications of radioisotope

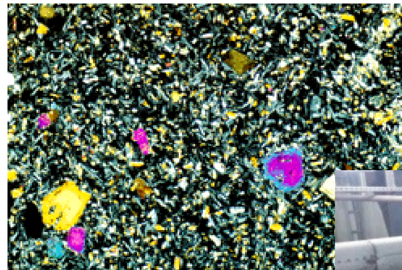
- **RIs are useful for various basic research.**

Tracer



Imaging of water absorption

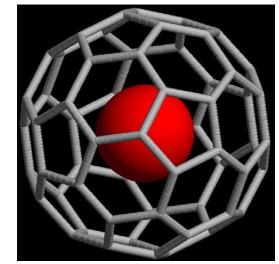
Nuclide Identification



Materials in Igneous rock

Metals in Household waste

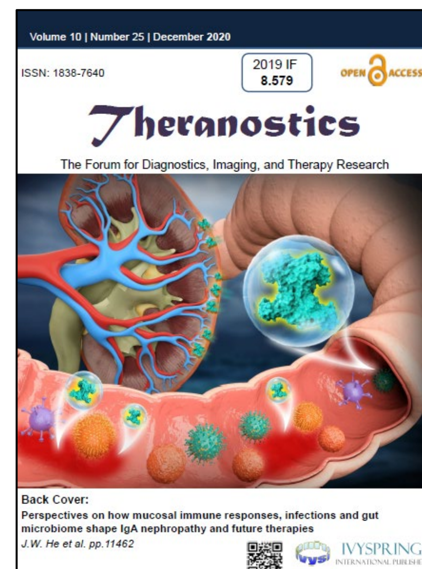
Exploring Chemical properties



Endohedral promethium-fullerene

- **RIs are applied to Nuclear Medicine & Therapy**
  - ✓ **Diagnostics**
    - γ emitter -> SPECT ^{99m}Tc
    - β^+ emitter -> PET ^{18}F, ^{68}Ga
  - ✓ **Therapy (Therapeutics)**
    - β emitter
    - α emitter
    - Auger electron

Diagnostics + Therapy -> **"Theranostics"**



https://www.thno.org/

Power efficiency (Normal-Cond.)

Power flow & efficiency (ex. S-band linear accelerator)

AC power

P_{AC}

Pulse modulator — $\eta_M \cong 80\%$

Microwave source (Klystron) — $\eta_K \cong 40\%$

Transmission Line (waveguide system) — $\eta_T \cong 90\%$

$\eta_{RF} \cong 29\%$

$$P_{RF} = \eta_{RF} P_{AC} = \eta_M \eta_K \eta_T P_{AC}$$

Accelerating Structure with beam loading — $\eta_S \cong 50\%$ (max ~70%)

Optimization

- Structure parameters (r, τ, t_f)
- RF-pulse length (ratio: T_p vs t_f)
- Beam parameters (Ip, Tp, Rp)

*T_p should be sufficiently longer than t_f.

$$P_B = \eta_S P_{RF} = \eta P_{AC}$$

Electron beam

Efficiency(η): ~15 % (ELPH ~6%)

Total efficiency: 10~12 % (*Cyclotron: 8~13%)

High power electron accelerator

MEVEX

Canadian Isotope Innovations Corp. Saskatoon
used for Mo99 production

35MeV, Nor. ~40kW
(up to 120kW)
Variable energy !!

Rhodotron(IBA)

iba

Up to 40MeV (12 passes)
3.1mA 125kW (Pulsed)

Ac-225 as Radiopharmaceutical

Requirements for α-emitter RI in clinical use

1. **Appropriate Half-life** (neither too short nor long)
2. Able to be **labeled by ligands (for TAT/TRT)**

~400 RIs emitting α-ray in (> Z=82)
Only 10 candidates
(^{149}Tb, ^{211}At, ^{224}Ra, ^{225}Ac,^{213}Bi etc)
for clinical development

The most promising alpha-emitter RIs

^{211}At $T_{1/2}$ = 7 h

✓ ^{209}Bi(α, 2n)^{211}At *α-beam (30MeV)

^{225}Ac $T_{1/2}$ = 10 days

✓ ^{229}Th generator ← "present"

JRC Karlsruhe：Germany
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IPPE (Institute of Phys. and Power Eng.) :Russia
Total (3 institutes) <100GBq/year

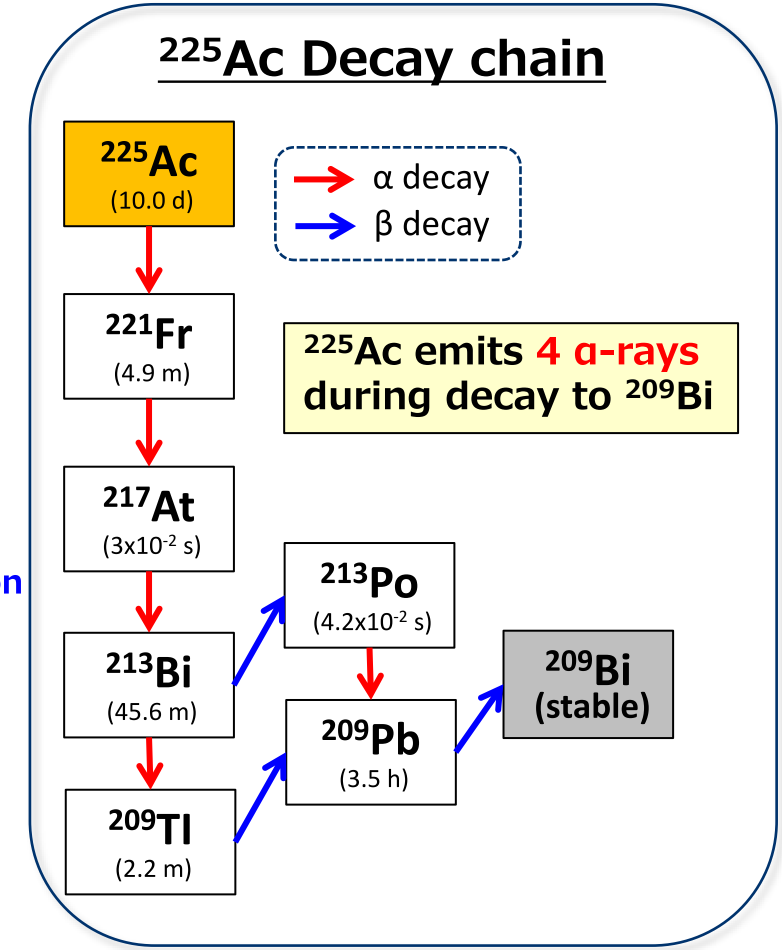
Large cyclotron

✓ ^{232}Th(p, spall) ^{225}Ac *cyclotron(>100MeV)

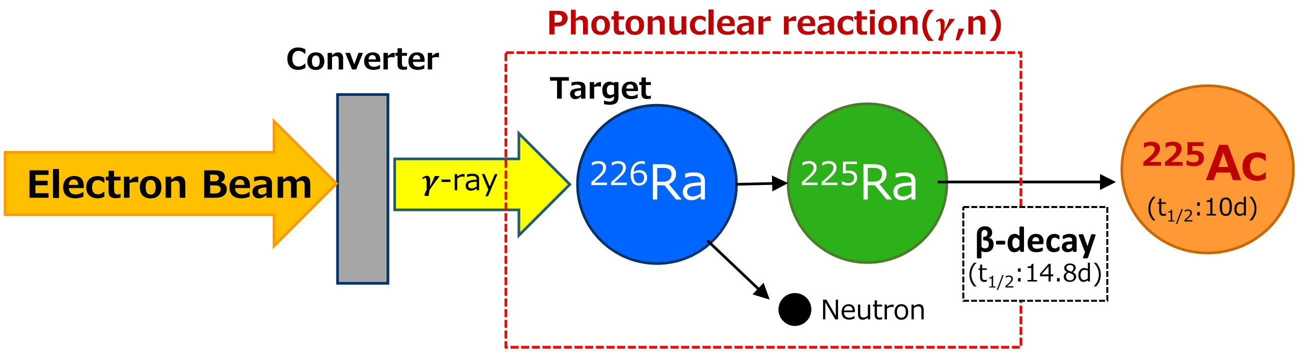
✓ ^{226}Ra(p, 2n) ^{225}Ac *cyclotron(<25MeV)

impurity nuclides are produced

✓ ^{226}Ra(γ, n) ^{225}Ra → ^{225}Ac
*Electron linac (~35 MeV)



Production of ^{225}Ac



$^{226}Ra(\gamma, n)\ ^{225}Ra \rightarrow\ ^{225}Ac$

No experimental data of cross-section, only theoretical calculation

< Advantages>

- Cost-effectiveness, Compact
- Can be scaled up by **the electron beam power & amount of ^{226}Ra**.
- **No <u>^{226}Ac or ^{227}Ac</u>** are produced by photonuclear reaction.
  (Impurity nuclide)

<Challenges>

- **Handling of ^{226}Ra target which decays to ^{222}Rn.**
- **Separation of ^{225}Ac from ^{226}Ra and ^{225}Ra.**

<u>Study Items</u>

- ✓ **^{225}Ac production test with different electron beam energy. (Cross-section)**
- ✓ **Target studies (^{226}Ra handling).**
- ✓ **Establish the chemical process of ^{225}Ac separation.**
- ✓ **"Scale studies" of ^{225}Ac production.**
  (In actual ^{225}Ac production, it is necessary to irradiate "GBq" order of ^{226}Ra at one time.) 10 [kBq] => 10 [MBq] ----> 10 [GBq]