DESIGN OF BEAM CHOPPING SYSTEM FOR JAERI AVF CYCLOTRON

W. Yokota, K. Arakawa, Y. Nakamura, T. Kamiya, M. Fukuda and R. Tanaka
Takasaki Radiation Chemistry Research Establishment
Japan Atomic Energy Research Institute
Takasaki, Gunma 370-12, Japan

T. Tachikawa, T. Mita, and T. Satoh
Sumitomo Heavy Industries, Ltd.
Niihama, Ehime 792, Japan

ABSTRACT

A beam chopping system is installed for the JAERI AVF cyclotron with external ion sources to supply pulse beams with wide variety of pulse interval, energy, ion species. A combination of a pulse voltage chopper in the injection line and a sinusoidal voltage chopper at the exit of the cyclotron is adopted to extract a single pulse beam from the cyclotron. The beam chopping process and optimization of chopping parameters are discussed.

1. INTRODUCTION

The JAERI AVF cyclotron under construction is intended to be used for advanced application of ion beam irradiation mostly in material science. In order to meet various requirements for beam utilization in the research program, the cyclotron provides various ion beam characteristics[1]. Pulsed beam irradiation of heavy-ion beams is one of the important characteristics and is planned in use mainly for the in-situ analysis of elementary process in irradiated materials and for basic reseach on radiation chemical reaction process.

These research programs require duration time within a few ns for each pulse and a wide range of pulse intervals of 1 μs to 1 s. The duration time is limited by that of individual pulse extracted from the cyclotron. The interval range of 1 ms to 1 s can be covered by mechanical choppers at the end of the beam lines, and that of 1 μs to 1 ms covered by an electrical chopping system.

We chose a combination of a pulse voltage chopper (P-chopper) and a sinusoidal voltage chopper (S-chopper) for the electrical chopping system. The P-chopper is installed in the injection line for slow chopping and the S-chopper in the high energy beam line for fast chopping.

A similar chopping system is in operation at the Tohoku University cyclotron system (CYRIC), and both choppers were installed in the high energy beam line[2].

Installation of the P-chopper in the injection line permits application of low voltage to the chopper electrodes, because of low momentum of ions. However, the long ion-transit time through the electrodes and limitation on the rising time of the voltage make it difficult to provide short duration time of the beam pulse after the P-chopper. Therefore, the P-chopper is designed to provide the pulse beam with a duration several times as long as the cyclotron RF period and an interval range of 1 μs to 1 ms.

Beam chopping in the injection line contributes to minimize the activation of the cyclotron, the beam transport system and experimental devices at target rooms, because the unnecessary beams are discarded in the injection line without being injected into the cyclotron.

The long duration of the beam pulse after the chopping and multi-turn extraction from the cyclotron result in a train of plural beam pulses. The role of the S-chopper is to extract only one pulse out of the train. The high momentum ion beams can be chopped by using high sinusoidal voltage wave.

The paper describes the beam chopping process to satisfy the requirement of the beam characteristics and optimization of chopper parameters.

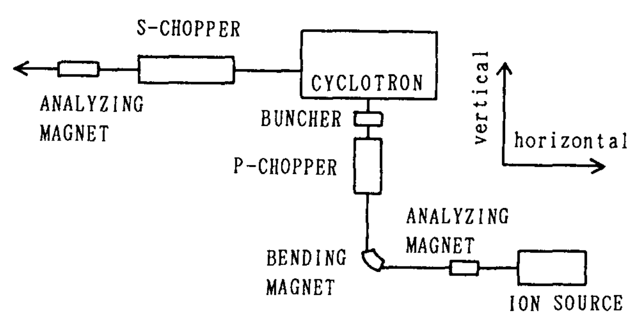

Fig. 1 Geometrical arrangement of P- and S-choppers, ion sources, buncher and cyclotron.

2. AVF CYCLOTRON AND BEAM CHOPPERS

Geometrical arrangement for P- and S-choppers is shown in Fig. 1. We install two external ion sources, ECR ion source (OCTOPUS) for heavy ions and a multi-cusp type ion source for light ions (H^+, D^+, He^{2+}) and their injection voltages into the cyclotron are up to 20 kV and 30 kV, respectively. The injection line is designed to transport all the ions (M/Q = 1 - 6.5) which can be accelerated by the cyclotron. A buncher is set at a distance of 1.5 m from the median plane. The slit of the P-chopper is set at a beam waist in the injection line, which is located just before the buncher.

The AVF cyclotron operates with a RF frequency range of 11 - 22 MHz and the harmonic numbers of 1, 2 and 3. The time width of the beam pulse from the cyclotron is estimated to be about 5 - 10 ns depending on the radio frequency, and it can be reduced within a few ns by adjusting the phase slit of the cyclotron. A dedicated inflector of spiral type is prepared for each harmonic number.

The slit of the S-chopper is set at a waist point located at 5.3 m from the exit of the cyclotron in the high energy beam line. The chopped beams are available at all the target ports after analysing magnet and the switching magnet.

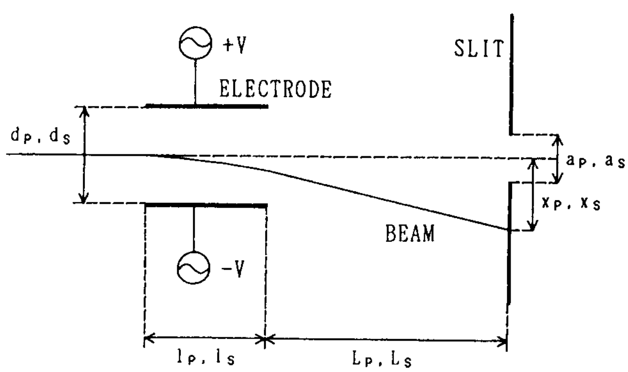

Fig. 2 Geometrical parameters of P-chopper (suffixed with p) and S-chopper (with s). Symbols l, d, L, a and x describe electrode length, electrode gap, drift length, slit width and beam deviation at slit, respectively.

3. BEAM CHOPPING PROCESS

We adopt a pair of parallel-plate electrodes for both choppers and their voltage waves synchronize with the cyclotron RF. The geometrical parameters of the chopper is shown in Fig. 2.

The beam chopping process is illustrated in Fig. 3. D.C beams from the ion sources are pulsated by the P-chopper voltage wave V_P (Fig. 3a-d) into beam pulses with the duration several times as long as the cyclotron RF period. The electric field is assumed to be uniform within the electrode gap and zero outside the gap.

The maximum deviation of beam at the slit (x_{Pmax}) and the chopping condotion are expressed by

$$x_{Pmax} = \frac{l_P(l_P+2L_P)}{4d_P} \cdot \frac{V_{Pmax}}{V_{inj}} \qquad (1)$$

$$x_{Pmax} > a_S \qquad (2)$$

where V_{Pmax} and V_{ini} are the peak voltage of the P-chopper and the injection voltage into the cyclotron, respectively. We set the width of the slit the same as the beam diameter estimated by beam optics calculation. The change of the beam deviation at the slit (x_P) with time is as shown in Fig. 3c. We made an approximation that x_P changes linearly with time in rising and decay of the voltage pulse, though the change is expressed by third polynominal of time.

It is reasonable to choose the value of τ_P (Fig. 3b) so that the duration at the maximum beam current equals the effective bunching phase time t_b (Fig. 3d, e, we assumed 150° of the cyclotron RF period), since only the ions in the phase pass through the S-chopper. The total width of the beam pulse T (Fig. 3d) after the P-chopper is experssed with rising time of P-chopper voltage τ_r, ion transit time through the electrodes t_{lP} and t_b,

$$T = \frac{2a_P}{x_{Pmax}}(\tau_r + t_{lP}) + t_b \qquad (3)$$

The resultant beam pulse is modulated by the buncher into the plural number (n_P) of bunches, followed by injection into the cyclotron (Fig. 3e, f).

The beam bunches are separated into a train of n_P pulses (Fig3. g) by natural bunching during acceleration, and each pulse is further divided into plural pulses (n pulses) by multi-turn exstraction at the deflector. Therefore, a P-chopper voltage pulse results in extracting n_P+n-1 pulses from the cyclotron (Fig. 3h). In the design of this chopping system, the division number of the pulses (n) is assumed to be 5.

As can be seen from Fig. 3d-i, the total width T has colse relation with the chopping rate (1/m) of the S-chopper. Since all the beam pulses which pass through the S-chopper electrodes when the voltage V_S is zero, the time length of the train must be shorter than the period of the S-chopper RF for extraction of one pulse from a beam pulse train (Fig. 3h, i). The condition for this is given by

$$\tau_S - \frac{\tau_S}{2m}(n-1) - t_b > T \qquad (4)$$

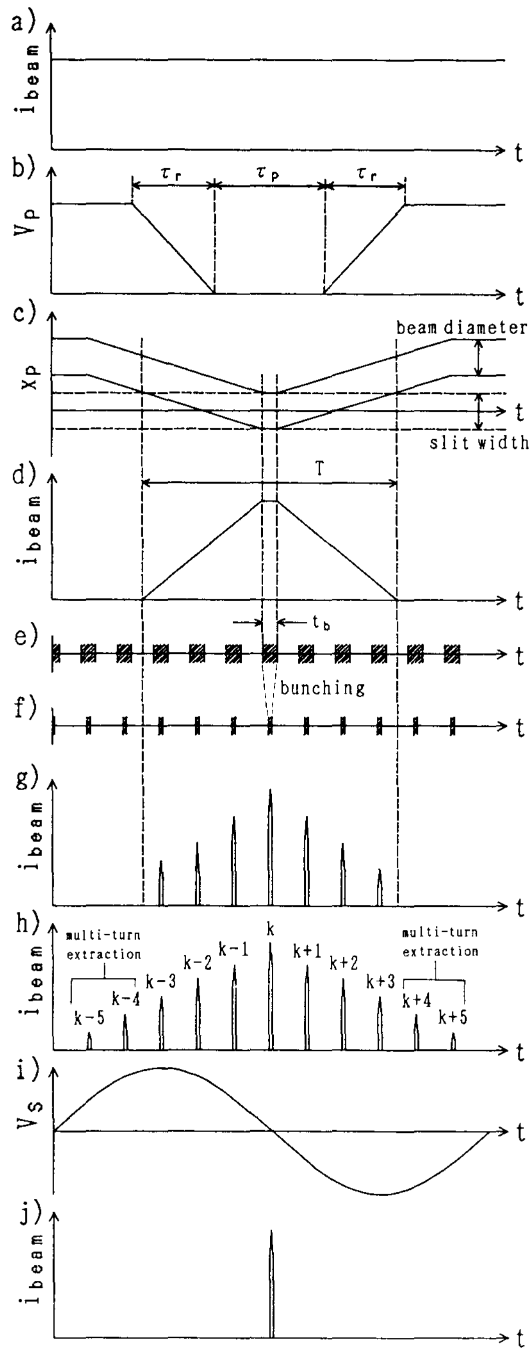

Fig. 3 Diagram of beam chopping process (an example for chopping rate 1/6).
a) D.C. beam current from ion sources.
b) P-chopper voltage.
c) Beam deviation at P-chopper slit.
d) Beam pulse after passing through P-chopper.
e) Effective buncher phase.
f) Acceleration phase.
g) A group of plural beam pulses in cyclotron.
h) A train of plural beam pluses from cyclotron.
i) S-chopper voltage.
j) Beam pulse after S-chopper.

$$\tau_S = \frac{2m}{f_c} \qquad (5)$$

here, f_c is the cyclotron RF frequency.

Moreover, to remove all the beam pulses in a train except for k th pulse (Fig. 3h), the neibouring beam pulses (k-1 and k+1 th pulses) are required to deflect the direction and not to pass the slit. Setting the slit width the same as the beam diameter, the maximum deviation of k±1 th pulses and the condition of chopping are written as follows,

$$x_{Smax} = \frac{l_S(l_S+2L_S)}{4d_S}\cdot\frac{q}{E}\cdot V_{Smax}\cdot\sin\left(\frac{\pi}{m}\right) \qquad (6)$$

$$x_{Smax} > a_S \qquad (7)$$

where V_{Smax}, q and E are the peak voltage of the S-chopper, charge state number and energy of ions, respectively. In these quation, we neglect the slight change of the chopper voltage during passing through the electrodes.

The voltage is nearly zero while ions in the k th pulse (see Fig. 3h, i) is passing through the electrodes. Strictly speaking, a small amount of the voltage variation during the passing causes a slight increase of divergence of the beam. However, the resultant expansion of beam size at the slit is negligibly small.

A single pulse can be extracted from a beam pulse train on conditions that all the conditions of eqs. (2), (4) and (7) are satisfied.

4. OPTIMIZATION OF CHOPPER PARAMETERS

The design of beam transport optics and the arrangement of optical elements around the choppers restrict the parameters concerning the chopper geometry. On the other hand we are allowed to choose the value of V_{Pmax} in a certain range within the technical limitation on high voltage application. It is shown by eqs. (1) and (4) that V_{Pmax} plays an important role to decide the value of T and then m. If we choose a large value of m, a large T and a small V_{Pmax} are allowed. Contrary to that, however, the chopping condition for the S-chopper (eq. (6) and (7)) is hardly satisfied because the applied voltages on k±1 th pulses are lower for larger m and that the value of V_{Smax} is required to be smaller than 40 kV to avoid dielectric breakdown. There is another restriction on the S-chopper that the frequency can cover a range within only over factor three because of a limitation on the capacitance of the tuning condenser. The essential point of the optimization is to search a combination of reasonable values of V_{Pmax} and m. In the eqs. (2) and (7) the chopping ability at the slit is expressed as the maximum beam deviation larger than the slit gap. In consideration of pracical allowance we required more strict condition that the deviation should be larger than 1.5 times the slit width.

It is found that 1.5 kV is practically reasonable for the maximum value of V_{Pmax} and results in a reasonable value of T for the S-chopper for almost all ion species and their energies. As a result of the above consideration we chose the number m of 4, 5 and 6, and the S-chopper frequency range of 1 to 3 MHz.

Finally optimized parameters are listed in Table 1. The H^+ beam with energy higher than 75 MeV is not chopped into a single beam pulse, because we cannot obtain sufficiently short T for the S-chopper to deflect k±1 th pulses with the above parameter set.

Table 1 Designed parameters of P- and S-choppers.

	P-chopper	S-chopper
geometrical parameter		
electrode length l (cm)	13	120
electrode gap d (cm)	8	4
drift length L (cm)	60	80
slit width a (cm)	2.4	0.4
voltage wave		
rising time τ_r (ns)	200	—
frequency (MHz)	0.001-1.0	1-3
maximum voltage Vmax(kV)	1.5	40
chopping rate	—	1/4, 1/5, 1/6

5. SUMMARY

In an AVF cyclotron with external ion sources, a combination of a pulse voltage chopper (P-chopper) installed at the injection line and the sinusoidal voltage chopper (S-chopper) at the high energy beam line are designed to provide a single beam pulse with a very wide range of interval (1 μs - 1ms). It is essential that the duration of a train of the cyclotron beam pulse resulting from a beam pulse chopped by the P-chopper is shorter than the period of the sinusoidal voltage wave. The chopping rate of the S-chopper also depends on the peak voltage of the P-chopper. All the parameters were optimized as shown in Table 1. Chopping of all the ions except for H^+ with energy higher than 75 MeV is realized with the above parameter set, under the formalism including a few approximation and an assumption that each beam pulse is devided into 5 pulses at the cyclotron deflector by multi-turn extraction.

REFERENCES

1) Tanaka, R., Arakawa, K., Yokota, W., Nakamura, Y., Kamiya, T., Fukuda, M., Agematsu T., and Maruyama, M., "JAERI AVF Cyclotron for Research of Advanced Technology Project", presented at this Conference (1989).

2) CYRIC Annual Report, (Tohoku Univ., 1980), pp. 263-267