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The isochronous cyclotron: principles and recent developments☆

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Abstract

The principals of a cyclotron are described. A magnetic field guides the ions in circular paths, while an electric field accelerates them. The main problem in any accelerator is not to accelerate ions, but to focus them. An isochronous cyclotron overrules the problems related to relativistic mass increase during acceleration. Harmonic operation and negative (vs positive) ion acceleration (and extraction) are explained, as they make dedicated PET cyclotrons a simple, reliable, and suitable tool. The characteristics of such PET cyclotrons are described, as well as their technical implementation. The IBA 18/9 PET cyclotron is given as an example.

Keywords: Cyclotron; Isochronous cyclotron; Negative ion cyclotron; Positron emission tomography; Positron emission tomography scanner

1. Introduction

This paper is limited to a dedicated PET cyclotron, as this is a major part of the technical equipment in a Positron Emission Tomography (PET) centre that does not use ^{18}FDG only. The paper is not intended for accelerator engineers, but for all staff members in a nuclear medicine department. The physical and technological principles will be explained, based on 'simple' high school physics that are briefly reviewed. The scope of this paper is that the reader should be able to read and understand product descriptions and claimed advantages from the manufacturers of such dedicated PET cyclotrons.

2. A charge in an electric and magnetic field

In a cyclotron (as well as in other types of accelerators [1]) an electric field is used to accelerate ions, such as protons or deuterons; a magnetic field is applied to 'guide' it. Therefore, the forces experienced on a charge in an electric and magnetic field are briefly reviewed.

An *electric field* (Fig. 1a) is generated by application of an electric potential difference U to two electrodes. A charge Q experiences a force and is accelerated. Its kinetic energy T equals

$$T = QU \tag{1}$$

For single charged ions, like protons and deuterons, the kinetic energy is 1 eV for $U = 1$ V. So, in principle one needs 10 MV to obtain 10 MeV protons, which is rather unpractical.

An ion with charge Q moving with velocity $\mathbf{v}$ perpendicular to a *magnetic field* with magnetic induction $\mathbf{B}$ (Fig. 1b), experiences the Lorentz force $\mathbf{F}$ given by

$$\mathbf{F} = Q(\mathbf{v} \times \mathbf{B}) \tag{2}$$

As the ion is deviated from its original direction, it experiences a centrifugal force F_f.

$$F_f = \frac{mv^2}{r} \tag{3}$$

The centrifugal force F_f balancing the centripetal force F_p (i.e. the Lorentz force, Eq. (2)), the ion will describe a circular equilibrium orbit with radius r, in a plane perpendicular to the magnetic field $\mathbf{B}$. Equaling Eqs. (2) and (3), one obtains the angular velocity,

$$\omega = \frac{v}{r} = \frac{QB}{m} \tag{4}$$

which is determined by the nature of the ion (Q, m) and the magnetic induction B. It is independent on the radius of the equilibrium orbit r.

The kinetic energy T can be calculated from Eq. (4).

$$T = \frac{mv^2}{2} = \frac{Q^2B^2r^2}{2m} = \frac{m\omega^2r^2}{2} \tag{5}$$

From Eqs. (4) and (5) the following conclusions can be drawn: (1) the kinetic energy T is determined by the nature

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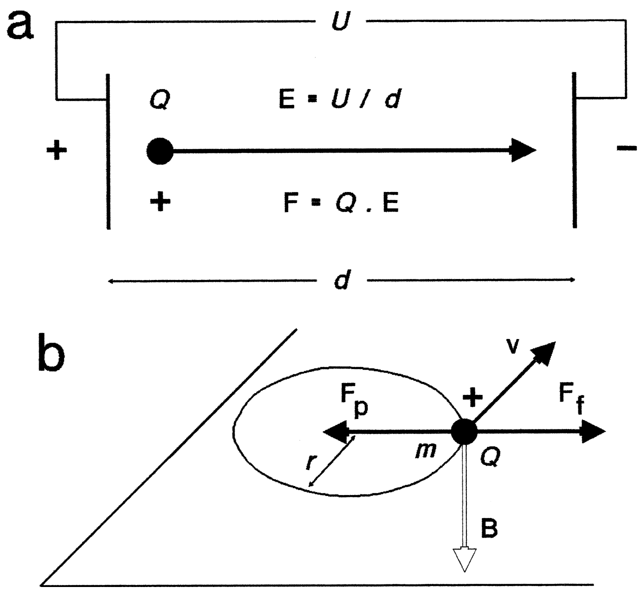

Fig. 1. (a) A charge Q in an electric field **E**. (b) A charge moving in a magnetic field **B**.

of the ion (Q, m), the magnetic induction B, and the radius of the equilibrium orbit r; (2) the magnetic induction B is related to the angular velocity ω by the nature of the ion (Q, m); and (3) the kinetic energy T, the velocity v, and the radius of the equilibrium orbit r are correlated to each other for a given ion (Q, m) and magnetic field B.

Ions being accelerated up to the speed of light, do not gain kinetic energy only, but also mass according to relativity. For 10 MeV protons e.g. the *relativistic mass increase* is about 1%.

3. Classic cyclotron

The classic cyclotron (Fig. 2a) consists of an electromagnet, providing a uniform magnetic field. Between the poles of the electromagnet two hollow electrodes are introduced, i.e. the two halves of a cylindrical box cut in two along the axis and slightly separated from each other. Because of the resemblance of this semicircular structure with the capital D, the electrodes have been called ‘dees’.

The dees are connected to an AC (alternating current) source (Fig. 2b). Positive ions (e.g. protons) are released in the center of the cyclotron. When the right handed dee is negatively charged, the ion is accelerated to the dee by the electric field in the gap between the two dees. Once the ion enters the (hollow) dee it experiences only the magnetic field. The path of the ion is consequently half a circle. When the ion leaves the dee, the polarity on the dees should be reversed, so that the ion is accelerated again to the opposite (left handed) dee. The same process is repeated in the other dee, but the orbit radius is higher as the velocity of the ion is higher. This process continues and the ion is spiraling outward towards the ‘border’ of the magnetic field. The ion

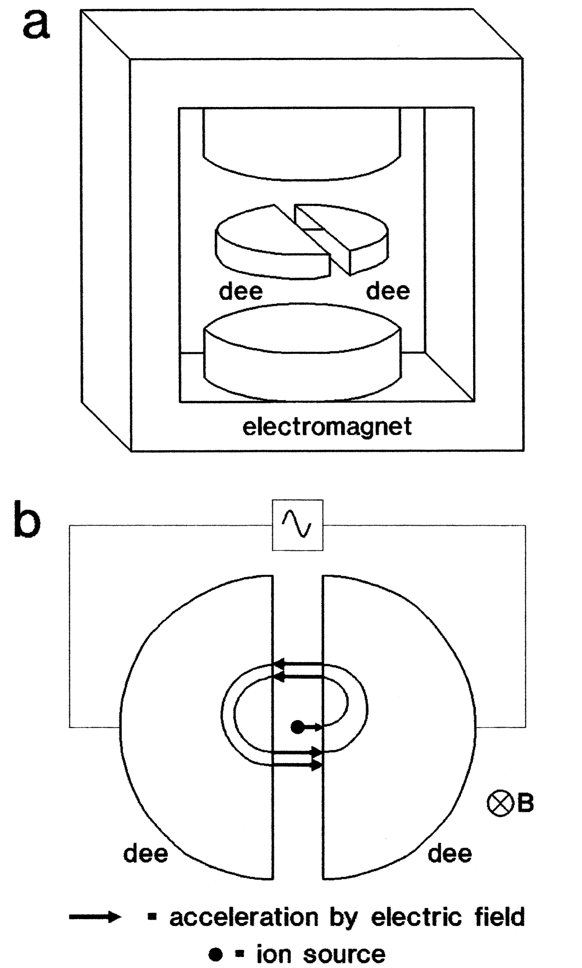

Fig. 2. Classic cyclotron: (a) 3D view; (b) 2D view in the mid-plane [reproduced with permission of John Wiley & Sons Ltd from Strijckmans K. Charged particle accelerators. In: Z.B. Alfassi, editor. Chemical analysis by nuclear methods. Chichester (UK), 1994].

gets an energy equal to the sum of all individual accelerations in the gap between the dees. To obtain 10 MeV protons, an electric potential difference of 10 MV was required in Fig. 1a. A cyclotron makes use, for example, of only 10 kV accelerating the proton in 1000 steps of 10 keV up to 10 MeV.

This story only holds true if the polarity on the dees is changed every time the accelerated ion appears again at the gap between the dees. As was shown in Eq. (4), the angular velocity of the ion is only a function of the charge to mass ratio of the ion and the magnetic induction. It is not dependent on the orbit radius r (or velocity v or kinetic energy T) of the ion. Thus, the resonance condition of a cyclotron is that the angular velocity of the electric field ($\omega_E = 2\pi f, f =$ frequency) is to be set equal to the one of the ion ω_{ion}.

The final kinetic energy can be obtained from Eq. (5) for a radius r equal to the extraction radius R, i.e. the ‘border’ of the magnetic field.

$$T_{max} = \frac{Q^2 B^2 r^2}{2m} = \frac{m\omega^2 r^2}{2} \qquad (6)$$

It is determined by the nature of the ion (Q, m) and the 'size' of the magnet (B, R). It is not dependent on the electric potential difference U applied on the dees. This is surprising at first sight, because U determines the energy gain for each dee-gap crossing. However, the lower U, the more rotations the ion makes before arriving at the extraction radius. The angular velocity ω (ion, electric field) is related to the magnetic induction B by the nature of the ion (Q, m), as shown in Eq. (4). Under practical working conditions, for a given ion (Q, m) and cyclotron (B, R), the kinetic energy T is set by the angular velocity ω (or frequency f) of the electric field and the magnetic induction B is tuned to obtain resonance.

The maximum energy attainable by a classic cyclotron is limited due to the relativistic mass increase of the ions accelerated. Until now, the angular velocity of the ions being accelerated has been supposed to be independent on the orbit radius (or velocity, or energy), as suggested by Eq. (4). However, the ion mass increases with its velocity (or energy, or radius), hence the angular velocity of the ion decreases with its orbit radius. If the angular velocity (or frequency) of the electric field is kept constant (which is always the case for cyclotrons), the ion comes more and more too late at the gap between the dees. Finally the ion will appear at the gap when the potential on the opposite dee is positive. The ion will be decelerated (in stead of accelerated). Then the energy has reached its physical limit.

A possible solution could be to increase the magnetic induction as a function of the radius to compensate the relativistic mass increase. However, this is not possible for a classic cyclotron, because of orbit stability. For an isochronous cyclotron this limitation will be overcome, as will be explained in the next two sections.

4. Orbit stability

The major problem in accelerators is not to accelerate the ions, but to keep the ions on their equilibrium orbit, i.e. the problem of focusing or orbit stability. Ions, guided by the magnetic field, travel a long distance before reaching their final energy. Although acceleration takes place in vacuum, collision with the residual gas molecules will deflect the ions. If the ions once hit the dees or vacuum chamber wall, they are lost. Therefore corrective steering forces must be applied. This force should be automatic for all ions, as it is not possible to steer individual ions. Moreover, the force should be proportional to the deviation. Finally the force should correct both up-down and left-right deviations.

To make this idea clear, the bowling alley model is shown in Fig. 3. For a concave alley, a ball, tending to leave the alley, experiences a corrective force. The larger the deviation, the larger this force. Deviations to the left as well as to the right are corrected. All balls are also corrected automatically to an equilibrium path, where correcting forces are zero. Hence, all balls are oscillating about the equilibrium path. No such forces exist for a flat alley, while opposite forces exist for a concave alley.

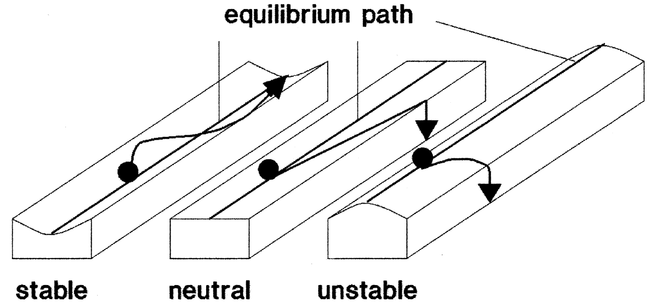

Fig. 3. Bowling alley model for a stable, neutral and unstable equilibrium system.

Before going to the cyclotron model, the *equilibrium orbit* has to be defined. This is the orbit of an undisturbed ion that is not accelerated. In this paper magnetic guidance will be separated from electric acceleration, for simplicity. The equilibrium orbit is a circle in the mid-plane perpendicular to the magnetic field (Fig. 4c). Orbit stability will be studied separately for radial deviations and axial deviations (Fig. 4c). Radial deviations occur in the mid-plane, and Fig. 4a represents radial stability: the ion oscillates about the circular equilibrium orbit in the mid-plane. Axial deviations occur perpendicular to the mid-plane, thus along the magnetic field. Fig. 4b represents axial stability: the ion oscillates, at fixed radius of the equilibrium orbit, under and above the mid-plane.

Orbit stability is related to the magnetic induction as a function of the radius. This function is described (at least for small variations) by the *field index n*.

$$B(r) = \frac{1}{r^n} \tag{7}$$

Flat magnet poles yield a magnetic induction that is independent on the radius, thus described by a zero field index. Magnet poles with a spherical surface yield a magnetic induction increasing resp. decreasing as a function of the

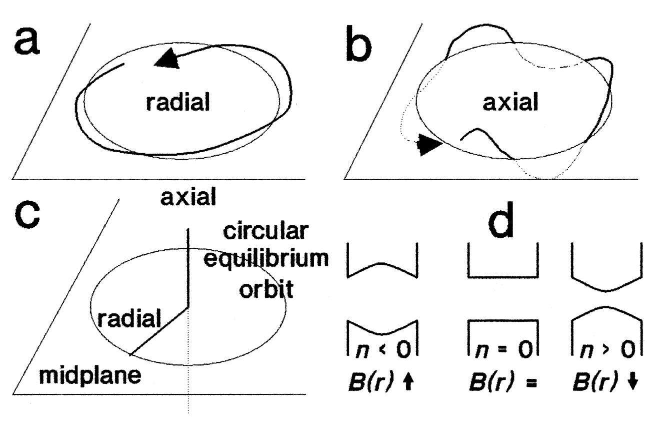

Fig. 4. Radial (a) and axial (b) oscillations about a circular equilibrium orbit (c); field index n (d).

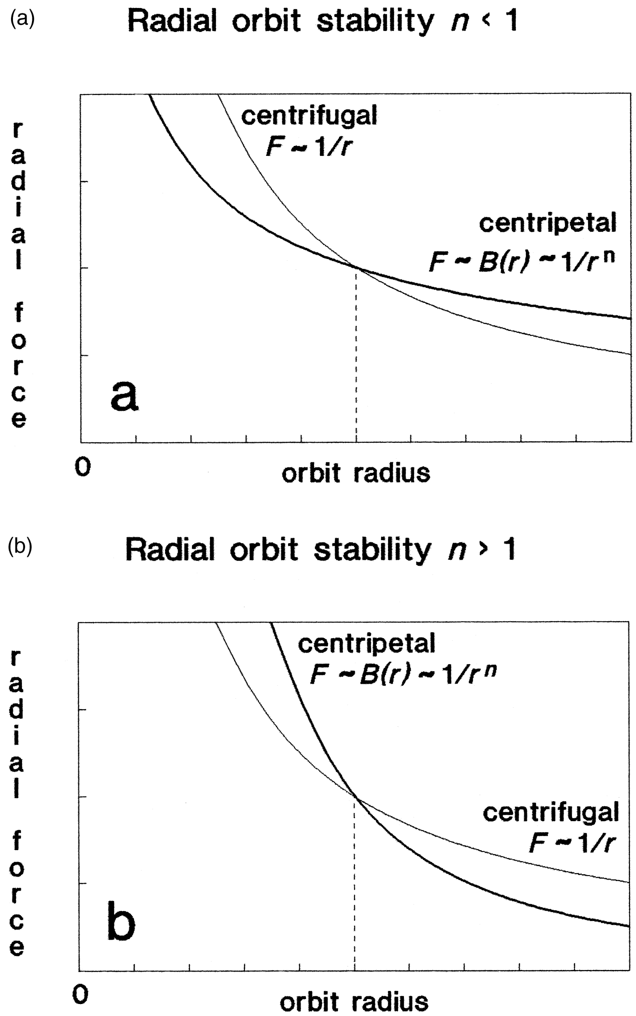

Fig. 5. Radial orbit stability (a) and instability (b) for $n < 1$ resp. $n > 1$.

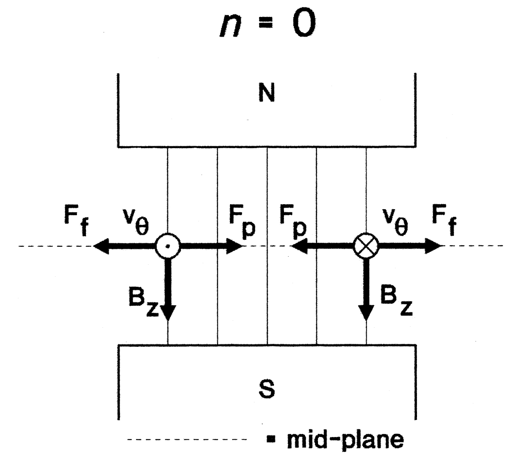

Fig. 6. Radial forces for a zero field index; also valid in the mid-plane of for any field index.

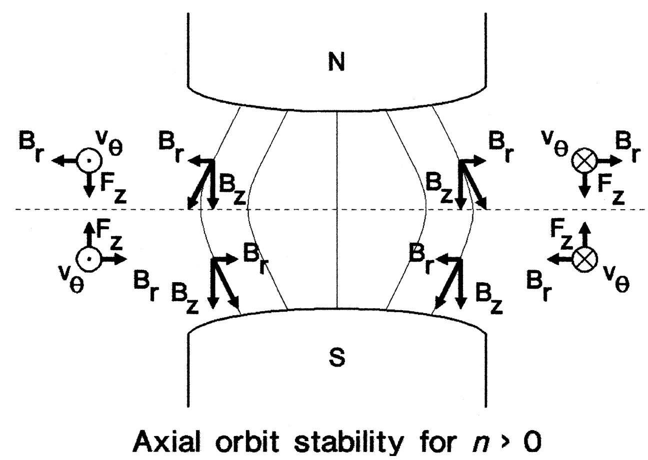

Fig. 7. Axially focussing forces $\mathbf{F}_z$ for a positive field index.

radius and thus described by a negative resp. positive field index (Fig. 4d).

Radial orbit stability is obtained for a field index lower than unity (Fig. 5a). The centripetal force F_p, i.e. the Lorentz force, is proportional to the magnetic induction B (Eq. (2)), and its dependence on the radius r is described by the field index n (Eq. (7)). The centrifugal force F_f is proportional to the inverse value of the radius r (Eq. (3)). Both radial forces are balanced for the equilibrium orbit radius. For ions leaving the equilibrium orbit in the mid-plane to the center of the cyclotron ($r = 0$) the centrifugal force overrules the centripetal force. The ions are thus forced to the equilibrium radius again. Reasoning in the same way, ions leaving the equilibrium orbit away from the cyclotron center experience a net centripetal force. Repeating the reasoning for a field index higher than unity, one observes radially unstable orbits (Fig. 5b).

To observe *axial orbit stability*, a cross-section is taken trough the axial and radial direction, thus perpendicular to the mid-plane, as shown in Fig. 6 for zero field index. The only interaction is the axial magnetic induction $\mathbf{B}_z$ with the azimuthal velocity $\mathbf{v}_\theta$ (azimuthal means perpendicular to the radial direction) yielding the radial Lorentz force **F**. This results in a circular orbit in the mid-plane, the equilibrium orbit. This interaction also happens in the mid-plane for any field index. For a magnetic field with positive field index, ions leaving the mid-plane experience axial forces, bringing them back to the mid-plane, i.e. axial stability, as shown in Fig. 7. Indeed, above and under the mid-plane the magnetic induction lines are bended. Consequently the magnetic induction vector **B** has, besides the axial component $\mathbf{B}_z$, also a radial component $\mathbf{B}_r$, that interacts with the (azimuthal) ion velocity $\mathbf{v}_\theta$, yielding an axial force $\mathbf{F}_z$, always directed to the mid-plane. For a negative field index (Fig. 8) these axial forces are always directed away from the mid-plane. Consequently, a positive resp. negative field index yields axially stable resp. unstable orbits.

The condition for both axial and radial orbit stability is a field index between zero and unity. It is now clear that the condition for isochronism, i.e. the magnetic induction increasing with the radius to compensate the relativistic mass increase ($n < 0$) can not be fulfilled in a classic

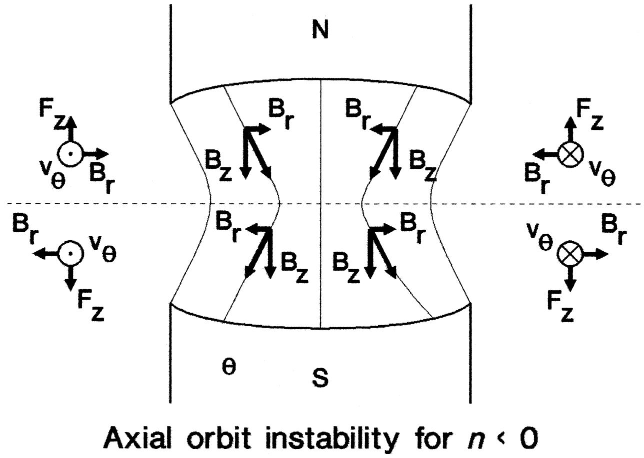

Fig. 8. Axially defocusing forces $\mathbf{F}_z$ for a negative field index.

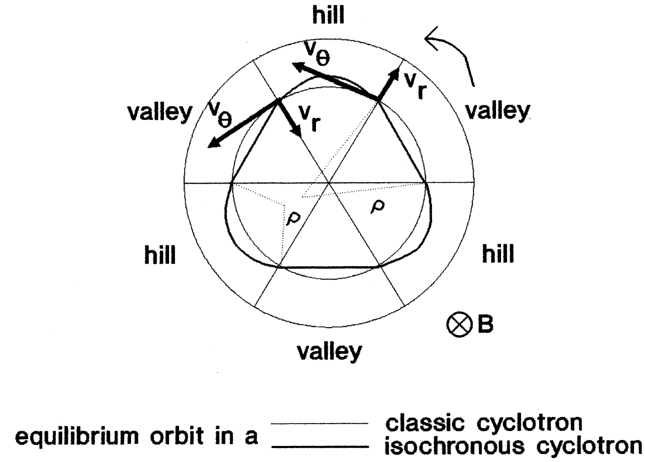

Fig. 10. Equilibrium orbit in an isochronous cyclotron: view in the mid-plane.

cyclotron. Consequently, the maximum energy of a classic cyclotron is limited.

5. Isochronous cyclotron

In an isochronous cyclotron a negative field index is applied to compensate the relativistic mass increase. The axial orbit instability, such a magnetic field causes, is overcompensated by strong *axially focusing forces*. These Thomas forces originate from the particular shape of the magnet poles (Fig. 9). Removing radial sectors (at least 3) from the magnet poles 'hills' and 'valleys' are created. Ions experience a strong magnetic field in the hills (because the N and S pole are closer than for the valleys) and a weak magnetic field in the valleys. In the azimuthal direction, i.e. perpendicular to the radius, along the equilibrium orbit, ions experience an azimuthally varying field, hence an 'AVF cyclotron'.

In such a field ions do not describe a circular equilibrium orbit any more (Fig. 10). Their radius of curvature ρ is smaller in the stronger field (hill), resp. larger in the weaker field (valley). The orbit weaves back and forth about a circle. Consequently, the ion velocity vector $\mathbf{v}$ has, besides the azimuthal component $\mathbf{v}_\theta$, a radial component $\mathbf{v}_r$, directed outward when moving from a to a weaker field (valley) to a stronger field (hill). When moving from a hill to a valley, the radial component is directed inward.

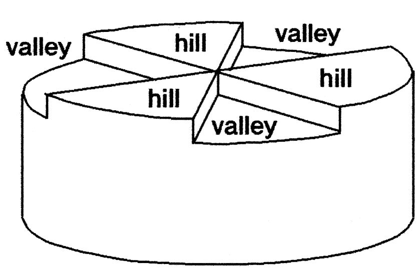

Fig. 9. Magnet pole of an isochronous cyclotron, i.e. a sector focussed or AVF (azimuthally varying field) cyclotron plane (reproduced with permission of John Wiley & Sons Ltd from Strijckmans K. Charged particle accelerators. In: Z.B. Alfassi, editor. Chemical analysis by nuclear methods. Chichester (UK), 1994).

Fig. 11 shows an 'unrolled' side view of the gap between the magnet poles seen from the centre along the axial and azimuthal direction. The magnetic field lines are bent at the edges of a hill–valley. Consequently, the magnetic induction vector $\mathbf{B}$ has, besides the axial component $\mathbf{B}_z$, an azimuthal component $\mathbf{B}_\theta$ above or under the mid-plane. Interaction of this azimuthal component of magnetic induction $\mathbf{B}_\theta$ with the radial component of velocity $\mathbf{v}_r$ yields an axial force $\mathbf{F}_z$ always directed to the mid-plane. These axial focusing forces overrule the axial defocusing forces due to a negative field index, necessary for isochronism (to compensate the relativistic mass increase) as already mentioned in the previous section.

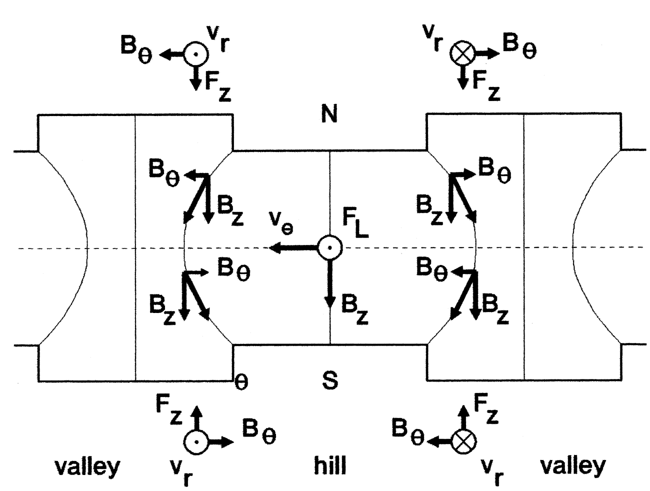

Fig. 11. Strong axially focusing forces $\mathbf{F}_z$ in an isochronous cyclotron: unrolled side view of the gap between the magnet poles seen from the centre along the axial and azimuthal direction.

6. Harmonic operation

Enough about orbit stability, let us return to what an accelerator is supposed to do: accelerate.

A cyclotron with two 180° dees is called a '*one dee cyclotron*'. The dee that is electrically grounded is not taken into account (Fig. 12). The other dee is driven by an AC source, and for each revolution the ion is accelerated twice, once at the first dee gap, when it is pushed away by the positively charged right-handed dee, and, once at the second dee gap, one half cycle later, when it is pulled by the negatively charged dee.

The angular velocity (or frequency) of ion and electric field has been supposed to be equal, until now. This means that for every half cycle of the electric field, the polarity on the dees is changed and the ion is accelerated when traversing gap 1 or 2 between the dees (Fig. 12). Suppose the angular velocity (or frequency) of the electric field is increased by a factor of 3: every 3/2 cycles of the electric field the ion makes half a turn, the polarity on the dees is reversed and the ion is also accelerated when traversing the gap. This is called *harmonic operation*, with harmonic number $h = 3$.

The angular velocity of the electric field should not necessarily be equal to the one of the ion, but 1, 3, 5, 7,… (any odd integer) times higher than the one of the ion. Eq. (4) should be revised as

$$\omega_E = h\omega_{ion} = h\frac{QB}{m} \tag{8}$$

with h any odd integer for a 'one dee cyclotron'.

Harmonic operation is of practical interest as the same electric and magnetic fields can be applied for different ions (to be understood as different charge to mass ratio). As shown in Table 1, $^1H^+$ and $^3He^+$ can be accelerated with the same settings, the harmonic number h compensating the different charge to mass ratio. The kinetic energy T_{max}, however, is different according to Eq. (6).

Is that the ideal cyclotron for routine PET applications? No. The ideal PET cyclotron accelerates protons and deuterons, as explained in Section 8.

Lets consider a '*two dee cyclotron*': two grounded 90° dees, and two 90° dees each driven by an AC source (Fig. 13). In such a cyclotron the ion is accelerated four times for each revolution, when passing the four dee gaps. Suppose dee A and B are driven in the *anti-phase mode* (i.e. A is positive when B is negative) and in the first harmonic mode (i.e. $h = 1$, one rotation per AC-source cycle). When an ion is in gap 1 as indicated in Fig. 13, the positive dee A pushes the ion; one

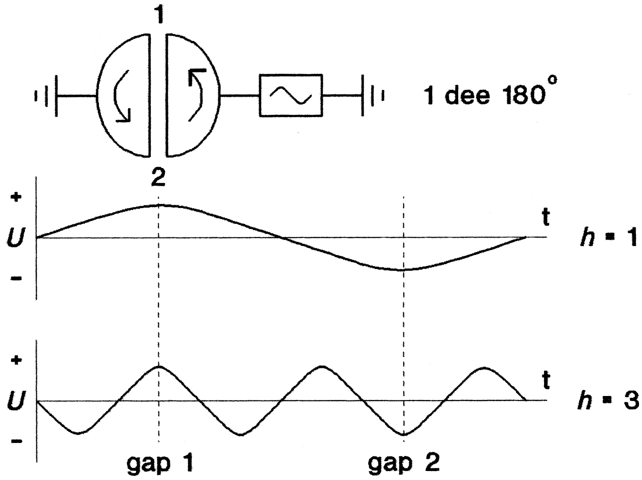

Fig. 12. Harmonic operation for a 'one dee cyclotron' (180°).

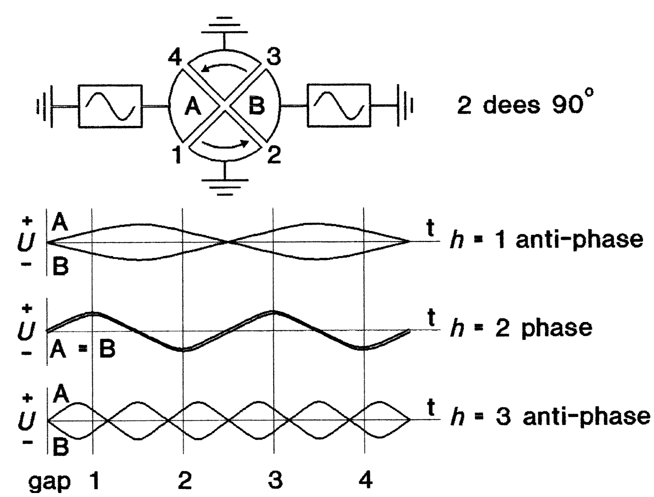

Fig. 13. Harmonic operation for a 'two dee cyclotron' (90°).

Table 1
Harmonic operation of a 'one dee' cyclotron (180°) at odd harmonic number and a 'two dee' cyclotron (90°) at odd harmonic number (antiphase) or even harmonic number (phase): for the same magnetic field B, different ions can be accelerated at the same electric field frequency; relative values for ω and T

	Ion	Q/m	h	$\omega_{ion} = QB/m$	$\omega_E = h\omega_{ion}$	$T_{max} \propto Q^2/m$
One dee 180°	$^1H^+$	1	1	1	1	1
h = odd integer	$^3He^+$	1/3	3	1/3	1	1/3
Two dee 90°	$^1H^+$	1	1	1	1	1
Anti-phase: h = odd integer	$^2H^+$	1/2	2	1/2	1	1/2
Phase: h = even integer	$^3He^+$	1/3	3	1/3	1	1/3
Two dee 90°	$^1H^+$	1	2	1	2	1
Phase: h = even integer	$^2H^+$	1/2	4	1/2	2	1/2

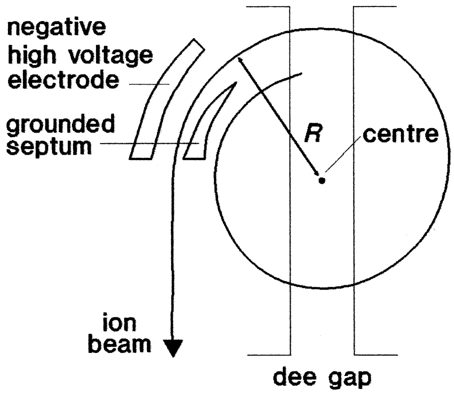

Fig. 14. Beam extraction in a positive ion cyclotron: electrostatic deflector.

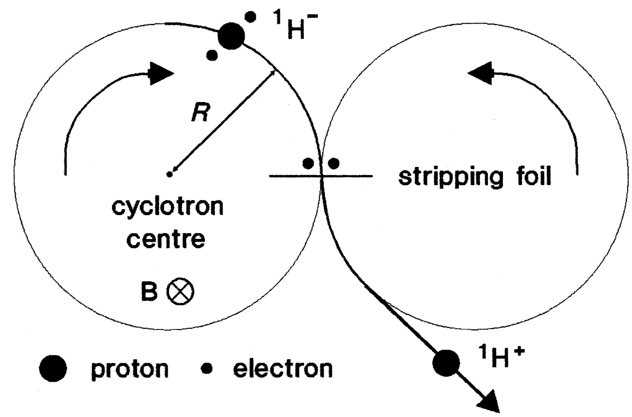

Fig. 15. Beam extraction in a negative ion cyclotron: stripping foil.

fourth AC-cycle later, the negative dee B pulls the ion in gap 2. Similarly another fourth AC-cycle later the positive dee B accelerates the ion in gap 3 and another fourth AC-cycle later the negative dee A accelerates the ion in gap 4. The same is possible in the third harmonic mode, i.e. $h = 3$, at triple AC-source frequency. Suppose dee A and B are driven in phase mode (i.e. dee A and B both going positive and negative together), then operation in the second harmonic mode ($h = 2$) is possible.

Such a 'two dee cyclotron' is still of more practical usefulness. The same electric and magnetic fields can now be applied for three different ions (to be understood as different Q/m). As shown in Table 1, $^1H^+$, $^2H^+$ and $^3He^+$ can be accelerated with the same settings, $^1H^+$ in the anti-phase mode for $h = 1$, $^2H^+$ in the phase mode with $h = 2$, and $^3He^+$ in the anti-phase mode with $h = 3$.

Is that the ideal PET cyclotron? Not yet, because acceleration of both protons and deuterons in the phase mode should be more practical, as then only one AC-source is needed. And this is the possible accelerating protons in the second harmonic ($h = 2$) and deuterons in the fourth harmonic ($h = 4$) mode. Then, the proton energy is twice the deuteron energy, as shown in Table 1.

7. Beam extraction

In principle, irradiations can be carried out inside the cyclotron, i.e. with an internal target placed at the 'border' of the magnetic field. However, in PET cyclotrons the accelerated ion beam is extracted from the cyclotron and guided to a suitable target.

Extraction of a *positive ion* beam is performed by an electrostatic deflector (Fig. 14), which consists of two electrodes placed at the extraction radius of the cyclotron: one (septum) at ground potential, the other at high negative voltage. The geometry is such that the last but one rotation is unaffected by the deflector. For the last rotation the ion beam experiences a strong electric field directed outward. This field guides the ion beam outside the magnetic field where it continues straight forward to an external target position.

In a *negative ion* cyclotron, negative ions (e.g. $^1H^-$) are accelerated, but positive ions (e.g. $^1H^+$) are extracted (Fig. 15). Beam extraction is quite different and much simpler than for a positive ion machine. Also high beam intensities can be extracted with minor activation of the extraction system, as compared to a positive ion cyclotron.

The principle of acceleration of negative ions is not different from the one of positive ions. All forces have the same direction but opposite sense, as Q is negative. If positive ions rotate counter clockwise, then negative ions will rotate clockwise in the same magnetic field. Once the negative ions have reached their final energy at radius R, they hit a stripping foil, that removes the electrons. The ion charge, being now positive, experiences the same force in the same direction but with opposite sense. The trajectory of the positive ion is the mirror image of the trajectory of the negative ion. In this way the positive ion leaves the magnetic field and continues straight forward to an external target position.

8. Dedicated PET cyclotrons

The principles of operation as such are also applicable to any isochronous cyclotron, e.g. research cyclotrons (multiparticle, variable energy), medium and high energy dedicated cyclotrons for SPECT isotope production, neutron- and proton therapy, brachytherapy, subcritical reactor,… However, e.g. in a research cyclotron, the harmonic mode operation is used to obtain the multi-particle, variable energy characteristics. And axial stability can still be improved by spiral ridge shaped sectors. As the scope of this paper was limited to the dedicated PET cyclotrons, the principles explained and their implementations are also limited to the dedicated PET cyclotrons. The last section deals with the question: what are the characteristics of such a PET cyclotron, and how is this realized. The IBA (Ion Beam Applications) 18/9 cyclotron will be given as an example.

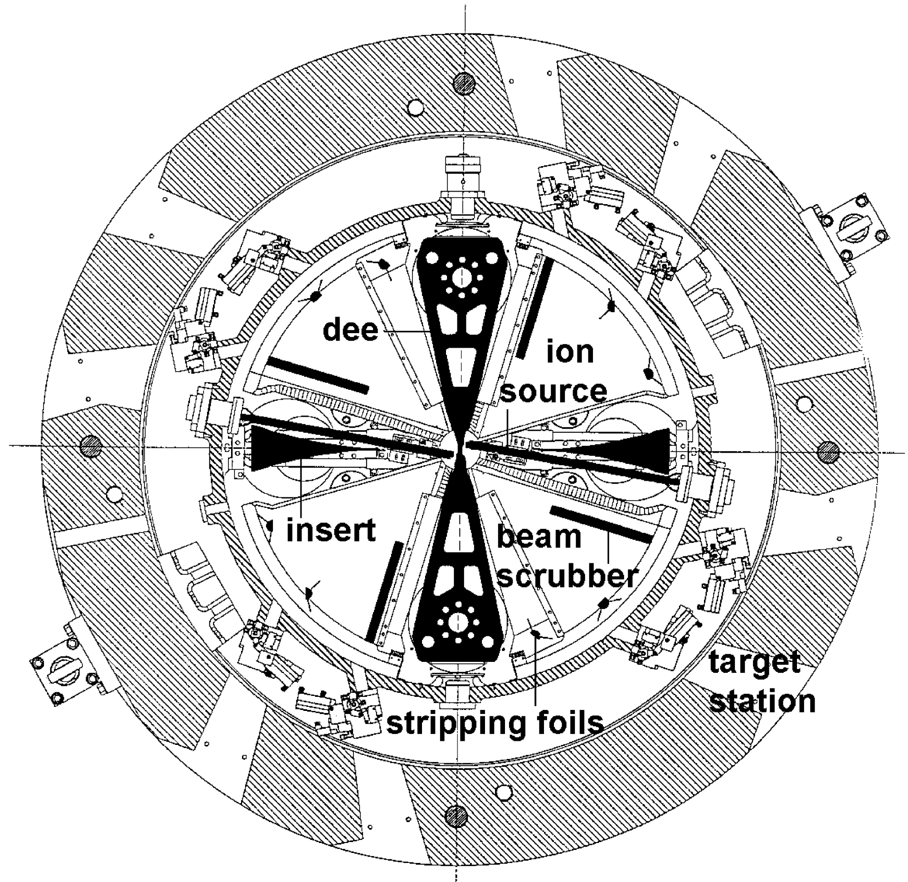

Fig. 16. View in the mid-plane of a dedicated PET cyclotron: IBA 18/9 (reproduced with permission of IBA, Ion Beam Applications s.a., Louvain-la Neuve, Belgium).

The characteristics of a dedicated PET cyclotron are:

1. *Two-particle cyclotron (proton–deuteron).* Protons are needed for the batch-wise production of the short-lived ^{11}C, ^{13}N, and ^{18}F (half-lives resp. approx. 20, 10 and 110 min). Deuterons are needed for the on-line production of ^{15}O labeled gases (oxygen, carbon dioxide, and carbon monoxide) and batch-wise production of the ^{15}O labeled water (half-life approx. 2 min). The option to design a single particle (proton) cyclotron, and hence producing ^{15}O by proton irradiation of ^{15}N enriched nitrogen gas, has been considered but rejected from the beginning. A deuteron single particle cyclotron, only for the production of ^{15}O has been developed, but is not in common use.
2. *Fixed energy.* There is no need for high nor different proton energies for the production of ^{11}C, ^{13}N, and ^{18}F. For ^{15}O a lower deuteron energy is sufficient.
3. *High beam intensity* (rather than a higher energy) to obtain a high production yield.
4. *Several beam lines*, but not in different irradiation vaults.
5. *Simple* design and operation yielding *high reliability*, and *low* investment and operation *costs*, as it is implemented in a nuclear medicine department for routine clinical applications.

The latter requirements have been fulfilled by the design of:

1. A proton–deuteron, fixed energy cyclotron, using a *two-dee* system, operated in the *phase mode* at the *second and fourth harmonic*, requiring only one single AC source, as explained in Section 6. For such a cyclotron the deuteron energy is half of the proton energy, which is highly convenient. Examples are the IBA 10/5 and IBA 18/9 (10 resp. 18 MeV protons/5 resp. 9 MeV deuterons).
2. An isochronous cyclotron with *four radial sectors* and '*deep valleys*'. It provides not only excellent axial focussing (Sections 4 and 5), but also opportunities in assembling the cyclotron (see below).
3. A *negative ion* cyclotron with several *stripping foils* providing several beam lines at the 'border' of the magnetic field (Section 7). The beam intensity is high enough for gas and water targets. An electrostatic deflector provides higher beam intensities, but it is much more activated during irradiation. Moreover, several beam lines are only possible by the use of one deflector and a complex beam transport system of bending magnets and quadrupole lenses.

As an example the IBA 18/9 cyclotron is shown in Fig. 16 [2]. In the mid-plane view one can observe four radial sectors

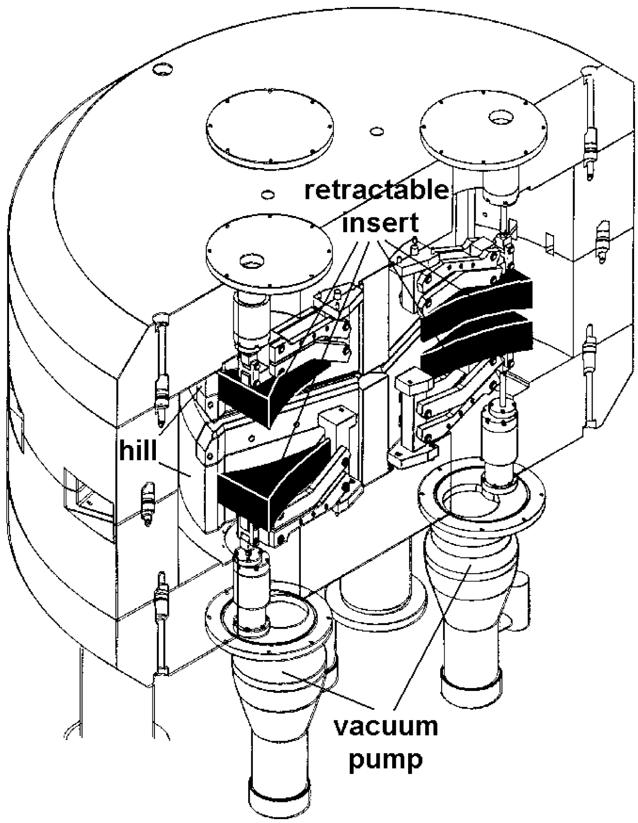

Fig. 17. Cross-section of a dedicated PET cyclotron (IBA 18/9) through the valleys: retractable inserts (reproduced with permission of IBA, Ion Beam Applications s.a., Louvain-la Neuve, Belgium).

(Section 5). Two opposite (deep) valleys are used to house the dees (30°), the other two opposite valleys to house two ion sources, one for protons, the other for deuterons, and the inserts. The grounded dees are not physically present as such, only the 'border' at the dee gap is. In this way the space gap between N and S pole can be kept as small as possible, which reduces the power demand of the magnet.

The magnetic field increases with the radius (to compensate relativistic mass increase, $n < 0$, see Section 3) by the use of four wedge shaped inserts: two in the N pole and two in the S pole, each in two opposite valleys. Deuterons, being accelerated to half the proton energy (Section 6), require a lower magnetic field increase with the radius. Therefore the inserts are axially movable, as shown in Fig. 17. For deuterons the inserts are retracted to the 'bottom' of the valley. As the space gap between N and S pole is very small, an excellent axial focussing is required. It is obtained by the deep valley (Sections 4 and 5). Moreover, 'beam scrubbers' are placed to prevent axially defocused ions hitting the dees or ion sources (the ions move counter clockwise in Fig. 16).

Eight carrousels with two stripping foils (1 spare foil) can intercept the beam and extract it to one out of eight target stations (Section 7), as shown in Fig. 16. By first intercepting half the beam spot, simultaneous irradiation in two targets is possible. High vacuum (also to prevent stripping of the negative ions by residual gases) is obtained by four vacuum oil diffusion pumps through the four valleys. The dees (Fig. 16) are perforated to improve pumping speed.

9. Summary

A dedicated PET cyclotron is a major part of the technical equipment in a Positron Emission Tomography (PET) centre that does not use ^{18}FDG only. The paper is based on 'simple' high school physics (that are briefly reviewed) and is intended for all staff members in a nuclear medicine department. The physical and technical principles of a classic cyclotron are described. A magnetic field guides the ions in circular paths, while an electric field accelerates them. The main problem in any accelerator is not to accelerate ions, but to focus them. An isochronous cyclotron overrules the problems related to relativistic mass increase during acceleration. Harmonic operation is explained as a tool to design a simple proton-deuteron cyclotron. Negative (vs positive) ion acceleration (and extraction) are explained, as they make dedicated PET cyclotrons a simple, reliable and a suitable tool. The characteristics of such PET cyclotrons are described, as well as their technical implementation. The IBA 18/9 PET cyclotron is given as an example.

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