CONCEPTS OF 220-MeV 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, 2]. 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. Some design parameters suitable for such RTM are shown together with the expected output beam qualities.

INTRODUCTION

At present four sets of 150-MeV RTM are in operation starting from 1990 [3]. 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 [4, 5].

The configuration of this existing 150-MeV RTM (Fig. 1) shows the approximate size W4m × L1.5m × H2m, excluding the injection part. One of the unique features of this type of 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 [4], 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). For 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. Energy gain 6 MeV/turn chosen for the 150-MeV RTM had better be modified.

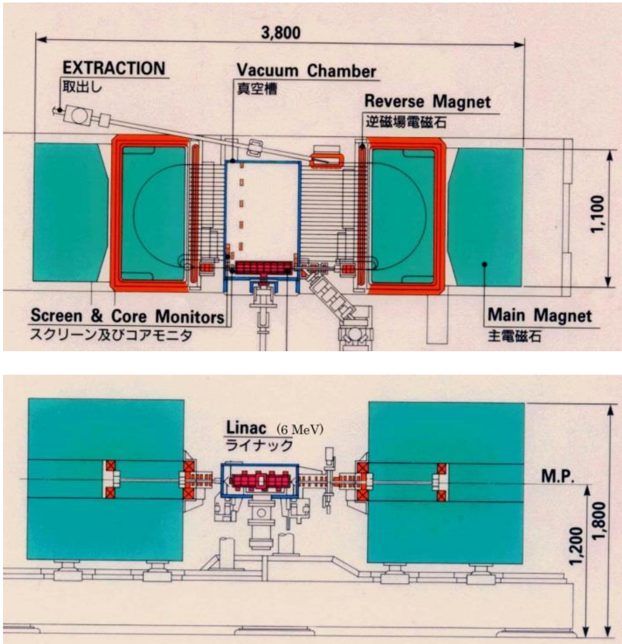

Figure 1: Cross sections of conventional 150-MeV RTM.

TOWARD HIGH ENERGY

The basic relationship [6] of RTM is;

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

Where ΔE: energy gain per turn, λ: wavelength 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 loss 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 precisely reported [6]. There are two directions towards the designing of higher energy versions, 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 ν≥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.

Expected electron energy for NMDS is at about 220 MeV, when detecting Uranium. In the previous report [5] the different way of increasing beam energy from extending the established RTM designing was argued. However, the process to modify the conventional 150-MeV RTM is most promising. In addition, it is proved to have much flexibility when achieving further higher energy, 250 MeV or more for instance upon the request. At present we consider this process is the best and the most practical.

It is already reported [6] that what will happen when we continue accelerating electrons over 25 turns with ΔE=6.0 MeV/turn. 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 [5]. 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 % at a glance from the result ~700/5000 survival particles.

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 hopefully up over 90% (Fig. 3).

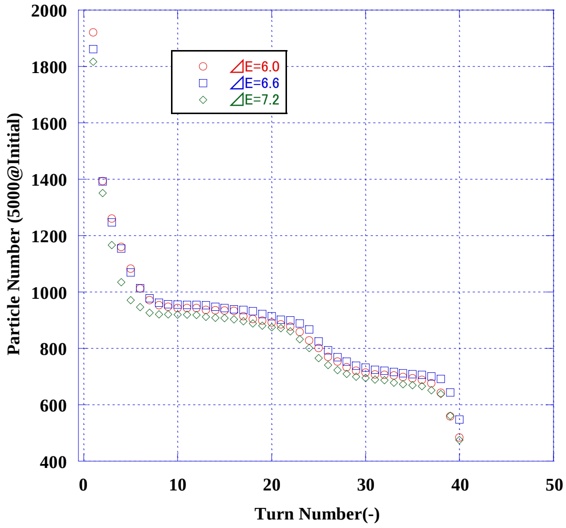

Figure 2: Comparison of transmission efficiency between 6.0-, 6.6- and 7.2-MeV/turn acceleration.

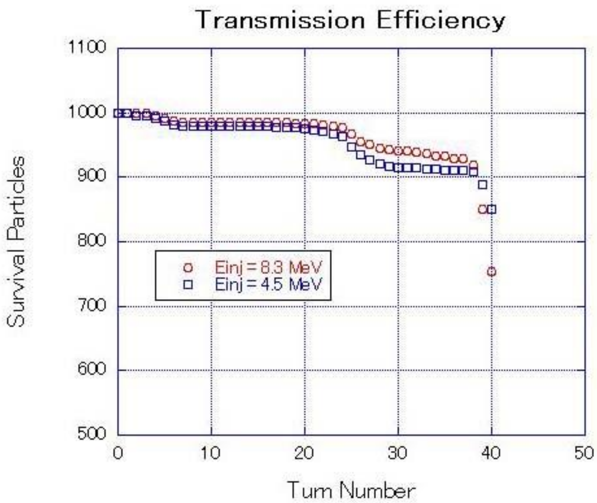

Figure 3: Difference of transmission efficiency when decreasing the injection energy from 8.3 to 4.5-MeV.

As already reported [5], we found that there exists not so much difference when changing the energy gain per turn from ΔE=7.2 to 6.0 MeV/turn. In addition, Fig. 3 shows that there exists little difference when decreasing the injection energy from E_{inj}=8.3 to 4.5 MeV (total-E of injected electrons). More than 90 % of injected electrons are survived at 220-MeV after 30 times acceleration for both the cases. This result suggests that the conventional 1.5- cell RF gun is well applicable to a new RTM without any boosting devices.

QUALITY OF 220-MEV BEAM

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 both initial conditions

E_{inj}=8.3/4.5 MeV were carried out with 1000 particles distributed in the phase space of normalized $\varepsilon_{x,z}$(rms)=10π mm·mrad and σ(ΔE/E, φ)=(0.01, 3.0 deg). The survival rates are 943/1000 and 915/1000, respectively, more than 90% transmission efficiency for the both.

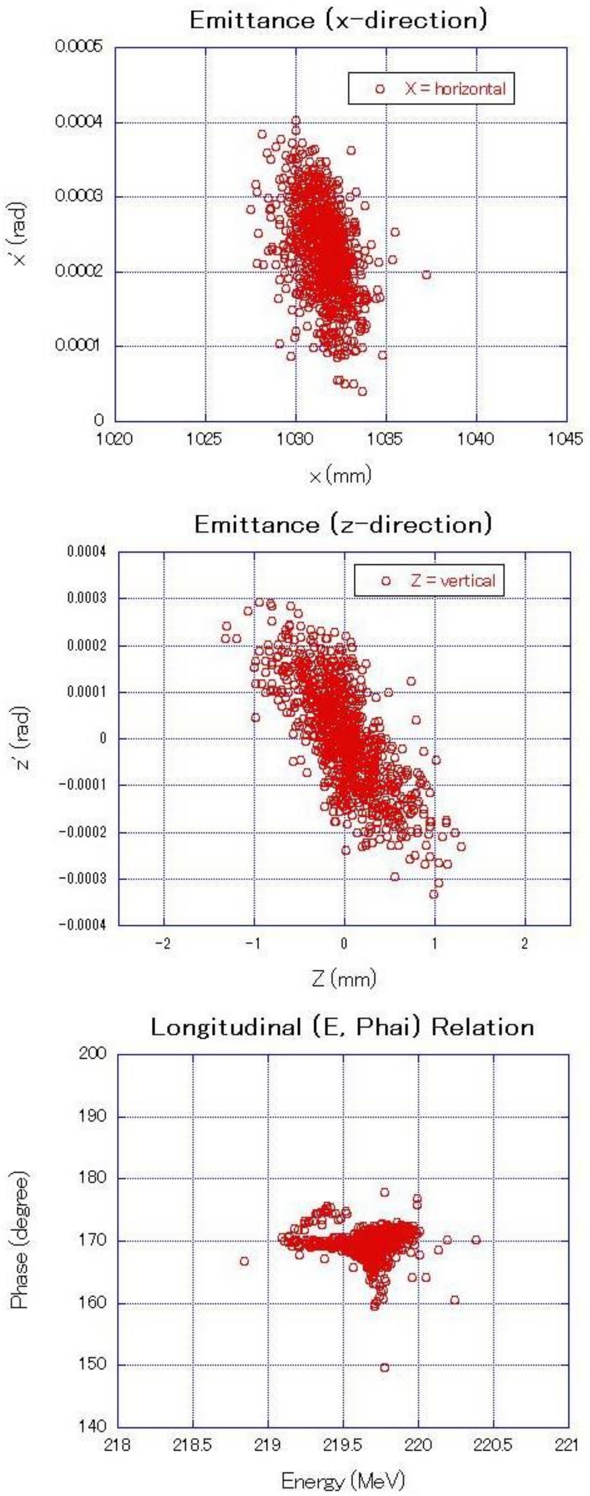

Figure 4: Distribution of survaival particles at 220 MeV in the case E_{inj}=4.5 MeV.

Distributions of these particles are plotted in Fig. 4 for the case E_{inj}=4.5 MeV. Transverse (x, z) and longitudinal emittances (unnormalized) are rms(ε_x, ε_z)=(0.071, 0.044)π mm·mrad and σ(ΔE, φ)=(0.17 MeV, 4.2 deg). When compared with the case E_{inj}=8.3 MeV [5], namely rms(ε_x, ε_z)=(0.066, 0.031)π mm·mrad and σ(ΔE, φ)=(0.23 MeV, 3.7 deg), it seems that there are no significant differences between them.

Another choice to obtain 220-MeV beam is to increase the number of circulation by the conventional 150-MeV RTM up to 36 times with the conventional acceleration rate ΔE=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 and σ(ΔE/E, φ)=(0.01, 3.0 deg) have also been executed [5]. The obtained survival rate 929/1000 equivalent to 93% transmission efficiency is about the same as the former cases with ΔE=7.2 MeV/turn acceleration. Output beam characteristics on this case rms(ε_x, ε_z)=(0.145, 0.035)π mm·mrad and σ(ΔE, φ)=(0.40 MeV, 9.5 deg) are somewhat increasing.

So far the simulations are carried out without taking into account the effect of space charge, therefore, we are considering how to evaluate the influence of space charge on the next step.

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