Chapter I.7

Injection and extraction

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A particle accelerator has limited dynamic range, so a chain of accelerators is required to reach high energies. A combination of septa and kicker magnets is used to extract and inject beam from one ring to the next. Injections can be performed on-axis in a single turn or off-axis in many turns. Off-axis injections are very different in the heavy-particle accelerators and in the electron/positron rings, where there is synchrotron radiation damping. The extraction from a intermediate stage of the accelerator chain is usually done in a single turn, but multi-turn slow extractions can be required for different applications. Different injection and extraction methods are explained in this chapter.

I.7.1 Injection

The injection into a particle accelerator consists in transferring some beam from a transfer line into the acceptance of the ring. If some beam is already circulating in the ring, the injection can't violate Liouville's theorem, so there can't be superposition in the phase-space between the injected beam and the stored beam. The injection of a beam in a particle accelerator can be performed in two main ways:

– The *single-turn on-axis injection*, where one single pulse is injected into an accelerator. This is typically done in the booster accelerators;
– The *multi-turn off-axis injection*, where one or several bunches are injected over several turns and accumulated one after the other. This is typically done in the storage rings.

The off-axis injections are very different for electron/positron accelerators and for heavy-particle accelerators, because in the first case the particles experience the synchrotron radiation damping. Most of the time the injection is performed horizontally, with the use of two kind of magnets: the kickers and the septa. The kickers are pulsed dipoles, with homogeneous field over the vacuum chamber cross section. The kickers with fast raising and falling time require precise synchronization of their pulse with the beam. The septa are magnets where the magnetic field is uniform on one side of a blade and absent on the other side. Example of a kicker and a septum are shown in Fig. I.7.1.

I.7.1.1 On-axis single-turn injection

Single-turn injection is usually the option chosen for the injection into an intermediate accelerator of a chain of accelerators. The full beam is extracted from a smaller accelerator to be injected in the next one.

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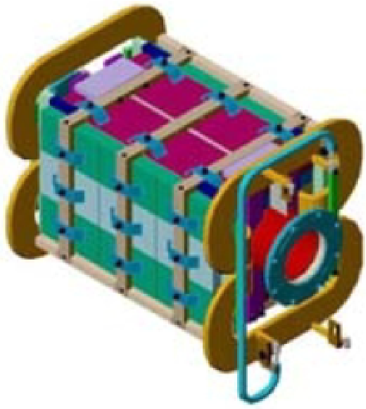
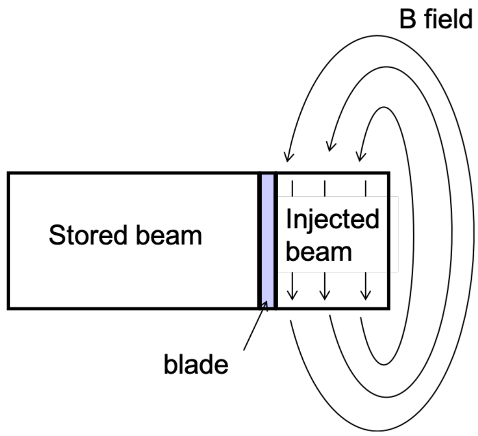

Fig. I.7.1: Kicker magnet on the left and septum magnet on the right.

The beam is injected in the central orbit using some electromagnetic elements, usually a septum magnet and a kicker. As the beam is put on the ring axis at the exit of the kicker, this is called on-axis injection. A schematic view for on-axis injection is shown in Fig. I.7.2. Real space and phase-space plots of the on-axis injection process are shown in Fig. I.7.3.

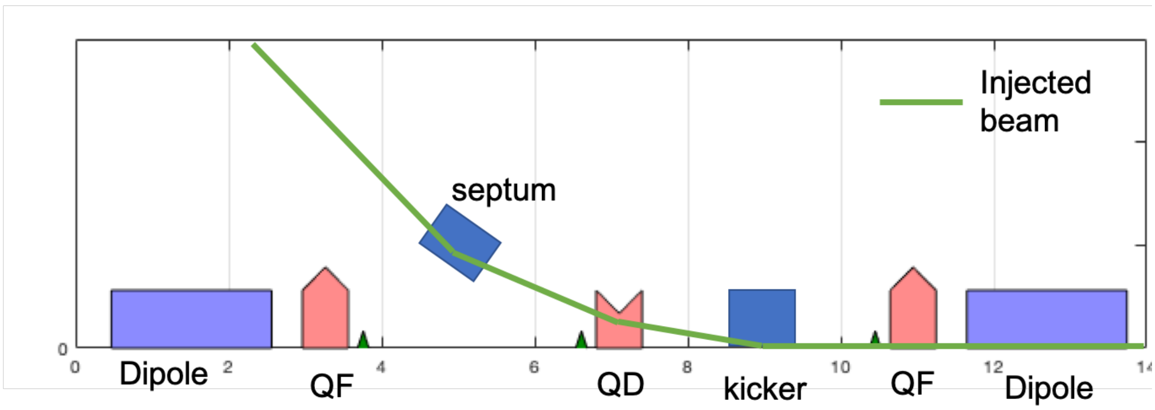

Fig. I.7.2: On-axis injection schematic view.

A requirement for the injected beam is that it is matched at the entry point to the ring. This means that, at the exit of the septum unit, the betatron and dispersion functions β_x, α_x, β_y, α_y, D_x, D'_x, D_y and D'_y must be identical to the machine lattice parameters at that point. This is mostly important when the emittance of the injected beam is comparable to the acceptance of the ring. The matching is performed using the dipoles and quadrupoles of the upstream transfer line. Even if the phase-space area of the injected beam is smaller than the accelerator acceptance, if the beam is not matched we could lose a fraction of it, as shown in Fig. I.7.4.

Parameters for on-axis injection

The distance between the injected beam and the accelerator axis at the septum location x_s is given by the distance of the septum blade to the accelerator axis, the thickness of the septum blade, the size of

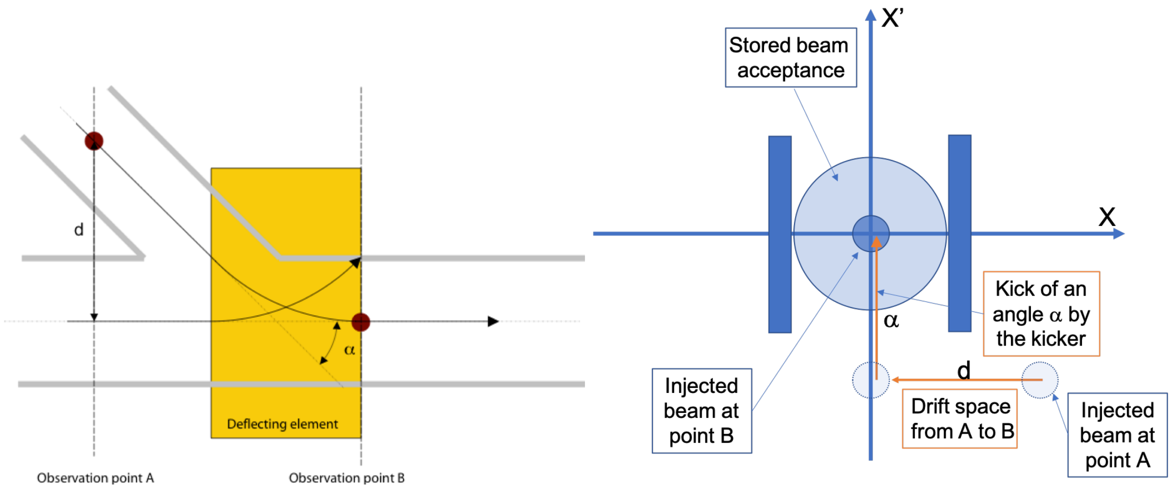

Fig. I.7.3: Phase-space diagram of on-axis injection.

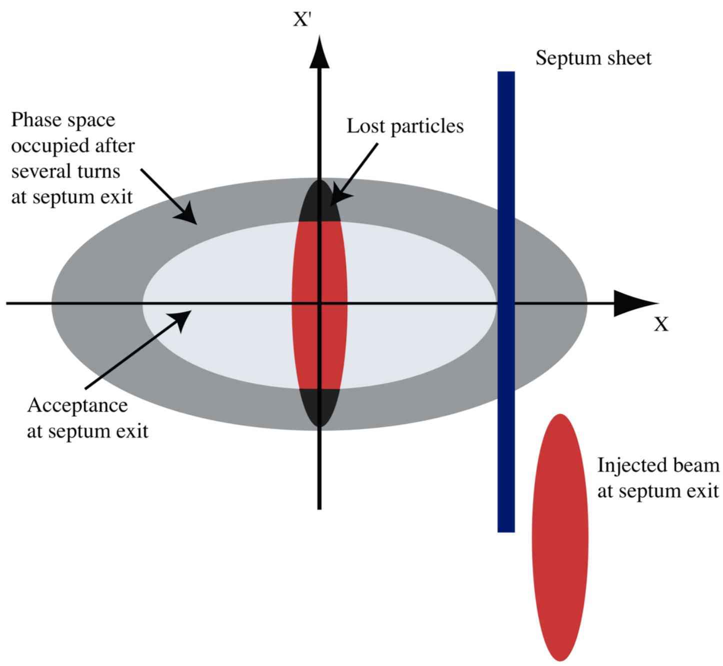

Fig. I.7.4: If the matching is not properly done, a fraction of the injected beam can be lost even if the size of the injected beam is smaller than the acceptance.

the injected beam and a margin to accept errors in the injected beam trajectory. In a standard on-axis injection scheme, we would like to know what the needed kicker angle θ_k is in order to optimise the parameters to minimise the kicker strength. In normalized coordinates, the transfer matrix between the septum and the kicker is a rotation matrix with a rotation angle μ

$$\begin{pmatrix} \mathrm{X}_k \\ \mathrm{X}'_k \end{pmatrix} = \begin{pmatrix} \cos\mu & \sin\mu \\ -\sin\mu & \cos\mu \end{pmatrix} \times \begin{pmatrix} \mathrm{X}_s \\ \mathrm{X}'_s \end{pmatrix} . \tag{I.7.1}$$

For on-axis injections, the coordinate $\mathrm{X}_k = 0$. Solving the system of equations we obtain

$$\mathrm{X}'_s = -\mathrm{X}_s \frac{\cos\mu}{\sin\mu} \tag{I.7.2}$$

and

$$\mathrm{X}'_k = -\mathrm{X}_s \sin\mu + \mathrm{X}'_s \cos\mu. \tag{I.7.3}$$

From these two equations we can obtain

$$\mathrm{X}'_k = -\frac{\mathrm{X}_s}{\sin\mu}. \tag{I.7.4}$$

We can now convert from normalized coordinates to normal coordinates using the Courant-Snyder transformations

$$\begin{cases} \mathrm{X} = \frac{x}{\sqrt{\beta}} \\ \mathrm{X}' = x'\sqrt{\beta} + \alpha\frac{x}{\sqrt{\beta}} \end{cases} \qquad \begin{cases} x = \mathrm{X}\sqrt{\beta} \\ x' = \frac{\mathrm{X}'}{\sqrt{\beta}} - \alpha\frac{\mathrm{X}}{\sqrt{\beta}} \end{cases}. \tag{I.7.5}$$

The beam angle at the exit of the septum, from X'_s to x'_s, is given by

$$x'_s = -\frac{\left(\alpha_s + \frac{\cos\mu}{\sin\mu}\right)x_s}{\beta_s}, \tag{I.7.6}$$

where α_s and β_s are the Twiss functions at the septum. And the kick angle that the kicker must provide to the beam to bring it back to the ring orbit is therefore

$$\theta_k = -x'_k = \frac{x_s}{\sin\mu\sqrt{\beta_k\beta_s}}, \tag{I.7.7}$$

where β_k and β_s are the β functions at the kicker and at the septum locations. To minimise the angle to be provided by the kicker we need to have

- Large β values at the septum and at the kicker locations,
- A phase-advance μ_x close to $\pi/2$.

This is the case in a standard FODO lattice where the septum and kicker are located in the vicinity of focusing quadrupoles at a distance of one cell.

I.7.1.2 Multi-turn injection without synchrotron radiation damping

If the phase-space of the accelerator is empty at the injection time, we can inject the beam on-axis, but if there is already a circulating beam this is impossible: the injection kicker would throw the circulating beam out from the accelerator acceptance. Off-axis injection is needed if the injection lasts more than one turn.

The conventional multi-turn injection uses an injection septum unit associated with a programmed closed orbit bump in the vicinity of the septum, as shown in Fig. I.7.5. Such localised bump can be produced by two or more kicker magnets. The role of the orbit bump is to shift the horizontal transverse acceptance of the ring towards the injected beam at the exit of the septum. The injection bump has to be removed quickly, because otherwise the injected beam would be lost on the septum blade after a few turns, depending on the betatron tune.

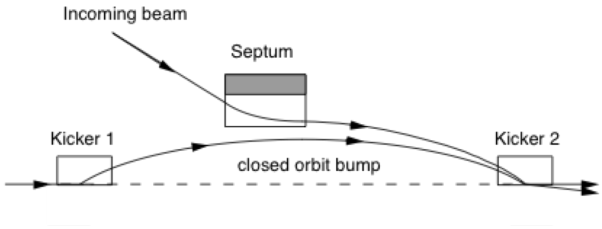

Fig. I.7.5: Off-axis injection scheme with a septum and two injection kickers.

In case of protons or other heavy-particle machines, the beam does not have any synchrotron radiation damping effect and the multi-turn injection depends on the tune of the accelerator. If the tune is 0.25, four consecutive injections can be performed for the same bunch in four turns (see Fig. I.7.6). At each turn, the beam is moved by 90 degrees in phase-space and the new injected beam finds some empty space. After the four injections, the bump has to be swhitched off in less than a turn in order not to perturb the first injected particles.

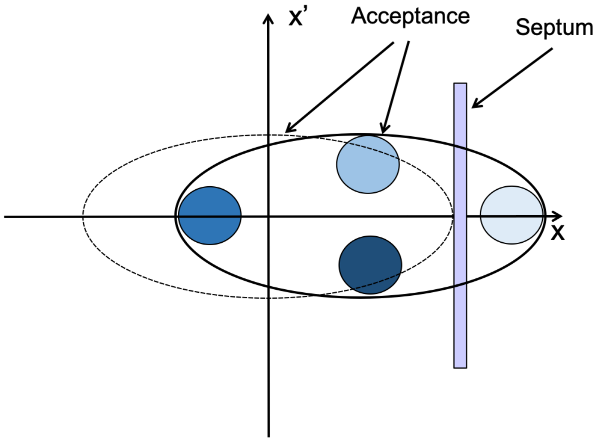

Fig. I.7.6: Off-axis injection with horizontal tune 0.25. Four injections can be performed in four consecutive turns before removing the injection bump.

This technique is also called phase-space painting. The first injection can be performed on-axis with a larger injection bump. For high-intensity and low-energy proton rings, it is common to inject H^- ions. The principle is to change the charge of the injected particle after it has passed a dipole magnet in common between the injected and the stored beam. This is done by inserting a thin stripping foil which removes the two loosely bound electrons of the H^-. The foil thickness is chosen to give a high stripping efficiency (about 98%) without introducing appreciable scattering and momentum spread. A schematic view of the charge exchange injection is shown in Fig. I.7.7.

The advantage of this process is that there is no need to shift the transverse acceptance outside the physical aperture: injection can be performed in a large number of turns with superposition in phase-space. An orbit bump is still useful to avoid crossing the stripping foil when the injection is finished. This method enables to fill the transverse acceptance with a uniform transverse density distribution to

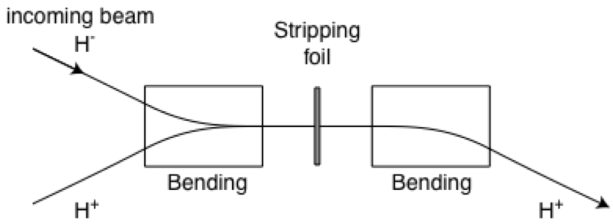

Fig. I.7.7: Schematic view of the charge-exchange injection.

minimise the space-charge forces. Such a uniform filling may be achieved by applying a painting of the acceptance: a vertical steering of the H^- in the injection line and a variation of the horizontal orbit bump in the vicinity of the stripping foil are applied simultaneously to fill the acceptance.

I.7.1.3 Multi-turn injection with synchrotron radiation damping

Electron and positron circular machines are submitted to synchrotron radiation damping: after a few damping times the emittance is the equilibrium from radiation damping and quantum diffusion.

The injection can be performed off-axis and the radiation damping effect sends the beam in the center of the closed orbit after a few damping times. In storage rings for synchrotron light sources, the damping times are order of few ms. A schematic view of the off-axis injection with damping is shown in Fig. I.7.8. The injection process does not limit the maximum intensity which can be stored in electron storage rings.

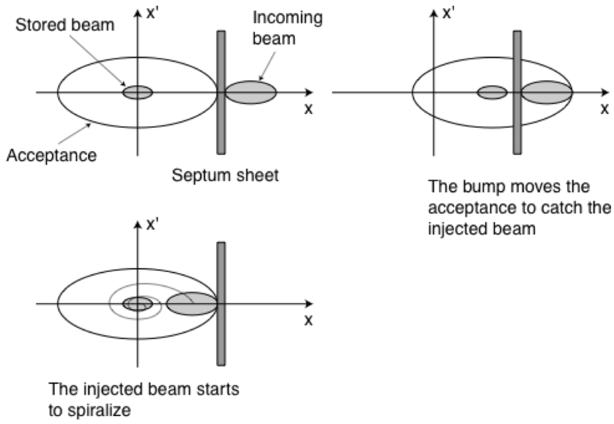

Fig. I.7.8: A closed-orbit bump is used to reduce the distance between the stored and the injected beams. After a few damping times, the injected electrons occupy the center of the density distribution and have freed the phase-space at the outer areas of the acceptance. The sequence is repeated until a sufficient current has been reached.

Innovative scheme: injection with a nonlinear kicker

In 2006, Y. Kobayashi and K. Harada proposed an innovative injection scheme using a pulsed sextupole [1]. The injected beam is outside the accelerator acceptance at the septum position, it drifts in the phase-space ellipse and it is kicked into the acceptance by a pulsed sextupole. The stored beam does not see any field, because it passes through the center of the sextupole. A schematic view of this injection scheme is shown in Fig. I.7.9.

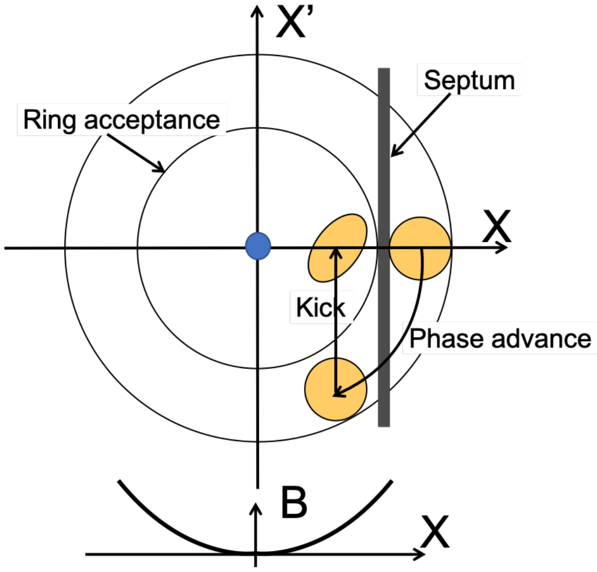

Fig. I.7.9: Schematic view of the phase-space for the injection with a pulsed sextupole.

The magnetic field of the kicker must be zero at the center, in order to keep the stored beam unperturbed. Using a sextupole magnet is not the only possibility. More complicated solutions have been tested at Bessy [2] and at Soleil [3]. The field profile and the nonlinear kicker design of the Soleil synchrotron are shown in Fig. I.7.10.

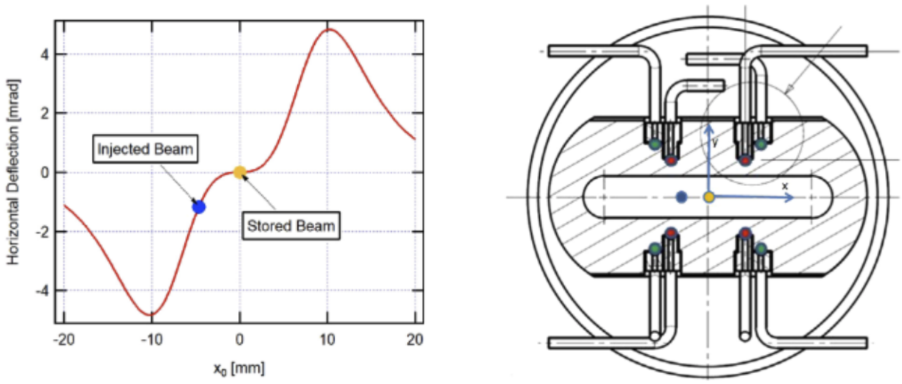

Fig. I.7.10: Field profile and nonlinear kicker design of the Soleil synchrotron.

I.7.1.4 RF capture

The injected beam has to be captured also in the longitudinal acceptance of the accelerator. Several cases are to be considered depending on whether the injected beam is already bunched or not, and when the RF system of the ring is turned on

- Bunched beam with RF on,
- Unbunched beam with RF on,

– Injection without RF.

The injection of a bunched beam with RF on is the only possibility in case of electron rings. The simplest case is when the frequency of the RF injector system is the same as the one of the ring. The phase between the two RF systems and the energy of the incoming beam have to be adjusted correctly so that the injected bunches fall just inside the ring RF buckets (Fig. I.7.11).

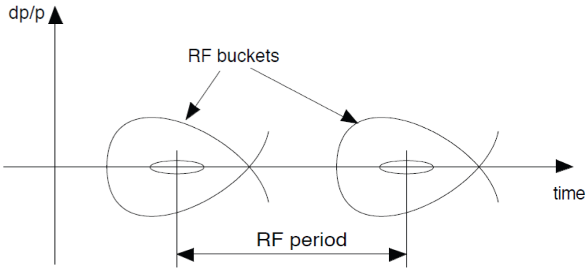

Fig. I.7.11: RF buckets of the ring.

Injecting an unbunched heavy-particle beam in a ring with RF on, only the particles that fall inside the RF buckets will be captured. The bucket size can to be optimised by changing the RF voltage.

The injection with RF off is possible in case of heavy particles. The RF can be progressively turned on in order to bunch the beam. This process is called adiabatic capture (see Fig. I.7.12). The RF ramp has to be optimised to limit the losses.

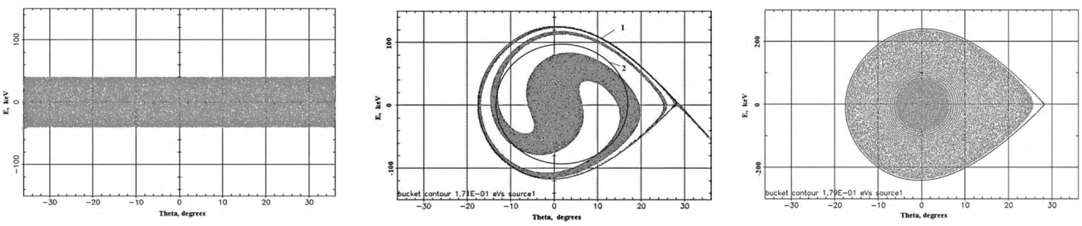

Fig. I.7.12: Adiabatic-capture process.

Longitudinal injection

In electron machines, the shape of the longitudinal bucket is not symmetric on the energy direction: high-energy particles emit more radiation than low-energy ones, so there is a *golf club* shaped acceptance. This allows to inject beam in a bucket on-axis but off-phase and off-energy with a very fast kicker ($\lesssim 1\,\mathrm{ns}$). A schematic view of the longitudinal injection in an electron storage ring is shown in Fig. I.7.13 [4].

I.7.1.5 Swap-out injection

Several fourth-generation synchrotron light sources have a lattice with an extremely small emittance, but also with a very small transverse dynamic-aperture. The size of the dynamic-aperture needed to perform off-axis injection depends on the thickness of the septum blade and on the size of the stored beam and the injected beam. In typical storage rings, a transverse dynamic-aperture of at least 4 or $5\,\mathrm{mm}$ is needed. If the dynamic-aperture is too small for off-axis injection, the only option is to do on-axis injection. In

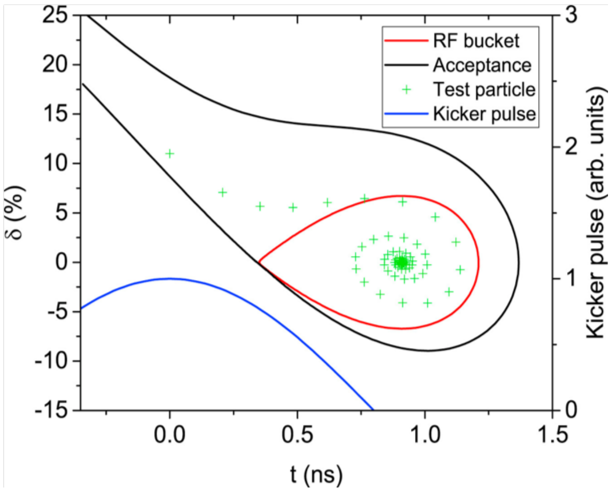

Fig. I.7.13: Injection on-axis and off-phase, using the *golf club* longitudinal acceptance in electron storage rings.

that case, the full bunch has to be injected in a single turn and therefore the injector has to provide a full-current bunch. The kick used to inject in the storage ring also extracts the stored bunch. The extracted beam can either be dumped or it can be injected back in the injector ring. The swap-out injection scheme is used in the APS (Advanced Photon Source) and ALS (Advanced Light Source) upgrade projects. The scheme of the ALS-U injection is shown in Fig. I.7.14.

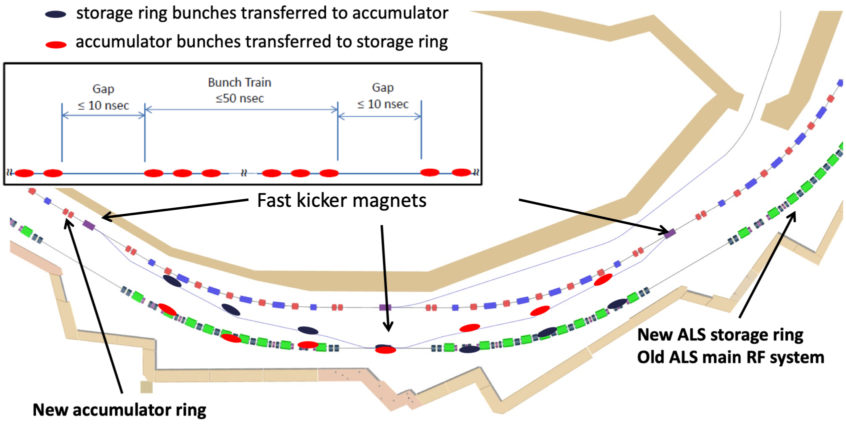

Fig. I.7.14: Scheme of the ALS-U injection. The magnet used to inject in the storage ring is also used to extract the circulating beam. The extracted beam is injected in the accumulator ring.

The swap-out allows to inject beam in a ring with very small dynamic-aperture, but it has some drawbacks. The injector ring must be able to accelerate a full-current bunch and this could be impossible for some old booster rings. An additional accumulator ring might be needed. Very high single-bunch current might be impossible with a swap-out injection system. The repetition rate for the uniform filling patterns are defined by how fast the injector kicker is. Generally, a very fast kicker is needed for swap-out injection.

I.7.1.6 Phase-space matching in the transfer line

The last stage of a transfer line must enable the matching of the optical functions in the two transverse phase-spaces. This means controlling at the exit of the septum unit the following Twiss and dispersion functions: β_x, α_x, β_y, α_y, D_x, D'_x, D_y and D'_y.

In order to match the Twiss and the dispersion functions, at least 8 quadrupoles are needed. In most cases, the injector and the ring are in the same plane, so the vertical dispersion would be 0 and only 6 quadrupoles would be needed. The septum and kicker magnets involved in the injection and extraction provide a horizontal bending angle, so they have to be included in the computation of the dispersion.

If the transfer line has several dipoles, it could be useful to locate some quadrupoles in locations without dispersion, in order to use them to match only the betatron functions. The final steering in the horizontal plane is generally made by fine tuning of the injection magnets, whereas two steerer magnets are required at the end of the transfer line to adjust the vertical beam angle and position at the injection point. For on-axis injections, the optimal betatron functions of the injected beam are equal to the betatron functions of the ring at the injection location. For off-axis injections, the conditions are more complicated: the curvature radius of the injected beam in the phase-space has to be equal to the one of the accelerator acceptance (see Fig. I.7.15).

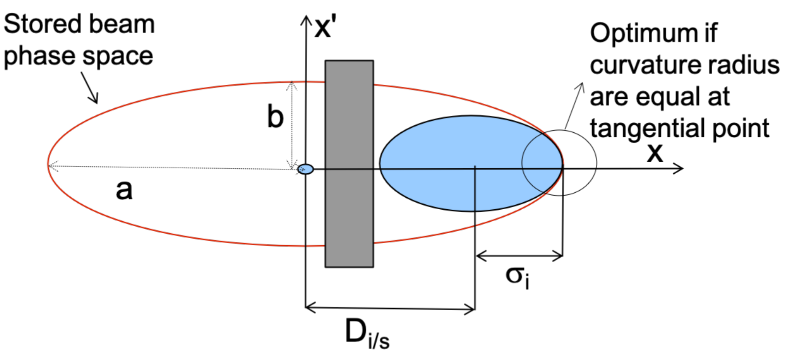

Fig. I.7.15: The optimum β function for the injected beam is the one giving the same curvature radius of the acceptance at the tangential point.

The curvature radius of the acceptance $r_s = \frac{b^2}{a}$ can be computed with

$$a = \sqrt{J_x \beta_s} = D_{i/s} + \sigma_i \tag{I.7.8}$$

and

$$b = \sqrt{\frac{J_x}{\beta_s}}, \tag{I.7.9}$$

where J_x is the horizontal maximum action of the stored beam, β_s is the betatron function of the stored beam at the injection point, σ_i is the size of the injected beam, $D_{i/s}$ is the distance between the injected and the stored beams. It yields

$$r_s = \frac{\sqrt{J_x}}{\beta_s^{3/2}} = \frac{a}{\beta_s^2} = \frac{D_{i/s} + \sigma_i}{\beta_s^2}. \tag{I.7.10}$$

The curvature radius of the injected beam r_i can also be computed (with a and b now related to the phase-space of the injected beam)

$$a = \sigma_i, \tag{I.7.11}$$

$$b = \frac{\sigma_i}{\beta_i}, \tag{I.7.12}$$

$$r_i = \frac{\sigma_i}{\beta_i^2}, \tag{I.7.13}$$

where β_i is the betatron function of the injected beam.

The optimum beta function of the injected beam (β_i) as a function of the beta function of the stored beam (β_s) can be obtained from Eqs. I.7.10 and I.7.13:

$$\beta_i^2 = \frac{\sigma_i}{D_i/s + \sigma_i}\,\beta_s^2. \tag{I.7.14}$$

This calculation assumes a linear machine, but injection takes place at the edge of the acceptance, where the phase-space is usually distorted by nonlinearities. Final tuning of beta functions looking at injection efficiency is usually needed.

I.7.2 Extraction

There are two types of extraction processes from a circular accelerator that can be used depending on the applications: the fast extraction, that is done in one turn, and the slow extraction, that can last thousands of turns or more.

I.7.2.1 Fast extraction

The fast extraction is used to transfer the full beam from an accelerator to the next stage of the acceleration process. The extraction line starts with a septum magnet and the circulating beam is sent to the other side of the septum blade with a fast kicker magnet. Before the extraction, a slow bump is usually powered to bring the beam as close as possible to the first extraction septum. Then a fast kicker magnet is powered such that the beam is deflected into the extraction channel where it receives sufficient angular deflection to leave the machine. If particles arrive at the kicker while it is ramping, they will be lost onto the septum blade. As a consequence, the rise time of the kicker must be as short as possible. A schematic view of the ESRF (European Synchrotron Radiation Facility) booster extraction zone is shown in Fig. I.7.16.

The duration and switch-on and switch-off times of the kicker pulse depend on the mode of extraction. Typical values of rise and fall times are 40 to 50 ns. The rise time must be short compared to the revolution period of the ring, the pulse duration is the revolution period and the switch-off time can be arbitrary because the machine is empty. For bunch-by-bunch extraction, the rise time and the fall time must be shorter than the time interval between two successive circulating bunches, and the pulse duration is the bunch repetition period (or less).

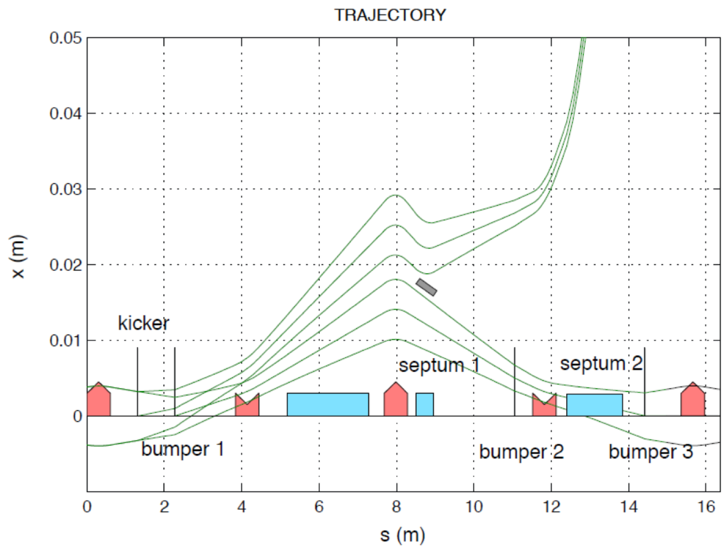

Fig. I.7.16: ESRF booster extraction zone.

As for the on-axis injection, the kicker must deflect the beam by

$$\theta_k = \frac{x_s}{\sin \mu_x \sqrt{\beta_x^k \beta_x^s}}, \tag{I.7.15}$$

where β_x^k and β_x^s are the horizontal beta functions at the kicker and at the septum, μ_x is the betatron phase-advance from the kicker to the septum and x_s is the required displacement at the septum entrance. The initial orbit bump is used to reduce the value of x_s.

I.7.2.2 Slow extraction

For some applications it is useful to extract the beam in a long time: for some particle physics experiments, a high-energy particle beam with low intensity is required for relatively long time; in hadronterapy treatments, the beam from the synchrotron has to be extracted in many turns, so that the beam can be sent to different parts of the tumor using trajectory correctors. The slow extraction can be achieved by a controlled excitation of a non-linear betatron resonance of the ring, usually a third-integer resonance.

In a linear machine with a sextupole magnet and the tune close to the 1/3 resonance, the angular kick and the position shift every three turns (also called spiral kick and spiral step) are very small and they depend on the sextupole strength and the distance from the resonance. In the limit of sextupole off and tune exactly on the resonance, the phase-space position of the particles is exactly unchanged every three turns. The spiral step and the spiral kick can be integrated obtaining the Hamiltonian of the system, which is called Kobayashi Hamiltonian [6] [7]. The Hamiltonian defines a triangular stable region in the phase-space and three separatrices. An example of stable regions for two different tunes in the Hadrontherapy synchrotron at CNAO (National Centre of Oncological Hadronotherapy), in Italy, is shown in Fig. I.7.17.

The extraction can be obtained by reducing the size of the stable region or by increasing the size of the stored beam. The size of the stable region can be changed by increasing the sextupole strength (sextupole-driven extraction) or by changing the horizontal tune of the machine. The tune can be changed

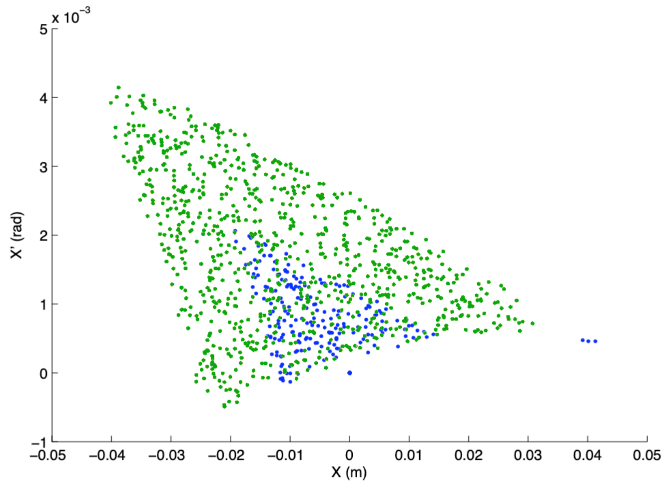

Fig. I.7.17: Horizontal phase-space triangular stable region in the CNAO synchrotron close to the third order resonance. The particles in blue have a tune closer to the resonance condition than the ones in green.

by ramping the quadrupoles (quadrupole-driven extraction) or by changing the energy of the particles in presence of chromaticity (acceleration-driven extraction). Alternatively, the size of the stable region can be kept constant and the extraction can be obtained by increasing the size of the stored beam with a magnetic shaker (RF-knockout extraction).

The efficiency of slow extraction depends on the thickness of the first extraction septum compared with the growth of the betatron amplitude due to the resonance in the final few turns before extraction. At the location of the extraction septum, within the last three turns, the betatron amplitude of the particle must grow enough to jump from one side of the septum blade to the other. This requires a very thin septum blade, that can be obtained with an electrostatic septum.

I.7.3 Magnetic elements for injection and extraction

I.7.3.1 Kicker magnets

Kicker magnets need to be switched on/off in times typically of 50 to $150\,\mathrm{ns}$. This is only possible with magnets with extremely small inductance. Small-inductance magnets are usually air-coil magnets, which cannot produce a high magnetic field without going to impracticable currents. The kickers are powered by pulse-forming networks (PFN) which are charged some time before the injection and rapidly discharged via fast switches called thyratrons. Ferrites are frequently used to contain the field. Usually they cannot be tolerated inside the vacuum of the ring and must be installed around the vacuum chamber.

The fast change of magnetic field generates electric fields which generate currents in the conductive vacuum chambers. In electromagnetism, such currents are called eddy currents. Eddy currents generate magnetic fields that are opposite to the field of the kicker, resulting in a screening effect. In order to reduce the eddy currents, the vessels can be built in ceramic, a non-conductive material, but they are internally coated with a thin layer of conductor, often titanium, in order to ensure the circulation of the beam image current. The field induced by the kicker has a frequency of order of $1\,\mathrm{MHz}$, if the pulse length is of the order of μs, the field induced by the beam has much higher frequency, because the bunch length is of the order of a few mm. The titanium coating can block the lower frequency current still allowing the high frequency ones. An example of ceramic vacuum chamber for the ESRF injection kickers is shown in Fig. I.7.18.

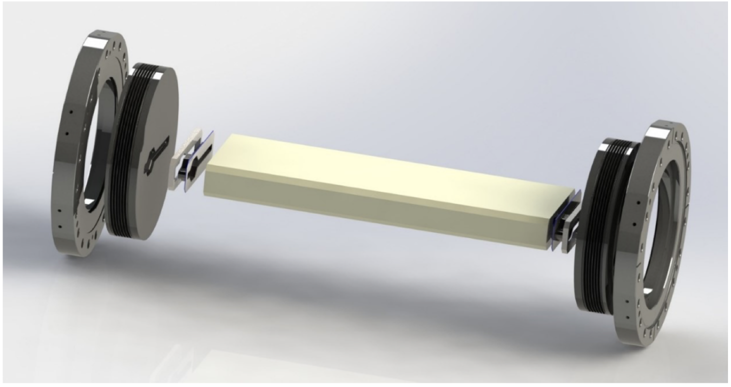

Fig. I.7.18: Ceramic chamber for the injection kickers of the ESRF storage ring. The chamber is coated with titanium.

For very fast kicks, stripline kickers are becoming more common. They allow faster rise times, but usually lower deflection than a magnetic kicker, but they need a fast high-voltage pulse. Multiple striplines can be combined to increase the total deflected angle. Stripline kickers allow to kick only selected bunches instead of the full beam. An example of stripline kicker is shown in Fig. I.7.19.

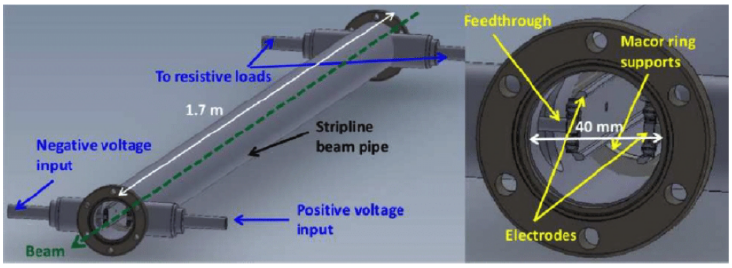

Fig. I.7.19: Stripline kicker, from C. Belver Aguilar thesis [8].

I.7.3.2 Septum magnets

A septum magnet gives a uniform magnetic field inside a small region and nothing outside. It is used to bend only the injected or extracted beam without perturbing the stored beam. The septum can be pulsed or not. If it is not pulsed, it can be a permanent magnet.

A septum gives a much larger bending angle than a kicker and allows to bring the injected beam close to the stored beam, without interfering with the stored beam. The septum blade separates the injected/extracted beam from the stored beam. The blade can be a few mm thick. The septum blade can be part of the coils (active septum) or can be an eddy current shield (passive septum). An example of septum where the field is shielded by the eddy current in the blade is shown in Fig. I.7.20. Passive septa are necessarily pulsed magnets, while the active can be DC. The blade of a passive septum has to be larger than the skin depth in the material of an electro-magnetic field at the frequency of the pulse. The pulse can be few tens of μs.

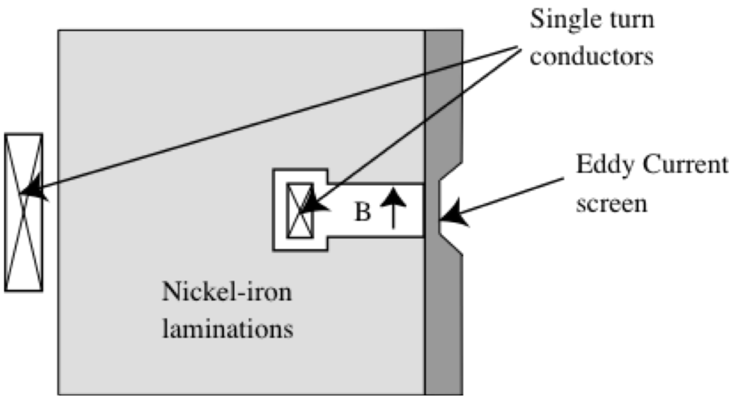

Fig. I.7.20: Septum magnet. The shielding is provided by the eddy current in the septum blade.

For very small blade size and small deflection angle, electrostatic septa can be used. In those devices, the deflection is performed by an electric field instead of a magnetic field. An example of electrostatic septum is shown in Fig. I.7.21.

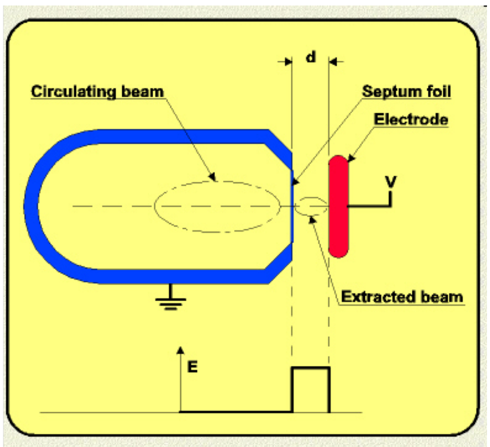

Fig. I.7.21: Electrostatic septum.

A Lambertson septum provides the deflection angle and the offset in different planes. In the septum shown in Fig. I.7.22, taken from [9], the deflection is horizontal and the offset is vertical.

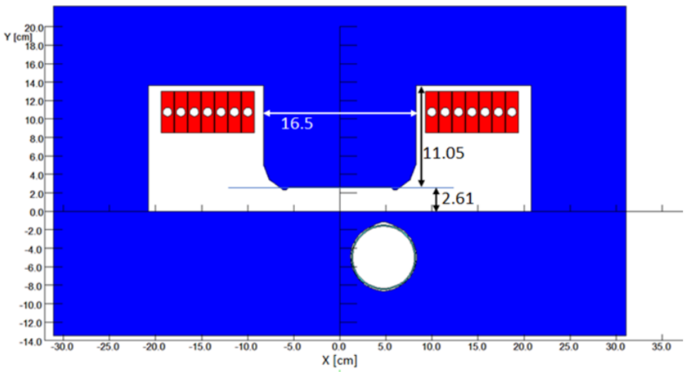

Fig. I.7.22: Lambertson septum for RHIC (Relativistic Heavy Ion Collider).

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