LONGITUDINAL MATCHING BETWEEN SFC AND SSC

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Abstract

In order to increase the beam current and to enhance the beam quality, an upgrading program of HIRFL is going on at HIRFL. As a part of this program, the longitudinal matching between injector SFC and main machine SSC will be improved. It consists of beam energy measurement, compensation of energy loss due to stripper and a new rebuncher system. In this paper, the study results are presented.

1 INTRODUCTION

HIRFL is an accelerator complex of two cyclotrons in cascade. Its injector is a Sector Focusing Cyclotron (SFC) and its main machine is a Separated Sector Cyclotron (SSC). Since the first beam in 1988, HIRFL has operated about 10 years, providing about forty heavy ion beams for nuclear physics experiments and application research. From the study and the years of operation, we think that the longitudinal matching between SFC and SSC is the key point to be solved to get high beam intensity from SSC. At first, the beam tuning in the center region of SSC is not too smooth sometimes, because the energy of beam from SFC is a little uncertain and the beam energy loss in the carbon foil stripper is not compensated. The second, the function of rebunching system is not good for longitudinal matching in some cases. When SFC is operating at the first harmonic, the effective voltage of rebuncher B1 is not high enough to longitudinal focusing for the beams with higher energy. When SFC is working at the third harmonic, the RF voltage nonlinear effect of B1 is serious, caused by larger energy spread due to multi-tern extraction at SFC. In order to improve beam current and beam quality and to enhance operation efficiency, a study about the longitudinal matching has been done. A new rebunching system is considered to build and a beam energy measurement device and an energy compensation apparatus will be installed. In the section 2, the study results of new rebunching system are given. The energy compensation and energy measurement will be given in section 3 and section 4.

2 NEW REBUNCHING SYSTEM

The injector SFC is a cyclotron of K=69, with extraction radius of 0.75 meter. Its frequency range of RF is 5.5-16.5 MHz, working at harmonic 1 or 3. The main cyclotron SSC, K=450 has the injection radius of 1.0 meter, RF range of 6.5-14 MHz, and works at harmonic 2,4 or 6. The beam line between SFC and SSC is about 66 meter long. Its function is not only to transfer the beam from SFC to SSC, but also match the beam to SSC in the six-dimensional phase space. There are two rebunchers on the beam line. The rebuncher B1 is located in the middle point of the beam line and the rebuncher B2 is 16.5 meter far from SSC. B1 and B2 are identical klystron type rebunchers with two gaps. The length of drift tube is 30cm. Maximum RF voltage is 70kV. Both B1 and B2 are working at the frequency of a factor of 4 of that of SSC-RF, therefore frequency range of 24—56MHz. The layout of rebunching system is given in Fig.1.

According to the formula (1), the effective voltages are

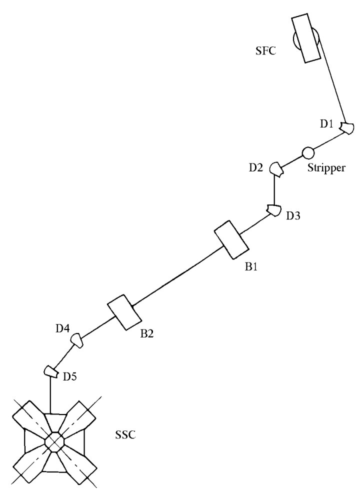


Fig.1 layout of rebunching system

$1.86V_m$, $1.35V_m$ and $0.886V_m$ for harmonic 2,4 and 6, respectively. The maximum voltage V_m is only 70 kV for the existing rebuncher B1, which can not meet the requirement in the case of high energy beam. It seriously effects the beam current and beam property of HIRFL.

$$V_B = 2V_m \sin\frac{\omega_B L}{2v}\sin\phi$$
$$\omega_B = 2\pi f_B, \quad v = 2\pi R_{inj2} / H_2 \qquad (1)$$

In order to change such a situation, a study has been done to improve the rebunching system. The main consideration is following. 1) The new rebunching system should fulfill the matching requirement of all sorts of accelerated beam in the energy range of SFC. 2)

The beam from SFC has larger energy spread due to multi-turn extraction. 3) The improvement takes as less as possible budget.

The study shows that the positions of existing B1 and B2 do not need to change. A new rebuncher B1 with higher RF voltage and new operation mode is needed, but B2 will keep the original one. The new B1 will be used as a main rebuncher, and the B2 will be an auxiliary one. The drift tube length of new B1 is 35cm. Both new B1 and B2 will work at the frequency based on that of SFC-RF. The operation modes of new B1 is given in Table 1. H_1, H_2 and H_B are the harmonic number of SFC, SSC and new B1 respectively. F_{RF1} is RF frequency of SFC and E_1 is the energy of beam from SFC.

Tab. 1 Operation Mode of new B1

Mode	H_1 / H_2	H_B	f_B	f_{RF1}	E_1
1	1/2	6	33-54	5.5-9.0	3.5-9.5
2	3/2	2	26-33	13-16	2.2-3.5
3	3/4	2	22-28	11-14	1.5-2.5
4	3/4	3	22-33	7.5-11	0.7-1.5
5	3/6	3	22-28	7.5-9.3	0.7-1.1
6	3/6	4	22-30	5.5-7.5	0.4-0.7

When the length of drift tube of new B1 is 35 cm, the effective voltage of B1 for different operation mode is following,

Mode 1: $V_B = 1.972 V_m \sin\phi$
Mode 2: $V_B = 1.972 V_m \sin\phi$
Mode 3: $V_B = 1.972 V_m \sin\phi$
Mode 4: $V_B = 1.729 V_m \sin\phi$
Mode 5: $V_B = 1.729 V_m \sin\phi$
Mode 6: $V_B = -0.661 V_m \sin\phi$

From the data above, it is obvious that Mode 1 to Mode 3 have much higher voltage factor, and Mode 4 to Mode 6 have a little lower one, especially for Mode 6. In fact, the lower effective voltage at mode 6 imposes no problem and is even beneficial, since the mode works in the case of low energy beam and the very low voltage is also difficult to maintain.

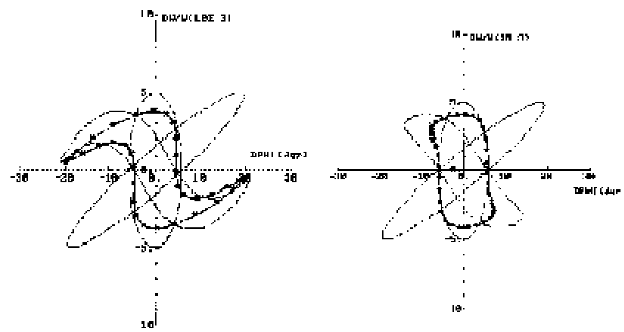
According to the calculations for several typical beams, when only new rebuncher B1 is used, the RF voltages V_m for 6 Modes are given in table 2.

Table 2, RF voltage of new B1 for typical ions

Mode	Ion	E_1 (MeV/u)	V_m (kV)
1	$^{16}O^{8+}$	8.5	146.2
1	$^{16}O^{*+}$	4.53	77.9
2	$^{40}Ar^{15+}$	3.25	74.5
3	$^{40}Ar^{15+}$	2.35	53.9
4 or 5	$^{129}Xe^{25+}$	0.77	26.2
6	$^{238}U^{29+}$	0.5	61.1

In order to decrease the RF voltage of new B1 in the case of higher energy with Mode 1, the existing B2 can be used as an auxiliary rebuncher. The calculation result shows if B2 is employed, V_m of 110kV is enough for new B1 to complete the longitudinal matching.

Using the new B1 with 6 modes, the nonlinear effect can be improved very much. Figure 2 shows the phase space transformations in the cases of both existing B1 and new B1. The calculation is for ion $^{129}X^{28+}$ of 1.112 MeV/u. The initial phase ellipse is erect with $\Delta\phi = \pm 6^o$ and $\Delta E/E = \pm 0.5\%$. The dotted line shows the phase ellipse at the entrance of SSC.



(a) (b)

Fig.2 Longitudinal phase space transformation. (a) in the case of existing B1, (b) in the case of new B1.

The main parameters of new B1 are following:

Drift tube length 35 cm
RF frequency range 22-54MHz
RF voltage (V_m) 60-110kV (higher frequency)
15-60kV (lower frequency)

3 ENERGY COMPENSATION

Stripper foil causes ion energy loss of ion beam as passing through it. A calculation shows that the energy losses are larger for heavier ion with lower energy. For instance, for ion $^{40}Ar^{15+}$ of 2.35MeV/u and $^{129}Xe^{9+}$ with energy of 0.77 MeV/u, the fractional energy losses are 1.25% and 1.57% respectively. In order to avoid the beam energy mismatching between SFC and SSC, the beam energy need to be compensated. There are two ways to do it. One way is that B2 can be used to increase

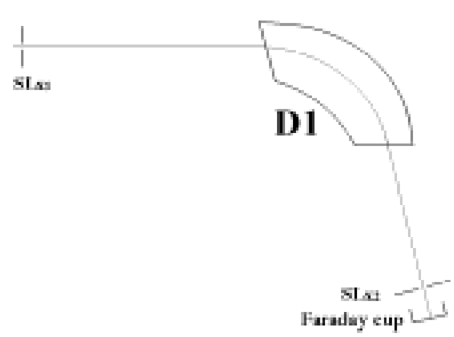


Fig.4 Layout of energy measurement

the beam energy when its suitable phase is tuned. Another way is to install a compensation device in the stripper. The principle of compensation is shown in the Fig. 3.

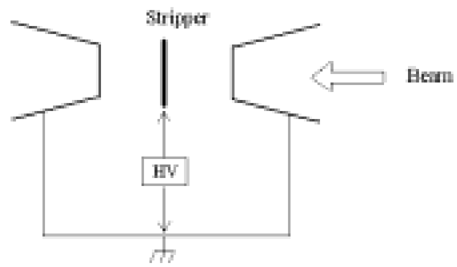


Fig.3 Energy compensation principle

When the potential on the stripper is U, the beam energy gains ΔE.

$$\Delta E = eU(q_2 - q_1) \tag{2}$$

q_1 and q_2 are the charge state of ions before and after stripping. With program RELAX3D, the shape of electrode is designed.

4 BEAM ENERGY MEASUREMENT

The Beam energy and divergence from SFC is not certain for each case. Sometimes it makes trouble to the beam tuning at the injection of SSC. If the beam energy can be measured, it can be changed to match SSC by adjusting the extraction system of SFC, normally adjusting harmonic coil current and voltage of electrostatic deflector. So, a device to measure the beam energy and energy spread near the exit of SFC is needed. In addition, Sometimes the definite beam energy is also needed by some physicists who do experiments with the beam from SFC.

The first dipole D1 on the beam line can be used to make the measurement as an analyzing magnet together with some beam diagnostics devices. Table 4 shows its main parameters.

Table 4, The main parameters of D1

Φ	ρ	β_1	β_2
74^o	100cm	20^o	20^o

Φ, ρ, β_1 and β_2 are bending angle, bending radius, entrance and exit pole face rotation angle of D1. The layout of energy measurement system is given in Fig.4. The object distance is 3.4m and image distance is 2.02m. A movable object slit and image slit are located at the object point and image point respectively. In order to decrease the measurement error of magnetic field, a probe of nuclear magnetic resonance (NMR) is put into the gap of D1. By considering $\Delta\rho/\rho$, $\Delta B/B$ and $\Delta L/L$ carefully, the measurement error of $\Delta E/E$ can be less than 0.5%. The length L equals to $\rho\Phi$, which is a function of magnetic field.

5 SUMMARY

As a part of upgrading program of HIRFL, the beam longitudinal matching between SFC and SSC is conducting at HIRFL. The new rebunching system, beam energy compensation device and beam energy measurement device will not only improve beam current and quality, but also enhance the operation effect of HIRFL. The work will be finished in two years.