Series combination of a tandem and a cyclotron and vice versa

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ABSTRACT

The addition of a relatively small cyclotron will greatly enlarge the potentialities of a tandem Van de Graaff with respect to the achievable energy of various particles. Light particles will be accelerated more suitably with the cyclotron as injector, heavier particles with the reverse arrangement. Consideration of the volume in phase space of interest for the beam transfer from one accelerator to the other is given. Furthermore injection into the cyclotron is discussed for polarised light particles, which necessitate bulky ion sources, as well as for particles pre-accelerated by the tandem. Lastly a new type of buncher will be presented, which will be capable of almost ideal bunching.

1. INTRODUCTION

In recent times physicists have wanted light polarised nuclei accelerated to higher energies than are at present achievable. Other physicists want to accelerate heavy particles for instance to energies beyond the Coulomb barrier. Often there is a tandem Van de Graaff available, so I want to discuss the experimental potentialities of adding a relatively small cyclotron, the two accelerators being combined in series. In the second part of my paper I will discuss some interesting details connected with these combinations, i.e. beam transfer, injection into the cyclotron, and bunching.

2. EXPERIMENTAL POTENTIALITIES

2.1. *The cyclotron as the injector*

This arrangement is to be preferred for the acceleration of light particles such as protons, deuterons, and so on, which are to be started off in a negative charge state, to be stripped to a positive charge in the stripper of the tandem. The energy contribution of the cyclotron is

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$$E_c = \frac{R^2 q_c{}^2 B_o{}^2}{2m_o} \qquad \ldots (1)$$

that of the tandem in its first stage is

$$E_{T_1} = -q_1 U_T$$

and in its second stage

$$E_{T_2} = -q_2 U_T$$

with R = average radius of outer orbit of the cyclotron
m_o = rest mass of the particles
q_c = charge of the particles in the cyclotron
B_o = central field of the cyclotron
U_T = terminal voltage of the tandem
q_1 = charge before the stripper ($q_1 < 0$)
q_2 = charge after the stripper, depending on the stripping energy $E_c + E_{T_1}$

Table 1. ENERGY CONTRIBUTION AND FINAL ENERGY FOR A SERIES ARRANGEMENT OF TWO ACCELERATORS WITH VARIOUS PARTICLES. (The charge state is given in parentheses)

	E_{T1}	E_{T2}	E_C	E_{T1}	E_{T2}	E_{end}
H			$30^{(-)}$	$6^{(-)}$	$6^{(+)}$	42
D			$18^{(-)}$	$6^{(-)}$	$6^{(+)}$	30
T			$12^{(-)}$	$6^{(-)}$	$6^{(+)}$	24
$_3$He			$12^{(-)}$ $48^{(++)}$	$6^{(-)}$	$12^{(++)}$	30 48
$_4$He			$9^{(-)}$ $36^{(++)}$	$6^{(-)}$	$12^{(++)}$	27 36
$_{12}$C			$3^{(-)}$ $26^{(3+)}$ $48^{(4+)}$	$6^{(-)}$	$24^{(4+)}$	33 26 48
$_{16}$O	$6^{(-)}$	$24^{(4+)}$	$9^{(--)}$ $110^{(7+)}$ $144^{(8+)}$	$12^{(--)}$	$36^{(6+)}$	57 110 144
$_{20}$Ne	$6^{(-)}$	$30^{(5+)}$	$115^{(8+)}$			115

so the opening can be used only near the centre. Another limiting reason may be the emittance and position of the ion source.

For a pre-accelerated beam, the strength of the lens at the entrance will be negligible, so that a bigger opening can be used. In addition to this effect the time of flight from the entrance to the stripper is much shorter for a pre-accelerated beam. In Fig. 1 the phase space at the stripper, with the position x and the momentum p_x as co-ordinates, is limited by the radius of the stripper and secondly by the transformation of the usable radius of the entrance aperture at the position of the stripper. The inclination of these transformed limits increases with the time of flight. From the formula the phase volume would grow as $(\sqrt{E_o} + \sqrt{E_1})R_T$ with E_o as the injection energy, $E_1 = E_o + E_{T_1}$ as the energy at the stripper and R_T as the radius of the usable entrance aperture. With the given Erlangen measurements and $E_o = E_c$

$$\varphi = 2{\cdot}6\,\pi \text{ mm mrad} \left[1+ \left(1+\frac{E_{T_1}}{E_c}\right)^{1/2}\right] E_c^{\,1/2}$$

not including the enlargement of R_T. This gives an emittance of the beam which can possibly be accepted at the entrance of the tandem as $5{\cdot}4\,\pi$ mm mrad for 30 MeV H^- up to $7{\cdot}1\,\pi$ mm mrad for 3 MeV ${}_{12}C^-$ and is expected to be at least twice as big by the enlargement of R_T. The emittance of the cyclotron, being 5 to 10 π mm mrad, can be matched in most cases without serious losses.

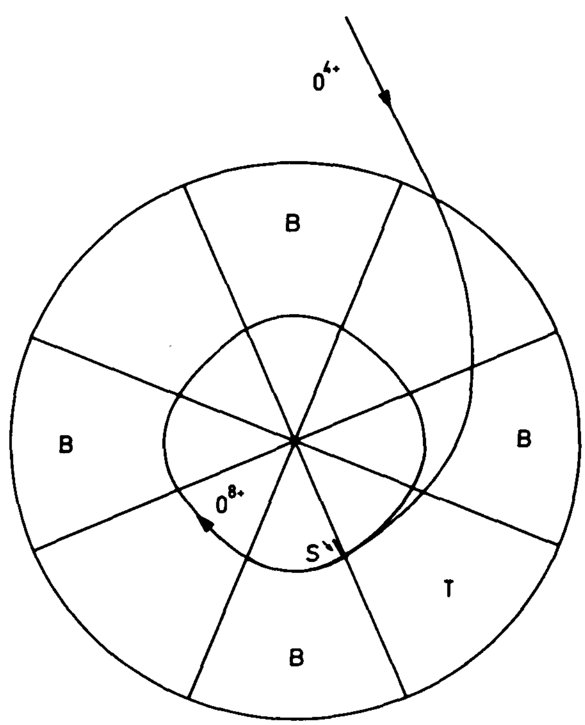

Fig. 2. Median plane injection of ${}_{16}O^{4+}$, to be stripped at S to ${}_{16}O^{8+}$ in the cyclotron

3.2. *Injection for the cyclotron*

With the cyclotron as the injector into the tandem, injection into the cyclotron itself has to take place at nearly zero energy and zero radius. As polarised particle production necessitates bulky ion sources, which cannot be built up within the cyclotron, axial injection is adequate and practicable. Ion mirrors of various types are available today.[1, 2, 3]

On the other hand, injection of a beam into the cyclotron, which has been pre-accelerated by the tandem, has to be done at a radius fitting the energy, the particle mass and the charge state achieved by stripping. Here median plane

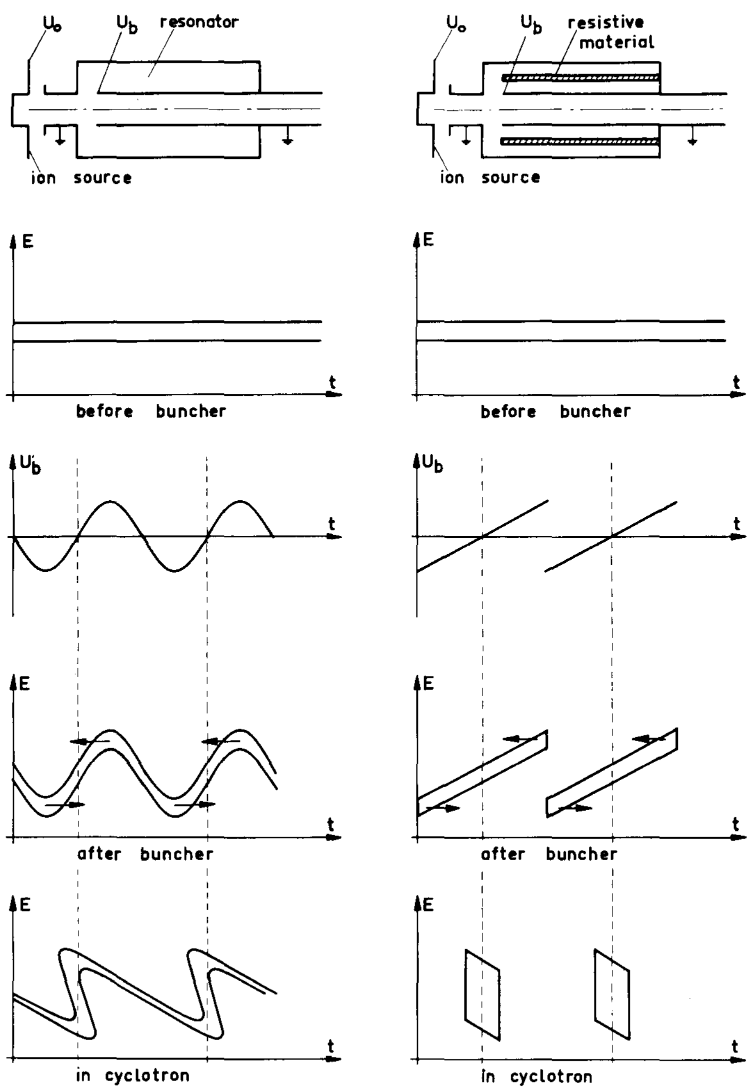

Fig. 3. Buncher and mode of action. Left: sinusoidal voltage, right: saw-tooth type of voltage

injection is the only practicable way, with the stripper inside the cyclotron on the equilibrium orbit of the stripped particles. Fig. 2 shows median plane injection with $_{16}O^{4+} \rightarrow {}_{16}O^{8+}$ as an example. If the beam enters the cyclotron in an essentially lower state of charge, no expensive beam guiding elements are necessary.

One thing which has to be worked out, is the matching of the emittance of the first accelerator to the acceptance of the second. For this reason a quadrupole lens has to be positioned between both accelerators capable of influencing the vertical and horizontal directions separately. This is because both extracting the beam out of the cyclotron and injecting it in the median plane has to be done across the fringe field which influences the horizontal and vertical emittances in a different way.

3.3. *Bunching*

Often the duty-factor, inherent to cyclotrons, is claimed as a serious disadvantage as compared to tandems. As long as this is because one wants all the particles to be accelerated (which can be dragged out of a poorly emitting ion source), the redress is bunching. By a periodic pre-acceleration one can have an originally continuous beam bunched to pulses which may fit the duty cycle accepted by the cyclotron. The basic frequency, of course, must be identical with the cyclotron rf. Simple bunchers work with a harmonic voltage wave form, some have higher harmonics superimposed to increase the bunching efficiency. A change of the cyclotron rf means in these cases a change of the buncher resonator. An ideal buncher would work with a saw-tooth-like voltage as in Fig. 4, right hand. A new type of buncher is now suggested, which is capable of working with a variable frequency and furthermore can accept a linearly rising, saw-tooth-like voltage. This is made possible by the resistive material inside the cavity, which damps away the rf voltage along the length of the buncher. The peak-to-peak-voltage is to be

$$U_{bpp} = \frac{2U_o}{f \times \Delta t}$$

with U_o as the ion source extraction voltage (which cannot be freely chosen when injecting axially into the cyclotron), with f as the cyclotron radiofrequency and Δt as the time of flight from the buncher to the cyclotron, essentially depending upon the distance from the buncher to the first accelerator, even if this is in the tandem. As a typical example for proton bunching over a distance of 2 m with U_o = 20 kV and f = 40 Mc, $U_{bpp} \approx$ 1 kV. The only disadvantage connected with this procedure is the heat losses in the buncher, which necessitate cooling, and which amount in this special case to some hundreds of watts.

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