EXPECTED LUMINOSITY AT MUSES

K.Yoshida, RIKEN, Wako, Saitama 351-01, Japan
T. Katayama, INS, Tanashi, Tokyo 188, Japan

Abstract

The luminosity of head-on collisions between electrons and unstable nuclei has been estimated for the accelerator complex of MUSES. The estimation was performed with the empirical model which describe the fragmentation process. The result shows that the luminosity of $>10^{27}$ is available for the nuclei whose life time is longer than 1 min.

1 INTRODUCTION

MUSES is the accelerator complex which consists of, an Accumulator Cooler Ring (ACR), a Booster Synchrotron Ring (BSR) and Double Storage Rings (DSR). Beams extracted from a Super conducting Ring Cyclotron (SRC) irradiate a target and unstable nucleus beams are produced through the fragmentation process. Unstable nucleus beams are the mixture of various nuclei, therefore, they will be purified by means of momentum- and charge state- selection at Big-RIPS. Then unstable beams will be accumulated in the ACR with use of multi-turn injection and RF stacking. Momentum cooling will be continuously applied for the stacked beam during the RF stacking process. After the accumulation of unstable nucleus beams in the ACR, they will be fast extracted from the ACR and injected into the BSR. In BSR, beams will be accelerated to the top energy, 1 GeV/u for $^{238}U^{92+}$ and 1.5GeV for the ions of charge to mass ratio of 1/2. These full energy beams will be injected into one of the double storage rings. Typical experiment investigated at DSR is the head-on collision of unstable nucleus beams with electron beams to study the form factor of the unstable nuclei. In the experiment, another ring of DSR will be filled with high current ~500 mA electron beams with energy of up to 2 GeV. In this paper, Luminosity of the collisions are estimated for various unstable nucleus beams.

Luminosity L of the collision of beams with Gaussian distribution in space is calculated as

$$L = n_1 n_2 c N_c E(\beta_1, \beta_2, \psi) \frac{1}{(2\pi)^3} \int \frac{dxdydzdt}{\sigma_{x_1}\sigma_{y_1}\sigma_{z_1}\sigma_{x_2}\sigma_{y_2}\sigma_{z_2}} \times \exp\left[-\frac{1}{2}\left(\frac{x_1^2}{\sigma_{x_1}^2} + \frac{x_2^2}{\sigma_{x_2}^2} + \frac{y_1^2}{\sigma_{y_1}^2} + \frac{y_2^2}{\sigma_{y_2}^2} + \frac{(z_1 - c\beta_1 t)^2}{\sigma_{z_1}^2} + \frac{(z_2 - c\beta_2 t)^2}{\sigma_{z_2}^2}\right)\right] \quad (1)$$

where n_i $(i = 1,2)$ is the number of particles in one beam bunch in the DSR, β_i is the ratio of beam velocity to the speed of light c, N_c is the number of collisions which occur in a unit time, $\sigma_{x_i}, \sigma_{y_i}, \sigma_{z_i}$ are sizes of beam bunch in x, y, and z direction, and ψ denotes the collision angle. Suffix $i = 1,2$ represents the electron and unstable nucleus beams, respectively. $E(\beta_1, \beta_2, \psi)$ is called as kinematical factor and given as

$$E(\beta_1, \beta_2, \psi) = \sqrt{\beta_1^2 + \beta_2^2 + 2\beta_1\beta_2 \cos\psi - \beta_1^2\beta_2^2 \sin^2\psi} \quad (2)$$

As seen in Eq. (1), L depends on the number of particle in a beam bunch and beam sizes. Therefore we need to evaluate those to obtain the luminosity.

2 NUMBER OF PARTICLES IN A BEAM BUNCH

2.1 Production of Unstable Nuclei

Production rates of unstable nucleus beams are estimated with the code INTENSITY2 [1]. In the code, the physical feature of the fragmentation process is treated as empirical way. The primary beam and the thickness of the Be production target are optimized so as to obtain the maximum production rate. In the calculation, the intensity of the primary beam is assumed to be 100 particle µA. The result of the calculation with the assumption of the acceptance of the Big-RIPS as 10 mrad in angle and 1 % in momentum is shown in Fig. 1

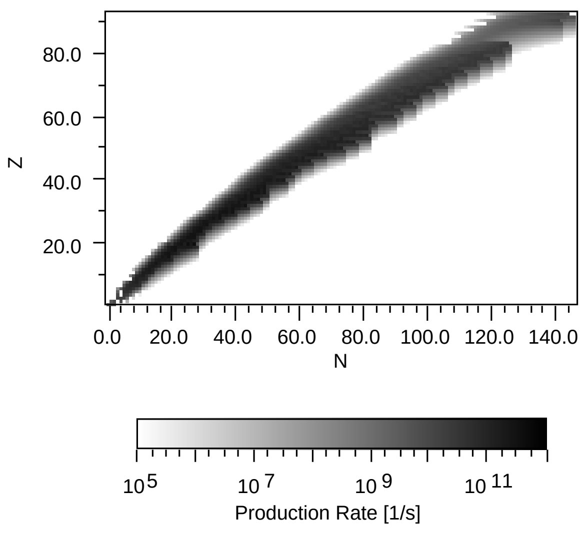

Fig. 1 Production rate of unstable nuclei at MUSES. Calculation assumes 100pµA primary beam. The separator acceptance is 10mrad in angle and 1% in momentum. The production target is Be and its thickness is optimized so as to get maximum production rate. The kind of primary beam is also optimized among whole stable nuclei.

2.2 *Cooling of Unstable Nucleus Beam*

Unstable beams separated by the Big-RIPS will be then stored and accumulated in ACR. In ACR, momentum cooling will be continuously applied to the stacked beam during the RF stacking process. Since we will take the time interval of the injection as the same as the momentum cooling time, the cooling time should be as short as possible to get the maximum intensity of stored beam.

Both electron cooling and stochastic cooling were studied for the momentum cooling of particles. [2,3] As a result, it is turned out that the stochastic cooling is always much faster than the electron cooling for the present case. Electron cooler with 3 m length and current density of 0.5 A/cm^2 gives the cooling time of 380s for ^{6}He and 0.42 s for ^{232}U, whereas the stochastic cooling with 10kW and a band width of 2GHz feed back amplifier gives 200 ms and 1.6 ms, respectively. This is due to the property of the unstable beam; the intensity is rather weak and momentum- and emittance- spread are large. In Fig. 2 shown is the momentum cooling time for various nuclei with stochastic cooling method.

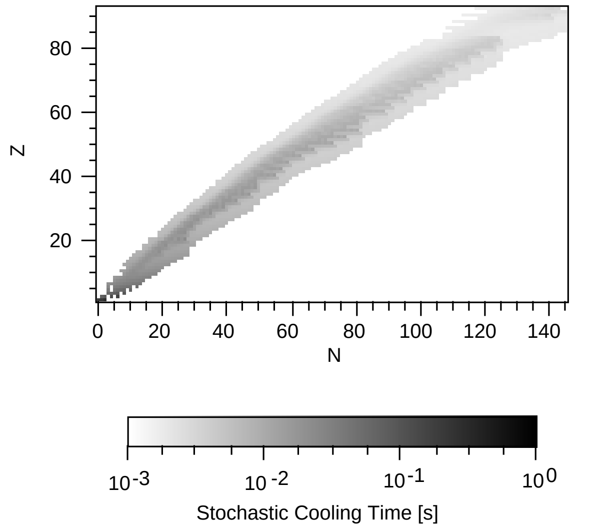

Fig. 2 Similar figure as Fig. 3 except for employing the stochastic cooling. Maximum specifications of the amplifier of 10 kW and 2GHz are assumed in the calculation. The temperature of the pick-up unit is taken as 18 K.

2.3 *Accumulation of unstable nuclei*

The accumulation of the unstable beam is performed by using the RF stacking technique. The unstable nucleus beam is injected into the ACR by means of multi-turn injection with the time interval of the cooling time. The supply rate is

$$R_s = \frac{R_p \varepsilon_{inj}}{\tau_{cool}}, \tag{3}$$

where R_p is production rate, ε_{inj} is the efficiency of injection and τ_{cool} is cooling time. ε_{inj} is given as

$$\varepsilon_{inj} = N_{mult} \frac{h_{SRC}}{f_{SRC}} \frac{L_{ACR}}{L_{SRC}}, \tag{4}$$

where N_{mult} is number of multi-turn injection, h_{SRC}, f_{SRC} are harmonics number and RF frequency, and L_{ACR}, L_{SCR} are circumference of ACR and the extraction orbit of SCR.

The beams accumulated in the ACR is decaying with its own life time τ. The maximum number of the nuclei stored in the ACR is determined by the balance of the supply rate and the decay rate and given as

$$N_{stl} = R_s \tau = R_p \varepsilon_{inj} \frac{\tau}{\tau_{cool}} \tag{5}$$

The space charge limit of the ACR also limits the maximum number of the nuclei stored in the ACR. The limit is important only for the high production rate nuclei such as stable nuclei and their neighbors. The space charge limit of the ACR is expressed as

$$\begin{aligned} N_{sp} &= \frac{\pi \beta^2 \gamma^3 Q_y}{r_p R} \frac{A}{Z^2} b(a+b) \Delta Q_y \\ &= 1.28 \times 10^{13} \beta^2 \gamma^3 \frac{A}{Z^2} \end{aligned}, \tag{6}$$

where r_p is a classical proton radius, Q_y is a vertical betatron tune, and a, b are horizontal and vertical beam radii, respectively. Therefore the maximum number of nuclei is limited by the smaller value of the Eq.(5) and Eq.(6).

The accumulated RI beam will be fast extracted from the ACR and injected into the Booster Synchrotron Ring (BSR) of MUSES. In the BSR, the beams will be accelerated to the energy required for the experiment within 1 sec, and then will be injected into the one ring of the DSR to collide with electrons stored in another ring. Since the RI beams are bunched by 46 pulses in the DSR, the maximum number of unstable nuclei in a bunch is obtained by dividing the maximum stored intensity in the ACR by the 46. Result is shown in Fig. 3.

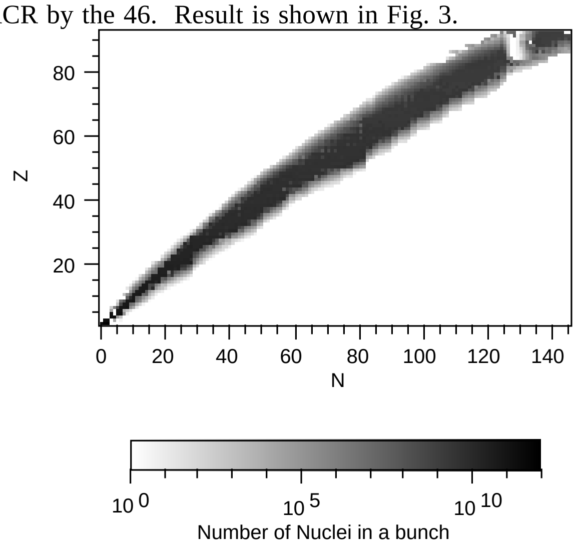

Fig. 3. The number of nuclei contained in a bunch at DSR. The accumulation in the ACR assumed to be continued to reach an equilibrium between accumulation and decay or to reach a space charge limit.

2.4 *Electron beam*

Electrons are accelerated up to 300MeV in the electron linac and then injected to BSR. BSR boost electron energies up to 2 GeV and supply electrons to the one of the rings of DSR. The expected beam current in DSR is about 500mA. In order to make a synchronous collision of electrons and nuclei, bunch number of electrons is varied from 30 to 45 according to the energy of unstable nucleus beams from 300MeV/u to 3.5 GeV/u. The number of electrons in a bunch is then 9×10^{10} and 6×10^{10}, respectively.

3 BEAM SIZE

The beam sizes of electrons and unstable nuclei at the collision point also affect the Luminosity. Transverse beam sizes near the collision point are given as

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta^*_{x,y}\left(1+\left(\frac{z}{\beta^*_{x,y}}\right)^2\right)} \qquad (7)$$

where $\varepsilon_{x,y}$ is the beam emittance and $\beta^*_{x,y}$ is beta function. The effect of the beam size was studied by inserting Eq.(7) to the Eq.(1) and calculating the overlap integral in numerical way. Bunch lengths $\sigma_{z_{1,2}}$ are determined by the RF voltage of DSR and to be 50cm for nucleus beam and 2cm for electrons. Fig. 4 shows the normalized luminosity as a function of $\beta^*_{x,y}$. As seen, the luminosity increases with decreasing the beta function. Asymmetric selection of β^* is preferable if it is difficult to decrease β^* for both particles; β^*= 2 cm for electrons is preferable for β^*= 10~50 cm for unstable nucleus beam.

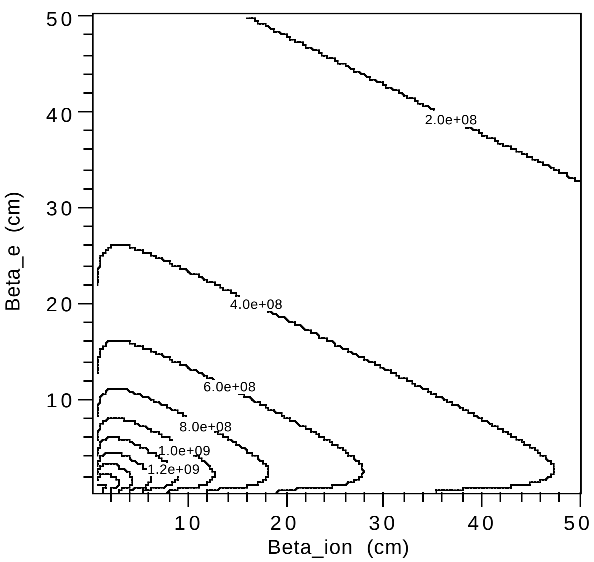

Fig. 4 Contour plot of normalized luminosity. Interaction region of 10cm is assumed in the calculation. Beam emittances are assumed as 1π mm mrad for unstable nuclei and 0.7π mm mrad for electrons in the calculation.

4 AVAILABLE LUMINOSITY

Luminosities at MUSES are now obtained by using Eq. (1). In Fig. 5, Luminosity of head-on collisions of electrons and unstable nuclei is plotted for various nuclei in an N-Z plane. In the figure plotted are only the nuclei whose luminosity $L \geq 10^{27}\, cm^2/s$, the value corresponds to the minimum luminosity required to measure the charge distribution from the elastic scattering. Those nuclei are their live times longer than about 1 min.

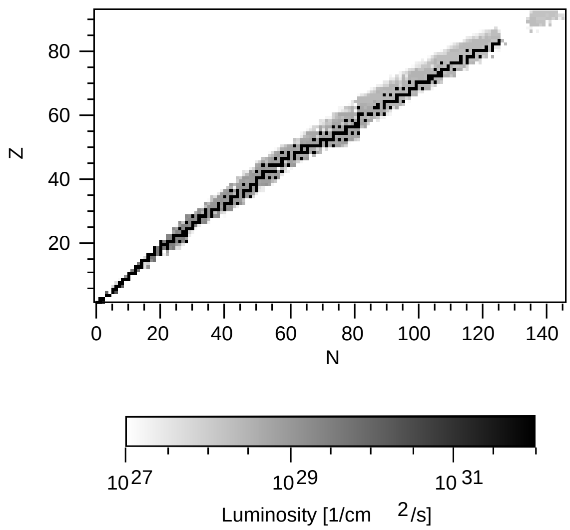

Fig. 5. Luminosity of head-on collision of electrons and unstable nuclei. The length of 10 cm is taken as the interaction region. Dark black squres in the figure represent stable nuclei.

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