Acceleration of very heavy ions by means of a two-cyclotron facility

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ABSTRACT

Acceleration of very heavy ions (uranium ions up to 9 MeV/nucleon) is discussed in connection with the use of a two-cyclotron facility. It is shown that the facility costs are at a minimum when the two cyclotrons are of equal size. The costs rise slowly if the second machine is the smaller one, and they rise rapidly if the first machine is the smaller. The technique of the joint operation of both machines is described, and the problems involved are discussed.

1. BACKGROUND

The acceleration of very heavy ions (up to uranium) is being planned for the production of hypothetical super-heavy nuclides with reasonable stability near the points of doubly magic numbers of nucleons. The machine concepts proposed so far are mainly:

(a) linacs with several charge change stations;
(b) isochronous ring cyclotrons with pre-accelerators, (either a small cyclotron or a d.c. machine), and with one charge change station between the machines;
(c) an electrostatic facility with two reflectors, containing an oscillating beam accelerated by virtue of the charge state difference after passing gas and foil strippers;
(d) a 'conventional' (non-ring shaped) isochronous cyclotron with beam injection from a small linac, and with charge change trapping of the ions (ALICE, Orsay).

The latter machine has been under construction for some time; however, only krypton ions can be accelerated. Nevertheless, this method is a promising one for building low cost facilities.

The reason why only ring cyclotrons have been discussed, apart from the ALICE facility, is probably the desire to have a separate charge change station rather than a charge change target within the cyclotron. If, as a consequence, a ring cyclotron is chosen as the second stage, it is reasonable to make the latter somewhat larger than the first stage. Otherwise, if the second stage is a full cyclotron, it will be shown that the cost minimum is attained when the first stage is also a cyclotron of the same size. The Maryland Cyclotron group is discussing a facility of this type but still using a pre-accelerator for injection into the first cyclotron. Though many laboratories have decided in favour of the first mentioned type of facility, it seems to be worthwhile to discuss again the question of the best type of heavy ion accelerator. On one hand, the costs can

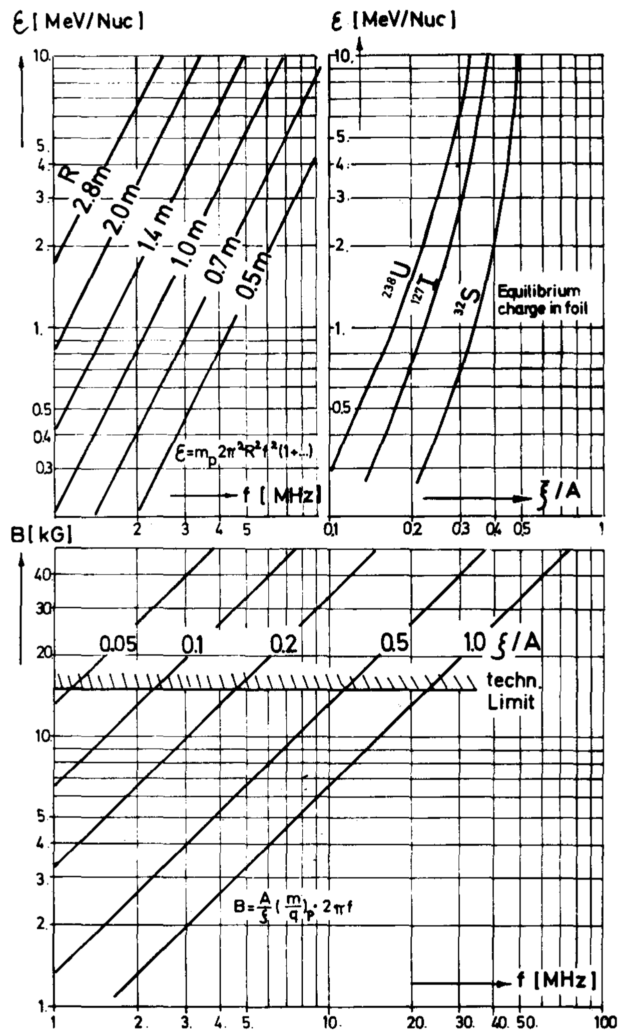

Fig. 1. Diagrams of related machine parameters

be lowered considerably, and on the other hand the versatility of the facility can be enhanced in some respects. The second design aim of the heavy ion ring machines is the meson factory. However, it may be in many cases better to have separate groups working on medium heavy ion physics on the two machines which the super-heavy element people use in combination.

2. OPTIMISATION OF MACHINE PARAMETERS

Let us first consider the machine size. To do this, we use as a base a threefold set of diagrams (Fig. 1).

The first (bottom) gives the well-known connection between the magnetic induction and the frequency of revolution for several ion species. The second one

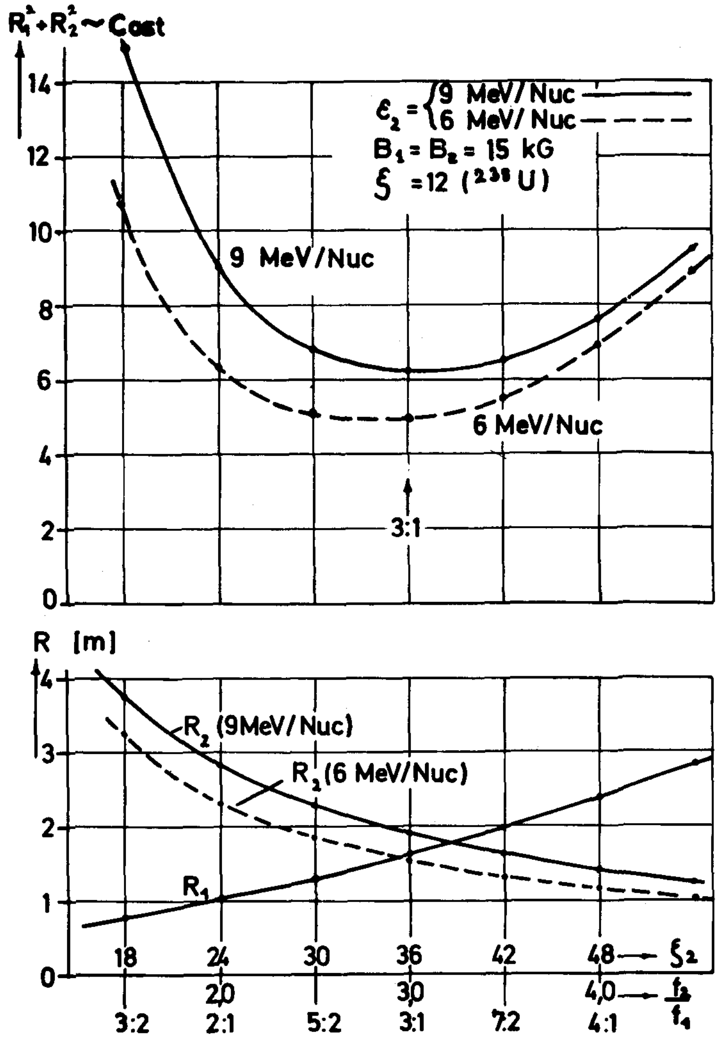

Fig. 2. Machine sizes vs frequency ratio

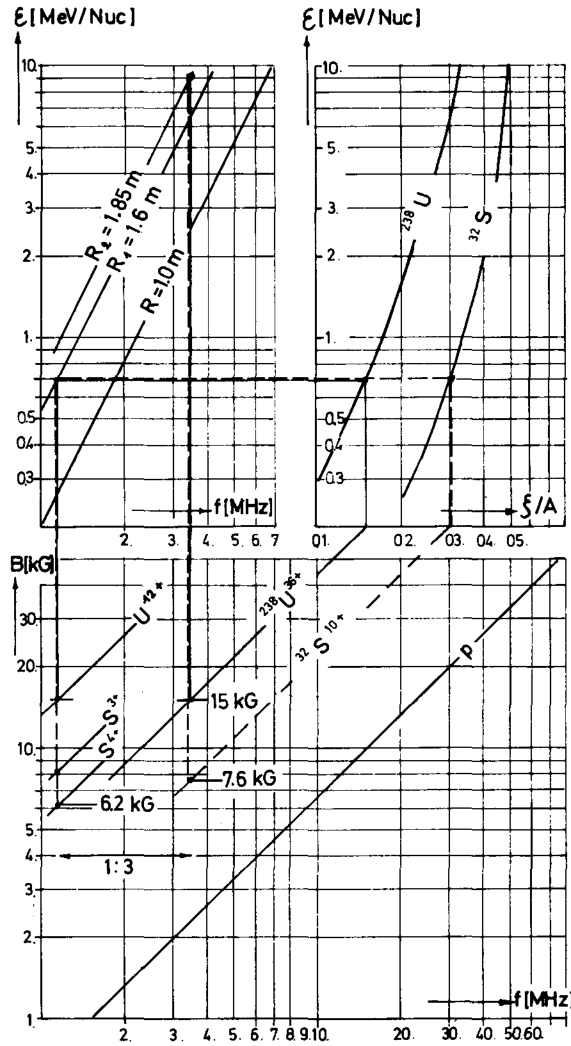

Fig. 3. Machine parameters for particle variation

(top left) describes the attainable energy per nucleon for machines of different sizes (R = mean final orbit radius) for the frequencies found in the lower diagram. (The lines in this diagram are slightly curved at the beginning of the relativistic region.) The third diagram (top right) gives the maximum of the equilibrium charge distribution, after passing the beam through a foil, drawn after data by Schmelzer. These three diagrams are arranged so as to yield rapid data of two-cyclotron combinations going 5/3 cycles through the diagrams. As a further condition one must keep in mind that the number of revolutions must be in a low natural number ratio to allow the radiofrequency of the second machine to be chosen as an integral multiple of that of the first machine.

Fig. 2 gives the result for two different uranium facilities of six and nine MeV/nucleon. As the relativistic mass increase is low, both machines can be equipped with low flutter, hence $\bar{B}$ = 15 kG for both machines. The source charge state has been chosen to be 12 for simplicity; it might equally well be 11 or 13, but then the curves of Fig. 2 would not be correct, since if the frequency ratios are half integral, the machines cannot be run with the same magnetic induction. It is quite customary that a larger first machine has to be used to attain higher charge states, so R_1 rises with f_2/f_1. On the other hand, the second machine is used more economically, so R_2 decreases with f_2/f_1. A cost minimum will therefore be found at $R_1 = R_2$, whatever type of cost function might be assumed (here, for simplicity, a radius squared cost law has been adopted). For a uranium facility the cost minimum takes place at the most convenient frequency ratio of 1:3, with only little dependence on the final energy per nucleon. Note that R_1 goes nearly linear with f_2/f_1, whereas R_2 falls somewhat more steeply at low f_2/f_1. This means that facilities with a small first stage and a big second stage are the most uneconomical. The situation does not change if the first small cyclotron is replaced by another type of machine, e.g. electrostatic. Secondly the charge change capture process within the second machine is easier to perform in systems described by the right-hand side of the diagram.

The costs for a facility of 9 MeV/nucleon would be in the region of about 10 million dollars (European Commercial prices, without buildings, extrapolated from existing machines).

3. PARTICLE AND ENERGY VARIATION

Starting from uranium, variation of the ion species requires only lowering of the magnetic field, and the final energy per nucleon will be the same. If no 1:3 charge state ratios fitting the charge state curve exactly are available, the magnetic fields are set to somewhat different values. Also, an energy variation can be achieved by varying fields and frequencies simultaneously, for lighter ions even beyond the energy per nucleon of uranium.

Lighter ions up to ^{40}A can be accelerated by each of the machines separately. For this purpose the machines have to be equipped with a wide-range frequency variation which depends on how far the species range is to be extended towards protons.

4. INJECTION AND EXTRACTION

A vacuum pressure of 10^{-7} torr or better is necessary for the first machine. External ion injection is therefore mandatory. There is the problem of either having a slow rf (less than 7 MHz) or a high harmonic number; the Maryland group therefore plans to use a 9 MV pre-accelerator, and stripping-capture in the first machine also. We are considering axial injection with not too low an energy, and a machine working on the sixth harmonic (f = 6·5 MHz). The injection path into the second machine is shown in Fig. 4.

The optics of this path are good; neither in the radial nor in the axial direction are extreme matching elements necessary before the beam enters the machine. The stripper target should be of the foil type; a gas stripper would destroy the beam quality too much, and would interfere with good vacuum requirements. The stress limit of foils is now estimated to be 10^{12} particles per second; that is

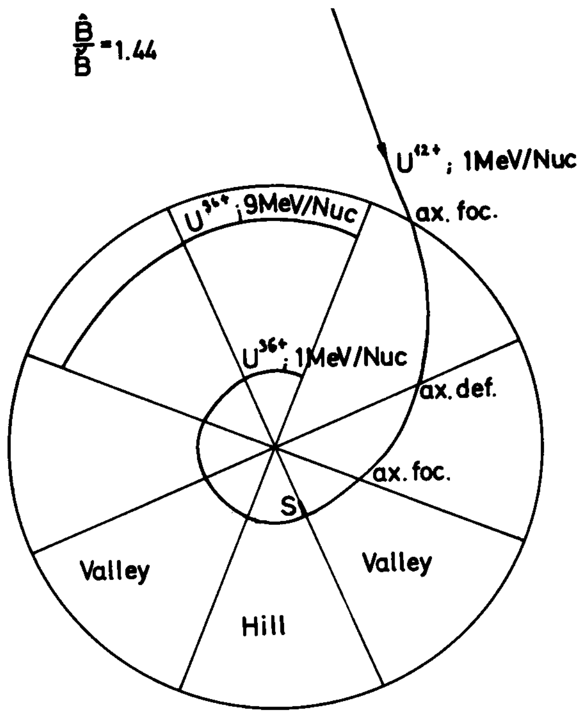

Fig. 4. Charge change capture

about 2×10^{-6} A of U^{36+} where a capture rate of 30% in the second machine is included (the remainder have the wrong charge states).

Extraction of the beam is easy from the first machine, and feasible from the second machine. The beam separation at the border of the second machine is in the order of 2·5 mm for a voltage gain per turn of 150 kV. Since the field index and the flutter are small (and hence $\nu_r - 1$ is small), a variety of magnetic orbit displacement techniques are applicable which preserve good beam quality. To diminish the extraction difficulties further, one may terminate the cyclotron acceleration at 5 or 6 MeV/nucleon and continue with linac acceleration.

Since the rf of the second machine is a factor of 3 higher than that of the first machine, the problem of matching the bucket lengths arises. In a two-linac combination, the problem is solved by the phase focusing behaviour of linacs. With cyclotrons, care must be taken that the bucket length in the first machine is of the order of 10°, so that it does not exceed 30° in the second machine, and single turn extraction remains possible.

This need implies the application of proper bunching techniques in the course of external injection into the first machine, and of phase clipping techniques on the first revolutions.

DISCUSSION

Comment by M. Reiser (Maryland)

We did not submit a paper on our plans for heavy ion acceleration at the University University of Maryland, and I would like to briefly mention where we stand and what we have in mind. Basically we are studying two possibilities: (1) A 9 MV FN tandem (with negative source and gas stripper) injecting into a cyclotron, which would be a copy of our present machine, then final stage acceleration in our present cyclotron. Advantages of this scheme are low costs–which in fact are less than those of any other proposed concept involving a new large cyclotron with T U tandem; it could be done in a short time since no major new developments are involved. The energies that could be reached are as high as 3 GeV for intermediate-mass projectiles, 2 GeV for Uranium. The main disadvantage is lower intensities than other proposed systems (a factor of 10 or even less).

(2) A more intriguing possibility in the long run is to develop the electron ring accelerator (ERA) with static compression scheme, which we proposed at the University of Maryland, as a heavy ion machine. Its advantage is the high repetition rate (which is difficult to achieve with the pulsed compressors in use at Dubna and Berkeley), its small size and simplicity (one merely needs to change the gas or vapour in the compression region to accelerate the type of ions desired). The fact that just recently at Dubna nitrogen was accelerated to 65 MeV demonstrates clearly that the ERA (or collective ion accelerator) has a great potential for the acceleration of heavy ions.