CONCEPTS OF 220-MEV RACETRACK MICROTRON FOR NON-DESTRUCTIVE NUCLEAR MATERIAL DETECTION SYSTEM*

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Abstract

A nuclear material detection system (NMDS) based on neutron / γ-ray hybrid approach has been proposed for the container inspection at sea ports [1]. While neutron is to be used for a fast pre-screening, quasi-monochromatic γ-ray beam from the laser Compton scattering (LCS) source will be used for an isotope identification on the precise inspection of the cargoes. Nuclear resonance fluorescence method is going to be employed for the isotope identification because of its superiority in high selectivity and in high penetration capability through the shielding objects. In the system a high energy electron beam of good quality is required for LCS. Racetrack microtron (RTM) is one of the most promising candidates as an electron source for such the practical use. Design parameters of such the 220-MeV RTM and expected output beam qualities are presented.

INTRODUCTION

At present four sets of 150-MeV RTM are in operation starting from 1990 [2]. While three of them are for the injector of electron storage ring, the fourth is for various experiments including LCS at JAEA. On the contrary to the former three RTMs which have a thermionic gun as the electron source, the fourth has an RF gun as the source. Therefore in principle the fourth accelerates a single bunch at a time. Higher energy RTMs over 200 MeV for NDMS has been considered on the basis of this well-established machine designing [3, 4].

The configuration of this existing 150-MeV RTM [2] is in Fig. 1. It is shown that the size of the main body is approximately W4m × L1.5m × H2m, excluding the injection line where the gun is located (not appeared in the figure). One of the unique features of this well-established RTM lies in two main (180°-bending) magnets which are the biggest components. In contrast with its large size, they have a narrow 10-mm gap between the upper and lower poles. These magnets are in operation at 1.2 Tesla. They obviously have a capability to be operated at much higher field, up to 1.5 Tesla for instance This approach is substantial on the new design as shown later. When the energy 220 MeV is required for the new design [3], it would increase the whole body size at about 20 ~ 30 %.

Another important component is a linac placed between two main magnets, on the center portion of the first orbit (see Fig. 1). In the 150-MeV RTM, S-band linac was adopted, and this RF system will be pursued for the new design because of the popularity of this frequency 2856 MHz. On designing RTM an operating frequency usually be fixed first, and the accelerating condition (energy gain per turn) should be reserved as a free parameter. Energy gain 6 MeV/turn was selected on the 150-MeV RTM.

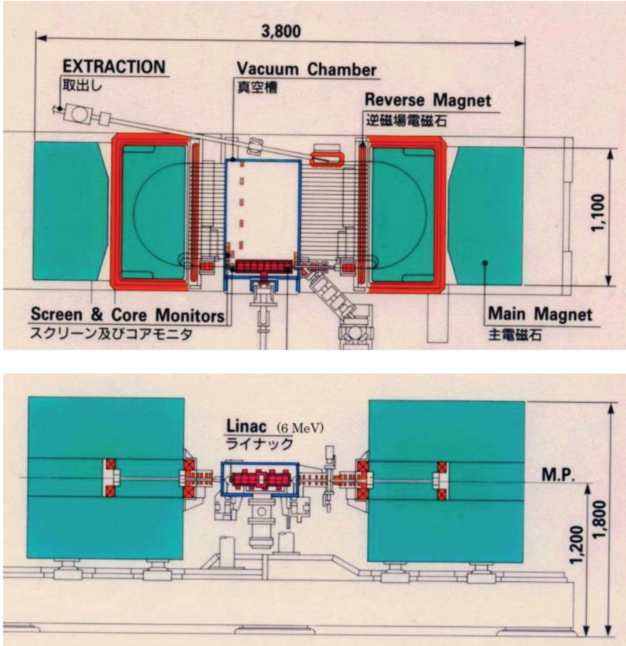

Figure 1: Cross sections of conventional 150-MeV RTM.

DESIGN CRITERIA

There are some constrants on a design of RTM [5]. The basic relationship shown below must be strictly fulfilled.

$$\Delta \mathrm{E(MeV)} = \frac{\nu \cdot \lambda(cm)}{2.096} B(Tesla)\,. \qquad (1)$$

Where ΔE: energy gain per turn, λ: wave length of frequency, B: magnetic field strength of main magnets, and ν (integer) is a characteristic parameter of RTM which indicates how much the circulating path elongated from the previous lap (L_n) to the next (L_{n-1}), normalized by λ, thus $\nu = (L_n - L_{n-1})/\lambda$.

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Violation of Eq.1 results in the lost of synchronization between accelerated electrons and accelerating RF fields in the linac. As already mentioned, typical parameters of the 150-MeV RTM are; ΔE=6.0 MeV/turn, B=1.23 Tesla, λ=10.5 cm, and ν=1. Energy 150 MeV is obtained after 25 times of acceleration. The simulation and experimental results of the 150-MeV output beam qualities were already reported in detail [5]. There are two directions towards the designing of higher energy RTMs, one is to increase the energy gain per turn (ΔE), and the other to increase the number of circulation with ΔE unchanged.

The ν-value is normally set to the minimum (ν=1), and rarely used $\nu \geq 2$ since we lose phase acceptance step by step upon the increasing of ν-value. The next Eq. 2 shows the relationship between ν-value and the width of the stable phase region, that is, phase acceptance.

$$0 < \tan\varphi_s < \frac{2}{\pi\nu}. \qquad (2)$$

It suggests that the widest phase stable region $0 < \varphi_s < 32°$ is obtained with ν=1, and decreasing to $0 < \varphi_s < 18°$ with ν=2. Even the widest phase acceptance at ν=1, it is rather narrow when compared with the linac's. Fortunately this unique characteristics reflect on the good beam quality which is inevitable to LCS, and also is well matched to the RF gun which generates short bunches ≤10 ps. On the contrary the noticeable demerit is obvious, namely RTM is inadequate to produce high current beams.

ENERGY INCREMENT

Expected electron energy for NMDS is at about 220 MeV, when detecting Uranium. In the previous report [4, 6] we referred the different way of increasing beam energy from extending the existing RTM method. The discussion here is, however, limited to the survey based on the actual 150-MeV machine by the reason that the way proposed here is most promising and practical. In addition, it has much flexibility when achieving further high energy, even 250 MeV or more upon the request.

Upgrading the 150-MeV RTM

It is already reported that what will happen when we continue accelerating electrons over 25 turns with ΔE=6.0 MeV/turn [5]. The result is clearly shown in the following survival plot (Fig. 2). The transmission efficiency is not affected by the parameter ΔE, but greatly influenced by the number of circulation. We found the limitation of output beam energy ~230 MeV for the case ΔE=6.0 MeV/turn, ~250 MeV for ΔE=6.6 MeV/turn, and ~270 MeV for ΔE=7.2 MeV/turn. Those simulations were executed assuming quite a large initial normalized emittance ε_x(rms)=150π mm·mrad in order to clarify the RTM acceptance [6]. Each field strength in the main magnets is B=1.23 Tesla for ΔE=6.0 MeV/turn, 1.35 for 6.6, and 1.48 for 7.2, respectively. Thus we obtained rather a poor transmission efficiency of 14 % from ~700/5000 survival particles.

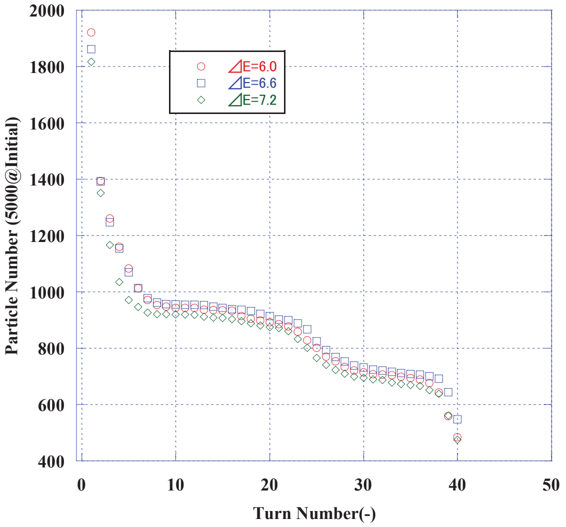

Figure 2: Comparison of transmission efficiency between 6.0-, 6.6- and 7.2-MeV/turn acceleration.

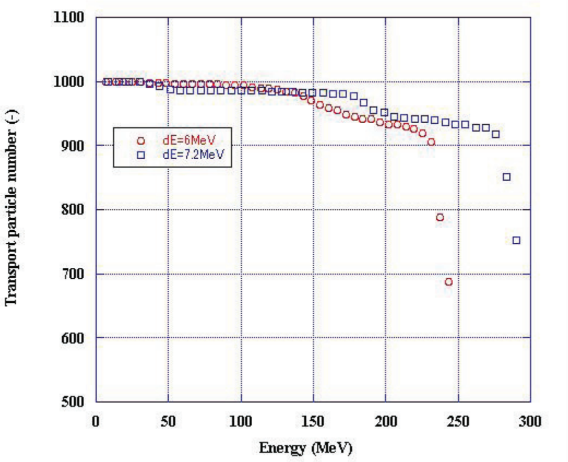

Figure 3: Transmission efficiency from RF gun injector with 6.0- and 7.2-MeV/turn acceleration.

On the other hand when the initial normalized emittance ε_x(rms)=10π mm·mrad which is close to an actual RF gun's is chosen, transmission efficiency is eminently up to >90 % (Fig. 3). From this results it seems that there exists not so much difference in both ΔE=6.0 and 7.2 MeV/turn accelerations.

Characteristics of 220-MeVBeam

When increasing ΔE=6.0→7.2 MeV/turn and B=1.23→1.48 Tesla, one can obtain 220-MeV beam after 30 times circulation. Simulations under the initial condition E_{in}=8.3 MeV with 1000 particles distributed in the phase space of normalized $\varepsilon_{x,z}$(rms)=10π mm·mrad were carried out. The survival rate is 943/1000 more than 94% transmission efficiency, and distributions of these particles are plotted in Fig. 4, where rms(ε_x, ε_z)=(0.066, 0.031)π mm·mrad and $\sigma(\Delta E, \varphi)$=(0.23 MeV, 3.7 deg).

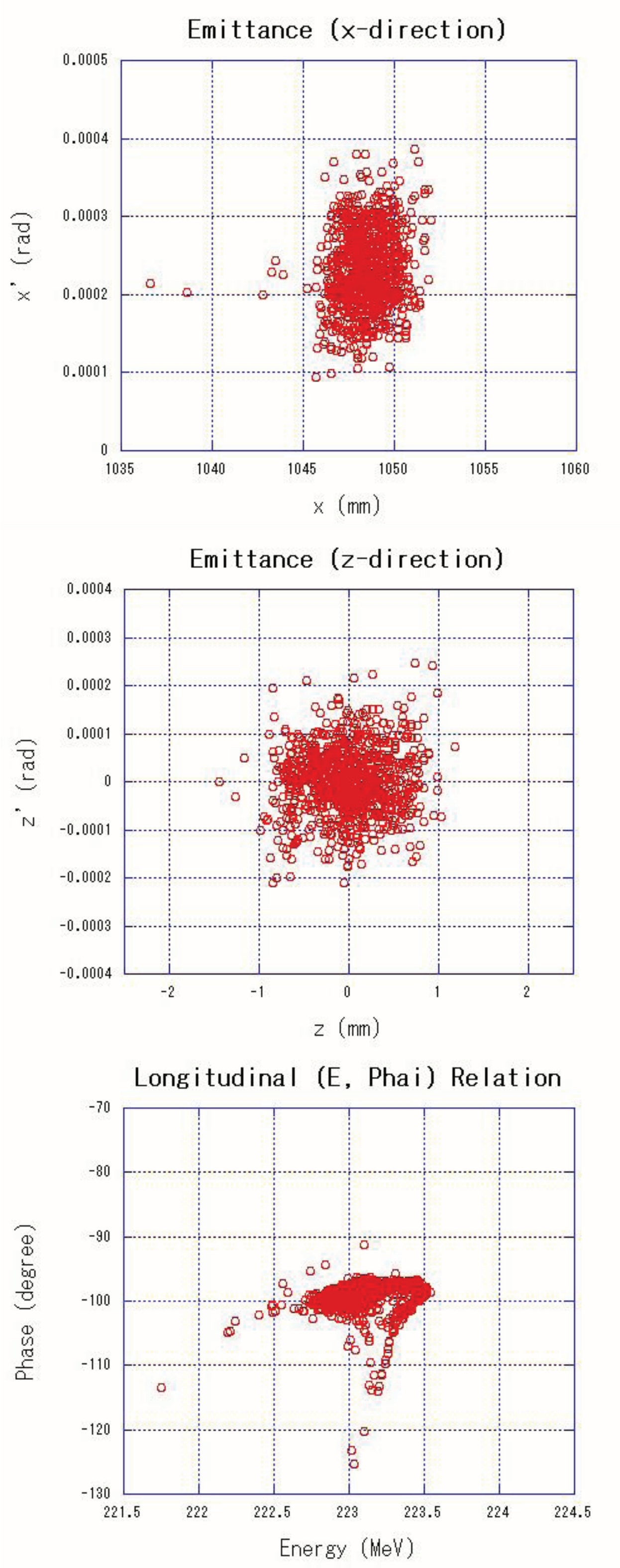

Figure 4: Distribution of survaival particles at 220 MeV.

unified to –0.14 Tesla/m in all designs. This causes inevitable phase drift continually on the circulating beam. There exist no defocusing quadrupole magnets in this type of RTM, therefore one cannot eliminate the n-value from main magnets.

Another choice to obtain 220-MeV beam is to increase the number of circulation of the established 150-MeV RTM up to 36 with the conventional acceleration rate $\Delta E=6.0$ MeV/turn. Simulations under the initial energy $E_{in}=6.8$ MeV with 1000 particles distributed in the phase space of normalized $\varepsilon_{x,z}$(rms)=10π mm·mrad have also been executed. The survival rate 929/1000 equivalent to 93% transmission efficiency is obtained, which is about the same as the case for $\Delta E=7.2$ MeV/turn. Output beam characteristics are rms(ε_x, ε_z)=(0.145, 0.035)π mm·mrad and $\sigma(\Delta E, \varphi)$=(0.40 MeV, 9.5 deg).

At a glance, the horizontal and longitudinal emittances seem gradually growing according to the increasing of circulation number, whereas not so much difference is detected in the vertical one. This suggests that to reduce the number of circulation might be better to obtain the 220-MeV beam in good quality.

The simulation results of 150-MeV RTM told us that the initial phase stable region 32° is decreased to ~20° after 25 turns of acceleration [5]. There exists a field gradient in the bending magnets to produce the enough vertical beam focusing force. The magnitude of n-value is

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