II. BEAM TRANSPORT SYSTEM

II. 1. General Description

Fig. 1 shows the beam transport system for the CYRIC cyclotron. The system has seven beam lines for different purposes. Beam lines 1 and 2 are for radioisotope production, 31 for on-line isotope separation and material irradiation, 33 for particle-induced X-ray analysis, and 34 for in-beam $\beta$- and $\gamma$-ray spectroscopy. Beam line 41 gives a high resolution beam by means of a beam analyzing system consisting of two dipole magnets, ANA1 and ANA2, and a sextupole magnet. Beam line 51 is for fast neutron time-of-flight measurement and has a beam swing consisting of BEND1 and BEND2. To provide a beam with a pulse repetition time longer than that of a natural beam, the beam transport system has three electrostatic beam deflectors, of which S1 and S2 are operated with sinusoidal voltage and P with rectangular pulses. Main features of each beam line are listed in Table 1.

Basic design of the beam transport system was made by the staff of Tohoku University, and construction was performed by Sumitomo Heavy Industry Co. Ltd.. Assemblage of the system was finished in August 1978 and performance tests were made in the period of September 1978 - March 1979. Parameter search for optimum conditions of beam transport was continued until the autumn of 1979.

II. 2. Beam Optics

The beam transport system was designed by assuming an initial beam condition that the beam forms an up-right ellipse in phase space in each of the horizontal and vertical directions at a location 4.4 m downstream from the exit port of the cyclotron. At this location a horizontal and a vertical slit are set, and a stigmatic image is formed there by adjusting acceleration and extraction parameters. A high-speed beam emittance analyzer$^2$, installed at m from the exit port of the cyclotron, greatly facilitates the beam transport.

The followings are beam-optical design procedures of the transport system: 1) First-order matrix calculations with the computer code TRAMP$^3$ determined the optical parameters of dipole and quadrupole magnets which allow the beam to satisfy waist-to-waist matching relations; 2) Second-order matrix elements were calculated with the code SAKKO$^4$ to find the field density of sextupole magnets to eliminate aberrations; 3) Numerical integration of equations of motion was performed with the code RAYCER$^5$ to find particle trajectories in the magnetic fields calculated with the code MAGMAP$^6$ on the basis of the parameters obtained in procedures 1) and 2); 4) After fabrication of the magnets, magnetic field distributions of individual magnets were measured, and ray tracing calculations were repeated for the measured fields with the code RAYCER.

Design specifications of the magnets used in the beam transport system are listed in Table 2. The dipole magnets are so designed that they are capable of
bending charged particles with a k-value of 55 MeV, which is larger than the k-value of the cyclotron by 5 MeV. Fig. 2 shows a cross section of the pole edge of dipole magnet ANA2. The corner of the pole edge is rounded off according to a "Rogowski curve" to minimize effects of local saturation. In practice the Rogowski curve is approximated by 11 rectangular steps as shown in Fig. 2. All the dipole magnets of the beam transport system have poles with rounded-off corners similar in shape to ANA2. Fig. 3 shows the position of the effective field boundary of ANA2 along the central ray as a function of excitation current; it is measured with respect to the mechanical boundary, and open and full circles stand for the data taken with and without a field clamp, respectively. Fig. 3 indicates that effects of local saturation are successfully suppressed by the Rogowski cut. In Fig. 4 a calculated profile of the magnetic field of ANA2 near the field boundary is compared with measured one. It should be noted that the theoretical curve was calculated for design purposes with the code MAGMAP before fabrication of the magnet. Fig. 5 shows a comparison between measured and calculated magnetic field distributions of a quadrupole magnet along the axis. The theoretical curve was calculated by the method of n-parameter representation, which is adopted also in the ray tracing calculations.

A typical result of the ray tracing for beam line 51 is illustrated in Fig. 6. Each curve stands for the trajectory of a charged particle that leaves a point on the circumference of the up-right ellipse in phase space with an area of 50 mm-mrad at the location mentioned above. The time spread of beam burst was estimated at several positions along beam line 51, and efforts were made to minimize the time spread of beam burst at the target position, because beam line 51 is used for fast neutron time-of-flight experiments.

II. 3. Vacuum System

The beam transport system is evacuated constantly by 11 turbo molecular pumps (TMP), two 500-l/s and nine 200-l/s pumps. When a beam is transported through a beam line, the line is evacuated also by additional ion pumps. The transport lines are built of stainless-steel tubes of 4" inner diameter, whose inner surfaces are carefully machined. The distance between any two adjacent TMPs in a beam line is less than 20 m along the line, and the effective pumping speed at any position in the line is estimated to be higher than 10 l/s. The sum of the leak rate of air through vacuum seals and the emission rate of gas from metal surfaces is estimated to be about $10^{-5}$ torr.l/s per 10 m of beam line. Hence a pressure as low as $10^{-6}$ torr is expected everywhere in the beam lines.

References


2) Ishii K. et al. to be published in Nucl. Instr. and Meth.
3) Gardner J.W. and Whiteside D., NTRL/M/21.
4) Takahashi M. et al., unpublished.
5) Takahashi M. et al., unpublished.
6) Takahashi M. et al., unpublished.
Table 1. Beam line, beam qualities, research fields and equipments.

<table>
<thead>
<tr>
<th>Beam line</th>
<th>Target room</th>
<th>Purposes</th>
<th>Acceptance (mm-mrad)</th>
<th>Magnification ( M = \frac{y}{m_1} )</th>
<th>Equipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Radioisotope production with liquid and gass target (for ( \epsilon_x ) and ( \epsilon_y ))</td>
<td>more than 50</td>
<td>( M_x = 1.45 ) ( M_y = 1.39 )</td>
<td>Target assemblies and rabbit transfer S1(^1) is available</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Radioisotope production with solid target Material irradiation in room temperature</td>
<td>more than 50</td>
<td>( M_x = 0.90 ) ( M_y = 1.79 )</td>
<td>Target assemblies S1</td>
</tr>
<tr>
<td>31</td>
<td>2</td>
<td>Nuclear- and solid state-physics with EMIS Material irradiation in helium temperature</td>
<td>more than 50</td>
<td>( M_x = 1.85 ) ( M_y = 2.31 )</td>
<td>On-line isotope separator and helium cryostat S1 and P (^2)</td>
</tr>
<tr>
<td>33</td>
<td>3</td>
<td>Atomic physics PIKE</td>
<td>more than 50</td>
<td>( M_x = 0.78 ) ( M_y = 2.19 )</td>
<td>Scattering Chamber and bent crystal x-ray spectrometer S1 and P</td>
</tr>
<tr>
<td>34</td>
<td>3</td>
<td>Nuclear physics by in-beam ( \gamma )-ray detection</td>
<td>more than 50</td>
<td>( M_x = 0.56 ) ( M_y = 1.49 )</td>
<td>Magnet for PAC measurement and goniometer for ( \gamma-\gamma ) correlation S1 and P</td>
</tr>
<tr>
<td>41</td>
<td>4</td>
<td>Nuclear physics by charged particle detection ( \epsilon_x = 20 ) ( \epsilon_y = 10 ) at ( \Delta p/p = 1/12000 )</td>
<td>( M_x = 0.18 ) ( M_y = 0.69 )</td>
<td>650 mm scattering chamber S1</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>5</td>
<td>Nuclear physics by neutron detection ( \epsilon_x = 30 ) ( \epsilon_y = 30 ) at ( \Delta p/p = 1/2400 )</td>
<td>( M_x = 1.03 ) ( M_y = 1.52 )</td>
<td>Time-of-flight spectrometer S1 and S2 1) Sinusoidal beam chopper 2) Pulse beam chopper</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Design Data of Magnets for Beam Transport System

### (1) Q magnets

<table>
<thead>
<tr>
<th></th>
<th>Q-105</th>
<th>Q-92</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape of pole tip</strong></td>
<td>circle, Rp/Rg=1.14</td>
<td>circular, Rp/Rg=1.30</td>
</tr>
<tr>
<td>Pole gap (cm)</td>
<td>10.5</td>
<td>92</td>
</tr>
<tr>
<td>Pole length (cm)</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Maximum field gradient (G/cm)</td>
<td>650</td>
<td>850</td>
</tr>
<tr>
<td>Stability of current (/8hrs)</td>
<td>&lt;1×10⁻⁴</td>
<td>&lt;1×10⁻⁴</td>
</tr>
</tbody>
</table>

### (2) Switching magnets

<table>
<thead>
<tr>
<th></th>
<th>SW1, SW2</th>
<th>SW3</th>
<th>DEF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape of pole tip</strong></td>
<td>circular</td>
<td>circular</td>
<td>circular</td>
</tr>
<tr>
<td>Pole diameter (cm)</td>
<td>76</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>Pole gap (cm)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Maximum field (kG)</td>
<td>13</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Maximum deflection angle for 50 MeV $^4\text{He}^{++}$ (deg)</td>
<td>45</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>Stability of current (/8hrs)</td>
<td>&lt;1×10⁻⁵</td>
<td>&lt;1×10⁻⁵</td>
<td></td>
</tr>
</tbody>
</table>

### (3) Steering magnet

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole gap (cm)</td>
<td>10.4</td>
</tr>
<tr>
<td>Pole length (cm)</td>
<td>20</td>
</tr>
<tr>
<td>Maximum field (G)</td>
<td>450</td>
</tr>
<tr>
<td>Maximum deflection angle for 50 MeV $^4\text{He}^{++}$ (deg)</td>
<td>0.5</td>
</tr>
<tr>
<td>Stability of current (/8hrs)</td>
<td>&lt;1×10⁻³</td>
</tr>
</tbody>
</table>
(4) Analyzer magnets

<table>
<thead>
<tr>
<th></th>
<th>ANA1</th>
<th>ANA2</th>
<th>ANA3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central radius (cm)</td>
<td>140</td>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td>Deflection angle (deg)</td>
<td>105</td>
<td>95</td>
<td>60</td>
</tr>
<tr>
<td>Pole gap (cm)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Pole width (cm)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Parallelism between poles (mm)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Entrance (exit) angle (deg)</td>
<td>36.0(36.0)</td>
<td>31.0(31.0)</td>
<td>30.2(-7.0)</td>
</tr>
<tr>
<td>Maximum field (kG)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.8</td>
</tr>
<tr>
<td>Weight (ton)</td>
<td>3.2</td>
<td>2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Stability of current (/8hrs)</td>
<td>&lt;1×10^{-5}</td>
<td>&lt;1×10^{-5}</td>
<td>&lt;1×10^{-5}</td>
</tr>
</tbody>
</table>

(5) Sextupole magnet

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape of pole tip</td>
<td>circle, Rp/Rg=0.565</td>
</tr>
<tr>
<td>Pole gap (cm)</td>
<td>10.4</td>
</tr>
<tr>
<td>Pole length (cm)</td>
<td>20</td>
</tr>
<tr>
<td>Maximum field coefficient (G/cm²)</td>
<td>50</td>
</tr>
<tr>
<td>Stability of current (/8hrs)</td>
<td>&lt;1×10^{-3}</td>
</tr>
</tbody>
</table>

(6) TOF beam swinger magnets

<table>
<thead>
<tr>
<th></th>
<th>BEND1</th>
<th>BEND2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central radius (cm)</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Deflection angle (deg)</td>
<td>105</td>
<td>95</td>
</tr>
<tr>
<td>Pole gap (cm)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Pole width (cm)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Parallelism between poles (mm)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Entrance and exit-angle (deg)</td>
<td>36</td>
<td>31</td>
</tr>
<tr>
<td>Maximum field (kG)</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Weight (ton)</td>
<td>3.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Stability of current (/8hrs)</td>
<td>&lt;1×10^{-5}</td>
<td>&lt;1×10^{-5}</td>
</tr>
</tbody>
</table>
Fig. 1. General lay-out of the beam transport system with some of the experimental set-ups and of the equipments installed in beam lines.
Fig. 2. A cross section of the edge in the typical dipole magnet named ANA2 (in fig. 1 and table 2). Beams are in the paper.

Fig. 3. Positions of the effective field boundary measured from the edge of the magnet as functions of magnet excitation.

Fig. 4. Field distribution of the dipole magnet. Open circles indicate measured values and the solid line means a prediction by the code MAGMAP. Magnetic fields are normalized to that in the uniform region.
Fig. 5. Field distribution of a quadrupole magnet. Open circles indicate measured values and solid line means a fitting by the function of
\[ h(s) = \frac{1}{1 + \exp \left( \sum_{n=0}^{3} C_n S^n \right) } \] with \( C_0 = -0.8429, \ C_1 = 0.5472, \ C_2 = -0.02127 \) and \( C_3 = 0.0060. \)
Fig. 6. Representative ray-trace of a [51] course.