Application of Lorentz (Force) Equation

(1) 高能物理中基本粒子動量的測量大多基於

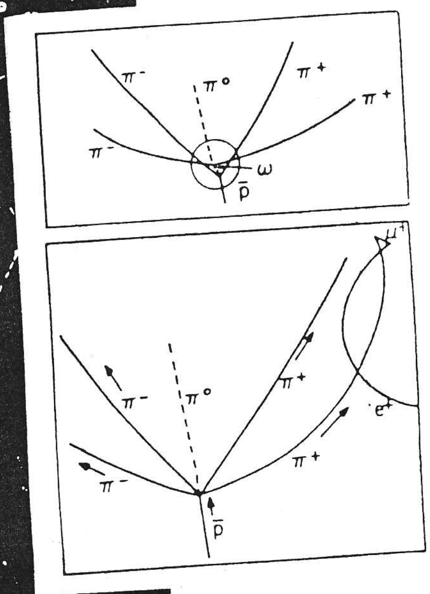
$$r = \frac{p}{qB}$$

很多高能物理中的儀器 ⟶ 觀察帶電的軌跡

Comments of measuring neutral particle

$$\pi^0 \to \gamma\gamma \to e^+e^-$$
$$\quad \hookrightarrow e^+e^-$$

Discovery of OMEGA MESON First Neutral Vector Meson



$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \nu_\mu$$

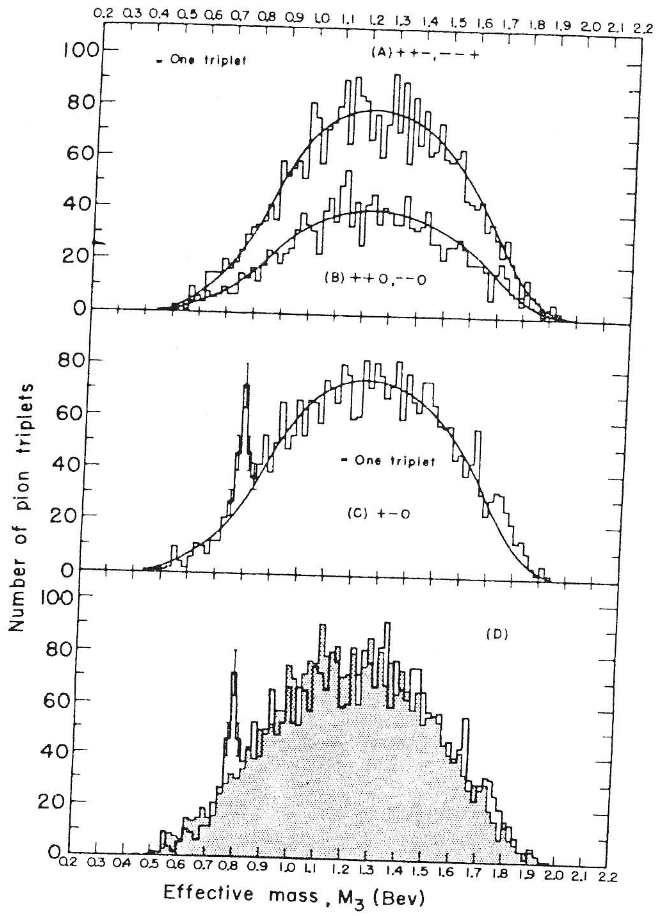


FIG. 1. Number of pion triplets versus effective mass (M_3) of the triplets for reaction $\bar{p}+p \to 2\pi^+ + 2\pi^- + \pi^0$. (A) is the distribution for the combination (4′), $|Q|=1$; (B) is for the combination (4″), $|Q|=2$; and (C) for (4), $Q=0$, with 3200, 1600, and 3200 triplets, respectively. Full width of one interval is 20 Mev. In (D), the combined distributions (A) and (B) (shaded area) are contrasted with distribution (C) (heavy line).

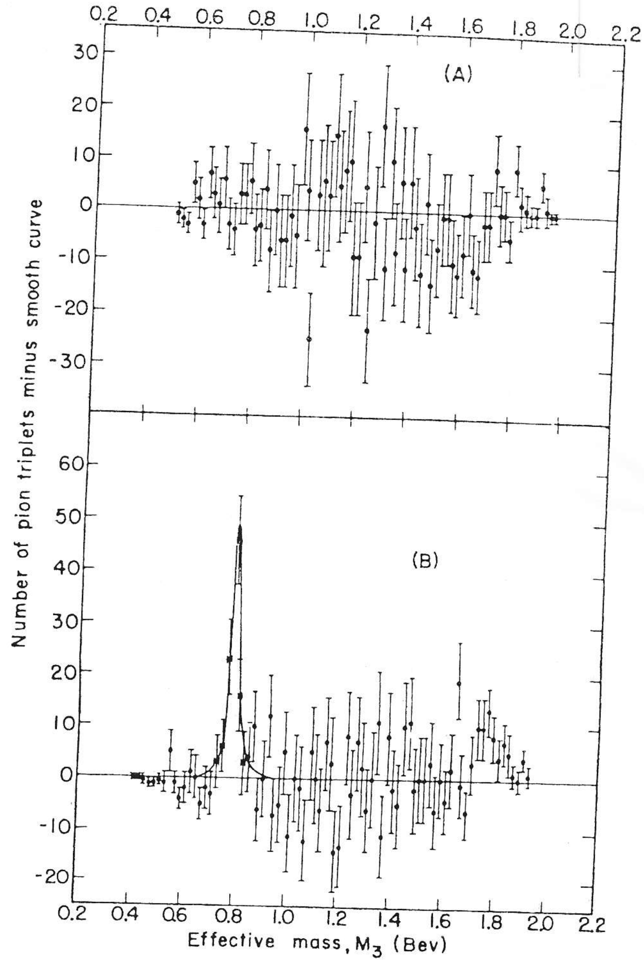


FIG. 2. (A) M_3 spectrum of the pion triplets in the combined distributions 1(A) and 1(B), with the smooth curve subtracted. (B) M_3 spectrum of the neutral pion triplets in distribution 1(C), again with the smooth background subtracted; a resonance curve is drawn through the peak at 787 Mev with $\Gamma/2 = 15$ Mev. The error flags are $\sqrt{N}$, where N is the total number of triplets per 20-Mev interval before subtraction of the smooth background curve.

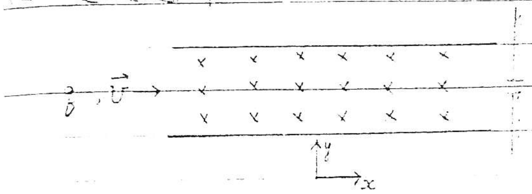
$$\bar{p} + p \to \pi^+ \pi^- \omega$$
$$\hookrightarrow \pi^+ \pi^- \pi^0$$

(2) Velocity Selector

Discovery of the electron

Mass Spectrometer

(2) 速度選擇器



$\vec{B}$ 是指向紙內，則 $\vec{B} = -B_0 \hat{k}$

若 $\vec{v}$ 是沿 x 方向，$\vec{v} = v\hat{i}$ 則該帶電質點所受之磁力

$$\vec{F}_{mag} = q\, v\hat{i} \times (-B_0 \hat{k}) = q v B_0 \hat{j} \qquad (27)$$

若我們同時再加一電場 $\vec{\varepsilon} = -\varepsilon_0 \hat{j}$，則速度為

$$v = \frac{\varepsilon_0}{B_0} \qquad (28)$$

之質點將不受外力而沿進行。也只有這些粒子才能通過以上的裝置。

THE MASS SPECTROMETER

This page describes how a mass spectrum is produced using a mass spectrometer.

How a mass spectrometer works

The basic principle

If something is moving and you subject it to a sideways force, instead of moving in a straight line, it will move in a curve - deflected out of its original path by the sideways force.

Suppose you had a cannonball travelling past you and you wanted to deflect it as it went by you. All you've got is a jet of water from a hose-pipe that you can squirt at it. Frankly, its not going to make a lot of difference! Because the cannonball is so heavy, it will hardly be deflected at all from its original course.

But suppose instead, you tried to deflect a table tennis ball travelling at the same speed as the cannonball using the same jet of water. Because this ball is so light, you will get a huge deflection.

The amount of deflection you will get for a given sideways force depends on the mass of the ball. If you knew the speed of the ball and the size of the force, you could calculate the mass of the ball if you knew what sort of curved path it was deflected through. The less the deflection, the heavier the ball.

Note: I'm not suggesting that you personally would have to do the calculation, although the maths isn't actually very difficult - certainly no more than A'level standard!

You can apply exactly the same principle to atomic sized particles.

An outline of what happens in a mass spectrometer

Atoms can be deflected by magnetic fields - provided the atom is first turned into an ion. Electrically charged particles are affected by a magnetic field although electrically neutral ones aren't.

The sequence is :

Stage 1: Ionisation

The atom is ionised by knocking one or more electrons off to give a positive ion. This is true even for things which you would normally expect to form negative ions (chlorine, for example) or never form ions at all (argon, for example). Mass spectrometers always work with positive ions.

Stage 2: Acceleration

The ions are accelerated so that they all have the same kinetic energy.

Stage 3: Deflection

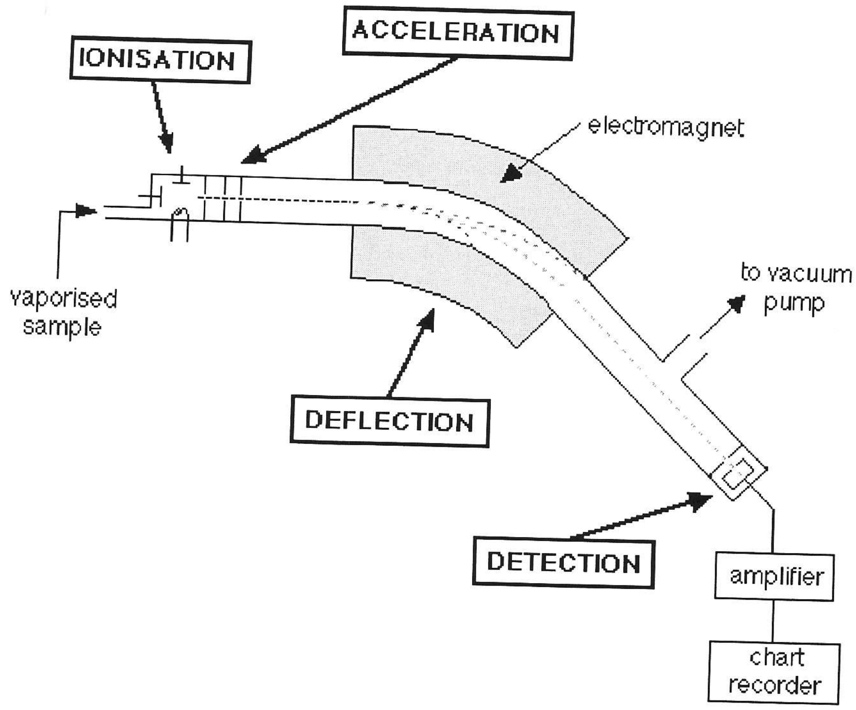
The ions are then deflected by a magnetic field according to their masses. The lighter they are, the more they are deflected.

The amount of deflection also depends on the number of positive charges on the ion - in other words, on how many electrons were knocked off in the first stage. The more the ion is charged, the more it gets deflected.

Stage 4: Detection

The beam of ions passing through the machine is detected electrically.

A full diagram of a mass spectrometer

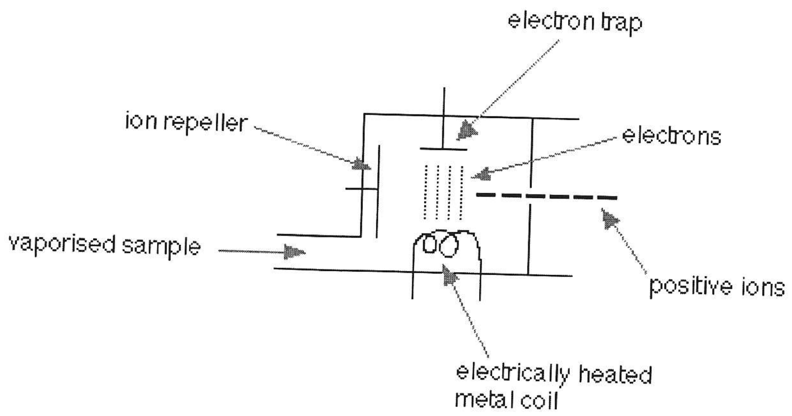


Understanding what's going on

The need for a vacuum

It's important that the ions produced in the ionisation chamber have a free run through the machine without hitting air molecules.

Ionisation



The vaporised sample passes into the ionisation chamber. The electrically heated metal coil gives off electrons which are attracted to the electron trap which is a positively charged plate.

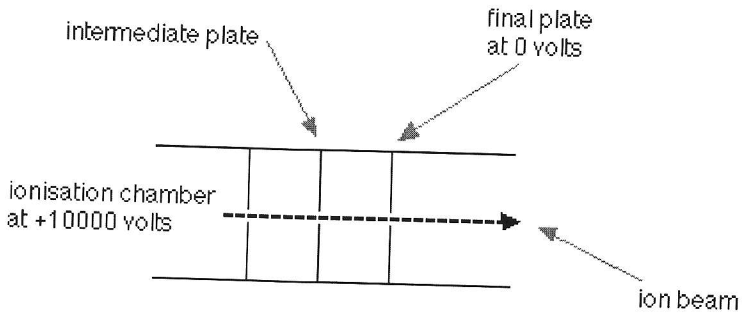
The particles in the sample (atoms or molecules) are therefore bombarded with a stream of electrons, and some of the collisions are energetic enough to knock one or more electrons out of the sample particles to make positive ions.

Most of the positive ions formed will carry a charge of +1 because it is much more difficult to remove further electrons from an already positive ion.

These positive ions are persuaded out into the rest of the machine by the ion repeller which is another metal plate carrying a slight positive charge.

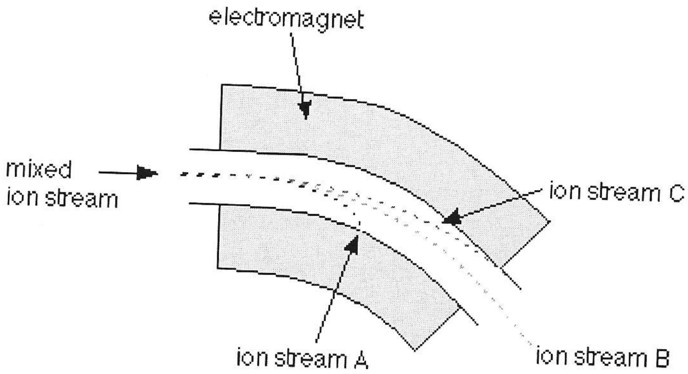
Note: As you will see in a moment, the whole ionisation chamber is held at a positive voltage of about 10,000 volts. Where we are talking about the two plates having positive charges, these charges are in addition to that 10,000 volts.

Acceleration



The positive ions are repelled away from the very positive ionisation chamber and pass through three slits, the final one of which is at 0 volts. The middle slit carries some intermediate voltage. All the ions are accelerated into a finely focused beam.

Deflection



Different ions are deflected by the magnetic field by different amounts. The amount of deflection depends on:

- the mass of the ion. Lighter ions are deflected more than heavier ones.
- the charge on the ion. Ions with 2 (or more) positive charges are deflected more than ones with only 1 positive charge.

These two factors are combined into the ***mass/charge ratio.*** Mass/charge ratio is given the symbol m/z (or sometimes m/e).

For example, if an ion had a mass of 28 and a charge of 1+, its mass/charge ratio would be 28. An ion with a mass of 56 and a charge of 2+ would also have a mass/charge ratio of 28.

In the last diagram, ion stream A is most deflected - it will contain ions with the smallest mass/charge ratio. Ion stream C is the least deflected - it contains ions with the greatest mass/charge ratio.

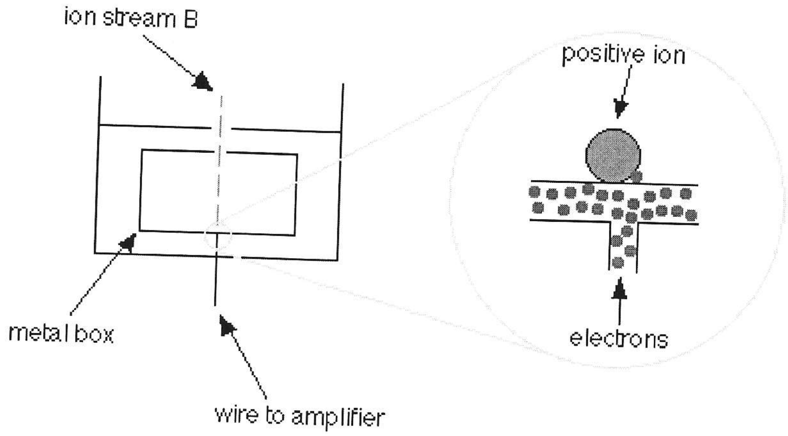
It makes it simpler to talk about this if we assume that the charge on all the ions is 1+. Most of the ions passing through the mass spectrometer will have a charge of 1+, so that the mass/charge ratio will be the same as the mass of the ion.

Note: You must be aware of the possibility of 2+ (etc) ions, but the vast majority of A'level questions will give you mass spectra which only involve 1+ ions. Unless there is some hint in the question, you can reasonably assume that the ions you are talking about will have a charge of 1+.

Assuming 1+ ions, stream A has the lightest ions, stream B the next lightest and stream C the heaviest. Lighter ions are going to be more deflected than heavy ones.

Detection

Only ion stream B makes it right through the machine to the ion detector. The other ions collide with the walls where they will pick up electrons and be neutralised. Eventually, they get removed from the mass spectrometer by the vacuum pump.



When an ion hits the metal box, its charge is neutralised by an electron jumping from the metal on to the ion (right hand diagram). That leaves a space amongst the electrons in the metal, and the electrons in the wire shuffle along to fill it.

A flow of electrons in the wire is detected as an electric current which can be amplified and recorded. The more ions arriving, the greater the current.

Detecting the other ions

How might the other ions be detected - those in streams A and C which have been lost in the machine?

Remember that stream A was most deflected - it has the smallest value of m/z (the lightest ions if the charge is 1+). To bring them on to the detector, you would need to deflect them less - by using a smaller magnetic field (a smaller sideways force).

To bring those with a larger m/z value (the heavier ions if the charge is +1) on to the detector you would have to deflect them more by using a larger magnetic field.

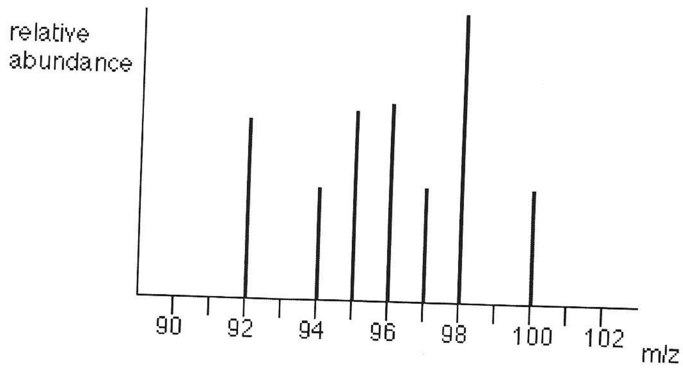
If you vary the magnetic field, you can bring each ion stream in turn on to the detector to produce a current which is proportional to the number of ions arriving. The mass of each ion being detected is related to the size of the magnetic field used to bring it on to the detector. The machine can be calibrated to record current (which is a measure of the number of ions) against m/z directly. The mass is measured on the ^{12}C scale.

Note: The ^{12}C scale is a scale on which the ^{12}C isotope weighs exactly 12 units.

What the mass spectrometer output looks like

The output from the chart recorder is usually simplified into a "stick diagram". This shows the relative current produced by ions of varying mass/charge ratio.

The stick diagram for molybdenum looks lilke this:



You may find diagrams in which the vertical axis is labelled as either "relative abundance" or "relative intensity". Whichever is used, it means the same thing. The vertical scale is related to the current received by the chart recorder - and so to the number of ions arriving at the detector: the greater the current, the more abundant the ion.

As you will see from the diagram, the commonest ion has a mass/charge ratio of 98. Other ions have mass/charge ratios of 92, 94, 95, 96, 97 and 100.

That means that molybdenum consists of 7 different isotopes. Assuming that the ions all have a charge of 1+, that means that the masses of the 7 isotopes on the carbon-12 scale are 92, 94, 95, 96, 97, 98 and 100.

Note: If there were also 2+ ions present, you would know because every one of the lines in the stick diagram would have another line at exactly half its m/z value (because, for example, 98/2 = 49). Those lines would be much less tall than the 1+ ion lines because the chances of forming 2+ ions are much less than forming 1+ ions.

If you want to go straight on to how you use these mass spectra to calculate relative atomic masses you can jump straight to that page by following this link rather than going via the menus below.

Where would you like to go now?

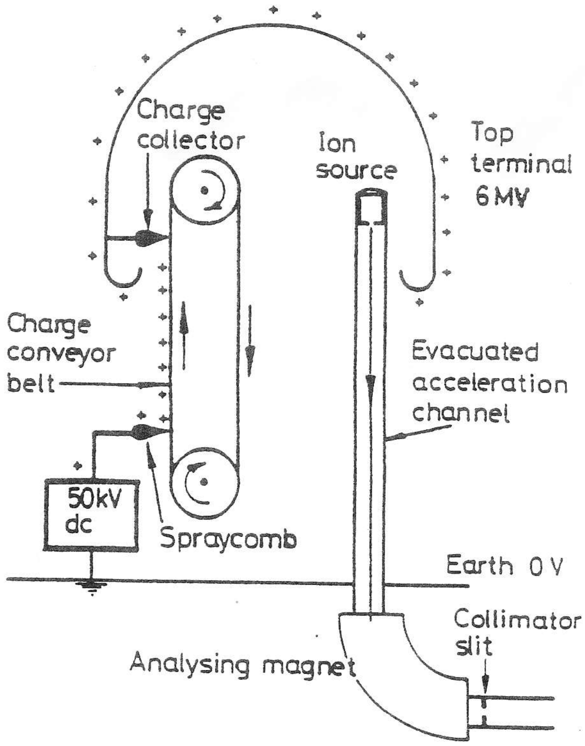
To the mass spectrometry menu . . .

To the instrumental analysis menu . . .

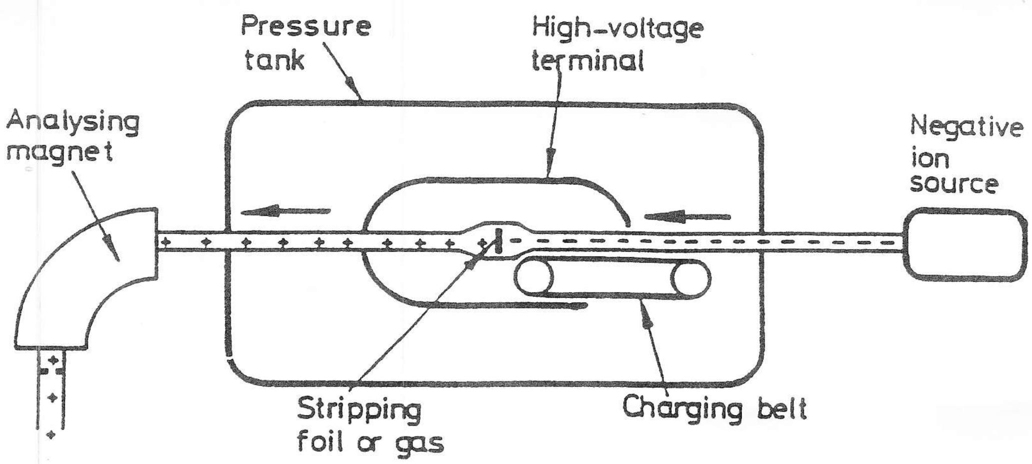
To Main Menu . . .

(3) 加速器

Van de Graaff electrostatic generator



Van de Graaff electrostatic generator



Two-stage Tandem accelerator

of cavities (in a linear machine), working typically in the MHz range. The underlying principle remains unchanged, but there are several variants of the accelerating structure design.

Ising's original idea can be considered as the beginning of the **'true' accelerator.** Indeed, the next generation of linear colliders, which will be in the TeV range, will probably still be applying his principle of resonant acceleration, except that the frequency will probably be in the tens of GHz range.

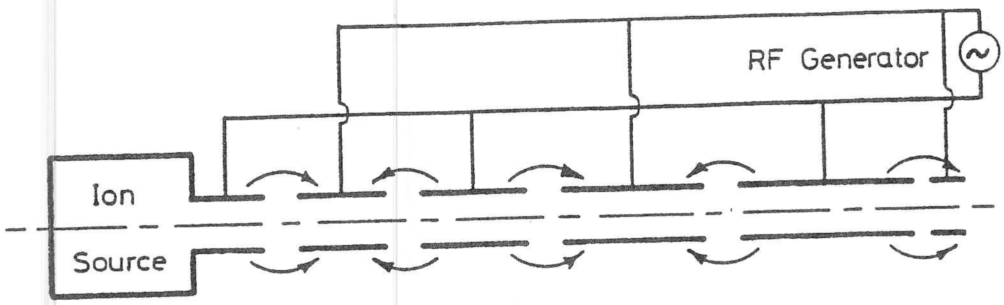


Fig. 4 RF linac

Technologically the linear accelerator, or **linac** as it is known, was rather difficult to build and, during the 1930's, it was pushed into the background by a simpler idea conceived by Ernest Lawrence in 1929 [6], the fixed-frequency cyclotron (see Fig. 5). Lawrence's idea was inspired by a written account of Wideröe's work and M. Livingston demonstrated the principle by accelerating hydrogen ions to 80 keV in 1931. Lawrence's first model worked in 1932 [7]. It was less than a foot in diameter and could accelerate protons to 1.25 MeV. He split the atom only weeks after Cockcroft and Walton. Lawrence received the Nobel Prize in 1939, and by that year the University of California had a 5-foot diameter cyclotron (the 'Crocker' cyclotron) capable of delivering 20 MeV protons, twice the energy of the most energetic alpha particles emitted from radioactive sources. The cyclotron, however, was limited in energy by relativistic effects and despite the development of the synchrocyclotron, a new idea was still required to reach yet higher energies in order to satisfy the curiosity of the particle physicists. This new idea was to be the **synchrotron**, which will be described later.

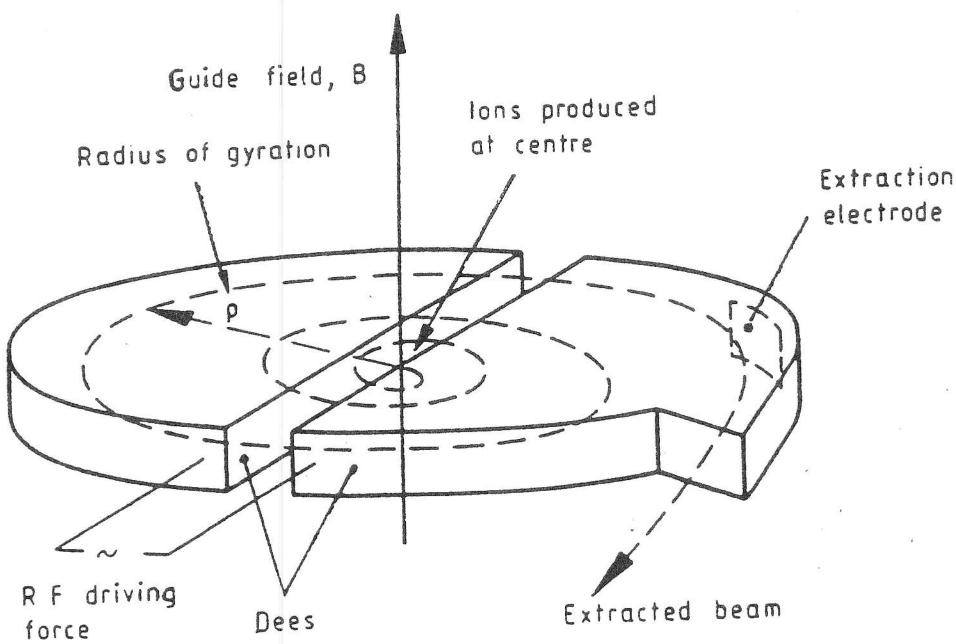
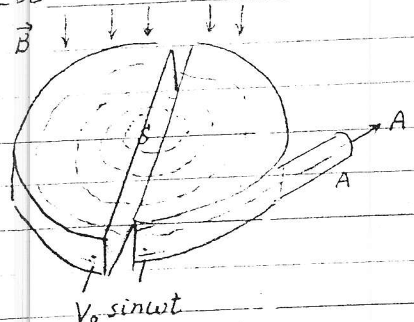


Fig. 5 Schematic cyclotron

(3) 迴旋加速器

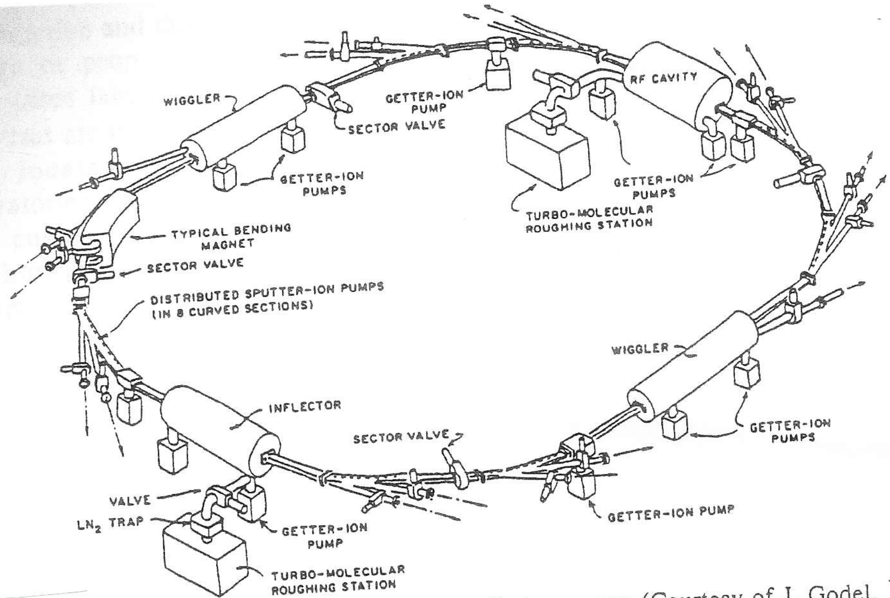


在兩個半圓之間利用交流電位差使粒子加速，並藉磁場使它作圓周運動。當其速度增加時由於 $r = \frac{mv}{qB}$ 而運動半徑，但其角速度 $\omega = \frac{q}{m}B$ 則保持不變所以 ω 稱為迴旋加速器頻率，當粒子到達極大半徑 R 時，其速度此時達到

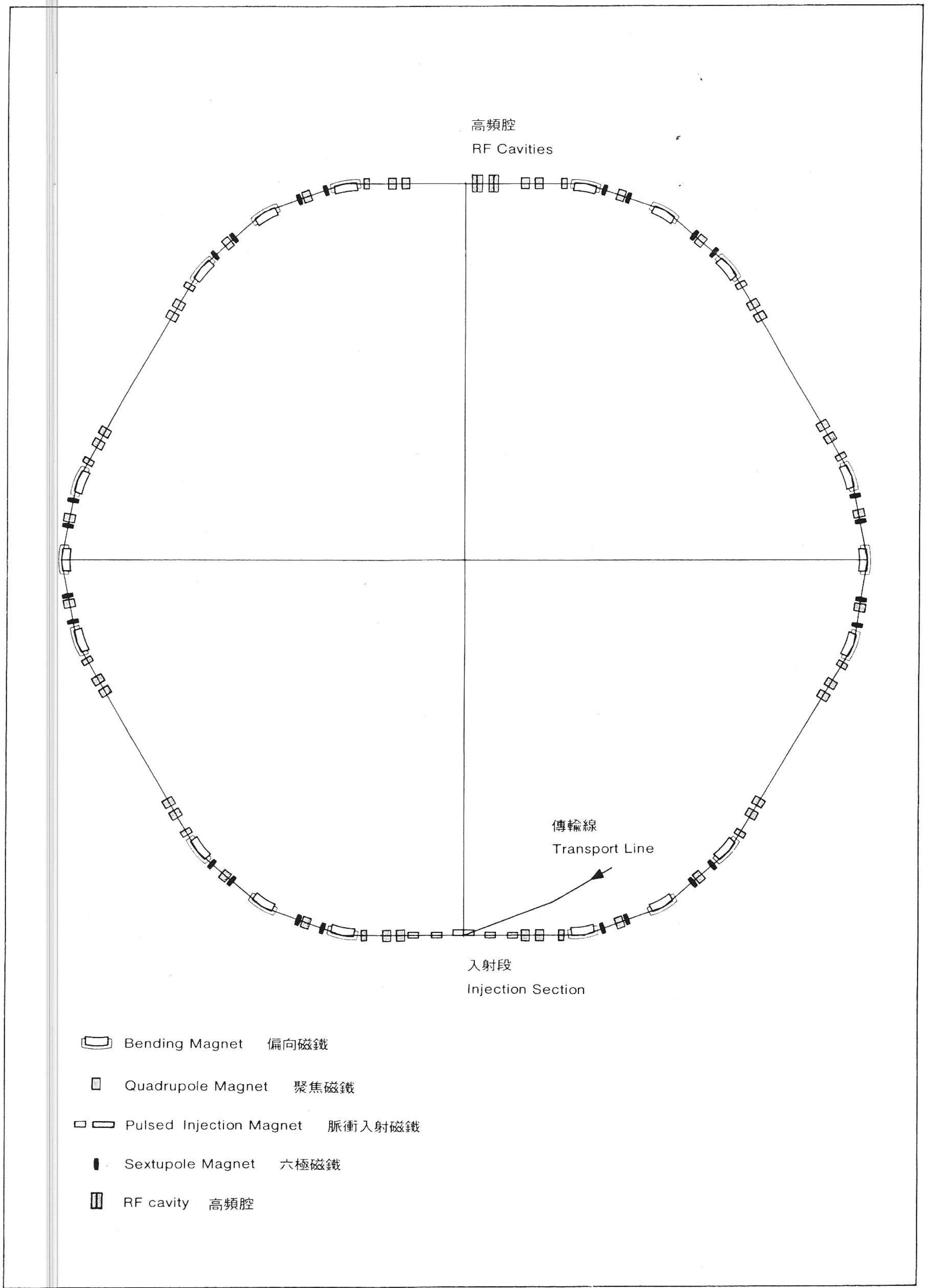
$$v_{max} = \frac{q}{m}BR \tag{29}$$

此時 B 之強度忽然減低，帶電質點沿切線方向經出口引出。此時它的動能

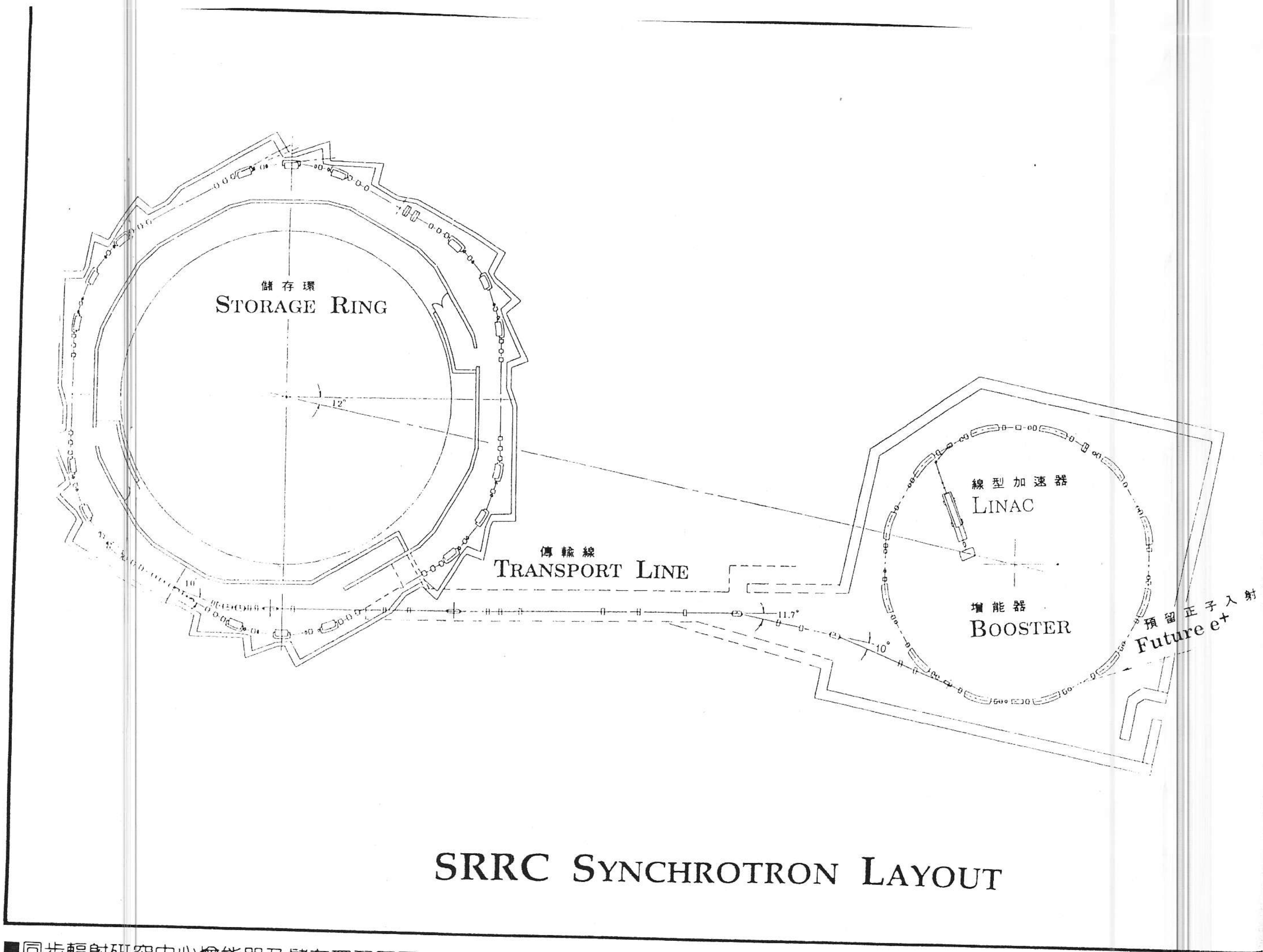
$$E_k = \frac{1}{2}mv_{max}^2 = \frac{1}{2}\left(\frac{q}{m}\right)B^2R^2 \tag{30}$$



Schematic of a small synchrotron radiation source (Courtesy of J. Godel, BNL).

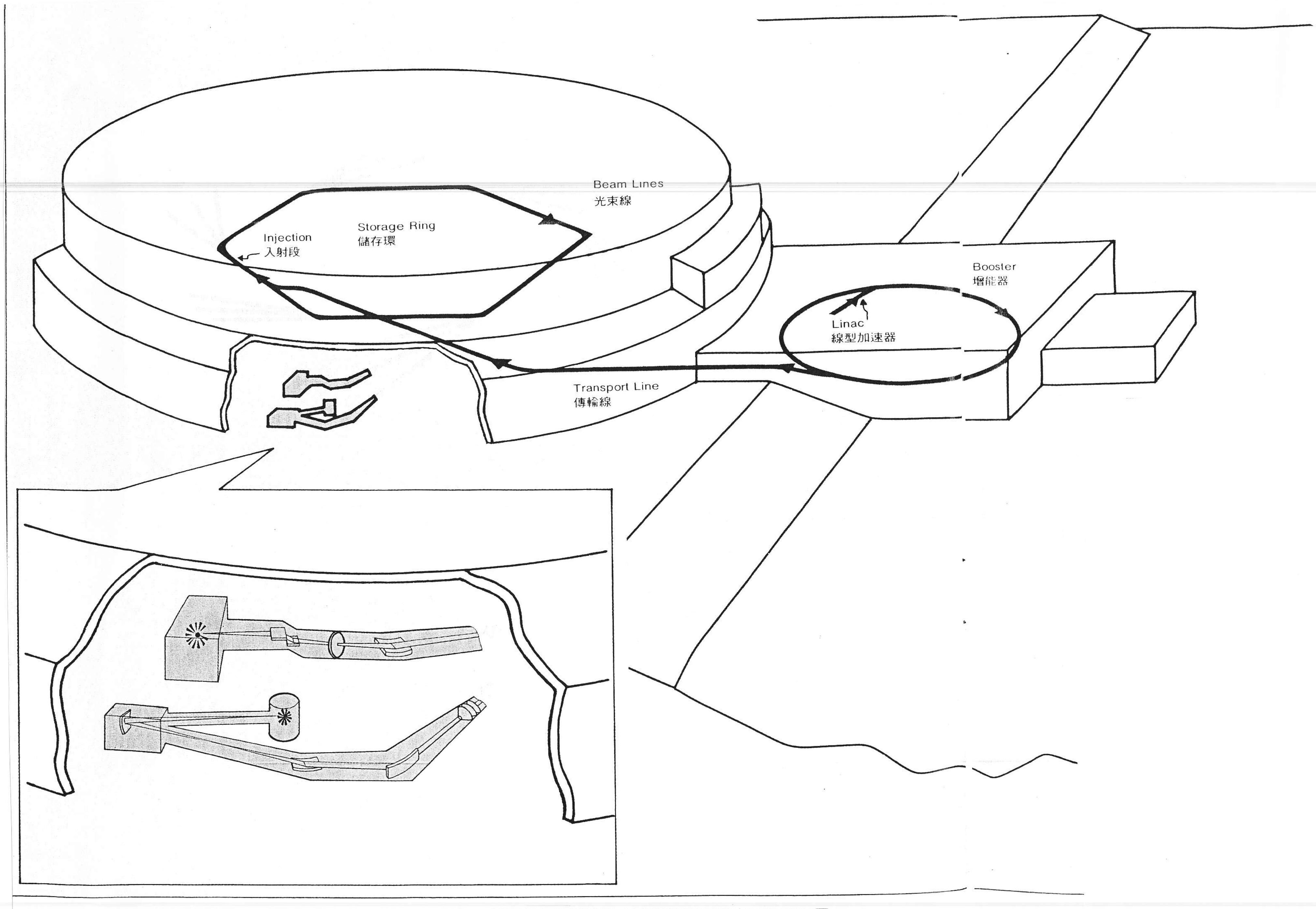


■儲存環上的主要元件。
（這是我國興建中的同步輻射研究中心儲存環磁格配置圖。）



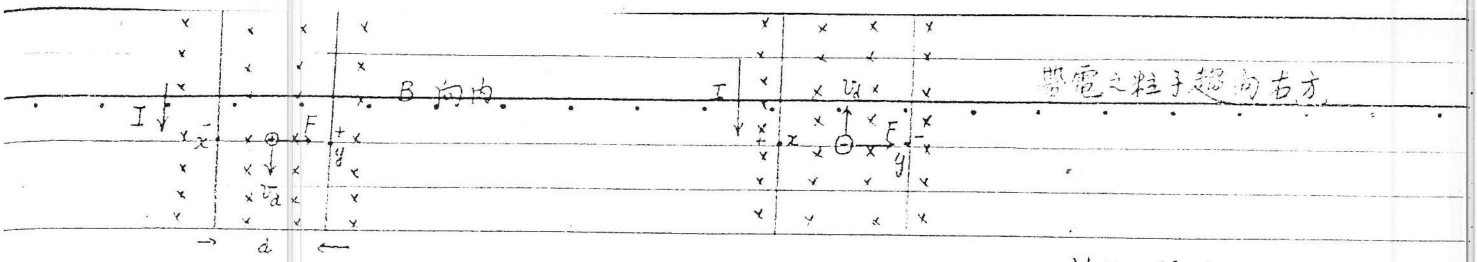
■同步輻射研究中心增能器及儲存環配置圖。

形狀	六邊形
周長	120 m
電子能量	1.3 GeV
射束電流	200 mA
儲存電子數	5×10^{11}
射束發射度(Emittance)	1.92×10^{-8} rad·m
長直段長度	6.0 m
磁格型別	Triple Bend Achromat (TBA)
迴轉頻率	2498.27 kHz
高頻頻率	499.654 MHz
諧振數	200
偏向磁鐵	
長度	1.22 m
半徑	3.495 m
磁場	1.24 T
數量	18
電子束縱向長度	0.74 cm
電子束橫向長度	
水平方向	145 µm
垂直方向	43 µm
眞空度需求	2.6×10^{-9} torr
光子臨界能量	1.39 keV
光子臨界波長	8.89Å



■同步輻射研究中心增能器館及儲存環館透視圖。

(4) Hall Effect



Hall effect

$V_x < V_y$ $V_x > V_y$

實驗顯示帶電体所帶之電荷是負。

但帶電之粒子不能不斷增加，因為趨向右方之帶電粒子在導体中產生一橫向霍爾電

$\mathcal{E}_H = V_{xy}/d$

當 $$q\vec{\mathcal{E}}_H + q\,\vec{v}_d \times \vec{B} = 0 \qquad (31)$$

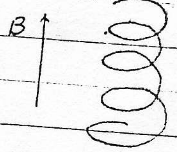
則可達到平衡。此時

$$\mathcal{E}_H = v_d B = \frac{j}{ne} B \qquad (32)$$

也即是 $$n = \frac{jB}{e\,\mathcal{E}_H} \qquad (33)$$

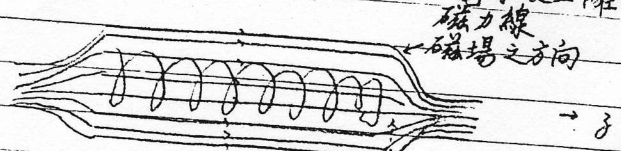
此處 n 是單位体積中帶電粒子數。

(5) 磁瓶及范艾倫帶



當帶電粒子速度小時，它將沿着螺旋線順着磁力線進行.

高温氣体游離而成由電子及正離子所構成之電漿



在端處 $\vec{B}$ 除了 B_z 方向外尚有徑向的分量，此一分量會使帶電粒子受 (−z) 向之加速度而使其在端處減速而最後反向進行，因此使電漿局限於一區域內。但有些粒子可由碰撞而逃逸。

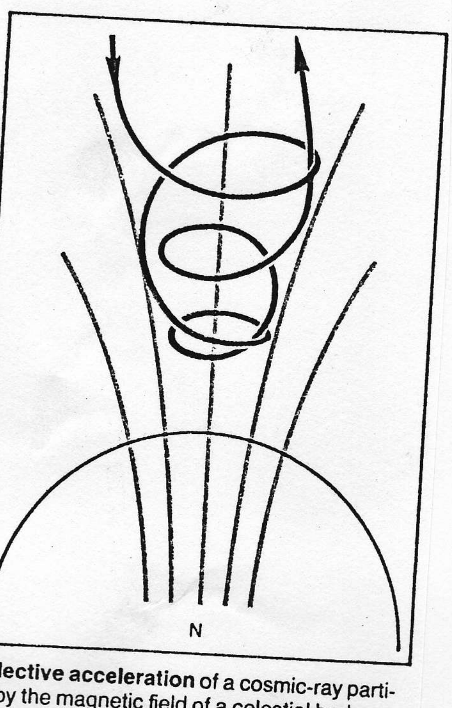
Explorer

由於地球可以看成一大磁鐵，因此帶電粒子被地球之磁力線捕獲而形成范艾倫帶。 1968 → 1958

inner 800 km–4000 km

outer 60,000 km

cosmic charged particle particles (e^-, p) interacting with the earth's magnetic field.



Collective acceleration of a cosmic-ray particle by the magnetic field of a celestial body, as proposed by Enrico Fermi. Figure 6