ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-THPB085

DEVELOPMENT OF HIGH-POWER 4K NB$_3$SN SUPERCONDUCTING RF ELECTRON LINAC FOR MEDICAL RADIOISOTOPE PRODUCTION

S. Kashiwagi[†], A. B. Kavar, K. Shibata, H. Abiko, F. Hinode, H. Hama, K. Kudo, T. Muto,
K. Nanbu, I. Nagasawa, K. Takahashi, H. Yamada,
Research Center for Accelerator and Radioisotope Science, Tohoku University, Sendai, Japan
K. Umemori, H. Sakai, H. Ito, T. Yamada, S. Shanab, KEK, Tsukuba, Japan
A. Kikuchi, S. Ooi, M. Tachiki, S. Arisawa, NIMS, Tsukuba, Japan

Abstract

Various radioisotopes (RIs) are used in the field of nuclear medicine for diagnosis, such as PET and SPECT. In recent years, RIs are applied to therapy of cancer and the actinium-225 has been confirmed to be effective in the therapy of advanced cancer. One of the promising RI production methods for medical application is the use of high-intensity beam in accelerators. In the case of an electron accelerator, a photonuclear reaction is used in the RI production process. We have started research and development of a 4K niobium-tin (Nb$_3$Sn) superconducting RF (SRF) electron accelerator system for RI production, which can be operated with a compact conduction cooling system and does not require a large-scale cooling system. As a first step, we plan to develop a single-cell Nb$_3$Sn superconducting cavity and a cryomodule, and to demonstrate its performance by beam acceleration experiments. In this presentation, we report the basic design of the SRF electron linear accelerator (linac) and R&D of Nb$_3$Sn SRF cavity.

INTRODUCTION

Radioisotopes (RIs) are widely used in nuclear medicine for nuclear diagnosis. In recent years, the use of RIs for medical use has taken a new development from diagnostics to therapy, as evidenced by the confirmation of the efficacy of RI-based internal therapy (Radionuclide Therapy, RNT) in therapy for cancer. In particular, the radionuclide therapy using actinium-225 (^{225}Ac), an α-emitter RI, is attracting worldwide attention as a therapy for advanced cancer [1]. At present, ^{225}Ac can only be produced with less than 100 GBq per year by a radioactive decay from thorium-229 (^{229}Th) at research institutes in Germany, the U.S., and Russia. Three times doses of nuclear pharmaceuticals for one patient requires 20 MBq of ^{225}Ac, therefore, it is difficult to deploy a full-scale radionuclide therapy worldwide at the current production rate. Medical RIs can also be produced using nuclear reactors and particle accelerators. Advantage of accelerator-based RI production can produce the required amount of RI when it is necessary. The ^{225}Ac can be produced by the reaction of ^{226}Ra(p, 2n) ^{225}Ac using proton beam. The amount of production cannot be increased by using the high intensity beam or a thick target, since the proton beam has a short range in a target material. On the other hand, in the case of ^{225}Ac production by photonuclear reaction (γ, n) using electron beams, the amount of RI production can be increased by using a high current electron beam and a thick target (Fig. 1). The advantage of this method using electron beam is that there are fewer impurities (unnecessary isotopes).

To achieve mass production of medical RIs using an electron accelerator, we have started research and development of a 4K niobium-tin (Nb$_3$Sn) SRF electron linac capable of high-current beam acceleration. From the development of SRF cavities in the United States, it is known that, in the case of a Nb$_3$Sn SRF cavity, the performance (Q_0) is almost equivalent to that of a bulk niobium SRF cavity cooled to 2 K by cooling the cavity to 4 K which can be achieved by conduction cooling [2]. Since a Nb$_3$Sn SRF cavity does not require a large-scale cooling plant, it is possible to construct a superconducting accelerator even in small facilities such as universities. As a first step, we plan to fabricate the S-band single-cell Nb$_3$Sn SRF cavity and build cryomodule with a conduction cooling for the SRF cavity. Experiments will be performed to demonstrate a beam acceleration using the Nb$_3$Sn cavity.

In this paper, we describe the basic design of the 35 MeV SRF linac for RI production and the demonstration of beam acceleration using the Nb$_3$Sn cavity.

RADIOISOTOPE PRODUCTION BASED ON ELECTRON ACCELERATOR

Bremsstrahlung γ-ray photons are generated by electron beam injecting a heavy metal such as platinum (Pt) or tantalum (Ta). Photonuclear reactions occur when atomic nuclei are exited via the capture of incident photons and relax by emitting one or several elementary particles or nuclei fragments. For photon energies below 30 MeV near the Giant Dipole Resonance (GDR), that are generally used for photonuclear production of Ris production [3].

In the production of ^{225}Ac using an electron beam, radium-226 (^{226}Ra) is irradiated with γ-rays to produce radium-225 (^{225}Ra) by photonuclear reaction, and then ^{225}Ac is produced by its β-decay. The photonuclear reaction cross section of ^{226}Ra is shown in Fig. 2 [4]. For efficient RI production, a large number of γ-ray photons around

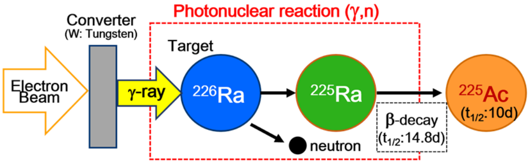

Figure 1: Actinium-225 (^{225}Ac) production via photonuclear reaction.

[†] kashiwagi@raris.tohoku.ac.jp

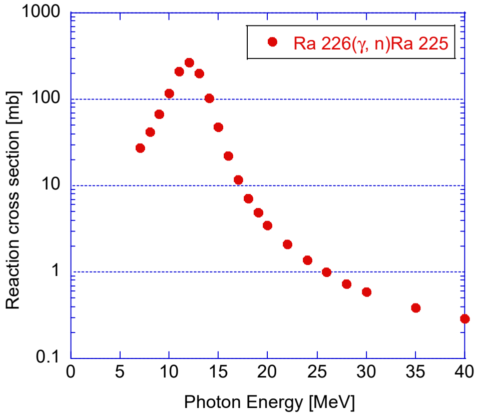

Figure 2: Cross section of photonuclear reaction of ^{226}Ra (γ, n)^{225}Ra [4].

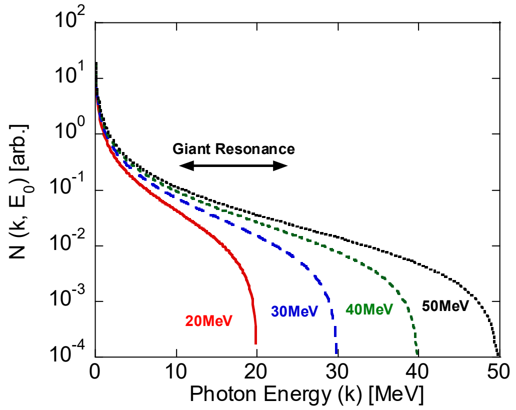

Figure 3: Bremsstrahlung spectrum with different electron beam energy [5].

10-20 MeV must be produced by the electron beam. Figure 3 shows the bremsstrahlung spectra of electron beams with different energies of electron [5]. Although higher energy electron beams can produce more γ-rays near the GDR, electron beams of 35-40 MeV are more suitable for RI production by photonuclear reactions because higher energy γ-rays produce unnecessary reactions that are not main reactions.

If an electron beam of 100 kW (35 MeV, 3 mA) is irradiated to ^{226}Ra (4.33 g) for 20 hours, approximately 230 GBq (enough for 10,000 patients) of ^{225}Ac can be produced in one irradiation. This will enable mass production and stable supply of the medical RI.

NIOBIUM-TIN SRF ELECTRON LINAC

SRF Electron Accelerator

High current electron beams with suitable energy are required for the mass production of RI. In a normal-conducting electron linac, the RF duty cycle is limited to about 0.1% because of pulsed operation due to the RF power loss in the accelerator cavity. Therefore, the average beam current in a normal-conducting electron linac is limited to about 1 mA.

On the other hand, in the case of superconducting electron linac, the Q-value of the cavity is on the order of 10^{10}, so there is no temperature rise of the cavity due to RF power loss, and continuous wave (CW) operation, in which RF is continuously fed to the cavity, is possible, and the average current can be increased to 10 mA or more relatively easily. In addition, since the RF power feed to the SRF cavity is sufficient at several 10 kW, it does not need a large RF source such as a klystron, and a small solid-state amplifier is sufficient.

Niobium-Tin (Nb_3Sn) SRF Cavity

Currently, 1.3 GHz niobium (Nb) superconducting cavities, which are widely used in the world, especially in Europe and the United States, are cooled down to 2 K by superfluid helium. We are developing the Nb_3Sn SRF cavity in collaboration with KEK and NIMS, Tohoku University, to realize medical RI production using a SRF electron linac, which does not require the large amount of liquid helium.

Previous studies on Nb_3Sn SRF cavities, mainly in the U.S., have shown that when a Nb_3Sn SRF cavity is cooled to 4 K, the same Q value (= 10^{10}) can be obtained as when a niobium SRF cavity is cooled to 2 K [2]. 4 K can be reached using a small refrigerator such as a GM cryocooler and does not require liquid helium. It is free from the barrier of superconducting cavity cooling.

There are several methods for fabricating Nb_3Sn superconducting cavities, including the evaporation-deposition method [2,6], direct bronze plating on niobium [7] and the bronze method [8], in which three layers of copper, tin, and copper are plated on the niobium surface. In this study, we will fabricate S-band (2856 MHz) Nb_3Sn superconducting cavities for beam experiments by the evaporation- deposition method at KEK.

35 MeV Nb_3Sn SRF Electron Linac

A conceptual design of an electron accelerator with beam power exceeding 350 kW (35 MeV, 10 mA) for RI production was carried out. The overall configuration of the accelerator is shown in Fig. 4. The linac is consists of an electron gun, a low-β 3cell-buncher cavity, 3cell-booster cavity and main accelerator section. All RF cavities in the linac are operated at 1.3 GHz. The RF cavies are Nb_3Sn superconducting cavities with conduction cooling.

The electron gun is a thermionic cathode electron gun with a grid for robustness and reliability. A 100 kV direct current (DC) is applied between the cathode and anode of the electron gun, and the cathode grid is driven by rf gating pulses [9,10]. The electron bunch repetition rate is 1.3 GHz, which is the RF frequency of the main accelerator, the bunch charge is 8 pC, and the average beam current is about 10 mA. The initial bunch length output from the electron gun is 300 ps (FW). The low-β buncher compresses the bunch to around 30 ps (FWHM), and the booster cavity accelerates to 3.5 MeV. To optimize the longitudinal phase space distribution of the bunch, RF phase and amplitude of the low-β buncher cavity and the booster cavity can be controlled independently. In the main acceleration section, a cryomodule contain three 3-cell cavities.

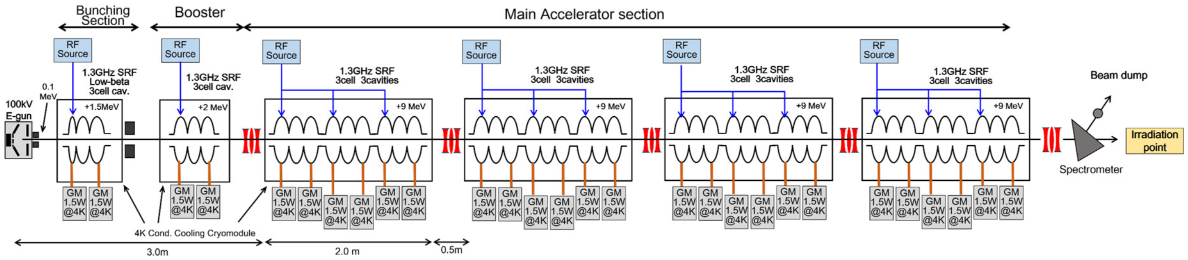

Figure 4: 35 MeV superconducting RF linac for RI production.

The cryomodule for SRF cavities was designed with assuming acceleration voltage of 1 MV per cell, and the acceleration gradient (E_{acc}) is 8.7 MV/m, since the acceleration length of one 1.3 GHz cavity cell is 115 mm, which corresponds to half wavelength of the 1.3 GHz RF. The heat load (dynamic loss) of 3-cell cavity is derived from the following formula.

$$P_C = \frac{{V_c}^2}{(R/Q)\cdot Q_0}, \tag{1}$$

where V_c is the acceleration voltage of 3MV and R/Q is proportional to the cavity length, $R/Q = 333$ and $Q_0 = 10^{10}$ based on the value of a 9-cell TESLA cavity. The heat load per 3-cell cavity is derived to $P_C = 2.7$[W]. Using the RDE-415D2 (1.5W@4.2K, SHI Ltd.) cryocooler for the cavity cooling, two GM cryocoolers are required for the 3-cell cavity. The first stage of the cryocoolers (35W@50K) is used for cooling of the 50 K thermal shield and couplers. The second stage connected to the cavity body. Since each GM cryocooler including a compressor of power consumption about 7.2 kW at 50Hz AC, the electric power required to cool one cryomodule is 7.2 × 6 = 43.2 kW for the four cryomodules in the main acceleration section, the power required is 172.8 kW. The electric power required to cavity cooling the low-β cavity and the one booster cavity in the injector part is about 28.8 kW. The total power for cavity cooling is estimated to be around 200 kW for cavity cooling.

Beam Acceleration Test of Nb_3Sn SRF Cavity

Beam acceleration test of a Nb_3Sn superconducting cavity will be performed at the test accelerator (t-ACTS) of the Research Center for Accelerator and Radioisotope Science (RARiS), Tohoku University [11]. The rf frequency of the accelerator cavity at t-ACTS is 2856 MHz of S-band, therefore a resonant frequency of the single-cell Nb_3Sn cavity set to 2856 MHz. A cryomodule for the S-band superconducting cavity is also developed with a conduction cooling using GM cryocooler. Figure 5 shows a preliminary design of cryomodule for S-band SRF cavity. The thermal links connect to the cavity body avoiding the equator part of the cavity. Conduction cooling tests of the cavity will be performed before installation in the beamline. Then, the microphonics caused by the GM cryocooler will be investigated in detail by measuring cavity vibration and fluctuations of resonance frequency.

In the beam experiments, a solid amplifier with a maximum output power of 200W and a pulse width of 100 ms with 1Hz will be used as the RF source for the cavity. The acceleration gradient (E_{acc}) is 20 MV/m, and the acceleration length (half-wavelength) of 52 mm per cell gives an acceleration voltage of V_c = 1.05 MV for one cell of the test cavity. In the beam test, an electron beam of 20 MeV is additionally accelerated by about 1.0 MeV (ΔE/E ~ 5%) by the Nb_3Sn SRF cavity. The energy gain can be measured as a change in beam position in the dispersion section (η = 0.4 m) downstream of the cavity.

CONCLUSION

We have started to study the SRF high-intensity electron accelerator (35MeV, 10mA, 350 kW) that will enable mass production of medical RI. In the case of a normal-conducting electron linac, the beam output power is limited to around 40 kW because the average current of beam is limited to about 1 mA. In the design study of Nb_3Sn superconducting electron linac, the electron source is the thermionic cathode electron gun with a grid, and the accelerating cavities are Nb_3Sn SRF cavities with conduction cooling that does not require a large cooling plant. The main accelerator consists of four cryomodules, each of which contains three 3-cell cavities, and the beam is accelerated up to 35 MeV. As basic studies, the single-cell S-band Nb_3Sn SRF cavity will be developed with a conduction cooling using the GM cryocooler. By the end of FY2025, a demonstration of beam acceleration will be performed using the S-band SRF cavity at t-ACTS in RARiS, Tohoku University.

ACKNOWLEDGEMENTS

This work is supported by JSPS KAKENHI Grant Numbers 23H00101, Grant-in-Aid for Scientific Research(A).

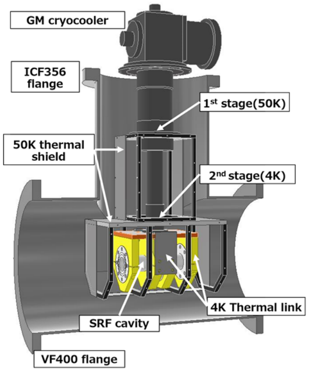

Figure 5: Cryomodule for S-band superconducting cavity.

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