Focus tuning method of the high-resolution beam line for the SHARAQ spectrometer

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New missing mass spectroscopy with an RI beams is planned at RIBF with the SHARAQ spectrometer [1]. The SHARAQ spectrometer is designed to achieve a resolving power of $p/\delta p = 1.5 \times 10^4$ and a high angular resolution of $\delta \theta = 1$ mrad for particles with a maximum magnetic rigidity of $Bp = 6.8$ Tm. To avoid loss of energy resolution due to the momentum spread of RI beams, the dispersion matching (DM) technique is applied in high resolution measurements [2].

A high resolution beam line has been constructed [3] based on the ion optical design described in Ref. 1. Figure 1 shows the layout of the high resolution beam line. An RI beam emitted from the production target at F0 is achromatically focused at F3. F3 is an ion-optical starting point of the high resolution beam line. The beam line after F3 consists of 30 superconducting quadrupole magnets, 3 normal-conducting quadrupole magnets, and 5 dipoles. Although the initial settings of magnets were deduced from the ion optical calculation based on the precise magnetic field measurement [4], a fine tuning is still needed in actual experiment to achieve the required resolution. In this report, the tuning method which is applied in the commissioning of the high-resolution beam line for the SHARAQ spectrometer [5] is described.

The fine tuning requires measurements of the transfer matrix $R$, which connects the initial and final coordinate vectors $X$ and $X'$ as $X' = RX$. The elements of $R$ are usually obtained from the correlation between quantities of the two focal planes. For example, to tune the focus condition, namely $(x|a)_{ef} = 0$ where each digit in the subscript means the corresponding focal plane, we use the correlation between the position $x_f$ at the final plane and the angle $a_i$ at the initial plane. The slope of the correlation corresponds to the magnitude of $(x|a)_{ef}$. Actually, for the beam tuning between F3 and F4 of the high-resolution beam line, the correlation of the positions at F4 with the angles at F3 can be used. In this report, we call this method to use the correlation between $x_f$ and $a_i$ directly as the standard focus tuning method.

Use of the $x - a$ correlation alone is not always effective in RI beam experiments. Figure 2 shows the correlation between the angle at F3 and the position at F6 with the primary $^{14}$N beam at the commissioning. The position and angle are determined experimentally by using the multwire drift chambers [6]. The magnetic field settings corresponding to the left and right panels of the figure are different. And then, the slopes in the panels should be different. However, the difference is not obvious. The difficulty is caused by the spread of the image at the focal plane due to the large dispersion and beam energy spread.

The value of dispersion at the focal planes in the DM mode are summarized in Table 1. The standard tuning method could be applied between F3 and F4 as described above because the spread caused by the dispersion is not so larger than other points. When the primary beam with the momentum spread of $\Delta p \sim \pm 0.1\%$ is used, the horizontal beam image, for example, at F6 spreads over $\pm 8$ mm due to the dispersion. The beam spread smears information about $(x|a)$. Even if momentum slits are used, the resulting momentum spread is almost the same order of the primary beam.
We propose a simple method which does not depend on the beam momentum. In this report, we call this the momentum independent tuning method. This method is efficient for the tuning in the focal planes which have the large dispersion. Let us consider the focus tuning between FH7 and F4 to achieve \( x | a \gamma_4 = 0 \): the beam momentum \( \delta \) could be assumed to be \( x_7 / (x | \delta \gamma_7) \) using the position at the largely dispersive focal plane of FH7. Then, phase space variables are related in the first order optics as,

\[
    x_4 = \left( \frac{\langle x \rangle \gamma_4}{\langle x \rangle \gamma_7} \right) x_7 = \langle x \rangle a \gamma_7. \tag{1}
\]

It is found that the left-side term in Eq.(1) is a quantity independent of the beam momentum by elimination of the effect due to the beam energy spread at FH7 using the data for F4 and FH7.

In the following, we will consider the simple case, for example, between F6 and FH7 since there is no dispersive element; i.e. dipole magnet. The quantity independent of the beam momentum can be below,

\[
    x_6 = \langle x \rangle \gamma_6 x_7 = \langle x \rangle a \gamma_6 \gamma_7. \tag{2}
\]

In Eq.(1), the particles are assumed to be emitted from FH7 to F6. To obtain the quantity described above, the magnification \( \langle x \rangle \gamma_6 \) is needed to be deduced, experimentally. Figures 3 and 4 show the correlation of positions and angles at F6 and FH7. Figure 3 is the correlation of \( x_6 \) with \( x_7 \) whose slope corresponds to the magnification, \( \langle x \rangle \gamma_6 \). Figure 4 shows the correlation between the quantities in the left side of Eq.(1) and the angle at FH7, \( \alpha \gamma_7 \), under the different magnetic field settings where we use \( \langle x \rangle \gamma_6 \) determined from Fig. 3 experimentally. In Fig. 4, it is clearly seen that the slope which indicates the magnitude of \( \langle x \rangle \gamma_6 \) is changed. If the standard tuning method is applied using the correlation of \( x_6 \) with \( x_7 \), the spread of image caused by the \( x_7 \) due to the large dispersion smear information for \( \langle x \rangle \gamma_6 \). The fine tuning is, thus, possible by introducing the momentum independent focus tuning.

### Table 1. Design dispersion \( \langle x \rangle \delta \) for the DM mode.

<table>
<thead>
<tr>
<th>Focal plane</th>
<th>F4</th>
<th>F6</th>
<th>FH7</th>
<th>FH9</th>
<th>FH10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design value</td>
<td>-19</td>
<td>76.7</td>
<td>-73.7</td>
<td>229</td>
<td>150</td>
</tr>
<tr>
<td>(mm%)</td>
<td></td>
<td></td>
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This is the expeditious tuning method because it doesn’t require the complicated procedure. This method enables us to quickly optimize the magnetic settings of the high-resolution beam line for the SHARAQ spectrometer. The quick-able beam tuning is important for the beam line with many focal planes.

### References