A NEW BUNCHER SYSTEM FOR SFC

J.Y. Tang, W. Lei, Y.F. Wang
Institute of Modern Physics, P.O. Box 31, Lanzhou 730000, P.R. China

Abstract: Due to the low bunching efficiency of the present buncher system, a new buncher system has been designed, which consists of two bunchers working at H=1 and H=3 modes corresponding to the SFC acceleration modes. They all use saw-tooth RF wave form, but with double-gaps drift tube electrodes and one gap grid electrodes, respectively. The special merit of the design is that we introduce the half-frequency bunching mode, which means the use of the half of the cyclotron RF frequency. With this we can make the theoretically perfect longitudinal match between the injector SFC and the main cyclotron SSC, presently it is 50% for most cases. Detailed studies such as space charge effects, longitudinal dispersions through the yoke hole and the spiral inflector, and nonlinearities both of the RF wave form and of the stray electric field of electrodes are discussed.

1. Introduction

The injector SFC of HIRFL accelerator complex is a sector-focused cyclotron (D=1.7 m, K=69). On the axial injection line which is deserved to transfer beam from ECR ion source to SFC, a saw-tooth wave form buncher[1,2] was installed together with the line in early 1992, see Fig.1. The buncher is at the position B02. But the operation since then showed that it worked well below the expectation. It can increase the extracted beam intensity by 4 times at the best cases for the first harmonic acceleration mode (H=1), and by 6 times at maximum for the third harmonic acceleration mode (H=3), compared with the case of no buncher in work. Therefore a detailed study concerning the bunching efficiency and injection efficiency was taken. It shows that the main reasons for the present low bunching efficeincy are low available bunch voltage, space charge effect, time dispersions through the injection line and nonlinearity of the wave form. Then on the base of the study, we make a new design for the buncher system which is under construction. The new buncher system consists of two bunchers, respectively working at the mode H=1 and at the mode H=3. But it leads also to adjust the injection line and central region[3].

2. Numerical calculations of the bunching process

The ideal buncher can be calculated easily by formula. But when including the various affects such as the space charge effect, the nonlinearity of the bunching wave form, stray magnetic field in the axial hole and stray electric field of buncher electrodes, and the time spread in the inflector, it becomes much more difficult. Here we use a charge disc model which considers the continuous beam as many equi-individed discs with equal radius (for example, 100 discs for each bunching period), and develop a computer program named SCEBUN. The bunching process is just the redistribution of the discs after the modulating of the bunching voltage on the discs and other disturbances. The bunching efficiency is decided by the portion of the discs within the RF phase range defined by SFC central region at

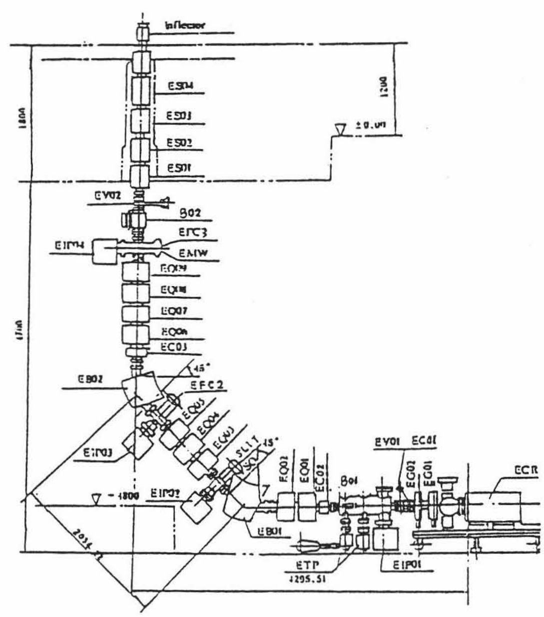

Fig.1 Axial injection line from ECR to SFC

the first acceleration gap. In our case we take the RF phase acceptance as $\Delta\phi=\pm15°$ for H=1 and $\Delta\phi=\pm10°$ for H=3. The movement of the discs is calculated by the second order Runge-Kutta integration method. (After we finish the implantation of a multiparticle tracing program, we can use it for more complete calculation). In the program

SECBUN, the influences on the bunching efficiency of all the factor mentioned above are considered.

2.1) Influence of the energy spread from the ion source

The factor may be important for some ion sources such as polarized ion source, but for ECR ion source the energy spread is about 1×10^{-3}, and can be ignored here.

2.2) Space charge effect

The space charge effect is important for the low energy beam transfer, both for transversal and longitudinal phase spaces, specially when the buncher squeezes the continuous beam into high density pulse. With the disc model, we can calculate the influence of the effect to the bunching process. With some higher bunching voltage, the influence of the space charge effec can be compensated to some extent. Fig. 2 shows the influence for the certain cases. The beneficial side of the space charge effect is that it decreases the energy spread created by the modulation of the bunching voltage.

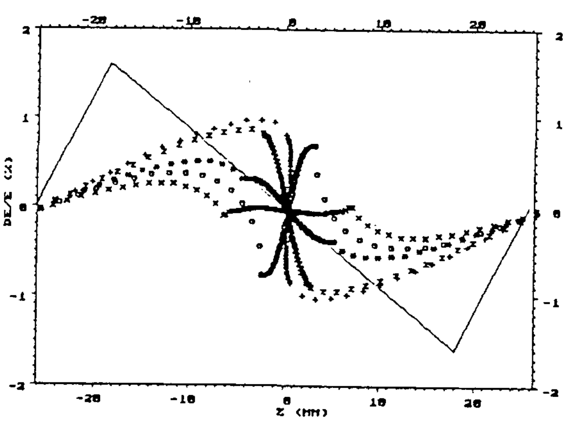

Fig.2 Space charge effect on the bunching efficiency
Vinj=15kV, z: I=20μA, V_B=240V;
*: I=40μA, V_B=240V; x: I=60μA, V_B=240V;
o: I=60μA, V_B=360V; z: I=20μA, V_B=240V;

2.3) Stray magnetic field in the axial hole

When beam passes through the strong stray magnetic field in the axial hole, not only is the transversal focusing affected, also is the longitudinal movement affected. For the axisymmetrical stray field, the longitudinal force on the beam is : $F_z = -\frac{1}{2} q v_0 B'(-\dot{x}y + \dot{y}x)$, where q the charge, v_0 the reference particle's velocity, B' the magnetic field gradient, $x, y, \dot{x}, \dot{y}$ describing the phase space point. The force generates time dispersion which decreases the bunching efficiency. The calculation shows that the factor has significant affluence in the case of H=3, and minor affluence in the case of H=1.

2.4) Time dispersion in the spiral inflector

The coupling between the transversal and longitudinal phase spaces gives rise to the time dispersion. As in the stray magnetic field, it has the significant affluence in the case of H=3, but even stronger.

2.5) Non-ideal electrodes of the buncher

When the grid electrodes as in the case of SFC's present buncher is used, we should consider the stray electric field outside the bunching gap. It may distort the bunching wave form and decrease there bunching efficiency But careful design of the electrodes and the shielding can make the affluence much smaller. Fig. 3 shows the affluence to the bunching wave form for the present buncher (H=1).

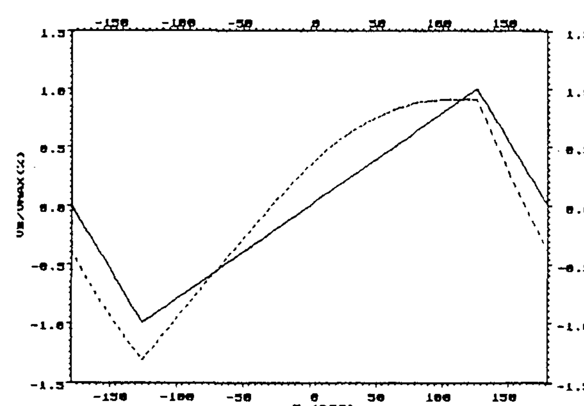

Fig.3 Deforming of bunching wave form by spray electric field
(B02 for H=1 mode, βλ=15.7cm)

Table 1 The matching modes between SFC and SSC

Mode	N_1/N_2	H_1/H_2	f_{BUN} (MHz)	f_{RF1} (MHz)	E_1 (Mev/A)	f_{RF2} (MHz)	E_2 (Mev/A)	η (%)
1	3/2	1/2	6-9.33	6-9.33	4.14-10	9-14	46-124.8	50
1'	3/2	1/2	3-4.67	6-9.33	4.14-10	9-14	46-124.8	100
2	1/1	3/4	6.5-14	6.5-14	0.54-2.5	6.5-14	5.6-27.1	100
3	1/2	3/2	13-18	13-18	2.16-4.14	6.5-9	23.3-46	50
3'	1/2	3/2	6.5-9	13-18	2.16-4.14	6.5-9	23.3-46	100
4	3/2	3/6	6-9.33	6-9.33	0.46-1.11	9-14	4.8-11.7	50
4'	3/2	3/6	3-4.67	6-9.33	0.46-1.11	9-14	4.8-11.7	100

Note: the modes with slash are half frequency bunching modes.

3. Results and new design

3.1) Present buncher system

The buncher locates at the 2.335 m from the SFC central plane, and it is used both in the case of H=1 and in the case of H=3 with the same frequency as RF in SFC. Not only can the bunching voltage not meet the requirement, the maximum bunching voltage is about 400 V, its bunching wave form for H=1 is also very deformed. So the bunching efficiency is quite low at most cases. It is difficult to augment the bunching voltage at the present position simply, in the case of H=1 it asks for V_{BUN}=1300 V at maximum which is difficult to achieve from the RF generator side because of the use of saw-tooth wave-form. And it is not desirable to use very strong modulation from the view of central region, as the energy spread in the case is some too high to lead strong the coupling of phase space and the decreasing of matching efficiency between the injection line and the central region. But for the case of H=3, it is well positioned if we can augment the bunching voltage to V_{BUN}=600V. The present bunching voltage is got from saw-tooth generator following by a wide-band amplifier. The amplifier has the problem to raise the voltage to above 400V, and generates also nonlinearity sometimes very serious. So we will use other technical way for the new buncher system.

3.2) New buncher system

On looking for the solution to the low bunching voltage in the case of H=1, the position to install the new buncher is studied when not to change the current beam injection line as possible. As the elements on the beam line are tightly arranged, it is not easy to find the right place. The vacuum chamber after the two Glaser lenses is chosen for the use, where the bunching drift distance is about L=7.5 m, a diagnostic device is removed. But the calculation shows that the space charge effect is too important in the case of H=3. So we use the new buncher only for the case of H=1, when keeping the present buncher on the line for the case of H=3. As mentioned in the last section, the presently used amplifier has the problem of power and of nonlinearity, we are taking the method of generating the saw-tooth wave-form with high voltage by the direct forming through recharging and discharging proccess. It should give much better nonlinerity condition and higher voltage.

3.3) Half frequency bunching mode to increase the match efficiency between SFC and SSC

When SFC works at the mode H=1 and SSC at the mode H=2, the match efficiency between the two cyclotrons is only 50% in theory, so are other cases except SFC at H=3 and SSC at H=4 where the efficiency is 100%. This is due to the dismatch of the SFC's extraction radius (R_{ext}=0.75 m) with the SSC's injection radius (R_{inj}=1.0 m). For the unequal radius match, there should be:

$$F_1 R_1^{ext} = F_2 R_2^{inj}$$

$$N_1 H_1 F_1 = N_2 H_2 F_2$$

where indices 1 and 2 represent SFC and SSC, F is particle's revolution frequency, R is mean radius, H is harmonic. N_1 and N_2 are integers expressing RF circle numbers of SFC and SSC when SSC and SFC return at the same RF matching phases. So $1/N_2$ represents the matching efficiency. We can see the matching for different cases in Table 1.

The longitudinal matches for the different cases between the two cyclotrons are shown in table 1. It is a great pity to lose the part of the beam intensity. We proposed to use the buncher system on the axial injection line of SFC to regain the lost beam. We simply reduce the bunching frequency by half ($f_{BUN}=f_{RF,SFC}/2$), the buncher can squeeze the original two packets into one. But it needs double bunching voltage and some changements on the RF systems due to the working frequency range expanded from 6-18 MHz to 3-18 MHz. Due to the decreased frequency, it is favourable to get higher voltage by the recharging and discharging method. Generally the half frequency mode, compared with the identical frequency mode, has higher requirement for the nonlinearity of the wave form, but here it gives no problem with direct forming method. In table 2, we can see that the bunching voltage requirement can be achieved not too difficultly. Considering the case of SFC at H=3 and SSC at H=6 is rarely used before, the half frequency bunching mode makes it favourable compared with SSC at H=4 when

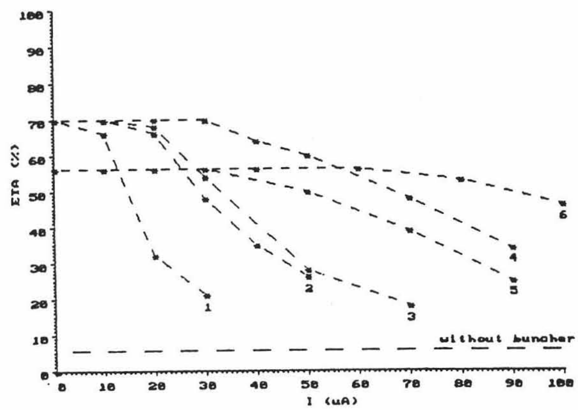

Fig.4 Bunching efficiency with new designed buncher system
1 : H=1/2, V_{inj}=15kV, L=7.5m; 2: H=1/2, V_{inj}=25kV, L=7.5m;
3: H=1, V_{inj}=15kV, L=7.5m; 4: H=1, V_{inj}=25kV, L=7.5m;
5: H=3, V_{inj}=15kV, L=2.335m; 6: H=3, V_{inj}=25kV, L=2.335m;

both modes are realizable, since the acceleration phase is frequency bunching mode is that we can choose two gaps drift tube type buncher structure as the new buncher due to switched to 90° from 60°. Another advantage to use half reduced transit time effect in the bunching gaps, since the bunching length $\beta\lambda$ doubles ($\beta\lambda=2\pi\rho_0/h$ for identical frequency mode, $4\pi\rho_0/h$ for half frequency mode). So it can provides double effective bunching voltage and does not loss the beam hit on the grid electrodes. With the half frequency bunching mode, the calculation shows that the system is stronger to resist the space charge effect.

The calculation results about the bunching efficiency are shown in Fig.4.

4. Conclusions

From the numerical calculations, we can get following conclusions:

Table 2 Nominal bunching voltages for different cases

H	L_B (m)	V_{inj} (kV)	V_B (V)
1	7.5	25	2×190
1/2	7.5	25	2×380
1	2.335	12.5	600
3	2.335	25	400
3/2	2.335	18.75	600

Note: Values without considering space charge effec. H with half value means half frequency mode, L_B for bunching distance, V_{inj} for injection voltage, V_B for bunching voltage amplitude. Two bunching gaps for L_B=7.5 m.

1)It is a chosen solution to keep the two bunchers on the line, respectively half frequency mode with two gaps drift tube type working at H=1 and same frequency mode with grid type working at H=3.

2)Half frequency bunching mode is possible, and it increases the theoretical match efficiency between SFC and SSC to 100%. It resists also better the space charge effect.

3)Bunching voltage of maximum 600V can meet almost all the case. The other requirements for RF generator system are: 2-3% for nonlinearity, 3-18 MHz for frequency range, 70% for the bunching section portion over the period.

4)Space charge effect limits the maximum injection beam intensity into SFC, the bunching efficiency decreases with the increasing intensity. The typical limitation is about 30-50 μA, that is the level of the present ECR ion source for heavy ions, but a diaphragm is needed to limit the beam intensity for light ions.

5)Stray electric field of the excited electrode of the grid type buncher, magnetic field in the axial hole, and the time spread through spiral inflector can produce bad affluence on the bunching efficiency. The first affect can be reduced to very low level by adjusting the electrode structure to get suitable stray field zone length. The affluence from the inflector is the most significant, specially for the case of H=3.

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