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**Publication Date**
1969-02-01

Presented at the National Particle Accelerator
Conference, Washington, D. C., March 5-7, 1969

UCRL-18778
Preprint
cy.2

# BEAM DYNAMICS PROBLEMS IN A MULTIPARTICLE RAPID CYCLING SYNCHROTRON

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February 1969

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## DISCLAIMER

# BEAM DYNAMICS PROBLEMS IN A MULTIPARTICLE RAPID CYCLING SYNCHROTRON*

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## ABSTRACT

The proposed Omnitron facility includes a synchrotron which will accelerate protons to 1.4 GeV and heavier elements to tens of MeV per nucleon. To obtain intense high energy beams of the heavier elements, after the first acceleration cycle the beam is placed in a storage ring, then on the next cycle is stripped, reinjected, and accelerated to hundreds of MeV per nucleon. As the particle species delivered by the injector is changed a range of e/m values from 0.05 to 1 must be accepted, and the intensity can change by orders of magnitude. Problems that arise in injection, bunching, acceleration, extraction, and reinjection are discussed.

Provisions for beam handling and control must be flexible enough to allow maximum possible exploitation of the accelerator facility. Possibilities for time-shared utilization of the machine are considered. For this to be most effective, each experimenter must be able to specify particle species and energy independently. It is also necessary to make a rapid changeover from one set of operating conditions to another. This sets requirements for reproducibility, for rapid tuning, and for fast troubleshooting.

## I. INTRODUCTION

A synchrotron for accelerating heavy ions is pretty much like a proton synchrotron, but with a few minor differences. The first is due to the fact that the charge to mass ratio $\epsilon$ can become much lower (.0042 for singly charged Uranium, compared to 1 for protons). Since the forces exerted upon a particle by electric and magnetic fields are proportional to $\epsilon$, as $\epsilon$ decreases it becomes increasingly harder to achieve a given energy per nucleon $T_n$. A second difference is that $\epsilon$ can be easily changed in stripping reactions. This fact introduces a new dimension into the job of selecting accelerator parameters and into accelerator operation. There is a problem of obtaining adequate intensity because the output of ion sources fall with increasing $\epsilon$ and for a given $\epsilon$, with increasing atomic number. This situation will improve as more development work is done on heavy ion sources but at present it is clear that some very weak beams will need to be accelerated. These will require somewhat different detection and control apparatus than that employed for intense beams.

The possibility of building a heavy ion synchrotron has been under study at LRL for some years. The Omnitron proposal,[1,2] is one result of this effort. The Omnitron parameters, given in Table I, will be used as an example in this discussion. Fig. 1 shows schematically the layout of this machine. The novel ideas mentioned here have originated with a number of individuals within the Omnitron group, led by R. M. Main.

## II. ACCELERATOR PROPERTIES

The value of $\epsilon$ used for injection into the synchrotron is very important in determining the energy that can be reached with a given rigidity $B\rho$ given by peak field times magnetic radius (upper curve, Fig. 2).

To reach 10 MeV/nucleon requires $\epsilon \geq .063$. For the lightest ions this means removing one or two electrons; for the heavy ions many more. An attempt to get a usable beam of heavy ions might result in a much lower $\epsilon$, say .03 which would reach about 2 MeV/n in the synchrotron. However, if after being accelerated in the 3 MV Cockcroft-Walton this particle is stripped to a higher charge state, a much higher energy can be reached. The equilibrium charge states reached with dense strippers are shown in Fig. 2, for Neon and Uranium. The curve for Neon is based upon experimental data;[3] the curve for Uranium is an extrapolation of the data for lighter elements.[4] Stripping curves for ions with A between 20 and 238 fall between the curves for Ne and U. With stripping, however, a distribution of charge states results, and as only one can be accelerated, the intensity is much reduced. Also, stripping will cause some dilution of phase space density. A large jump in $\epsilon$ is penalised, in that the top energy becomes limited by the RF frequency band. This can be deduced in Fig. 3, which shows curves of h (the harmonic number) = const., at 3 MV dc injection, and for maximum $B\rho$. The acceleration of a typical unstripped particle (shown for $\epsilon = .05$) starts with a lower h curve within the frequency band, and proceeds to the corresponding upper one. Stripping does not change the velocity so that h (here $h = 48$ for $\epsilon = .05$) is unchanged. But to reach full energy the frequency must reach a value on the upper curve corresponding to the stripped value of $\epsilon$ (denoted as $\epsilon^*$). For $\epsilon^* > .11$, this requires a frequency greater than 33 MHz, so there is no advantage to stripping an $\epsilon = .05$ particle to greater than $\epsilon^* = .11$.

After accelerating a partially ionized beam to peak field in the synchrotron, we can go to still higher energy by storing the beam, then pass it through a stripper and reinject on the next cycle. If 5-10 MeV/n has been reached on the first cycle, stripping can produce high values of $\epsilon$, and hundreds of MeV/n can be reached on the second cycle. Here again losses and dilution are a necessary consequence of stripping.

## III. INJECTION

Multiturn injection will be necessary in order to achieve satisfactory circulating currents of heavy ion beams. Because of the low velocity of these particles at injection, injecting a number of turns takes an appreciable time. With a dc injector, in order to prevent introducing either large radial errors or large momentum errors in the beam, injection must be at the field minimum. Adiabatic trapping should be employed in order to conserve as many particles as possible for acceleration. Some details of a possible injection and trapping scheme are shown schematically in Fig. 4, for 10 turns, $\epsilon = .05$. Injection commences while the field is decreasing, acceleration starts when trapping is complete. In order to minimize trapping time, the voltage is turned on and rises to 120 kV in 50 μs, which is about the time required for one phase oscillation at this voltage. This should trap essentially 100%.[5] The injection energy is chosen so that the equilibrium orbit is centered at the start of acceleration. Because the field is changing the E.O. moves several mm during injection. As at the maximum excursion $\Delta r$ the beam is not yet its full width this should not result in a decrease of useful aperture.

## IV. TIME SHARING

Let us consider the case where two experimenters are to share the machine, each receiving a specified fraction of the 45 cycles per second. Each wishes to specify particle species and energy independently. The maximum magnetic field $\hat{B}$ is set according to the maximum $B\rho$ required. Each particle can be extracted at the proper energy with a fast kicker magnet, one at $\hat{B}$ and one on the rising field. One of the particles can be diverted to the storage ring and use a slow extraction channel. The extraction channels and the storage ring are operated dc.

If stripping occurs at injection, it can be shown that in the nonrelativistic limit the injection parameters of the particle $\epsilon_1$ and $\epsilon_2$ will satisfy the relation

$$\frac{B_{i,1}^2}{V_1}\frac{\epsilon_1^{*2}}{\epsilon_1} = \frac{B_{i,2}}{V_2}\frac{\epsilon_2^{*2}}{\epsilon_2} . \qquad (1)$$

$B_{i,1}$ and $B_{i,2}$ are the respective injection fields, $V_1$ and $V_2$ are dc injector voltages. Consider the case $B_{i,1} = B_{i,2} = \check{B}$. For both particles, this allows multiturn injection and adiabatic trapping to be carried out as previously described. With no stripping, we get

$$V_2 = (\epsilon_2/\epsilon_1)\, V_1 \qquad (2)$$

Taking $V_1$ as the maximum injector voltage and $\epsilon_1 > \epsilon_2$, $V_2$ is below maximum voltage. This means that if the injection lines share the same inflector, it must be pulsed. Compared with the case where $\epsilon_2$ is injected at maximum voltage $V_1$, the injection velocity is lower by the factor $(\epsilon_2/\epsilon_1)^{1/2}$, so that for the same number of injected turns the injection time is longer by the factor $(\epsilon_1/\epsilon_2)^{1/2}$. The space charge limit is proportional to the energy and is lower by $\epsilon_2/\epsilon_1$. Since $\epsilon_2$ is likely to be the heavier particle, which may be of low intensity anyway, lowering the space charge limit might not be serious. Increasing the injection time means larger $\Delta r$; at some point the increasing $\Delta r$ limits the useful aperture and no further increase in injection time is useful. Thus one effect of large $\epsilon_1/\epsilon_2$ is to restrict the number of particles that can be injected. Another effect of lowering $V_2$ is to increase the required frequency swing. For particles with $\epsilon_2 = .3$ and larger, which require the full frequency swing with $V_2 = 3$ MV, this will lower the maximum energy that can be reached. For $\epsilon_2 < .1$ the frequency swing is less and this effect is not as likely to limit the top energy.

By allowing $\epsilon_2$ to be stripped at injection, we get

$$V_2 = (\epsilon_2^{*2}/\epsilon_1\epsilon_2)\ V_1. \qquad (3)$$

Since $V_2$ is proportional to $\epsilon_2^{*2}$, a modest amount of stripping can be a big help in raising the injection voltage. If the inflector is shared, the case when the inflector voltage is the same for both particles is of special interest. This is so when $\epsilon_2^* = \epsilon_1$; then (3) becomes

$$V_2 = (\epsilon_1/\epsilon_2)\ V_1,$$

with now $V_2$ greater than $V_1$.

What if $B_{i,1} \neq B_{i,2}$? With no stripping (1) becomes

$$V_2 = \frac{B_{i,2}^2\ \epsilon_2}{B_{i,1}^2\ \epsilon_1}\ V_1. \qquad (4)$$

When $\epsilon_1 >> \epsilon_2$ a drastic lowering of $V_2$ can be avoided by injecting at a somewhat higher field $B_{i,2}$. A difficulty is that injection is not now at the field minimum. The field in this case can change by several percent during injection. This can be accepted only if the energy of the injected beam is increased to keep in step with the rising field. Adiabatic trapping must be given up, with the trapping efficiency being lowered to 30-50%.

Another complication is the necessity for pulsing injection transport line elements.

## V. WEAK BEAMS

Heavy ion beams of less than $10^7/q$ particles per pulse will be difficult to detect with induction electrodes or other non-destructive means. For such beams completely programmed operation might be necessary, which will cause more stringent requirements to be placed on the magnetic field and rf stability. Beams of low $\epsilon$ undergo relatively few revolutions during acceleration ($2\text{x}10^3$ for $\epsilon = .05$) which eases this problem somewhat. To rapidly update the acceleration program, a sampling technique could be used. With a fast kicker magnet, occasional pulses would be deflected to strike a solid state detector placed just outside the aperture. Then by programming the kicker to operate at successively later times from injection to peak energy, a picture of beam behavior would be built up in a short time.

It should be possible to mix a heavy ion beam with a light ion beam of greater intensity, but with an $\epsilon$ value which is very nearly the same. As an estimate, we can suppose that the weak beam would remain in phase during acceleration if $\Delta\epsilon/\epsilon$ were no greater than the spread in $\Delta p/p$ which the accelerator will accept. This would place an upper limit of about $4\text{x}10^{-3}$ on $\Delta\epsilon/\epsilon$. If we look at the separation of $\epsilon$ states for light and heavy ions (Fig. 5) it appears with some luck, a light ion could be found to pair with a given heavy ion.

Another possibility, which would allow a much larger $\Delta\epsilon/\epsilon$ than the foregoing is to use a timeshare mode of operation, with the light and heavy ions being accelerated on alternate cycles, and the light ion being used for accelerator control. This would require a greater cycle-to-cycle reproductibility than a mixed beam, but less so than for a programmed mode.

## VI. REINJECTION

When a double acceleration cycle is used for a particle such as Argon, h must be changed for the second acceleration. For the first acceleration $h = 48$ to 96 can be used with $\epsilon = .05$, but for the second acceleration with $\epsilon = .45$ h must be 15 or lower if top energy is to be reached (Fig. 3, top curves). This rebunching can be done near the top of the acceleration cycle, before extracting from the synchrotron. This has the advantage of making the problem of extraction with a fast kicker magnet easier, as the bunch separation will increase when the beam is rebunched.

For reinjected beams that experience a large change in $\epsilon$, the space charge limit can be lower than for the first acceleration cycle. The transverse incoherent space charge limit can be expressed as[6]

$$N_{sc} = (\text{const})\ E_z(1+a/b)\ \bar{B}\ \beta^2\gamma^3/\epsilon^2. \qquad (5)$$

The constant factor incorporates those terms which do not change appreciably between first injection and reinjection. Assuming ideal acceleration the transverse emittance varies inversely as the momentum, the factor $\beta^2\gamma^3$ varies approximately with energy, the bunching factor $\bar{B}$ decreases only slightly with higher energy, so that approximately

$$N_{sc} \cong (\text{const})\ T_n^{1/2}/\epsilon^2. \qquad (6)$$

For the case where $\epsilon = .05$ for first acceleration and .45 for reinjection, the expression (6) is 12.5 times higher for the first acceleration. A possibility exists for increasing the transverse phase area in the stripping process, which does not necessarily conserve phase area. Also, it may be possible to increase $\bar{B}$ in the rebunching process.

## VII. REFERENCES

*This work was performed under the auspices of the U.S. Atomic Energy Commission.

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2. The Omnitron - A Multipurpose Accelerator, Lawrence Radiation Laboratory report UCRL-16828, (July 1966).
3. H. H. Heckman, E. L. Hubbard and W. G. Simon, Phys. Rev. 129, 1240 (1963).
4. R. M. Main, Private communication.
5. J. M. Peterson and P. L. Morton, Lawrence Radiation Laboratory internal report UCID 10181, (February 1966).
6. Ref. 2, page V-8.

Table I. Parameters of the Proposed Omnitron Accelerator

| | | |
|---|---|---|
| Nominal peak guide field | $\hat{B}$ | 10 kG |
| Magnetic radius | $\rho$ | 7.24 m |
| Average radius | R | 16.79 m |
| Magnetic field cycling rate | | 45 Hz |
| Maximum energy | see Fig. 2 | |
| Calculated space charge limit at injection for charge state q, and $\lvert \Delta\nu_z \rvert = .25$ | $N_{sc}$ | $1.5 \times 10^{11}/q$ ppp<br>$7.5 \times 10^{12}/q$ pps |
| Maximum dc injector voltage | $V_{cw}$ | 3 MV |
| " " " current | $I_{cw}$ | 10 mA |
| Maximum frequency range | | 2.3-33 mHz |
| Peak voltage, LF resonator cavity | | 40 kV |
| " " HF " " | | 50 kV |
| No. of rf cavities | | 3LF, 3 HF |

# FIGURE CAPTIONS

Fig. 1. Schematic layout of Omnitron. The accelerator is the inner ring, the outer is the storage ring.

Fig. 2. Omnitron injection and maximum energy as a function of $\epsilon$, and showing equilibrium charge states for Ne and U passed through a dense stripping foil.

Fig. 3. RF frequency limits as a function of h and $\epsilon$.

Fig. 4. Scheme for injection and trapping.

Fig. 5. Graph of $\epsilon$ states for some light and heavy ions.

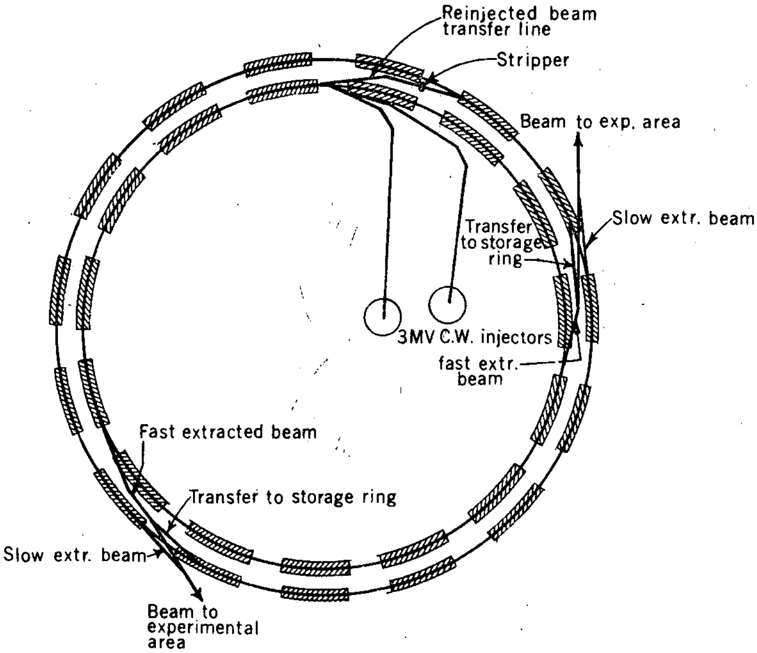

Reinjected beam transfer line
Stripper
Beam to exp. area
Slow extr. beam
Transfer to storage ring
3MV C.W. injectors
fast extr. beam
Fast extracted beam
Transfer to storage ring
Slow extr. beam
Beam to experimental area

Fig. 1

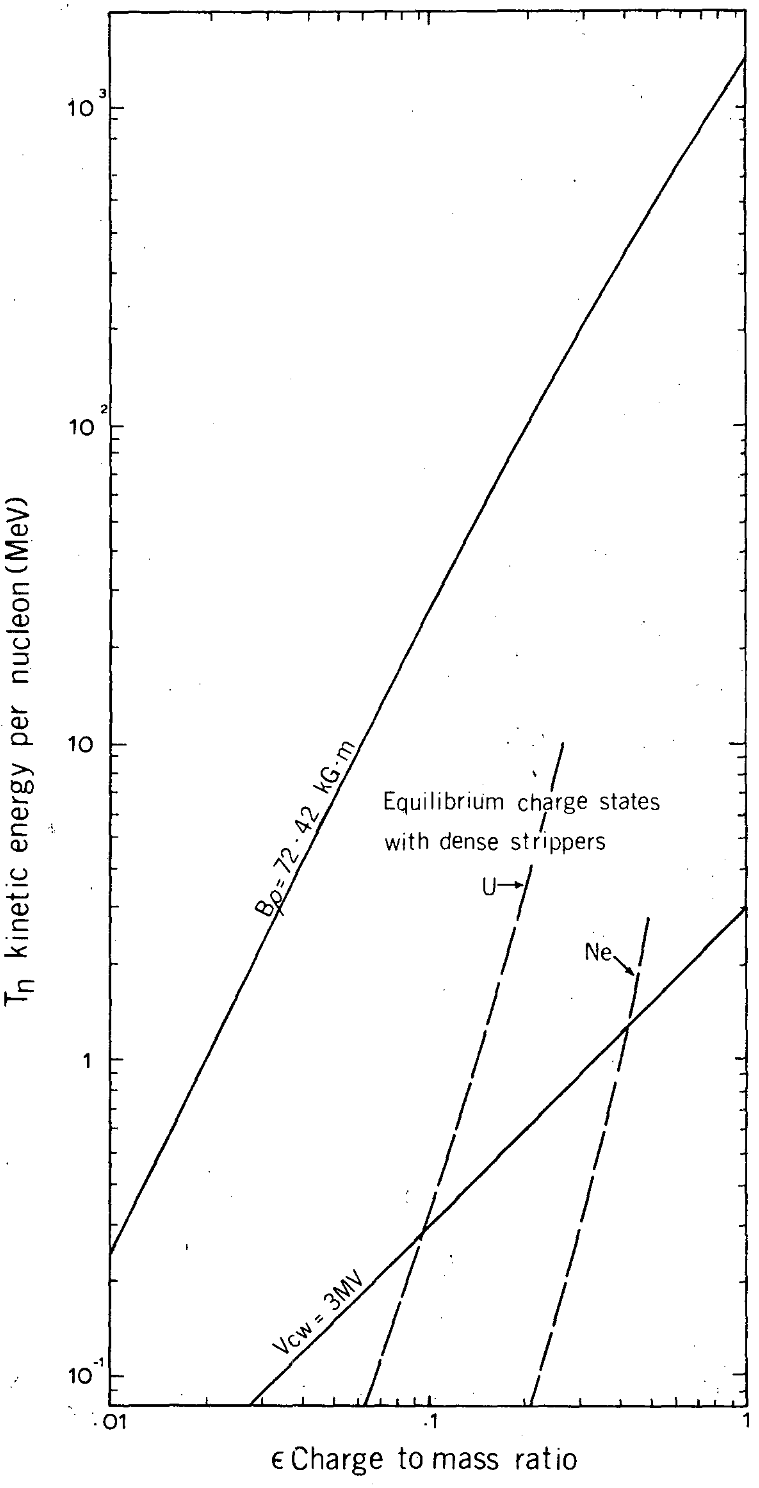
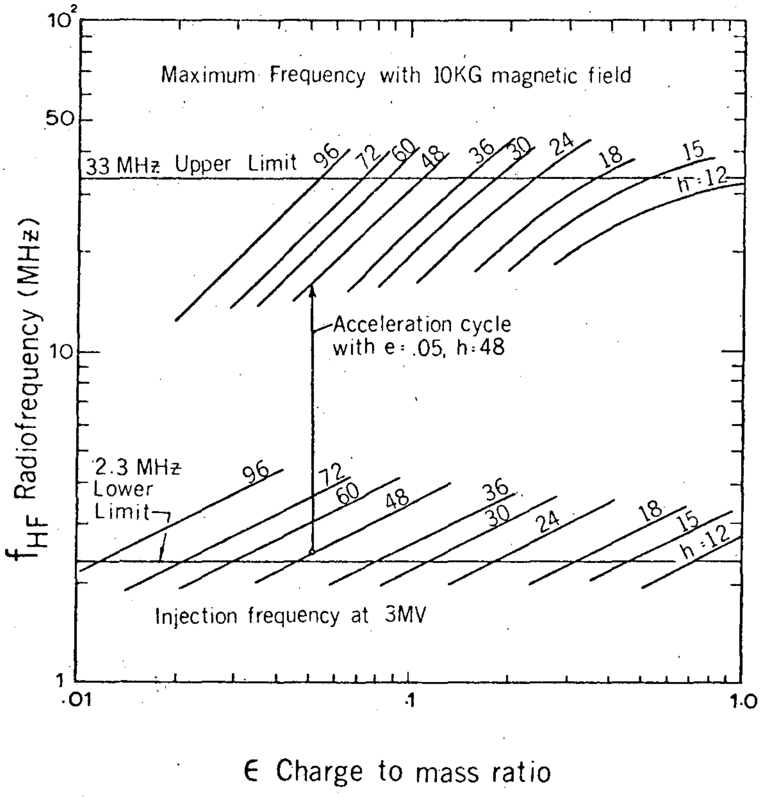

$10^3$
$10^2$
10
1
$10^{-1}$
.01
.1
1
$T_n$ kinetic energy per nucleon (MeV)
ε Charge to mass ratio
$B\rho = 72 \cdot 42$ kG·m
$V_{cw} = 3$MV
Equilibrium charge states
with dense strippers
U→
Ne

Fig. 2



$10^2$
50
10
1
Maximum Frequency with 10KG magnetic field
33 MHz Upper Limit
96
72
60
48
36
30
24
18
15
h:12
Acceleration cycle with e: .05, h:48
2.3 MHz Lower Limit
96
72
60
48
36
30
24
18
15
h:12
Injection frequency at 3MV
.01
.1
1.0
$f_{HF}$ Radiofrequency (MHz)
ϵ Charge to mass ratio

Fig. 3

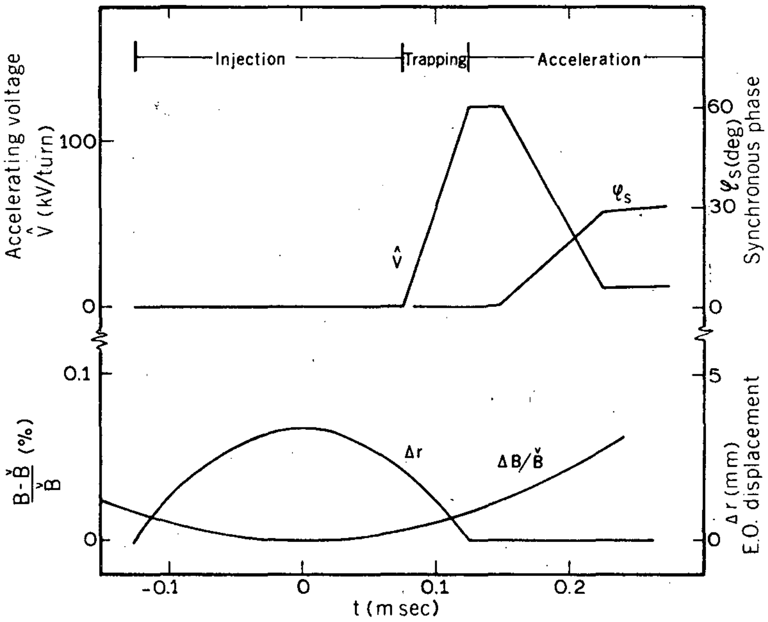

Injection
Trapping
Acceleration
Accelerating voltage
$\hat{V}$ (kV/turn)
100
0
$\hat{V}$
$\varphi_s$
60
30
0
$\varphi_s$(deg)
Synchronous phase
0.1
0
$\frac{B-\check{B}}{\check{B}}$ (%)
Δr
ΔB/$\check{B}$
5
0
Δr (mm)
E.O. displacement
-0.1
0
0.1
0.2
t (m sec)

Fig. 4

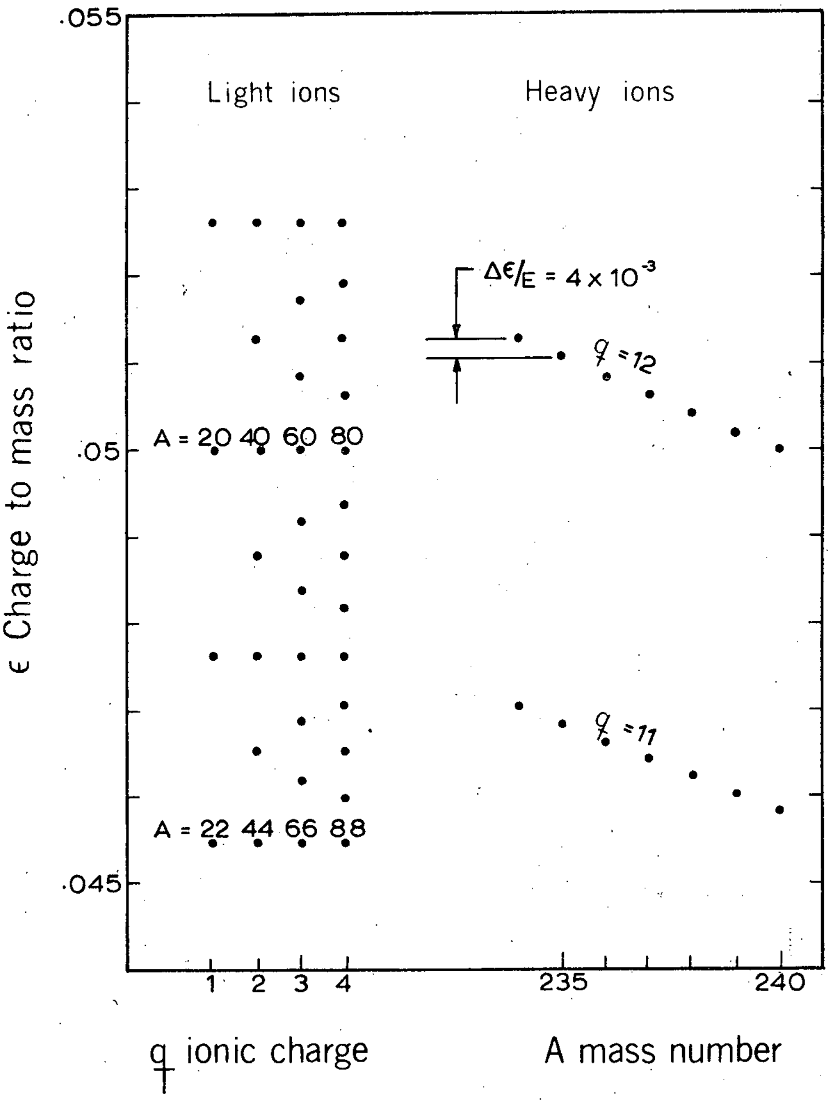

.055
.05
.045
ϵ Charge to mass ratio
Light ions
Heavy ions
$\Delta\epsilon/\epsilon = 4 \times 10^{-3}$
q = 12
q = 11
A = 20 40 60 80
A = 22 44 66 88
1 2 3 4
235
240
q ionic charge
A mass number

Fig. 5

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