DEVELOPMENT OF A COMPACT X-BAND ELECTRON LINAC FOR PRODUCTION OF Mo-99/Tc-99m

Jaewoong Jang†, Mitsuru Uesaka, The University of Tokyo, Tokyo 113-8656, Japan
Masashi Yamamoto, Accuthera Inc., Kawasaki, Kanagawa 215-0033, Japan

Abstract

In response to the need of alternatives to the exhausted research reactors supplying Mo-99/Tc-99m, we are developing a compact X-band electron linear accelerator (linac). As an initial step, beam dynamics simulations were performed and as a result electron beams of 35 MeV and 9.1 kW were obtained. We expect that sixteen linacs having these beam parameters can cover the demand of Tc-99m in Japan.

We found that the combination of X-band RF and high beam power can give rise to instability of beam loading. We will therefore adjust the beam power while keeping Mo-99 production efficiency as high as possible.

INTRODUCTION

In nuclear medicine, Tc-99m is the most widely used radionuclide due to its radiopharmaceutical versatility [1]. Medical Tc-99m is in general obtained from the beta decay of Mo-99, and more than 95% of the global demand for Mo-99 is met by only five research reactors [2].

As all of the five reactors aged over 40 years [2, 3], securing alternative source of Mo-99/Tc-99m production became an urgent agenda of the nuclear medicine society. A low enriched uranium (LEU) reactor, a cyclotron, and a large scale S-band electron linac, all of which share the idea of "concentrated production of Mo-99 (Fig. 1)", have been proposed as the alternative Mo-99 supplier [3].

Our group, on the other hand, is aiming at "distributed production of Mo-99 (Fig. 1)" with electron linacs that are downsized by X-band radio frequency (RF). Taking advantage of the compactness, our electron linacs can be installed at several districts and provide the local hospitals with Mo-99/Tc-99m in a more direct way. Photonuclear reactions will be used for producing Mo-99, which is discussed in detail in the last section.

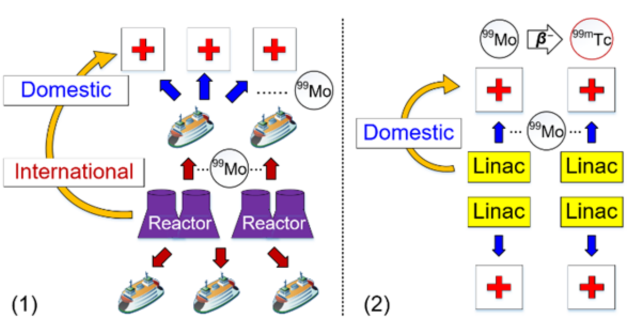

Figure 1: (1) Concentrated production and (2) distributed production of Mo-99/Tc-99m.

† jang@nuclear.jp

DESIGNING A COMPACT X-BAND ELECTRON LINAC

To design a compact X-band linac, beam loading curve was evaluated and simulations of beam dynamics were performed. The results will be explained following the basic characteristics of the compact linac.

Basic Features of X-band Linac

The production efficiency of Mo-99 improves when electron beams have either high energy or high current. However, as beam energy increases, the amount of impurity nuclides such as Nb-92m grows as well. Moreover, maximum beam current is limited by X-band RF. Taking these conflicts into account, we determined the basic features of the compact X-band linac as follows:

- X-band RF and side-coupled cavities are adopted.
- Beam energy will be 35 MeV.
- Targeted beam power is several kW.
- Two 6 MW X-band klystrons will be adopted.

Figure 2 shows a schematic design of the compact X-band electron linac.

Simple Analysis: Beam Loading Curve

First, we evaluated how large beam current can be obtained when electrons are accelerated up to 35 MeV. SUPERFISH was used to get accelerating voltage V_s and beam current I_b in a standing wave accelerator (Eq. (1)).

Because the side-coupled cavities are not axially symmetric, and SUPERFISH cannot calculate the effect of the coupling slot, the shunt impedance r_s was set to 80% of its SUPERFISH result. The results are shown in Table 1.

$$V_s = \left(2\sqrt{\beta}\sqrt{P_0 r_s L} - r_s L I_b\right)/(1+\beta) \quad (1)$$

Table 1: Parameters of Eq. (1) Obtained from SUPERFISH

	1st tube	2nd to 4th tubes
Q-value	6,082	6,757
Shunt impedance, r_s [MΩ/m]	109	122
Tube length, L [m]	1.0	1.0
RF power, P_0 [MW]	2.0	2.1
Coupling coefficient, β	2.5	2.5

By evaluating Eq. 1 with the values in Table 1, and using two 6 MW klystrons and four accelerating tubes, we obtained beam loading curve (see Fig. 3). According to the curve, the maximum beam current can be 160 mA at 35 MeV. Therefore, we set these beam parameters as the target values for beam dynamics simulation.

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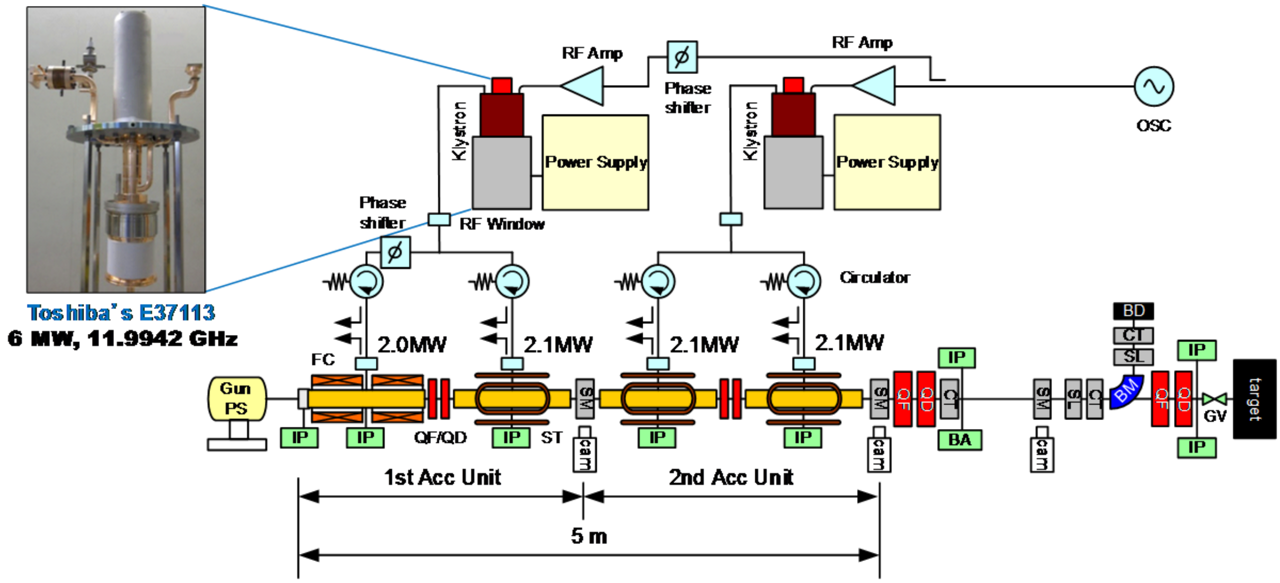

Figure 2: A schematic representation of the compact X-band electron linac. The klystrons are Toshiba's *E37113*.

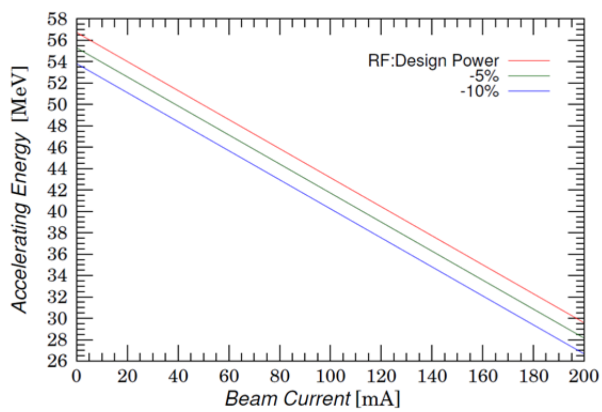

Figure 3: Beam loading curve.

The length of accelerating tubes was determined in such a way that power conversion between X-band RF and electron beams (or electron acceleration) is most efficient. The efficiency η can be expressed by rearranging Eq. (1):

$$\eta = \frac{V_s\left[2\sqrt{P_0 r_s L}\sqrt{\beta} - V_s(\beta + 1)\right]}{P_0 r_s L}$$

Using the values in Table 1 again, the acceleration efficiency η was evaluated. The efficiency increased sharply from L of 2 m, reaching the maximum at L of 3.1 m. From perspectives of manufacturing accelerating tubes and the compactness of the linac, we decided to use two accelerating units, each of which consists of two 1 m-long tubes (Fig. 2).

Detailed Analysis: Beam Dynamics

Next, we performed simulations for beam dynamics with General Particle Tracer (GPT) in order to verify whether the "beams of 35 MeV and 160 mA", which was the result of the beam loading curve, can be gained in the X-band linac. Of the results, acceleration phase, beam size, and beam energy distribution will be introduced.

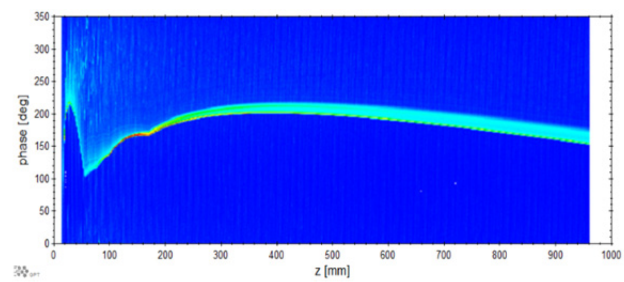

Figure 4: Acceleration phases of electron beams in the first accelerating tube.

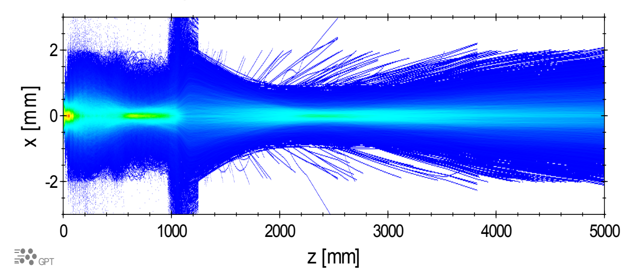

Figure 5: The size of electron beams.

The phase spread of the beam at the exit of the first accelerating tube was 20 degrees, which might be considered as a large error (Fig. 4). In the production of radionuclides, however, 20 degrees of phase spread should not pose a noticeable problem.

We also checked the electron beam size and confirmed the effect of the Q-magnet installed at around 1 m on the beam axis (Figs. 2 and 5).

We intended to install two Q-magnets at 1 m and 3 m on the beam axis, respectively. However, the second Q-magnet could not be placed in the GPT simulations due to technical problems, and as a result we obtained beam current of 130 mA, which was 30 mA lower than the target current of 160 mA (Fig. 6). It is expected that 160 mA can be obtained by placing the second Q-magnet in GPT simulations.

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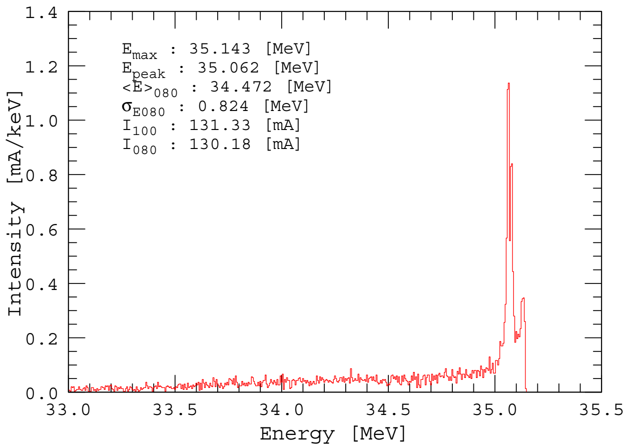

Figure 6: Energy distribution of electron beams at the exit of the last accelerating tube.

In summary, it was found that electron beams of 35 MeV and 130 mA can be obtained from our compact X-band linac. Also, since RF pulses of 4 μs and 500 pps are produced from *E37113* (Toshiba's X-band klystron [4]), the duty factor is 0.002, and hence the average beam power is 9.1 kW.

PRODUCTION OF MEDICAL RADIO-NUCLIDES WITH ELECTRON LINACS

To produce medical radionuclides from an electron linac, photonuclear reactions will be utilized. Our approach of electron linac based radionuclide production is explained in this section.

Photonuclear Reactions

In the X-band linac, electron beams will be accelerated up to 35 MeV, and interact with high-Z target material such as W or Ta, from which braking radiation or bremsstrahlung will be generated. The braking radiation will then initiate photonuclear reactions to produce radionuclides of interest:

$$^{A}_{Z}\mathrm{X}(\gamma, x\mathrm{n})^{A-x}_{\ \ Z}\mathrm{X} \tag{2}$$

$$^{A}_{Z}\mathrm{X}(\gamma, x\mathrm{p})^{A-x}_{Z-x}\mathrm{Y} \tag{3}$$

where *x* in *x*n of Eq. (2) is the number of ejected neutrons as a result of the photonuclear reaction, or simply the number of photoneutrons. Likewise, *x* in *x*p of Eq. (3) is the number of photoprotons.

Depending on cross sections for photonuclear reactions, radiochemical properties, and beam energy and power, a variety of radionuclides can be produced by a linac photon source. Examples include ^{68}Zn(γ,p)^{67}Cu, ^{178}Hf(γ,p)^{177}Lu, and ^{189}Os(γ,p)^{188}Re, all of which are being studied by our collaborative research group [5].

For the production of Mo-99 via photonuclear reaction, Eq. (2) can be rewritten as

$$^{100}_{\ 42}\mathrm{Mo}(\gamma, \mathrm{n})^{99}_{42}\mathrm{Mo}$$

Giant dipole resonance (GDR) of the photonuclear reaction of Mo-100 occurs at around 15 MeV photon, and the corresponding cross section is around 0.16 b.

Mo-99 Production Capacity of X-band Linac

When a radionuclide of interest, i, is obtained from the radioactive decay of its parent radionuclide, denoted by $i-1$, the Bateman equation for the daughter nuclide i is expressed as [6]

$$A_i(t) = N_i{}'(t) = \lambda_{i-1}N_{i-1}(t) - \lambda_i N_i(t) \tag{4}$$

Let $i = 2$, then the general solution to Eq. (4) is given by

$$A_2(t) = \frac{A_1}{A_2 - A_1} A_1(0)\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) + A_2(0)e^{-\lambda_2 t} \tag{5}$$

where λ, N, and A are decay constant, the number of radioactive atoms, and radioactivity, respectively, with the subscripts 1 and 2 denoting the parent and daughter radionuclides, respectively. t is unit time.

On top of that, for a parent nuclide that decays by more than one channel, to multiply Eq. (5) by a branching ratio (B.R.) is necessary [7]. The B.R. of Mo-99/Tc-99m, for example, is 0.865.

By using Eq. (5) multiplied by 0.865, and by revaluating the amount of annual Tc-99m consumption in Japan, we estimated Mo-99 production capacity of our compact X-band electron linac. The revaluated procedures of Tc-99m radiopharmaceutical is 4,200 per week [2, 8]. Also, we assumed the average dose of Tc-99m to be 925 MBq (25 mCi). Under these conditions, sixteen of X-band electron linacs having beams of 35 MeV and 9.1 kW can meet the whole demand for Tc-99m in Japan.

SUMMARY

Aiming at distributed production of Mo-99/Tc-99m, we are developing a compact X-band electron linac. For the basic design of the linac, we performed SUPERFISH for beam loading curve and GPT for beam tracking, from which 35 MeV and 9.1 kW beams were obtained. Sixteen X-band electron linacs having the beams of 35 MeV and 9.1 kW can cover the entire Tc-99m consumption in Japan.

We hope that we can build a new Mo-99/Tc-99m supplying system with our compact X-band linac, with dimensions being similar to those of a cancer therapy linac.

FUTURE WORK

Although the beam energy of 35 MeV was chosen by considering a high production yield of Mo-99 and a low amount of byproduct nuclides, it is not optimized yet. To determine the optimal beam energy for efficient production of Mo-99, we will conduct a series of beam dynamics analysis and Monte Carlo simulations.

Also, we figured out that the use of X-band RF and having beam power higher than several kW can induce beam loading instability. We are currently trying to solve this problem.

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