2025 가속기 여름학교
Introduction

(Part 2)

The beam travels within a vacuum chamber in the form of a tube with an internal aperture of (typically) a few centimetres.

The tube (beampipe) is bent in (roughly) the shape of a circle with a circumference that could be anything from a few hundred metres to several kilometres.

Particles are guided and focused using magnets placed at intervals around the ring.

Electrons lose energy by synchrotron radiation; to replace the lost energy, radiofrequency (RF) cavities are used to provide an electric field that accelerates the particles on each revolution.

The electric fields in the cavities oscillate at frequencies of (typically) a few hundred MHz with being synchronised with the revolution frequency of particles around the ring (roughly constant energy of a few hundred MeV $\sim$ many GeV for storage rings).

Understanding the principles of a synchrotron storage ring and much of the beam dynamics requires some knowledge of the magnets and the RF cavities.

- Main subsystem 1: The magnets, with their power supplies, cables, and cooling systems. (also girder system)

- Main subsystem 2: The RF cavities, with the RF power source, waveguides (for transporting the RF power to the cavities) and electronics for controlling the amplitude and frequency of the fields in the cavities. (sometimes cyrogenic system)

- Other subsystems: vacuum system, diagnostics, feedback systems, control system, injection system, and personnel protection system.

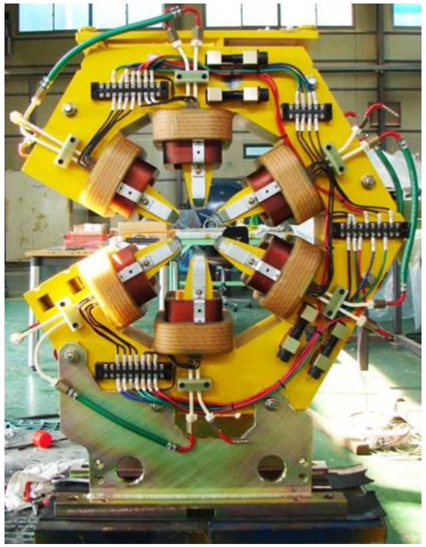
Dipole magnets produce a uniform vertical field (order of Tesla) that deflects the particles in the beam horizontally, so that the beam follows a defined path enclosed by the vacuum chamber.

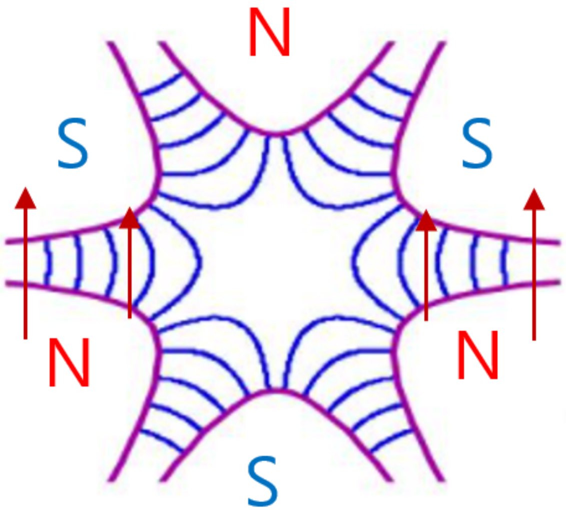
Quadrupole magnets produce a magnetic field that varies linearly with distance from a path through the centre of the magnet: this type of field acts as a ‘lens’, providing the means to focus and control the size of the beam.

Other kinds of magnet are used for more refined control over the beam properties: sextupole, octupole, corrector (a few hundred Gauss), skew-quadrupole magnets etc.

Chromaticity: Particles in the beam will have some (small) variation in energy, with the result that the focal length in a given quadrupole magnet will be different for different particles (tune change/instability).

Sextupole magnets can compensate it, in which the field varies as the square of the distance from a line through the centre of the magnet (sometimes they are combined with correctors and skew-quads).





Most of the magnets in a storage ring will provide static fields; that is, the fields will be constant in time. Also, within the vacuum chamber, the current density (neglecting the beam itself) will be zero.

$$\nabla \cdot \vec{B} = 0, \text{ and } \nabla \times \vec{B} = 0. \tag{1}$$

In 2D, these equations are satisfied by fields with Cartesian components:

$$B_x = C_n r^n \sin(n\theta), \quad B_y = C_n r^n \cos(n\theta), \quad B_z = 0, \tag{2}$$

where $C_n = |C_n| \exp(i\varphi_n)$ is a (generally complex) constant. Fields that can be expressed in the above are known as multipole fields.

A field with $n = 0$ is a dipole field, $n = 1$ gives a quadrupole field, $n = 2$ a sextupole field, and so on. Be careful! Index convention (mostly n from 0 in US vs. n from 1 in Europe) differs by authors and textbooks.

In terms of Cartesian co-ordinates, a general multipole field (with arbitrary n) is most easily expressed using complex notation:

$$B_y + iB_x = C_n r^n e^{in\theta} = C_n(x+iy)^n, \quad B_z = 0. \tag{3}$$

- In a dipole, $B_x = 0$ and $B_y = C_0$.
- In a quadruple, $B_x = C_1 y$ and $B_y = C_1 x$.
- In a sextupole, $B_x = 2C_2 xy$ and $B_y = C_2(x^2 - y^2)$.

Here, we assume real valued coefficients C_n (i.e., $\varphi_n = 0, \pi$), and these fields are known as normal multipoles.

A rotation of the field (about the z-axis) through an angle $\frac{\pi}{2(n+1)}$ gives a skew multipole, with the relevant coefficient C_n having a pure imaginary value (i.e., $\varphi_n = \pm\pi/2$). A skew dipole deflects a beam vertically. A skew quadrupole allows control over coupling in the beam.

Field strengths in accelerator magnets can vary quite widely:

- Depending on whether the conductors in an electromagnet are normal- or super-conducting.
- Depending on the type of material used in a permanent magnet.

Normal-conducting electromagnets are perhaps the most widely used type of magnet in electron storage rings:

- Dipole magnets of this type typically achieve field strengths of order 1 T.
- Quadrupole magnets can achieve around 0.8 T at the aperture limit set by the pole tips.

$$\frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x} = C_1 = B' \approx \frac{B_{\text{tip}}}{a_{\text{tip}}} \tag{4}$$

The advantage of electromagnets is that the field strength can be readily adjusted by controlling the flow of current through the coils of the magnet: although the field strengths in the magnets will be fixed during operation, commissioning and tuning a storage ring generally requires some adjustments to be made to the magnet strengths.

The drawback of electromagnets is that high currents (several tens or hundreds of amperes) are usually needed to achieve the specified field strengths, so that providing the power, and cooling the magnets, can be an issue.

Superconducting magnets are able to provide significantly higher field strengths than normal-conducting magnets; however, the additional cost and complexity associated with the cryogenics system are needed.

Although magnets with adjustable field strength can be constructed using permanent magnetic materials, the mechanisms needed to provide the adjustment for such magnets are not straightforward.

The magnets in a storage ring will usually be constructed so that one particular multipole component is dominant; in the ideal case

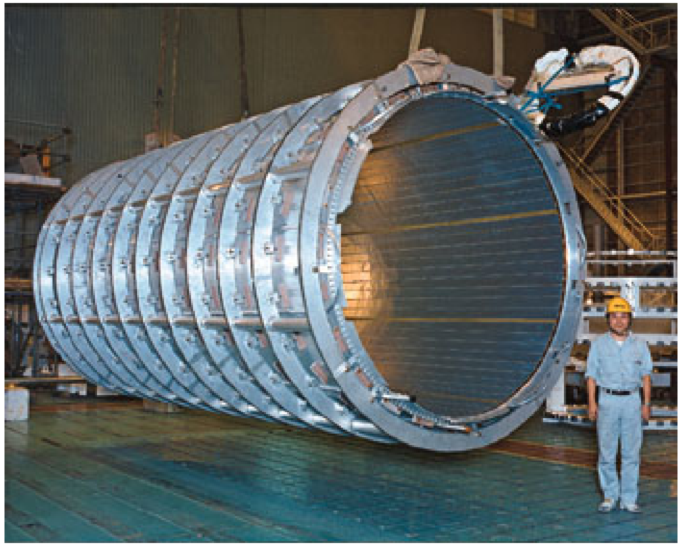
- The steering magnets (used to control the beam trajectory) will be ‘pure’ dipoles.
- The focusing magnets (used to control the size of the beam) will be ‘pure’ quadrupoles.

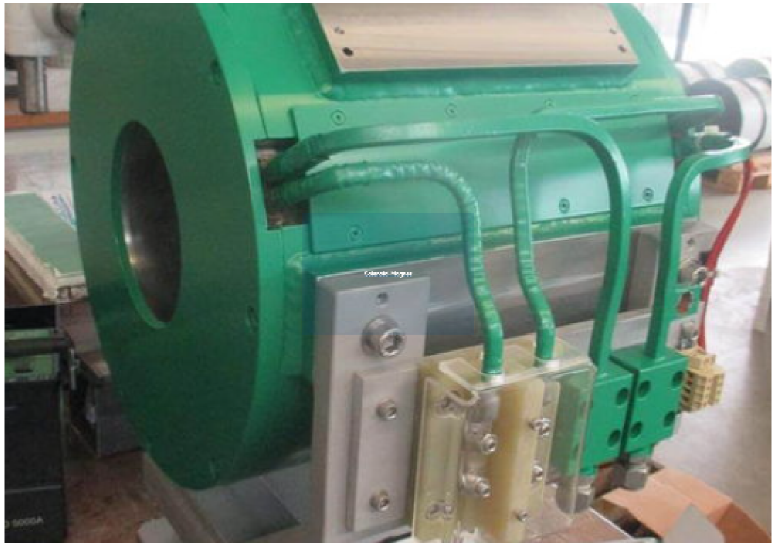
In practice, the field in any multipole magnet will contain components from all multipole orders, though one specific order will usually be very much larger than the others.

In some cases, the steering magnets will be designed to control both the beam trajectory and the size of the beam: magnets in this case will contain both dipole and quadrupole components of significant strength (combined function magnet).

Magnets other than multipole magnets are used in storage rings for particular purposes. For example,

- Strong solenoid fields are often used around the detector in a collider and low-energy injectors.





- Insertion devices (IDs) consisting of sequences of (short) dipole magnets of alternating polarity are used in light sources to enhance the production of synchrotron radiation

A radiofrequency (RF) cavity contains an oscillating EM field, with a dominant electric field component parallel to the trajectory of the beam as it passes through the cavity.

The energy gain of a particle of charge q as it passes through the cavity is

$$qV_0 \cos(\phi), \quad \text{어떤 책에서는} \quad qV_0 \sin(\phi), \tag{5}$$

where V_0 is the peak voltage across the cavity, and the particle arrives at a phase ϕ of the field oscillation.

Although the energy lost in a single turn of the ring is usually only a small fraction of the energy of a particle, several cavities with peak voltages of the order of a MV or more are usually needed to maintain a beam in an electron storage ring operating with beam energy of a few GeV. The maximum voltage that can be achieved in a cavity is limited by the point at which electrons (in material) are stripped from the inner surface of the cavity, leading to field breakdown.

The oscillation frequency of the field in the RF cavities must be matched to the revolution frequency of particles in the ring: this is the basic principle behind operation of a synchrotron (the magnetic fields and RF frequency are often ramped simultaneously).

A small change in the RF frequency will lead to a change in the beam energy, which will in turn change the revolution frequency.

The dependence of the revolution frequency (or period T) on the particle energy is characterised by the phase slip factor of the ring (see section 2.7)

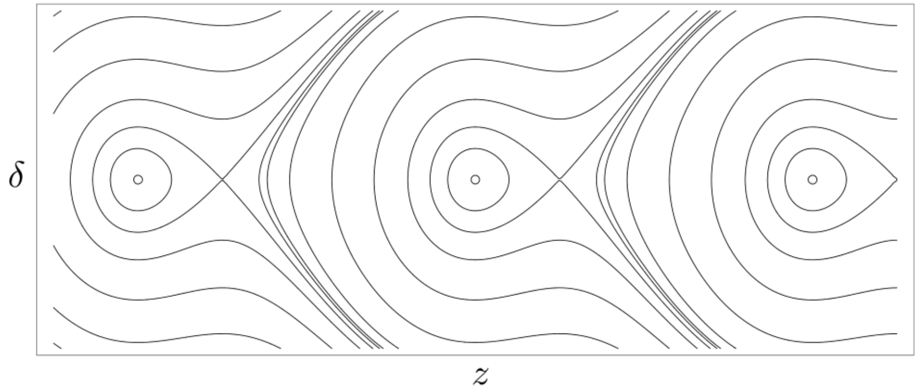
$$\eta_p = \frac{1}{T_0}\frac{dT}{d\delta}, \tag{6}$$

which allows stable operation of a storage ring even if the RF frequency is not set perfectly (phase stability).

The phase of the RF field oscillation at which the voltage across the cavity exactly matches the energy lost by a particle to synchrotron radiation is known as the synchronous phase.

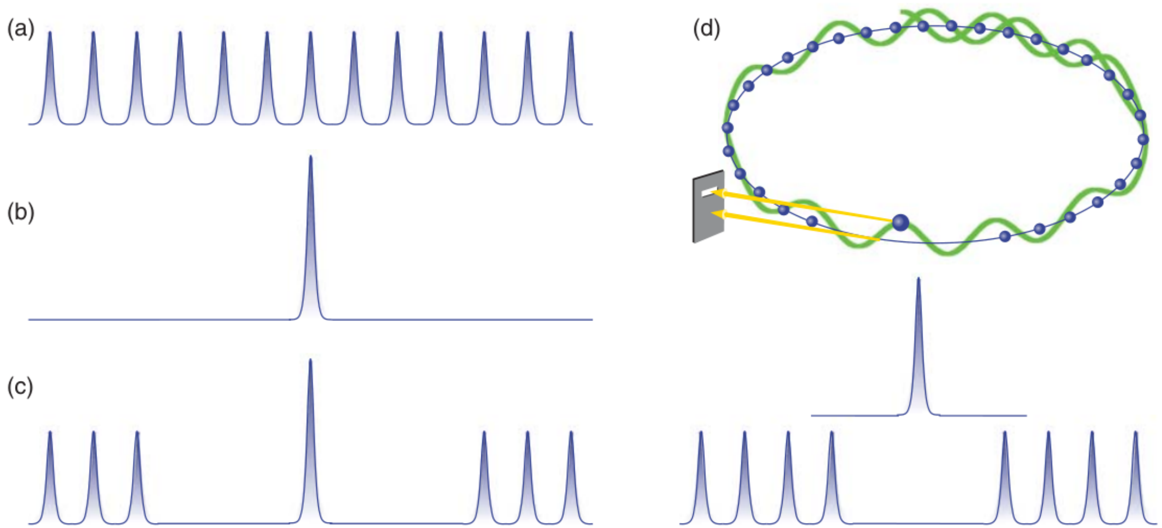
If particles arrive at a phase slightly ahead of, or behind, the synchronous phase, then their motion around the ring can remain stable, through the mechanism of phase stability (see section 2.8).

However, there are limits (longitudinal acceptance ∼ RF bucket ∼ separatrix) on the maximum distance from the synchronous phase for which stable motion can be maintained (figure below: head is right, above transition, CCW phase rotation). Particles arriving too far from the synchronous phase will be lost.



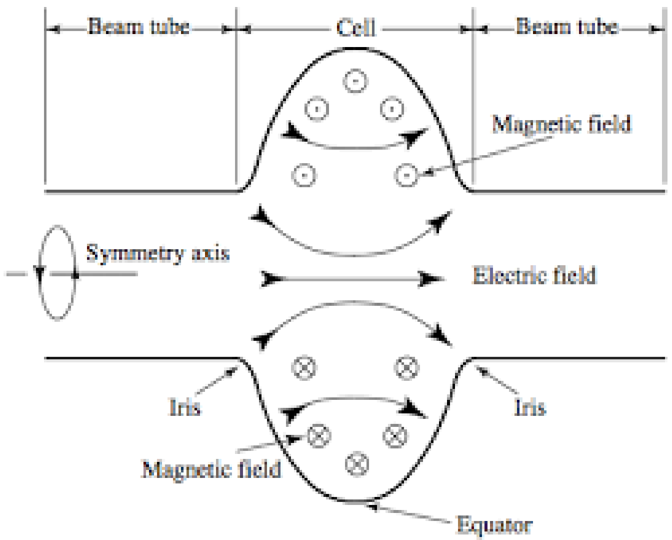
As a result, the beam in an electron storage ring will consist of bunches of particles, separated by gaps with length corresponding to the RF oscillation period. Number of available bunch in a ring is called the harmonic number (h = Revolution period / RF period).

Typically, a bunch in a storage ring will be of order 10 ps (a few millimetres) in length, and the gaps between bunches will be of order 2 ns (about two-thirds of a metre), corresponding to an RF frequency of 500 MHz.



The oscillating electric field will induce a magnetic field in the cavity; in a simple cavity with a geometry that is approximately cylindrical (pillbox), the electric field will be parallel to the axis of the cylinder, and the magnetic field lines will form circular loops centred on the axis.

The longitudinal electric field accelerates particles passing through the cavity (fundamental mode). The magnetic field can deflect particles passing through the cavity, and since the strength of the magnetic field increases with distance from the axis, this can lead to focusing effects.



The fundamental mode is driven by EM fields generated by the RF power supply (such as a klystron, or a solid-state amplifier) and fed into the cavity through a waveguide and RF coupler.

In addition to the fundamental mode, the fields in an RF cavity can occur in higher-order modes (HOMs) in which the fields oscillate at higher frequencies, and form different patterns within the cavity.

The HOMs can be driven by the EM fields around the particles in the beam as they travel through the cavity. In some circumstances, the HOMs can reach amplitudes large enough that particle trajectories are deflected by an amount large enough for the beam to become unstable (see chapter 5).

The cavity modes (the fundamental mode, as well as the HOMs) occur at discrete frequencies and with field patterns determined by the boundary conditions set by the shape of the cavity.

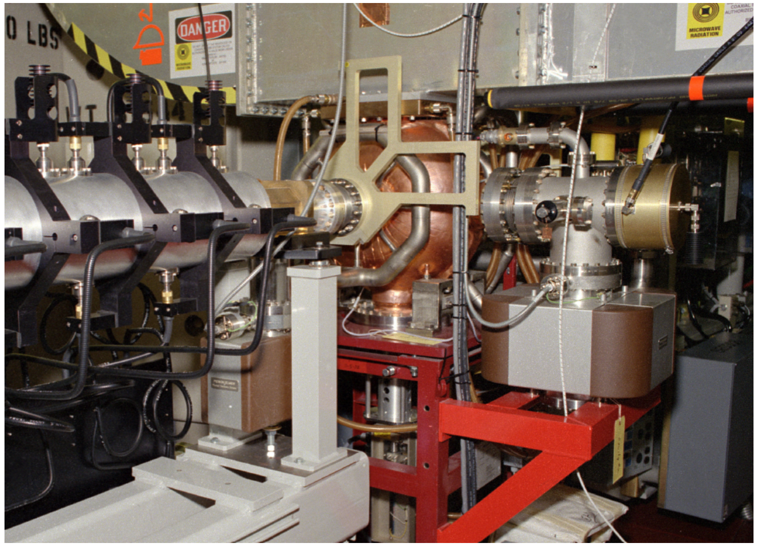
If the frequencies of any of the HOMs coincide with frequencies present in the beam current spectrum, then resonances can occur in which the HOMs are driven to large amplitudes.

An important step in the design of a storage ring is the optimisation of the design of the RF cavities, to avoid as far as possible any overlap between the cavity mode spectrum and the beam current spectrum.

Nevertheless, the parameter regimes specified for modern electron storage rings can be extremely challenging, and feedback systems (as outlined below, in section 1.2.3) are often needed to maintain beam stability.

To minimise the dissipation of RF power in the walls of the cavity, RF cavities must be made from materials with a good electrical conductivity. The material must also have appropriate mechanical and thermal properties to allow easy fabrication and stable operation.

For cavities designed to operate at room temperature, copper is a common choice.



However, at high field strengths, the amount of power dissipated in the walls of the cavity through induced electrical currents can be considerable, and it is usually necessary to provide cooling, by means of water flowing through pipes or channels fitted around the cavity.

Some electron storage rings use superconducting (SC) RF cavities, which have the advantage of achieving relatively low power dissipation because of the extremely high conductivity of SC materials (although the DC resistivity of a superconductor is zero, oscillating currents are associated with some energy dissipation).

The rate of decay of an oscillating EM field in a SC cavity can be slower by several orders of magnitude than the rate of decay in a comparable normal conducting cavity (higher quality factor Q).

The drawback with SC cavities is that it is necessary to operate below the critical temperature for the material from which the cavity is made. Although high-temperature SC materials do exist, their mechanical properties make them unsuitable for the fabrication of RF cavities. Most SCRF cavities are made from niobium, which has a critical temperature of 9.2 K.

However, the operating temperature needs to be significantly lower than this (typically around 4.5 K, using liquid helium bath or cryocooler-assisted helium systems) so that the cavity remains superconducting in the presence of the strong magnetic fields that are inherent in the function of the cavity.

The need for a cryogenic system, which brings additional cost and complexity to the RF system, often outweighs the benefits of SC technology: the choice between copper and niobium cavities is not a straightforward one.

It is important that the beam trajectory (i.e. the orbit) is tightly controlled in a light source so that the synchrotron radiation are directed accurately through the radiation beamlines to the experimental stations.

Small changes in orbit can occur from a number of causes over different timescales:

- Electrical noise on the magnet power supplies
- Mechanical vibrations from pumps or other equipment
- Temperature variations causing magnet supports to deform

The first step is to minimise the environmental effects: magnet power supplies need to be of high quality (low noise), pumps should be mounted on supports that provide mechanical isolation from any vibration, magnet supports should be designed to minimise sensitivity to temperature variations, and the temperature in the tunnel should be kept stable (in practice, often to a fraction of 1 °C).

The orbit is measured using a set of beam position monitors (BPMs) distributed around the ring, and can be adjusted using small dipole (corrector) magnets.

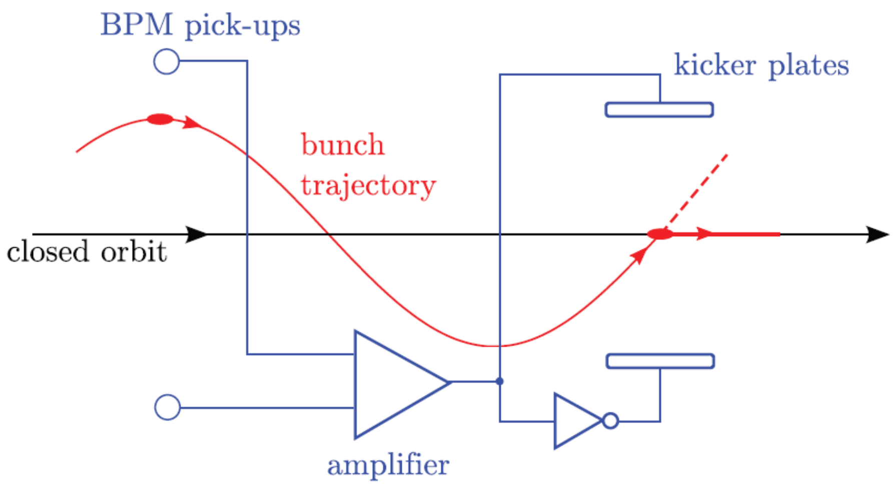
Calculating the appropriate correction to be applied by a feedback system from a set of measurements is not always a straightforward process.

- The way that the orbit responds to given changes in strength of the steering magnets depends on the strengths of all the other magnets in the storage ring. If the strengths of these magnets change slightly, then the orbit may respond in an unexpected way to changes in the steering magnets.
- The same consequences can result if the signals from the BPMs are noisy, so that the correction applied by the feedback system is based on inaccurate data.

Timescale on which a feedback system may need to operate:

In the case of an orbit feedback system, orbit changes in response to ground motion or temperature variations may be on the timescale of minutes, hours or days: such timescales do not pose significant problems for modern feedback systems.

However, electrical noise may cause oscillations in beam position with frequencies of the order of hundreds of Hz, or several kHz. Collecting data from a large number (maybe dozens) of BPMs, then calculating and applying a correction within a few ms can be very challenging.



In a storage ring, beam instabilities driven by wake fields (EM fields within the beam pipe generated by the beam itself) can occur on the timescale of a few μs ($\gtrsim$ revolution period).

It is possible, using specialised fast feedback systems, allowing storage rings to operate in parameter regimes that would otherwise be inaccessible. Fast (bunch-by-bunch) feedback systems for suppressing beam instabilities require enough bandwidth, gain, and power.

Because the signal cannot be transmitted faster than the speed of light, the kick (e.g., by stripline) is applied one or more turns after the signal from the pick-up is detected (and over several turns).

Other feedback systems:

- To maintain beam optics parameters (such as the betatron tunes), the beam energy and intensity.

- (within technical subsystems) To maintain the stability of the current from a magnet power supply, or to improve the stability of the frequency and amplitude of the fields in an RF cavity.

Particles in the beam may collide with gas molecules, leading to a loss of beam current.

Gas molecules may become ionised by collisions, and the resulting positive ions can be 'trapped' in the negative electrical potential around a beam of electrons. Interactions (sort of two-stream effects) between the electrons and the ions can then cause the beam to become unstable: ion trapping (long term) and fast ion (short term) effects.

In positron storage rings, electrons from the ionisation of gas molecules can collide with the walls of the beam pipe, releasing additional electrons. Under some circumstances, the density of electrons (the electron cloud) can build up to the point where the beam becomes unstable.

In colliders, scattering of particles in the beam from gas molecules in the vicinity of the interaction region can lead to backgrounds in the detector.

$$1 \text{ atm} = 760 \text{ Torr} = 760 \text{ mmHg} = 1013 \text{ mb} = 1013 \times 100 \text{ Pa} \quad (7)$$

The pressure in the vacuum chamber of an electron storage ring is typically specified to be of order 1 nTorr, or roughly 10^{-12} times atmospheric pressure.

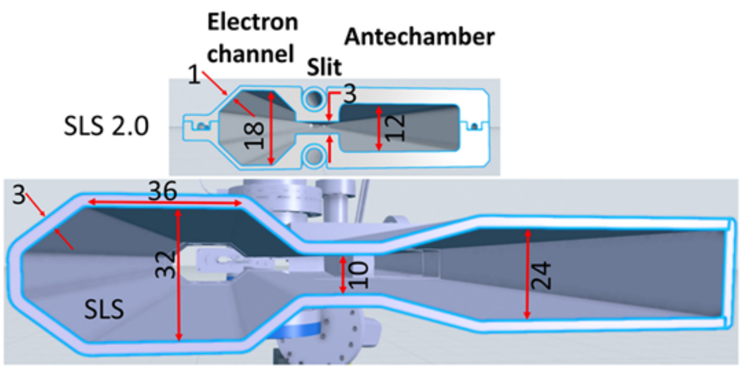
At this pressure, the beam lifetime (the time taken for the beam current to fall by a given factor) is likely to be dominated not by gas scattering, but by other effects, in particular Touschek scattering.

In practice, the pressure in a storage ring can vary considerably depending on the location around the ring and the operational conditions.

When an electron beam is present, synchrotron radiation falling on the walls of the vacuum chamber can release gas molecules through photodesorption, leading to a significant increase in the local pressure.

In a light source, there can still be considerable amounts of radiation, for example from dipoles, remaining within the beam pipe (reflecting multiple times).

A common technique is to shape the vacuum chamber so that it has a slot running along one side that opens into an 'antechamber' (대기실, 입구방). The slot allows radiation to pass out of the main chamber, but since it has a lower conductance than the main chamber for the flow of gas, it is possible to maintain a lower pressure.



The specified pressure is usually only achieved after a long period (maybe some weeks or months) of pumping and conditioning.

Different types of pumps (and pressure gauges) are needed to cover the range of pressures, environments, and species in the residual gas.

Turbo-molecular pumps (TMPs) can operate from atmospheric pressure to below 0.01 nTorr, and can pump any kind of gas molecule. However, the pumping is localised. (not typically the primary pumps during operation, but for initial pump-down / bake-out).

Titanium sublimation pumps (TSPs) can achieve high pumping speed at relatively low cost, and can be implemented to provide ‘distributed’ pumping, i.e. operating to pump long sections of the beam pipe. However, TSPs will not pump molecules of inert gases. (newer facilities rely more on NEG coating and ion pumps).

The outgassing rates from materials used in an accelerator beam pipe should be low enough to allow the specified pressure to be maintained without excessive numbers of pumps.

The chamber walls should have good electrical conductivity to minimise the electromagnetic fields generated by particles in the beam as they travel through the chamber (in particular, to minimise resistive-wall wake fields).

The material should have good mechanical properties to allow the different parts of the chamber to be fabricated easily.

Finally, the chamber should be able to withstand heating by a couple of hundred degrees, which may be required to condition the chamber or to activate certain types of coating, in particular, non-evaporable getter (NEG) coatings.

Aluminium is a common choice of material for the vacuum chambers of electron storage rings (recently more copper for heat dissipation and to limit resistive wakefields).

Some of the properties of aluminium are not ideal; for example, it can lose mechanical strength when heated to the temperatures need to activate NEG coatings.

Nevertheless, aluminium can meet many of the requirements for the vacuum chamber in an electron storage ring, at a reasonable cost.

[Note] In positron storage rings, it may be necessary to choose a material with a low probability of releasing electrons, either from photoemission or from the incidence of primary electrons or ions, to avoid the build-up of an electron cloud.

[Geometry]

- The aperture should be large enough to accommodate the beam, allowing for particles performing transverse oscillations of large amplitude, or with significant energy errors. Steering errors and processes occurring during injection can also lead to large deviations of the beam trajectory from the ideal orbit. From point of view of the vacuum, a large aperture helps to achieve a good gas conductance through the chamber.

- The chamber should be designed to allow as much synchrotron radiation as possible to leave the main chamber without striking the walls; the impact of synchrotron radiation on the walls of a vacuum chamber can lead to photodesorption, or to local heating. The operation of some beam diagnostic devices can be affected by synchrotron radiation, and may need to be shielded in some way. In a light source, extraction ports are necessary to allow the radiation to exit the ring towards experimental areas.

- The chamber needs to allow some flexibility for changes in position or length in different sections, in response to the motion of components attached to the chamber or to changes in temperature. Some components fixed to the chamber (e.g., BPMs) also need to be isolated as far as possible from vibrations or other mechanical motion that may be transmitted along the chamber. Flexibility and a certain amount of mechanical isolation can be provided by 'bellows'.

- The geometry of the inside of the chamber needs to be as smooth as possible, avoiding gaps or sudden changes between different apertures or cross-sections. This is because abrupt transitions can trap EM fields generated by particles in the beam, leading either to localised heating as the energy of the fields is dissipated in the walls of the chamber, or to wake fields that act back on the beam potentially causing beam instabilities.

The requirements on the chamber geometry are often in conflict; for example, it can be difficult to provide ports for vacuum pumps or for extracting synchrotron radiation while maintaining the 'smoothness' necessary to minimise wake fields.

Bellows also tend to be associated with cavities that can lead to strong wake fields. The solution is often to provide some 'RF shielding' using strips of metal arranged to present a smooth, unbroken screen to EM fields oscillating at microwave (and lower) frequencies, while allowing the relevant components (vacuum pumps, bellows, etc) to perform their appropriate function.

Optimising the design of a vacuum chamber can be a complex, iterative task involving modelling the vacuum, mechanical, and electromagnetic properties.

Self study.

Self study.

The simplest system conceptually is 'single-turn' injection, in which a dipole magnet is located at the point where the trajectory of an incoming bunch crosses the closed orbit.

Under normal circumstances, this dipole magnet is turned off, so that it does not deflect bunches that are already on the closed orbit. However, during injection the dipole is turned on, so that an incoming bunch, initially travelling at some angle to the closed orbit, is deflected so that it follows the closed orbit on leaving the dipole.

It is then necessary to switch off the dipole before another bunch already on the closed orbit arrives, otherwise this bunch will be deflected out of the storage ring.

This scheme requires a dipole magnet that can be turned on and off very quickly: a magnet of this type is often called a kicker magnet.

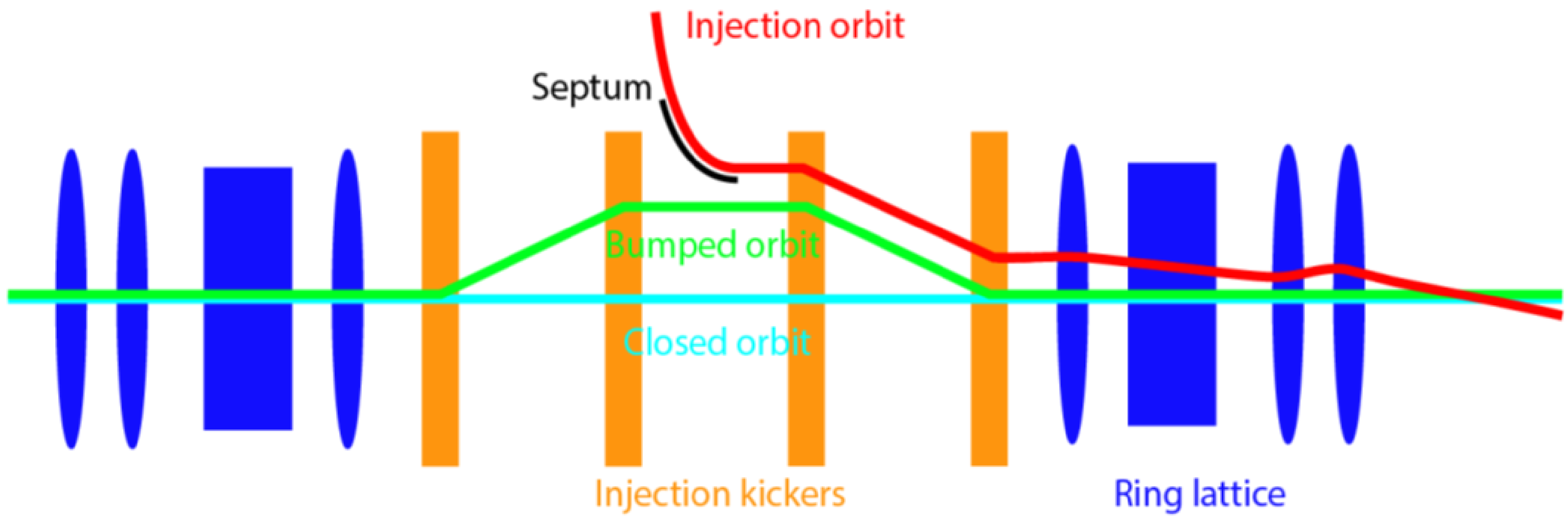
Even with a fast kicker magnet, single-turn injection usually means leaving a gap in the train of bunches long enough for the field in the kicker to be turned on and off.

A gap in the bunch train in an electron storage ring may be needed in any case, to avoid ion trapping (see section 5.2).

However, another problem with single-turn injection is that the source must be capable of delivering in a single pulse a train of bunches each with the full charge specified for each bunch in the storage ring (0.2–2 nC per bunch for multi-bunch mode, 1–10 nC per bunch for single-bunch mode).

This can place severe demands on the particle source.

An alternative injection scheme involves filling the storage ring over several turns, merging additional charge with the charge already in the storage ring. This can be accomplished using a septum magnet.



A septum magnet consists of a dipole magnet with two apertures separated by a narrow plate, or 'blade'. By passing an electric current through the blade, it is possible to arrange for the dipole field to appear only in one of the apertures. In the aperture on the other side of the blade, the field is zero.

1. A set of dipoles is used to move the closed orbit so that it comes very close to the septum blade.

2. A bunch from the source is directed through a transfer line towards the storage ring, where it arrives at the septum on the side of the blade where there is a strong dipole field.

3. The field deflects the incoming bunch so that it is travelling parallel to the closed orbit, but at some displacement from it.

4. Since the injected bunch is not on the closed orbit, it will oscillate around the closed orbit as it travels around the ring.

5. The magnets in the storage ring are set so that once the bunch arrives back at the septum after completing a turn of the storage ring, it is at a phase of its orbit oscillation such that it passes through the septum through the field-free aperture.

6. The final step in the process is then to turn off the dipole magnets that were used to distort the closed orbit, so that (usually after several turns) the beam follows its original closed orbit.

7. Meanwhile, the oscillations of the newly injected bunch around the closed orbit will steadily decrease in amplitude as a result of processes such as synchrotron radiation damping.

8. Thus, after several turns, the charge in the ring has increased and the beam is once again on the original closed orbit.

9. This process can be repeated as often as necessary to reach the full beam current needed in the storage ring.

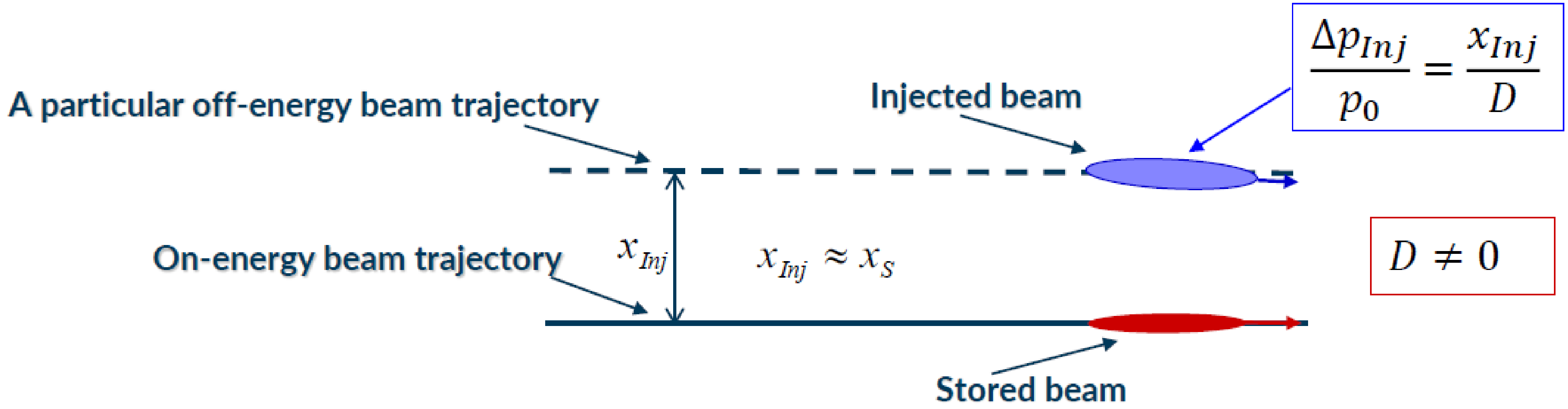
Although dipoles are still needed in this scheme that can be turned on and off quickly, the timescale is now on the order of several revolution periods, rather than a fraction of a revolution period.

The demands on the particle source are also greatly relaxed, compared to single-turn injection.

A drawback with multi-turn injection is that there is a risk of significant beam losses on the septum, or other components: the septum blade in particular can easily be damaged if the heat load from particles lost from the injected or stored beams is too high.

The injection system needs to be carefully designed and the entire storage ring needs to be finely tuned to minimise beam losses during injection. Indeed, there are a number of variations on the scheme outlined above for multi-turn injection.

[Note] Also, it is possible to take advantage of the variation in particle trajectory with the energy of the particle (an effect known as dispersion) by injecting bunches with some difference in energy: a 'dispersion bump' can then be used in addition to (or even instead of) an 'orbit bump' in the region of the septum.



Here, x_S is the distance to the septum, and D is the dispersion.

Particles can collide with residual gas in the vacuum chamber or with other particles in the beam: these collisions or scattering events can result in the loss of particles from the beam, leading to a decay in the beam current (e.g., by half over the course of a few hours).

Traditionally, storage rings have been operated in such a way as to refill the ring a couple of times each day (decay mode), which reduces the impact on users from variations in beam orbit and beam size associated with the injection process. The IDs were opened to minimize the perturbation to the beam during the injection.

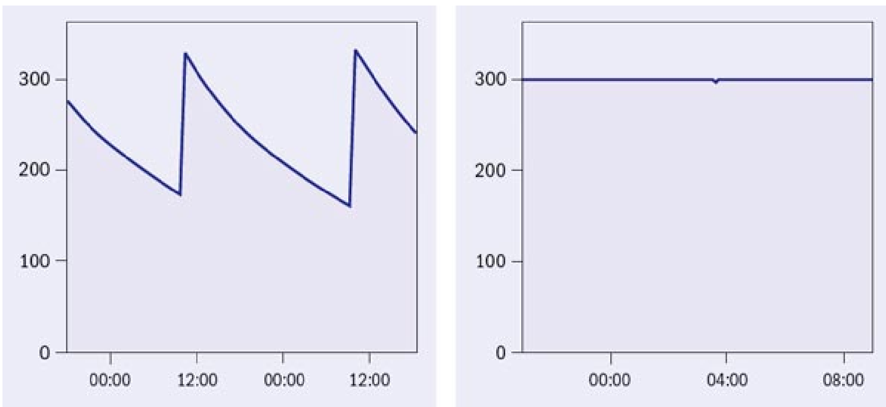
However, it has the disadvantage that there are large variations in the brightness (in a synchrotron light source) or the luminosity (in a collider) over time.

Also, the heat load on different components in the accelerator can change substantially in response to changes in current, making it difficult to maintain temperature stability.

To address these problems, light sources have developed ways of operating with ‘top-up’ injection, in which small amounts of charge are injected at short, regular intervals of perhaps no more than a few minutes.

The storage-ring current is allowed to drop by approximately 1 mA, or less than a percent, before it is topped up.

If the effects on the beam from the injection process can be kept small enough, then top-up injection provides better overall beam stability for users than the traditional mode of refilling at intervals of several hours.



[1] Introduction to Beam Dynamics in High-Energy Electron Storage Rings, Andrzej Wolski.

[2] Beam Dynamics In High Energy Particle Accelerators, Andrzej Wolski.

[3] An Introduction to Synchrotron Radiation: Techniques and Applications, Philip Willmott.