A VARIABLE FREQUENCY LINAC AND ITS USE AS AN INJECTOR FOR A SEPARATE SECTOR HEAVY ION CYCLOTRON

M. Odera and T. Tonuma
Cyclotron Laboratory, The Institute of Physical and Chemical Research, Saitama, Japan

ABSTRACT

Design of a variable frequency π-mode linac and its use as a prestripper accelerator for a separate sector cyclotron are described. Acceleration of ions of almost all of the elements is possible with moderate intensity. Wide range of difference in charge-to-mass ratio can be handled with frequency variation proportional to $(q/m)^{\frac{1}{2}}$. Variable energy operation is also feasible.

A two-stage accelerator combined with a separate sector cyclotron is proposed. With deliberate design the system can be a versatile heavy ion accelerator. Use of the separate sector cyclotron as a post-stripper accelerator has several advantages which are elucidated.

1. INTRODUCTION

The variable energy cyclotron of IPCR is now accelerating proton, deuteron, ^{3}He, alpha, carbon, nitrogen and oxygen ions on a 24 hour/day system. Many kinds of research as solid state physics, radio and radiation chemistry, biology and production of radio-isotopes for various usages are carried out as well as nuclear physics study. Severe want of machine time is foreseeable in the near future, especially for heavy ion beams. Construction of a new accelerator facility is now desired.

This is a proposal to build a variable frequency linac to accelerate heavy ions of wide range of charge-to-mass ratio. Maximum energy attainable by this scheme is not high. But, many researches can proceed into new field of study by use of vastly expanded projectile species. There is also a possibility to use this type as a prestripper accelerator to form a two-stage versatile heavy ion machine. Combination of this type with a separate sector cyclotron is considered most suitable as the future facility of the Institute.

2. VARIABLE FREQUENCY LINAC FOR BROAD RANGE OF CHARGE-TO-MASS RATIO

Length L of transit of a particle of mass m, charge q and energy qV in time T is given by

$$L \propto T\sqrt{\frac{qV}{m}}\,. \tag{1}$$

It is apparent from eq. (1) that for a usual linac where the period T of the radio-frequency field and the length L of a particular drift tube section are fixed, the equivalent potential drop V to represent particle energy must be proportional to m/q to maintain synchronized acceleration. Thus, for a certain selected drift tube geometry and frequency, the range of acceptable value of m/q is relatively narrow for the fixed frequency linac. Energy per nucleon of the ion is independent of charge-to-mass ratio.

On the other hand, if T were to be made to change proportionally to $\sqrt{m/q}$, the necessary value of the drift tube voltage could remain the same, irrespective of charge-to-mass ratio. Energy per nucleon is proportional to q/m in this case.

Of course, variable frequency operation of high power amplifiers coupled with cavities of high Q values presents severe difficulties. Nevertheless, realization of variable frequency linac seems possible at least for a configuration consisting of only single or a few number of cavities.

There is another profit by making frequency proportional to $\sqrt{q/m}$. It is well known that the radial focusing of the ions of small charge-to-mass ratio in a linac requires high gradient quadrupoles, if use of grids at drift tube apertures is to be avoided.[1] In the variable frequency scheme, low frequency is used for a large mass ion of relatively small charge. The necessity of high gradient can be relaxed. If electrostatic quadrupoles are used, the same voltage on the electrodes ensures the same trajectory for ions of different charge-to-mass ratio when the voltage on the drift tube is the same in spite of frequency change. The defocusing force at the gap can be expressed as

$$\frac{\Delta r'}{r} = \frac{E_0}{\ell}\,\frac{e}{m}\left(\frac{\pi}{\omega}\right)^2 \cos\phi_0 \,\sin\frac{\pi d}{2} \tag{2}$$

for π mode operation.[2] Here E_0 is the mean field at the gap, ℓ is the distance between centres of consecutive drift tubes, ϕ_0 is the rf phase of the equilibrium particles and d is the length of the gap. All the lengths along the direction of acceleration are expressed in units of ℓ. Effect of focusing element is represented by

$$K^2 = \frac{e}{m}\left(\frac{\pi}{\omega}\right)^2 G$$

$$E_x = \pm Gx,\ E_y = \pm Gy. \tag{3}$$

E is the radial electric field in an electrostatic quadrupole. Thus, once the focusing condition for ions of arbitrary charge-to-mass ratio--for instance, for the lightest particles compatible with the given E and maximum frequency--is established, focusing of ions of other m/q is assured by making frequency proportional to $\sqrt{q/m}$. This greatly simplifies adjustment of focusing condition for various particles. Fig. 1 is the required field gradient of EQ along the beam trajectory.

We have chosen the range of frequency from 20 to 50 MHz and the smallest m/q as three. The largest m/q is then nearly 19. Moderate intensity of large mass ions for this range of m/q can be expected from the conventional PIG source presently in use with the cyclotron.[3]

3. RESONANT CAVITY

A quarter-wave coaxial cavity is chosen as the basis of design of the resonator. As shown schematically in Fig. 2, the drift tubes are attached to the open end of the quarter-wave line. By varying volumes of cavity where the radio-frequency magnetic and electric field is most intense, resonant frequency can be obtained in the desired range. These methods are familiar to the variable energy cyclotron technology. Of course, a wide range of frequency change presents several problems. But difficulty seems to lie in the exciter and coupling systems rather than in the cavity design.

Fig. 3 is the calculated values of Q and shunt impedance as a function of frequency when MS scheme is used. MP scheme gives higher shunt impedance at low frequency and much lower one at high frequency. A decision of the scheme to be used will be made after study of the models.

Effective shunt impedance defined by the square of voltage gain per unit length divided by the power lost per unit length amounts to 120 MΩ/m for a cavity injected from an ion source on the 300 kV terminal. The effective shunt impedance deteriorates rapidly with increase of particle velocity and that of the cavity injected from a 17 MV injector is only 17 MΩ/m. It is planned to use several cavities in tandem to obtain 20 MV voltage gain. Ions of m/q = 20 will obtain 1 MeV per nucleon, and those ions of m/q = 3 will be 6.7 MeV per nucleon. A fixed frequency linac designed to give 1 MeV per nucleon for m/q = 20 will give only the same energy per nucleon for the lighter ions.

Although variable frequency operation of several cavities may seem awkward, the technique is an inevitable premise to build a separate sector cyclotron recently proposed by so many institutes.[4]

4. ENERGY VARIATION

Change of energy is possible by change of frequency and corresponding reduction of the field strength. Of course, the procedure will not be simple as in the tandem Van de Graaffs. Energy change is necessarily discrete. When smooth interpolation between the discrete interval is desired, we plan to use a charge-stripper on a high voltage terminal of say 300 kV maximum. Change of number of charge times value of voltage gives change of energy. By choosing charge state and varying terminal voltage, continuous variation of the particle energy can be achieved. However, usable intensity of beam must be reduced by the charge selection process.

5. COMBINATION WITH A SEPARATE SECTOR CYCLOTRON

Further acceleration of ions by the linac scheme would not be advantageous from the point of view of power economy, unless the superconducting cavity technique was introduced. As this technique is not firmly established yet, a Gordon-type[5] separate sector (S.S.) cyclotron seems the best candidate for a post-stripper accelerator. There are many proposals to combine a big tandom Van de Graaff with the S.S. cyclotron. We examined the possibility of using the variable frequency linac as an injector and found it feasible. There are many attractive features in this combined system:

i) As pointed out by K. Matsuda[6] and shown in Fig. 4, necessary magnetic rigidity of the cyclotron as a post-stripper facility does not differ drastically for ions of large mass difference. For instance, the magnetic rigidity of the uranium ion is larger by only 50% or less than that of the argon ion. If gas media is used as a stripper for argon instead of solid foil, the rigidity of argon exceeds that of uranium. Also for each ion specie the magnetic rigidity is approximately independent of the injection energy except at the very low and high energy region. Those magnitudes of magnetic regidity are modest and do not require a huge-sized magnet.

ii) By the stripping process, the charge of ions suddenly increases and equivalent voltage representing energy of the ion when multiplied by charge decreases by the ratio q_0/q_s, where q_0 and q_s are the charge before and after stripping. As can be seen in Fig. 5, the voltage increases only slowly as a function of energy of ions injected. This means turn separations of the orbit of the heavy ions at injection and extraction radii are the same as that of protons of energy of the equivalent voltage and assures rather large separation. High efficiency in injection and extraction can be expected.

iii) The acceleration electrodes may be delta-shaped as in recent design.[7] The width of the delta at the injection orbit shall be the same with the length of the drift tube which corresponds to a flight path during odd multiple of the half-period of the linac.

By choosing the same frequency and suitable phase relation between linac cavity and cyclotron resonator, synchronization of the velocity of ion and accelerating radio-frequency is automatically satisfied. There is no need of the debunching and rebunching process.

iv) From the point of view of ion source technology, combination with linac will permit many more kinds of elements and larger intensity to be accelerated in the S.S. cyclotron than in the case of combination with the tandem Van de Graaff. Table I gives some tentative parameters of the combined accelerator.

Table I. Tentative parameters of the combined accelerator system

Injector: Variable frequency linac

q/A	0.05 - 0.3
Energy	20 q/A MeV/u
RF loss	900 kW
Frequency	20-50 MHz

Post-stripper Accelerator: Separate sector cyclotron

No. sectors	4
B max	18 kG
Outer ρ	132 cm
Inner ρ	44 cm
$(\rho_{out}/\rho_{in})^2$	9
Gap	8 cm
Angular width	47 deg
Weight	1400 ton
No. dees	2
Dee width	30 deg
Harmonic no.	6
Frequency	20-50 MHz
Dee voltage	250 kV
RF power	600 kW

ACKNOWLEDGEMENTS

We are grateful to T. Wada and T. Fujisawa for supplying us the cords. Mrs. F. Yoshida has carried out calculations. Constant concern of the members of the cyclotron laboratory has been the most precious encouragement for us.

REFERENCES

1. D. Böhne and Ch. Schmelzer, Linear Accelerators, Ed. P.M. Lapostolle and A.L. Septier, (North Holland, Amsterdam, 1970) 1047
2. L.C. Teng, Rev. Sci. Instr. 25, 264 (1954)
M. Promé, Linear Accelerators (North Holland, Amsterdam, 1970) 785
3. I. Kohno, Y. Miyazawa, T. Tonuma, T. Inoue, A. Shimamura and S. Nakajima, IEEE Trans. Nucl. Sci. NS-19, 109 (1972)

4. R.S. Livingston, "Nuclear Reactions Induced by Heavy Ions", Ed. R. Bock and W.R. Hering (North-Holland, Amsterdam, 1970) 498
5. M.M. Gordon, Nucl. Instr. and Meth. 58, 245 (1968); Ann. Phys. 50, 571 (1968)
6. K. Matsuda, to be published in Science Papers I.P.C.R. (1972)
7. M.E. Rickey, M.B. Sampson and B.M. Bardin, IEEE Trans. Nucl. Sci. NS-16, 397 (1969)
A. Zucker, "Nuclear Reactions Induced by Heavy Ions", Ed. R. Bock and W.R. Hering (North-Holland, Amsterdam, 1970) 583
G.C. Morrison, ibid., 601

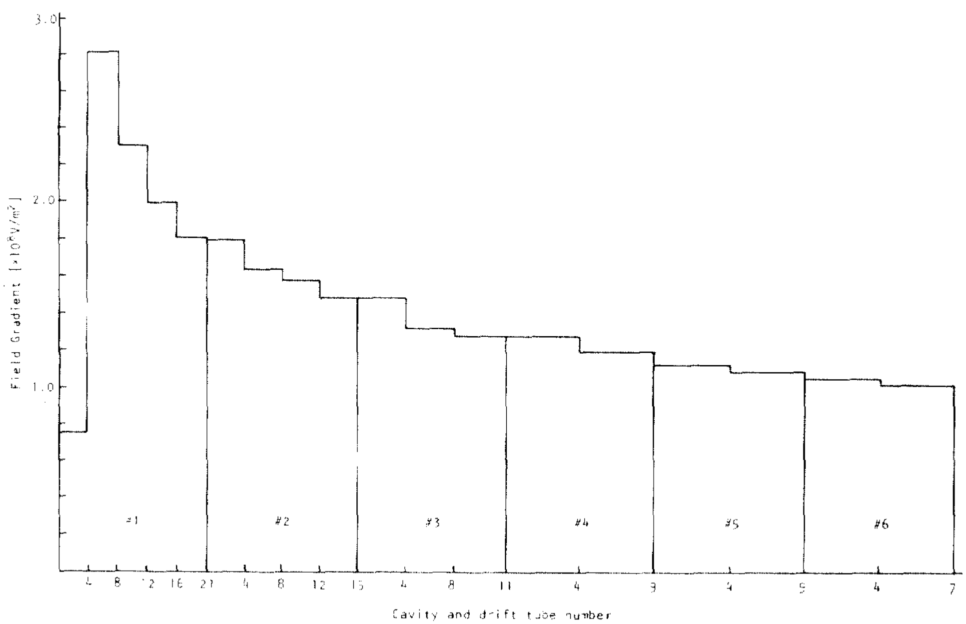

Fig. 1. The required field gradient of electrostatic quadrupoles along the beam trajectory. The length of first four tubes is 3π instead of π. Mean acceleration rate is 1.2 MV/m. Phase of equilibrium particle is 25 deg before crest.

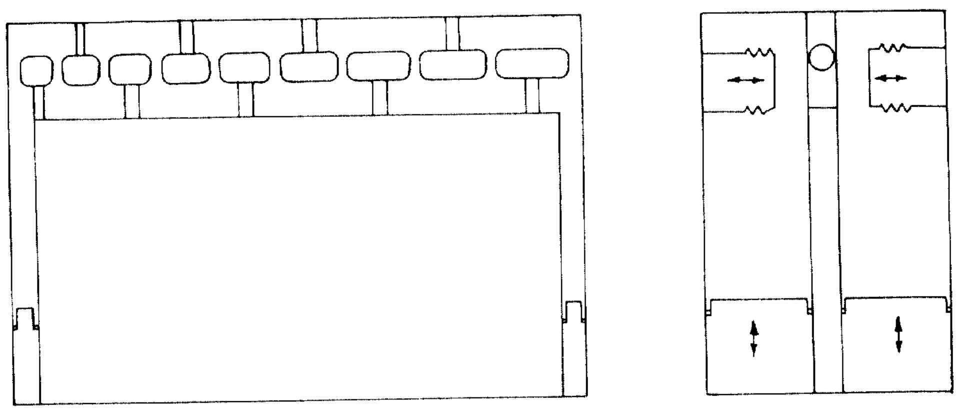

Fig. 2. The quarter-wave resonator loaded with drift tubes.

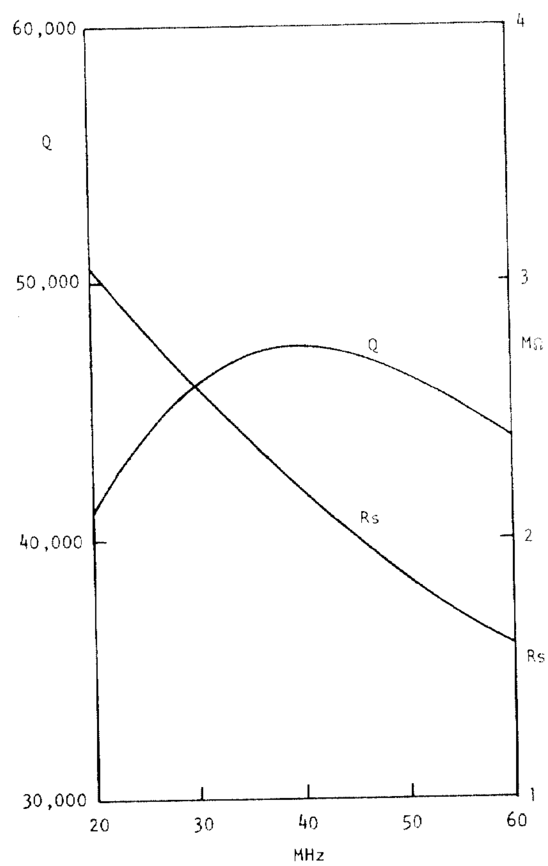

Fig. 3. Calculated shunt impedance and Q values as a function of resonant frequency.

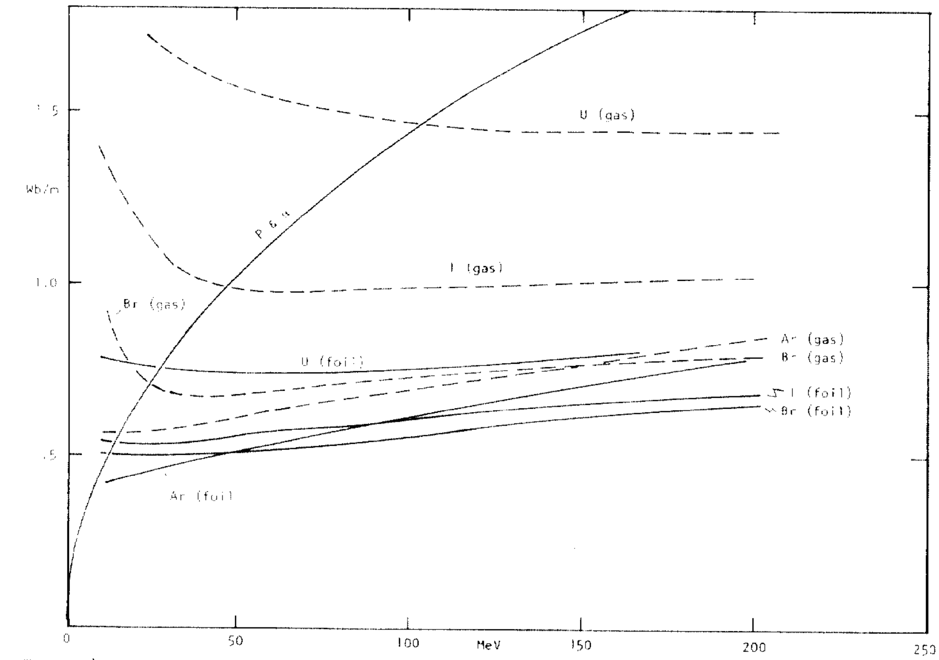

Fig. 4. The necessary magnetic rigidity of a separate sector cyclotron as a function of particle energy at injection. The most intense charge state after stripping was chosen in calculation.

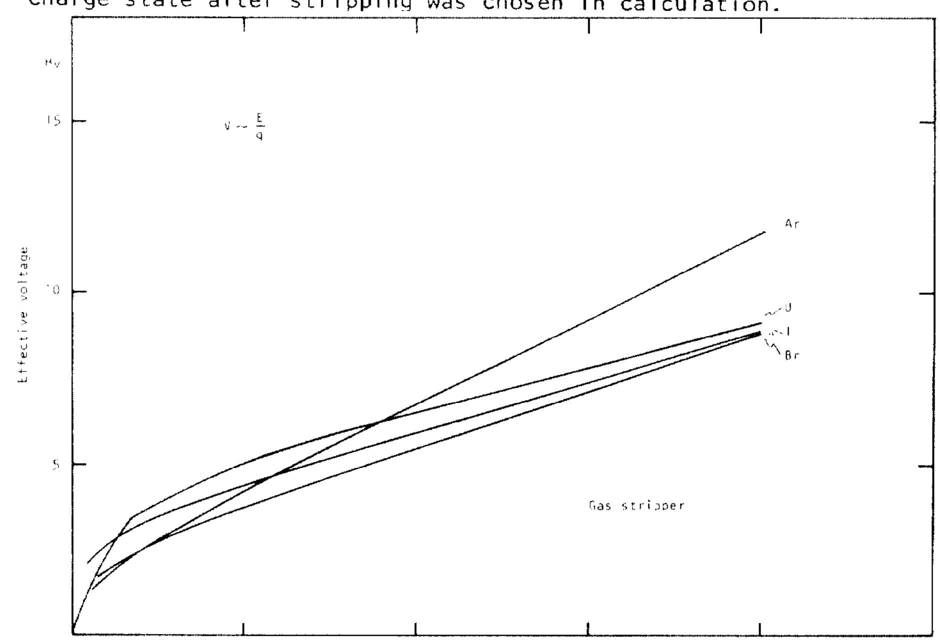

Fig. 5. The effective voltage for various heavy ions after charge stripping. The charge state selected is the same as in Fig. 4.