RACETRACK MICROTRON FOR NONDESTRUCTIVE 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. Some adequate combinations of basic design parameters are investigated for the RTM over 200 MeV acceleration.

INTRODUCTION

At present four 150 MeV RTMs are in operation in Japan [2]. While three of them are for the injector of a compact electron storage ring, the fourth is for various researches including LCS at JAEA. On the contrary to three injector 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 designed on the basis of this established machine settings [3, 4].

The configuration of the practical 150 MeV RTM [2] is shown in Fig. 1 and 2. It is shown that about the size of the main body is approximately W4m × L1.5m × H2m , excluding the injection line where the gun is located (not appeared in Fig. 1). It shoud be pointed out that one of the unique features of this type of RTM lies in the design of the main (180° bending) magnets which are the biggest components in the RTM. In contrast with its big body, they have a narrow gap, only 10 mm in height between the upper and lower poles. This method continues on the design of high energy RTMs. Assuming 220 MeV required for the new RTM [3], it would increase at about 20 ~ 30 % on its total size. The magnetic field of the main (bending) magnets has been set to around 1.2 Tesla, not so much difference between old and new designs.

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 system will be kept on for the new design because of the popularity of this frequency 2856 MHz. Later shown are some exception on this design. When considering further high energy RTM, 300 MeV for instance, L-band (1300 MHz) linac is another superior candidate. First of all frequency is fixed, however, the condition of acceleration (energy gain per turn) will be remained as one of the flexible parameters. It is decided to 6 MeV/turn on the base design of 150 MeV RTM.

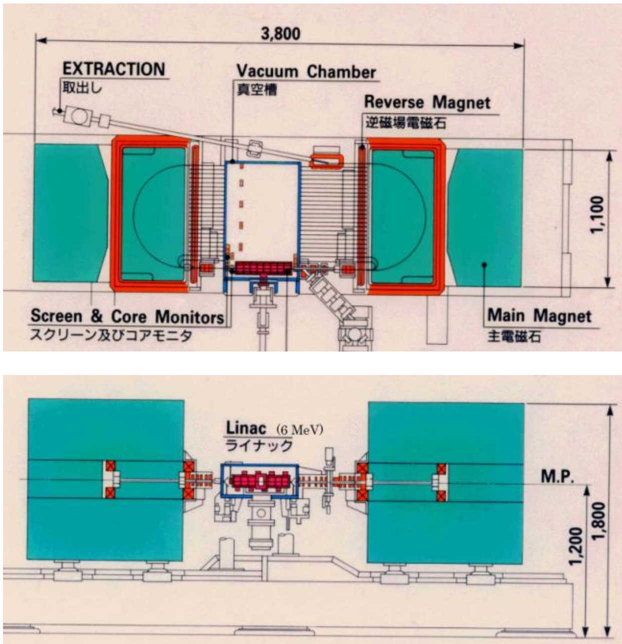

Figure 1: Cross sections of conventional 150 MeV RTM.

DESIGN CRITERIA

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

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

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Where ΔE: energy gain per turn, λ: wave length of frequency, B: magnetic field strength of the 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 $\nu = (L_n - L_{n-1}) / \lambda$. 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; $\Delta E = 6.0$ MeV, $B = 1.2$ Tesla, $\lambda = 10.5$ cm, and $\nu = 1$. 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 little changed.

The ν-value is normally set to the minimum digit (ν=1), and it is rare to use $\nu \geq 2$ 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 obtainable stable phase region, in other words 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. This gives us a occasion to design a high energy RTM under the condition ν=2, as actually shown later. On the contrary the noticeable demerit is obvious, namely RTM is inadequate to produce high current beams.

THE WAY TO HIGHER ENERGY

Required electron energy for NMDS is expected at about 220 MeV, when detecting Uranium. It is preferable, however, to have the capability to accelerate electrons further, 250 MeV for instance, when considering the possibility to investigate other nuclei.

Upgrading the 150-MeV Version

It is already reported that what will happen when we continue accelerating electrons over 25 turns by the existing 150 MeV RTM [5]. The result is clear in the following survival plot up to 50 turns (see Fig. 2).

After 25 turns, a part of the beam gradually dropped out until 30 turns. However, after that the survival rate keeps in constant till ~40 turns. Thus three fourths of the beam get more energy than 220 MeV at 37 turns of acceleration. The reason of this 25% beam loss between 25~30 turns can explain by the phase drift of the circulating beam (see Fig. 3). The phase drift occurs continuously from the first. The simulation results of 150 MeV RTM tell us that the initial phase stable region 32° is decreased to ~20° after 25 turns of acceleration. Suppose electrons be accelerated further, the phase stable region should be decreasing more, and some electrons would inevitably be dropping out one after another.

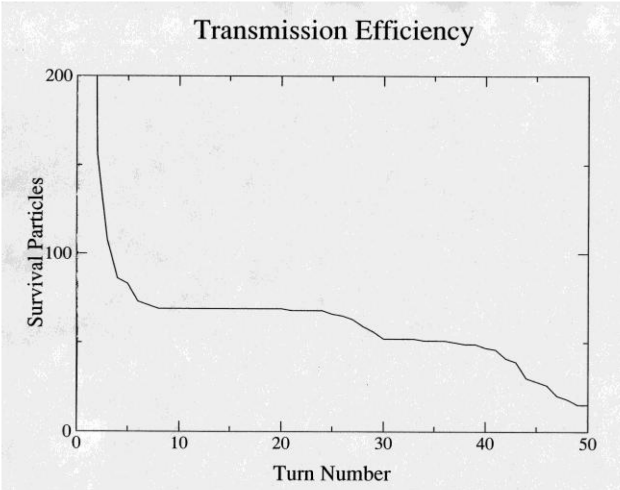

Figure 2: Transmission efficiency in the case of 300 MeV acceleration with 6 MeV/turn.

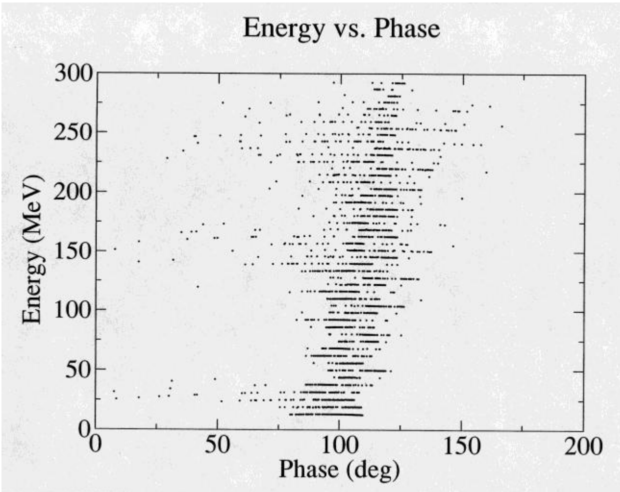

Figure 3: Phase drift of survival electrons until 50 turns (300 MeV) of acceleration with 6 MeV/turn.

It is well known that the field gradient in the bending magnets, which is necessary to produce the vertical beam focusing force, causes this phase drift. There are no QD magnets in this design, therefore one cannot remove the n-value from the main magnets. However the strength of n-value, fixed to –0.14 Tesla/m at present, might be adjustable.

When increasing ΔE from 6.0→7.2 MeV and B from 1.2→1.5 Tesla, one can obtain 220 MeV beam after 30 times circulation. Simulations under the initial condition E_{in} = 8.3 MeV with 5000 particles distributed in the phase space of normalized $\varepsilon_{x,y}$(rms) = 150π mm·mrad were executed. The survival rate is 714/5000, and distributions of these particles are shown in Fig. 4, where rms (ε_x, ε_y) = (0.20, 0.16)π mm·mrad and $\sigma(\Delta E, \varphi)$ = (0.3 MeV, 5.3 deg). These values are equivalent to the acceptance of this RTM, which are 5~10 times larger than the 150-MeV conventional RTM's.

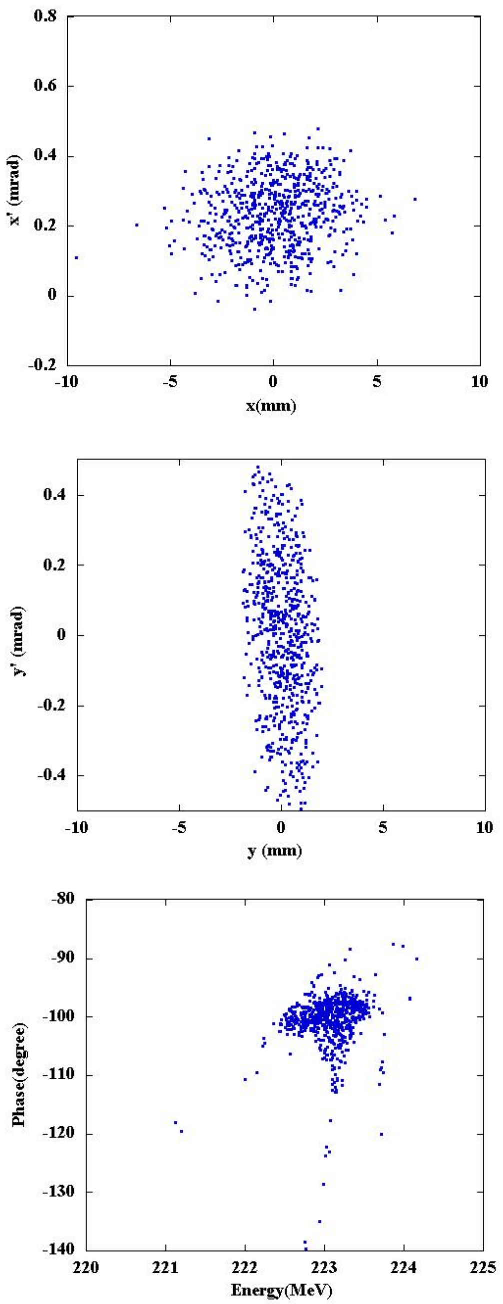

Figure 4: Distribution of survaival particles at 220 MeV.

High Energy Gain per Turn (ν=2)

Assuming that RF gun would be employed, there arises another possibility to adopt ν=2 on the sacrifice of the phase acceptance becoming narrow. The stable phase region 18° of S-band is equivalent to ~18 ps, which seems sufficient for the acceleration of single bunch from the RF gun. One example of the design parameter is already reported [3]. The phase acceptance is checked by the simulation using a zero transverse emittance beam on the linac axis. The obtained phase stable region is ~6° after 18 turns of acceleration at 12 MeV/turn. Less than 10° of this phase stable region might be insufficient. Alternatively the combination of much more enrgy gain, 15 MeV/turn, with reducing turn number to 15 is another candidate. In this case 9° of phase acceptance is reserved under the assumption B=1.5 Tesla for the main magnets and S-band linac. The magnet gap is narrow only 10 mm, so no difficulty is expected for realizing 1.5 Tesla.

However, so far as RTM adopts the weak-focusing system in the bending magnets, it is found by the recent simulations that the parameter ν=2 is in general not suitable to the purpose of increasing beam energy, because the influence of this phase drift is relatively too large compared with the case ν=1. The parameter ν=2 might be only allowable for the circulation less than 15, which is equivalent to four times of the synchrotron oscillation in the RTM.

Acceleration by L-band (1.3 GHz) Linac

There was a design report on the 300 MeV RTM, 14.3 MeV×21 turn, using L-band (λ=23 cm) linac [6]. The simulation results have not so much difference from the RTM's with S-band linac. Emittances of the 300 MeV beam, rms (ε_x, ε_y) = (0.5π, 0.2π) mm·mrad, are about one order larger than those of 150 MeV beam. Main reason will be derived from the large aperture of the linac bore, 10 mm / S-band vs. 22 mm / L-band. When a small emittance of RF gun is assumed, the emittance of output beam might become somewhat smaller. The effect of n-value is also noticeable, only 10° phase acceptance is obtained for the case ν=1. These parameters are worth to consider in NMDS, suppose we might take into account the compensation of heavy beam loadings.

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