SOME PECULIAR FEATURES OF A MINI-CYCLOTRON AS A MASS SPECTROMETER FOR DATING

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Introduction

Accelerator Mass Spectrometer (AMS) has been rapidly developed since the late of seventies. Nevertheless, a small specialized accelerator is preferred in view of the economy and practical application. Recently, small commercial Tandams have been available, and Berkeley laboratory has initiated to build a small cyclotron for ^{14}C dating. The design work of a mini nonuniform magnet cyclotron specialized for dating application is also under way in our laboratory, and the preliminary study has been carried out to explore its inherent regularities. Arising from such a 'mini' condition which is characterized by both small working radii and high operating harmonic, the calculated results have revealed some unusual features. Other than a conventional cyclotron, a mini AMS should not only deliver radioactive particles to be detected as intensely as possible, but also should thoroughly get rid of all kinds of backgrounds (isobar, molecule and multiple particles). The later places severe restraints on mini AMS, because the reached energy in a mini cyclotron is too low to identify the measured particles with nuclear detector. Consequently, cyclotron parameters as a mini AMS must be decided by quite other criterion, which will be discussed on our calculation basis. Along with the following description, a number of versions including different accelerating systems associated with different magnet structures (Fig.1) are compared.

Phase grouping
(phase convergence & phase divergence)

It is conceivable that the fraction of particle orbit within the penetrating electric field due to working at small radii is large enough to induce the phase grouping, which is then significantly enhanced owing to operating with high harmonic. Such strong effect plays an important role in choosing version and parameters of a mini cyclotron. Among other things, this effect puts the central phase of particles to be detected and phase shift of backgrounds to be cleaned off under restriction. It can be qualitatively understood from Fig.2b for two accelerating structures, remembering that the mechanism of the phase grouping is the superimposition of the force produced by radial component Er of electric field on the Lorentz force F_L, which changes the revolution frequency of the particle. In Fig.2b, two arbitrary points a and b are symmetrically located at two sides of the central line of accelerating gap. If the particle crosses the gap line at r.f moment O, then $Er_a=Er_b$, thus the increase of the instantaneous revolution frequency at point a happens to be compensated by the decrease at point b (neglecting the velocity change of the particle before and after crossing gap). On the average, the revolution frequency keeps constant, no phase grouping will occur. However, if the gap line crossing moment is at O' of r.f wave, then $Er_a < Er_b$, as a result, the average revolution frequency is decreased, the particle phase will move rightward. Likewise, the particle phase will move leftward, if crossing gap line at moment O". Obviously, in DH structure of Fig.2a, the particle phase will be shifted back to the phase of peak voltage, so long as its local phase at gap line deviates from it. The farther the local phase deviates from it, the stronger the phase convergence is, which prevents backgrounds from phase shift, and is then unfavour of cleaning them away. Here the local phase $Q_o=90^o$ at gap line is a stable equilibrium phase Qe, which should be taken as a central phase Qc to keep the reference particle having a nearly constant phase until extraction. In contrast, for DTDH structure of Fig.2a, the particle phase will be shifted away from the zero phase of r.f voltage, unless its local phase at gap line is at moment O. The farther its local phase deviates from it, the stronger the phase divergence is, which facilitates the phase shift of backgrounds, and is thus in favour of cleaning them off. Here the local phase $Q_o=0^o$ at gap line is an unstable equilibrium phase Qe which should also be taken as a central phase Qc.

For constant orbit geometry, the phase grouping effect is independent of the strength of the magnetic and electric field, it exclusively depends on the fraction of orbit within the electric field. Clearly, in parallel accelerating gap, the phase grouping will decrease as orbit radius increases, whereas the wedge-shaped gap (Fig.1c) with apex at the center of machine will keep the effect unchanged all the way. Needless to say, the exaggerated DH system in Fig.1a is excluded, where orbits are entirely immersed into the electric field. On the other hand, infinitely narrowing the gap will not alleviate the phase grouping effect, because the boundary of the penetrating electric field changes quite unvisibly, unless the accelerating aperture 2H is dramaticly decreased, when beam intensity is extremely weaken.

Resolution (nH number & modulation acceleration)

The cyclotron as AMS possesses a unique feature which can sensitively reject nonresonant particles even with mass difference Δm only due to mass defect. The resolution R of a conventional cyclotron can be expressed as:

$$R = m/\Delta m = (360^o nH)/Q^o \qquad (1)$$

where H-- the harmonic number. n-- the total turn number and Q-- the effective amount of the phase shift, which backgrounds with same initial condition as the reference particle experience before entering into deceleration. For accurate estimation of the necessary turn number of various backgrounds in a mini cyclotron, the amount Q must be estimated as:

$$Q = Q_d - (Q_c \pm Q_w) + Q_{pg} + Q_a \qquad (2)$$

where Q_w -- half phase width of the beam bunch; Q_d -- final phase when the background particle starts to decelerate, and $Q_d - Q_c = 90^\circ$ for both structures (Fig.2a); Q_{pg} -- amount of the phase shift attributed to phase grouping, its sign depends on which electric structure is used; Qa -- phase fluctuation during acceleration resulting from non-isochronous, orbit precession and un-proper initial condition etc. In fact the exact value Q can be obtained through digital calculation.

From (1), it is apparent that the high resolution can be achieved by making the product nH large. However, H can not be set high: the influence of coupling effect between longitudial and transversal motion on particle behaviour will increase H times; it will put strict restraint on mechanical allowance; and the drasticly reduced effective accelerating voltage makes it difficult to directly extract ions from the internal ion source. Turn number can not be made large either owing to very weak negative ions and mini size of machine. During large n operation, the turn separation is too small to clear the ion source (injector) on the first turn and the septum at the last turn. It seems that the modulation acceleration is a better idea to increase turn number without reducing turn spacing. Unfortunately, the drift beam on the first turn can not clear the ion source or injector, the beam intensity will thus decrease the same times as modulation ratio.

Energy gain
(Dee geometry & single side acceleration)

Unlike a conventional cyclotron where maximum energy gain is required, the energy gain as low as possible is preferred in a mini cyclotron as AMS to contain more turns, except that high energy gain is desired on the first turn for injection and at the last turn for extraction. On the other hand, radio-particles to be detected must acquire the relatively highest energy gain within beam bunch to make them with the least turns reach the extraction radius where no background can reach, otherwise the non-resonant particles would escape with less turns. The approach to these demands ought to make use of the unique feature of the Dee structure rather than adjusting Dee voltage.

Figure 2c is the curves of the calculated maximum potential distribution U(x) for two specified Dee structures. The instantaneous potential U(x,t) at any point and time is:

$$U(x,t) = U_o \sin(\omega t + Q_o)\, u(x) \qquad (3)$$

where U_o -- the peak voltage; Q_o -- local phase at gap line and u(x)-- shape factor. To facilitate to understand the inherent characteristics of Dee structures on energy gain, for simplicity, let's consider an idealized case by assuming 2H =0 (no electric field penetration) and u(x)=1 (uniform field). In such ideal case, the energy gain crossing the gap is estimated by:

$$Eg = (U_o/(Q_2-Q_1)) \int_{Q_1}^{Q_2} \sin(Q)\,dQ \qquad (4)$$

then for DH and DTDH structures respectively:

$$Eg = -360 \sin Q_o \sin\Delta Q/\pi\Delta Q \qquad (5)$$

$$Eg = 360 \cos Q_o (1-\cos\Delta Q)/\pi\Delta Q \qquad (6)$$

It shows that the energy gain is related to r.f phase width ΔQ of the gap and local phase Q_o. From $\partial Eg/\partial Q_o=0$, we find that the relatively highest gain can be reached when $Q_o = 90^\circ$ in case DH, and $Q_o=0^\circ$ in case DTDH, which happen to be the equilibrium phase Qe. Thus we should also choose Qe as central phase Qc in view of energy gain. Furthermore, from $\partial Eg/\partial \Delta Q=0$, it can be seen that the maximum energy gain is obtained when $\Delta Q=0^\circ$ for DH case, and $\Delta Q=133.56^\circ$ for DTDH case. It means that the energy gain increases as gap is narrowed for case DH; and conversely as gap is widened until $\Delta Q=3\pi/4$ for case DTDH. Obviously, the energy gain can be changed by adjusting harmonic H and gap geometry D and 2H. For the parallel accelerating gap, the r.f phase width of gap decreases as orbit radius increases, thus energy gain during acceleration is increasing in DH case, and decreasing in DTDH case. Nevertheless, the wedge-shaped gap of Fig.1c can keep ΔQ unchanged, but there is no obvious necessary to keep energy gain constant.

With respect to the DTDH case, if single side acceleration like microtron is adopted as shown in Fig.1d, then energy gain per turn will be decreased by half as compared with two side acceleration. It is benificial either to incresing turn number for given Dee voltage, or to enlarging turn spacing for given turn number. Unfortunately, we are under the necessity of giving up such version for the sake of focusing.

Electric focusing
(decelerating & alternating polarity effect)

In a mini cyclotron, the particle energy is so low that the isochronous field almost keeps constant. Considering engineering compact, the uniform magnet is put on the first consideration. However, a uniform magnetic field can provide particles with no axial focusing, thus it must entirely rely on the electric focusing.

As it is well known, the predominent role of electric focusing in a cyclotron is the phase focusing, which could exist at rising and falling moment of r.f wave during high harmonic operation and might be enhanced due to extended r.f phase width of gap. If ΔQ is extended so wide that the particle will enter into deceleration after crossing the gap line, then the decelerating electric field will still impose a focusing force on the particle (fig.2a). At the first sight, the maximum additional focusing is introduced if the particle phases at both entry and exit of gap are near the peak voltage a and b (fig.2d), and it seems that the wedge-shaped system would be benefited by such deceleration focusing. Unfortunately, it is not the true story, because energy gain would be zero under such condition, and the phase fluctuation of particle would make particle decelerated. Even though the phases of gap boundaries are programmed at a' and b' (Fig.2d), the local phase Q_o at gap line still would largely deviate from the Qe, thus the strong phase grouping will force phase Q_o to move towards Qe, as a result, the phase focusing is gradually weaken. In fact, the phase focusing would be the weakest when local phase Q_o=Qe because of the nearly symmetric phase distribution around gap line. Therefore, the phase for the strongest focusing is inconsistent with that for the highest energy gain or the minimum phase grouping.

The another electric focusing may appear if $\Delta Q > 180^\circ$ (Fig.2e), when particles will encounter the electric pulse mixed with focusing (f) and defocusing (d) as crossing the gap. However, the electric pulse mainly happens at near both boundaries of gap. As regards at near central line of gap, the line of electric force is very flat, and the strength of electric field is very weak. Therefore, such alternating polarity focusing may occur, but is trivial.

Our orbit calculations show that the resultant axial focusing frequency including velocity focusing is only about 0.05 during first turns, and is rapidly decreasing as acceleration. Thus it is conceivable that the single side acceleration must have even lower axial focusing frequency, and has to be excluded. Just like usual central region of a cyclotron, putting sectors on a mini sized uniform magnet won't improve axial focusing too much. Nevertheless, it appears that a non-uniform magnet would serve the purpose of improving axial focusing.

Non-uniform magnet structure (external injection & deceleration mode)

The main advantage of using non-uniform magnet with slightly larger size than the one of a uniform magnet is that it avoids phase grouping and focusing troubles, and keeps'mini'structure --low field, low energy, low power and small size as compared with conventional separated magnet cyclotron. Such magnet structure leaves enough room for external injection which is highly desirable for a dating AMS to eliminate backgrounds and memory effect; to make fast sample changing and to alleviate pumping speed of vacuum pumps for the vacuum chamber.

Similar to the influence of the penetration of electric field, the fringing magnetic field at smaller radii should also be paid more attention to, the soft edge complicates the shaping of magnet without using trim coils, in particular for the single side acceleration of Fig.1f.

With respect to externally injecting beam into mini cyclotron, there exist two problems: (a). it is difficult to inject beam into the center of a uniform magnet; (b). the injecting energy, which is much lower than extracting energy from the ion source, is too low to keep initial beam quality, or the main magnetic field has to be significantly increased to match the injecting energy. An alternative method is adopting deceleration mode, where the beam is injected into outer radius of the mini cyclotron. The merits and demerits of deceleration mode are open to question: The main magnetic field to match the injecting energy can significantly decreased, but the non-normalized emittance of the beam is deteriorated during deceleration. In such mode, the beam transport line is shorten and compact, but the detector must be placed at near the center of the machine (inside or outside vacuum chamber), and the detected energy is very low. Because the turn spacing at inner radii is larger than that at outer radii, it facilitates extraction, but the wall of injector must be thin enough for clearing beam up. In addition to velosity defocusing, some concepts of the phase grouping effect should be reversed. As shown in Fig.2f, here Qe becomes an unstable equilibrium phase for DH case, and a stable equilibrium phase for DTDH case. Furthermore, the backgrounds will experience the stronger phase grouping as they are decelerated towards the inner radii.

We are greatly indebted to Dr. San-Lin Xu for his helpful discussion and suggestion.

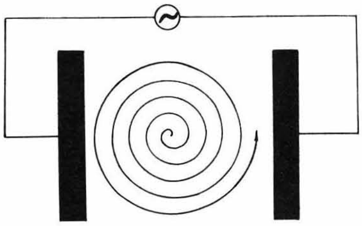


Fig.1a.
wide parallel
accelerating
gap.

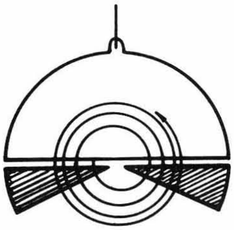


Fig.1b.
narrow parallel
accelerating
gap.

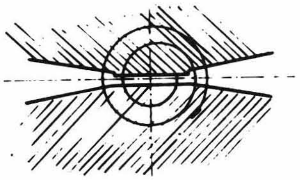


Fig.1c.
wedge-shaped
accelerating
gap.

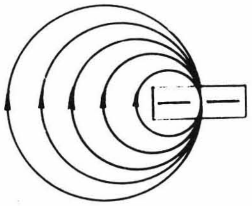


Fig.1d.
single side
acceleration

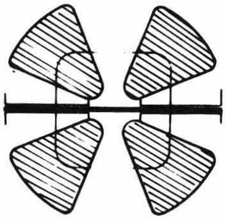


Fig.1e.
separated magnet structure.

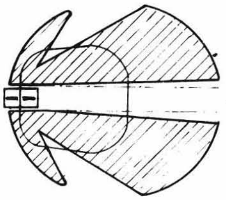


Fig.1f.
single side
acceleration
(non-uniform
magnet).

Fig.1

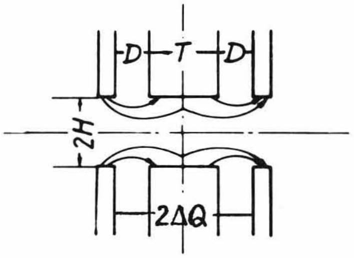
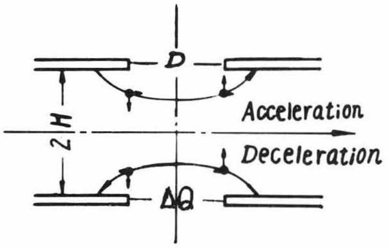


Fig.2a.
DTDH and DH
structure;
decelerating
focusing.



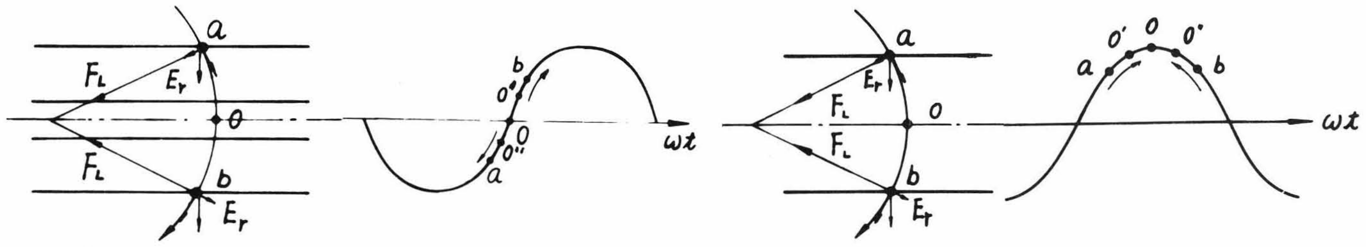


Fig.2b. phase divergence & phase convergence (acceleration mode).

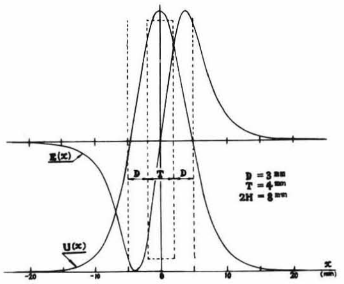
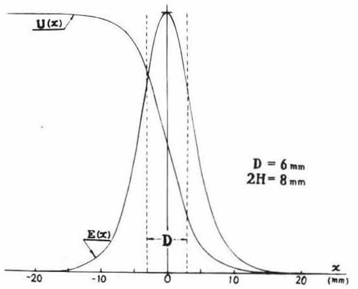


Fig.2c.
the curves of
potential
distribution
u(x).



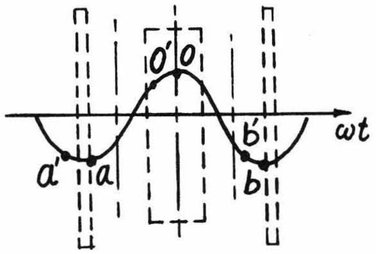
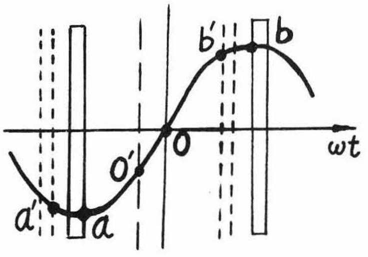


Fig.2d.
the phases of
the maximum
phase focusing



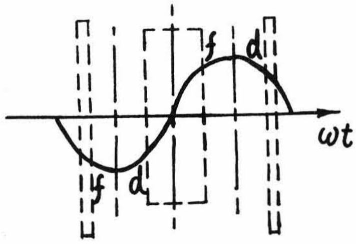
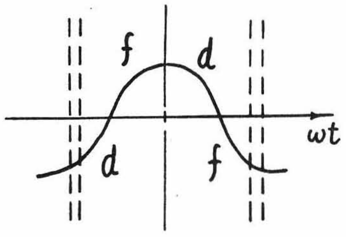


Fig.2e.
alternating
polarity
focusing.



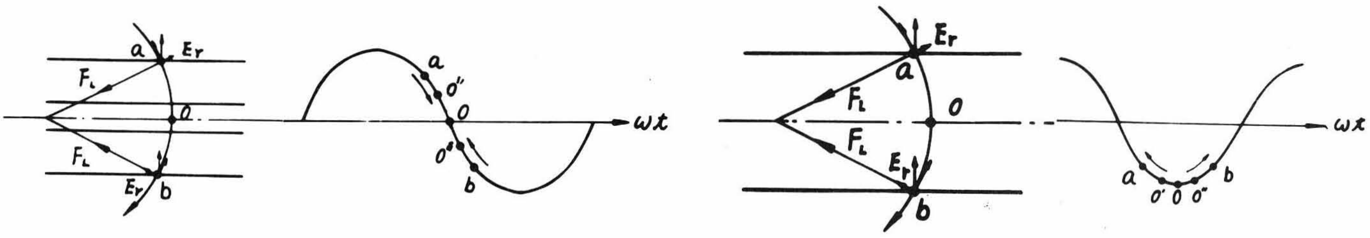


Fig.2f. phase convergence & phase divergence (deceleration mode).

Fig.2