Introduction to Particle Accelerators: How do Particle Accelerators work? [a]

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Particle accelerators are the tools driving research in high energy physics. They are also commonly used for leading edge research in material science, biology, chemistry and medical science. In this document we will study the main physical phenomenon that happen in a particle accelerator and see some of their applications.

1 History of particle accelerators

The history of particle accelerators goes back to more than a century. In 1909 Rutherford was the first to use a "probe" (a radioactive source) to study the structure of the atom, discovering the existence of a nucleus surrounded by a cloud of electrons.

The resolving power of a probe is proportional to its wavelength and therefore inversely proportional to its energy ($\lambda = \frac{h}{p}$). A better resolution could therefore be achieved by accelerating the particles in an electric field, however very high electric field are not easy to produce. In 1929 Van de Graaff proposed a generator consisting of two terminal, one at ground potential and the other at high voltage. The charges were mechanically carried by a belt from the ground terminal to the high voltage terminal (see figure 1, left). Such generator can reach several megavolts. If a source of particles is placed inside the high voltage terminal (with the opposite charge) the particles produced will be accelerated by the voltage difference. For ions this design can be improved by starting at ground potential with negatively charged ions. The ions are accelerated to the high voltage terminal where they pass a stripping foil and lose several electrons. Having now a positive charge they are repelled by the high voltage terminal and are further accelerated

[a] The latest full version of this document is available at http://lal.delerue.org/teaching/accelerators/

toward ground potential (see figure 1, right). Such accelerators are called “tandem” accelerators and are still used in low energy nuclear physics and mass spectrometry (for example for radiocarb … discussed in

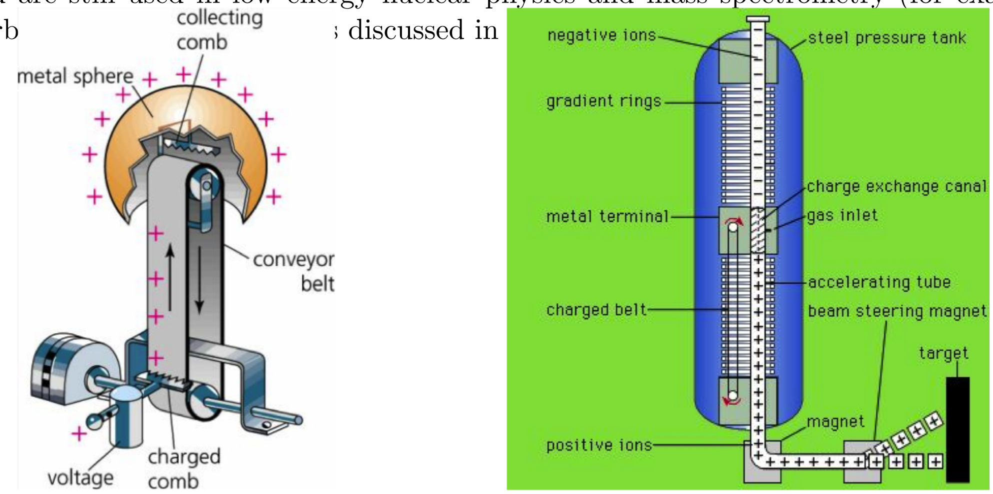


Figure 1: (Left) A Van de Graaff generator used to generate a high voltage by mechanically moving electrical charges to a high potential. (Right) A tandem Van de Graaff used to accelerate ions to higher energies by stripping their charge in the middle.

To reach a high electric field Cockroft and Walton suggested a different method: they used an array of diodes and capacitors feed by an alternative current (AC) line. The diode and capacitors were arranged so that they would load on positive AC cycle but discharge only very slowly on the negative cycles (see figure 2, bottom left). After several cycles a steady state will be reached with a high voltage at the upper terminal. To prevent electrical breakdowns the intermediate nodes had to be within reasonable distance of each other, leading to rather large apparatus typically several meters high (see figure 2, left). Using such device Cockroft and Walton were able to accelerate protons to several hundred KeV. In 1932 they bombarded a lithium target with hydrogen nuclei (protons) accelerated to 700 keV and transmuted it into Helium and other elements (see figure 2, right). This was the first time that a particle accelerator had been used to trigger a nuclear reaction. They were awarded the Nobel prize in physics for this work in 1951.

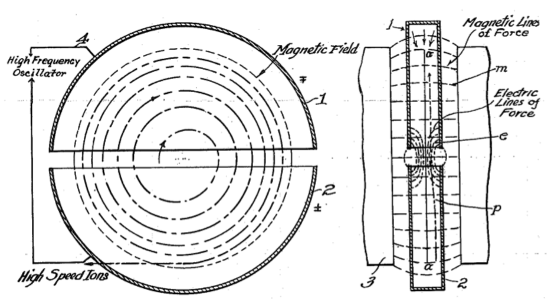


Figure 3: A drawing of an early Cyclotron by Lawrence.

At the same time in the United States of America Lawrence studied a different design. Instead of generating a high voltage he decided to use a circular design in which the particles were accelerated several times. In his device, called a cyclotron, electrodes are placed between two half circular magnets. Particles are injected at the center and are accelerated a first time by an AC field applied between the electrodes. They then enter one of the magnets where they make a half circle before returning to the electrodes where the field is now in the opposite direction and therefore accelerate them further. As the particles gain energy their radius of curvature increases and their trajectory looks like a spiral until they reach the exit of the cyclotron with a high energy (see figure 3). With an alternating field of only 2000V Lawrence was able to accelerate protons to an energy of 80 keV. He was awarded the Nobel prize in Physics in 1939 for this work. One should note that cyclotrons can only accelerate non relativistic particles as the change of speed of relativistic particles is no longer linear with their energy gain.

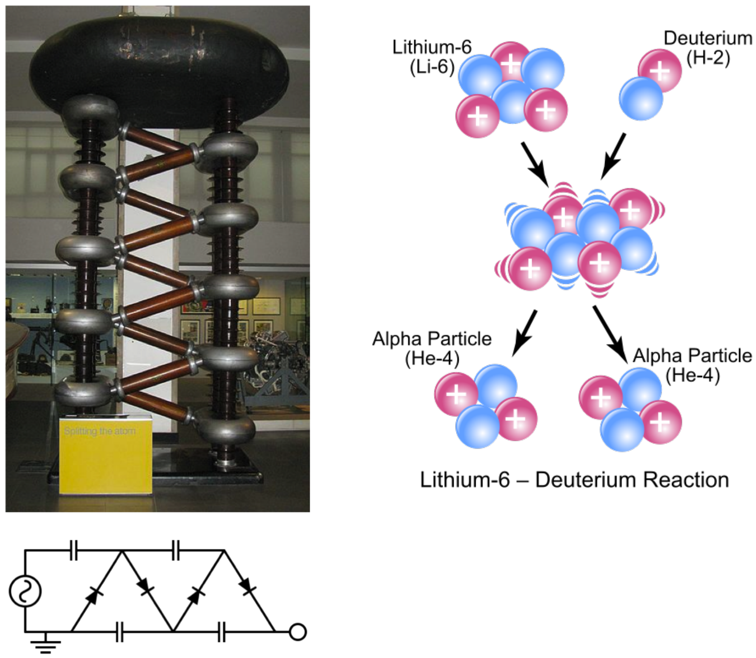


Figure 2: A Cockroft walton generator (left) with its equivalent circuit (below) and the nuclear reaction made by Cockroft and Walton (right).

Nowadays cyclotrons are still used to generate rare isotopes, for example those used in medicine (see section 5.2).

2 Basic principles of particle accelerators

The early success of particle accelerators in nuclear physics has led to the construction of many of them after the second world war. We will now look at the main features of the accelerators used for research in nuclear and high energy physics. They are usually made of a source of particles, an accelerating section and (in most cases but not always) one or more rings.

2.1 Production of particles

Electrons

Electrons fill energy levels in metals according to a distribution law similar to the Maxwell-Boltzmann law. This means that when a metal is heated some electrons will fill energy levels beyond the ionization potential of the metal and be emitted. This is called thermionic emission. The application of an electric field to a heated metal can therefore result in the extraction of these electrons (see figure 4 and 5 left).This is the principle used in Cathodic Ray Tubes (CRT; the tubes that "paints" the images on non-flat televisions). Thermionic guns are the most widely used source of electrons in particle accelerators.

The energy that the electrons must gain to escape from a metal is called the work function. It is different for different metals and it can also be affected by other parameters such as the crystalline state or the surface roughness. The work function is typically is few electron volts with Cesium having one of the lowest work function (Fe: 4.7eV, Cu: 5eV, Al: 4.1eV, Cs: 2eV).

A drawback of thermionic emission is that the electrons emitted have their energy distributed according to the Maxwell-Boltzmann law, leading to a large spread in longitudinal and transverse momentum. A choice must be made between heating to a temperature near the emission limit

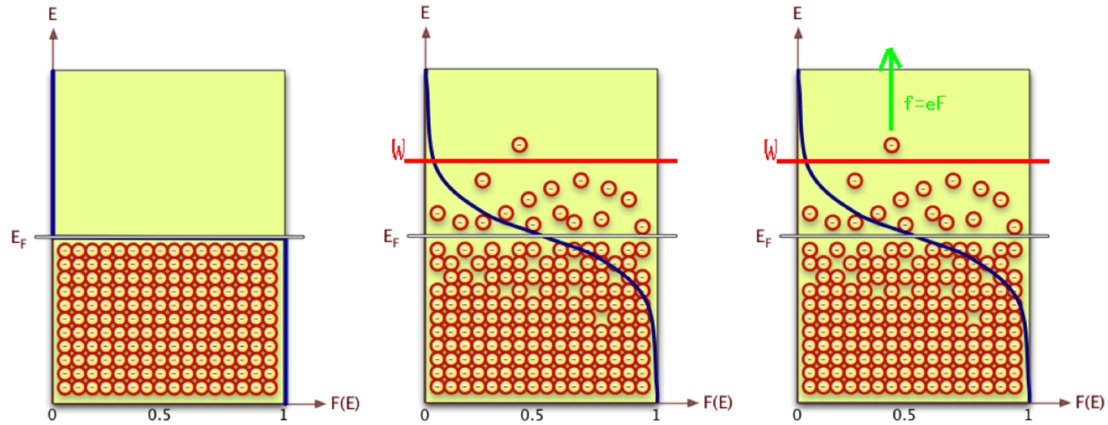


Figure 4: Thermionic effect: In a heated metal some electrons may acquire more energy than the work function of the metal and become "free". An electric field may then be used to extract them/

to produce an homogeneous beam but of low intensity or heating much more to get a more intense beam but less homogeneous. In most accelerators the beam inhomogeneity (also called beam emittance, see section 3.1) produced by the source is a limit to the performances of the machine.

External parameters can be used to modify the work function. For example an electric field will reduce the work function by an amount $\Delta W = \sqrt{\frac{e3F}{4\pi\epsilon_0}}$. The emission of electrons under an intense electric field is called "Schottky emission" (see figure 5, center). Because the work function is reduced Schottky emission can be used to produce better quality beams than those created only by thermionic emission.

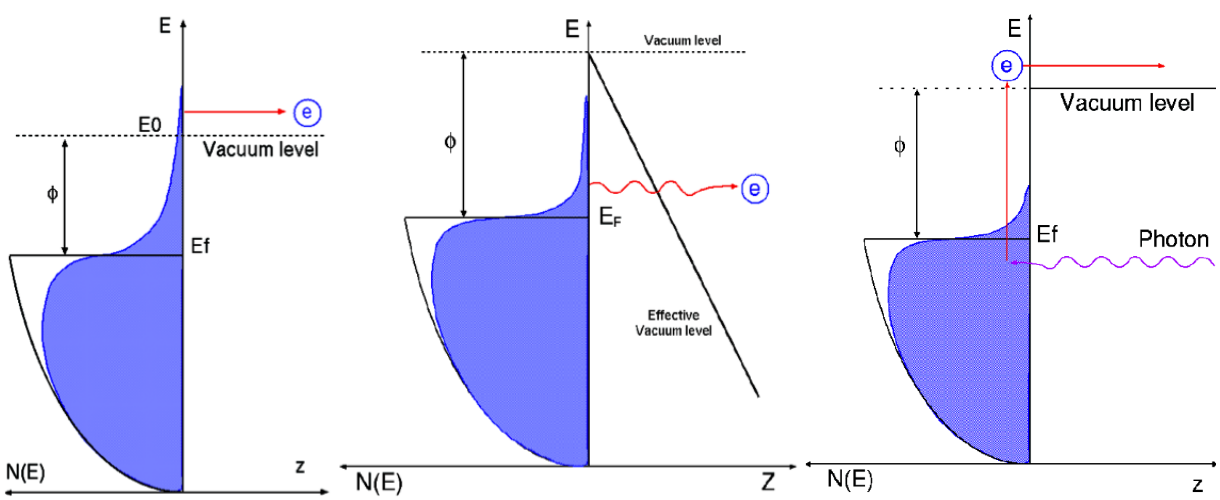


Figure 5: Different type of electron emission: thermoionic (left), schottky (middle) and photoemission (right).

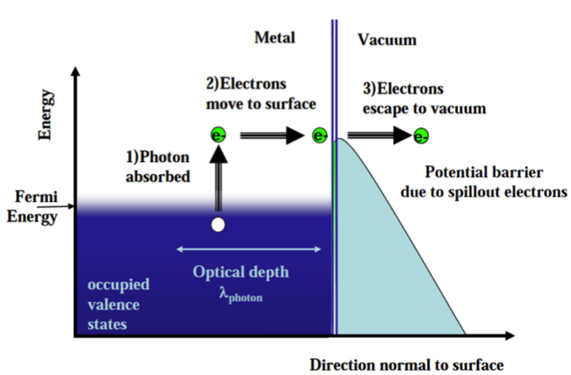


Figure 6: The three steps of emission by photoelec-

Instead of relying purely on heating to extract the electrons beyond the work function it is possible to communicate to individual electrons the energy they require to be extracted. This is known as the photoelectric effect and it is used in photoguns: a short wavelength laser pulse (typically UV) is sent on a cathode. Some of the laser photons will transfer their energy to an electron which will now have more energy than the work function and therefore be emitted (see figure 5, right and figure 6). Because all the photons have the same energy the momentum spread of the electrons emitted is much smaller than with a thermionic gun however the electrons to which the energy is transmitted may be on different energy levels or at some depth inside the metal and therefore they will not be completely homogeneous. Another advantage of photoguns is that the time constant of the emission process is very small and thus the length of the electron pulse emitted is comparable to that of the laser pulse. This is used to generate sub-picoseconds electron pulses.

Protons and ions

The production of protons and ions relies on a different mechanism: a plasma is created by electric discharges in a chamber. In the plasma there are charged ions and electrons. By applying an electric field inside the chamber the positive ions will go toward the anode and the negative ions and electrons will go toward the cathode. A hole in either the anode or the cathode will lead to the emission of the type of ions desired (see figure 7). However it is likely that the beam will be polluted by other ions of the same charge and a magnetic field must be used to keep only the ions of the correct charge to mass ratio.

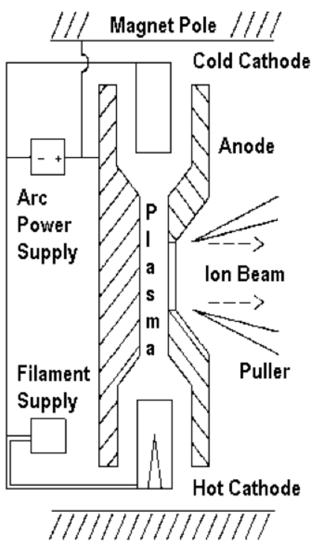


Figure 7: An example of ion source using a plasma.

2.2 Particles Acceleration

The generators proposed by Van de Graaff and Cockroft and Walton are limited by safety concerns: high electric fields can lead to massive breakdowns. On the opposite the idea of accelerating particles in an AC field as proposed by Lawrence does not suffer of such limitations.

Structures made of several AC cavities in which the field is alternatively accelerating and decelarating are the most commonly used device to accelerate particles to high energy. The particles are injected when the field in the first cavity is accelerating. The length of the cavity must be matched to the AC frequency so that when the particle enters the next cavity the field in that cavity is accelerating (see figure 8). At high energy the particles are relativistic and therefore travel nearly the same distance during an AC cycle regardless of their energy, however this is not true at low (non relativistic) energy where the spacing between the cavities has to be adjusted.

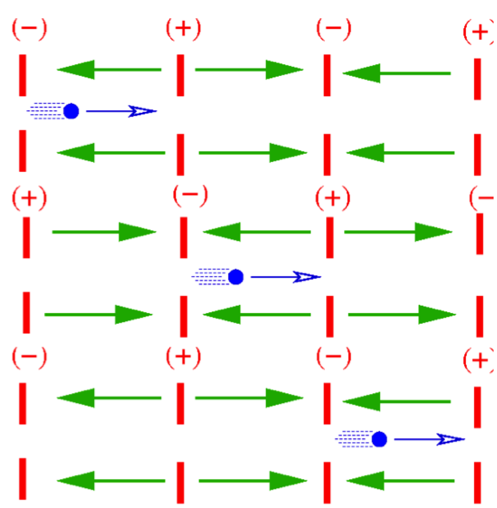


Figure 8: Particle acceleration in an Alternating Current cavity: the frequency of field oscillations must match the travel time between two electrodes.

Such technology has strongly benefited from the developments of radars made during the second world war. Typical cavities use radio-frequency (RF) waves with frequencies of the order of several hundred MHz to a few GHz giving accelerating gradients of 30 to 100 MV/m.

There is virtually no limit in the number of accelerating RF structures that can be placed after each other. The International Linear Collider is foreseen as a long linear accelerator that would reach 1 TeV over 20km!

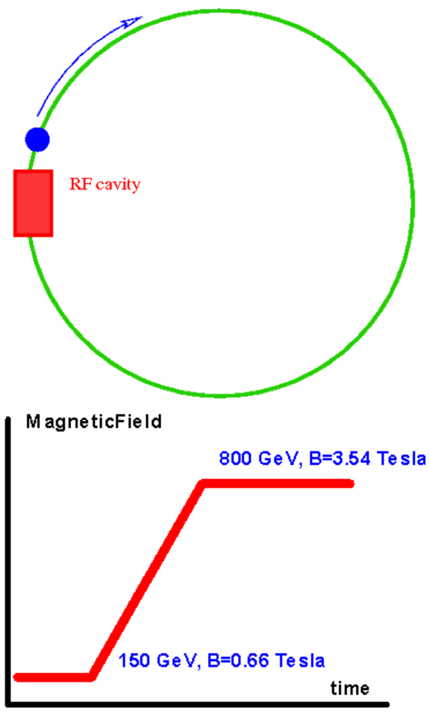


Figure 9: (Top) Basic layout of a synchrotron. (Bottom) Ramping the magnetic field during particle acceleration at HERA.

Instead of using a large number of accelerating structures one after each other one can use a ring to bring back the particles turn after turn to the same accelerating structure. However because the energy of the particles increases after each turn the field of the bending magnets must be increased to keep the bending radius of the particles constant (see figure 9). Because the magnetic field has to be kept synchronous with the particles energy such machine is traditionally called a synchro-cyclotron.

Synchrotron rings allow to recycle particles turn after turn making them the ideal choice for most colliders where the collision cross-section is low (such as the LHC) however as particle are accelerated (and to make the particle go in circle they must be transversely accelerated) they emit radiation. In rings this radiation is called synchrotron radiation and it increases like the fourth power of the beam energy divided by the square of the bending radius. Therefore the ring radius must be large enough to optimize the cost of power loss versus the cost of building a larger ring.

Steering the particles

Whether in a ring or in a linac the trajectory of the particles has to be adjusted. This is done by using electric and magnetic fields to deflect the particles. For equivalent deflecting power magnetic fields consume much less energy than electric ones and therefore it is mostly magnets that are used in particle accelerators.

A simple magnet, made of a north pole and a south pole, will deflect the whole bunch of particles. Such magnet is called a dipole and there are usually two types of dipoles in an accelerator: very large dipole magnets which are used to control the overall trajectory of the beam (for example to follow a circular path in a ring) and small dipole magnets called "steering magnets (steerers)" which are used for fine adjustments of the beam trajectory.

More complex arrangements of magnets are used to change the shape of the beam. A quadrupole magnet is made of two north pole and two south poles arranged so that poles of similar charge face each other as shown on figure 10, top. Such layout results in the field being null in the middle and then more intense further away from the quadrupole's axis. This will result in the particles further away from the axis in being more strongly deflected than those near the axis. In one plane of the magnet the deflection will be toward the axis (focussing) whereas in the other it will be away from the axis (defocussing). To get a net focussing effect two quadrupoles must be placed a few meters apart (see figure 10, bottom). With such arrangement, called a FODO (FOcussing DefOcussing) cell the first quadrupole will focus in one plane and defocus in the other whereas the second quadrupole will do the opposite. Because the particles that have been defocussed in the first quadrupole are now further away from the axis they will be strongly focussed whereas the particles initially focussed are now close from the axis and therefore they will be weakly defocussed. Therefore a quadrupole results in a net focussing of the beam.

Higher order magnets called sextupoles (with 3 north poles and 3 south poles) are sometimes used to compensate the fact that particle with slightly different energy will be deflected with different intensity (this is called beam chromaticity).

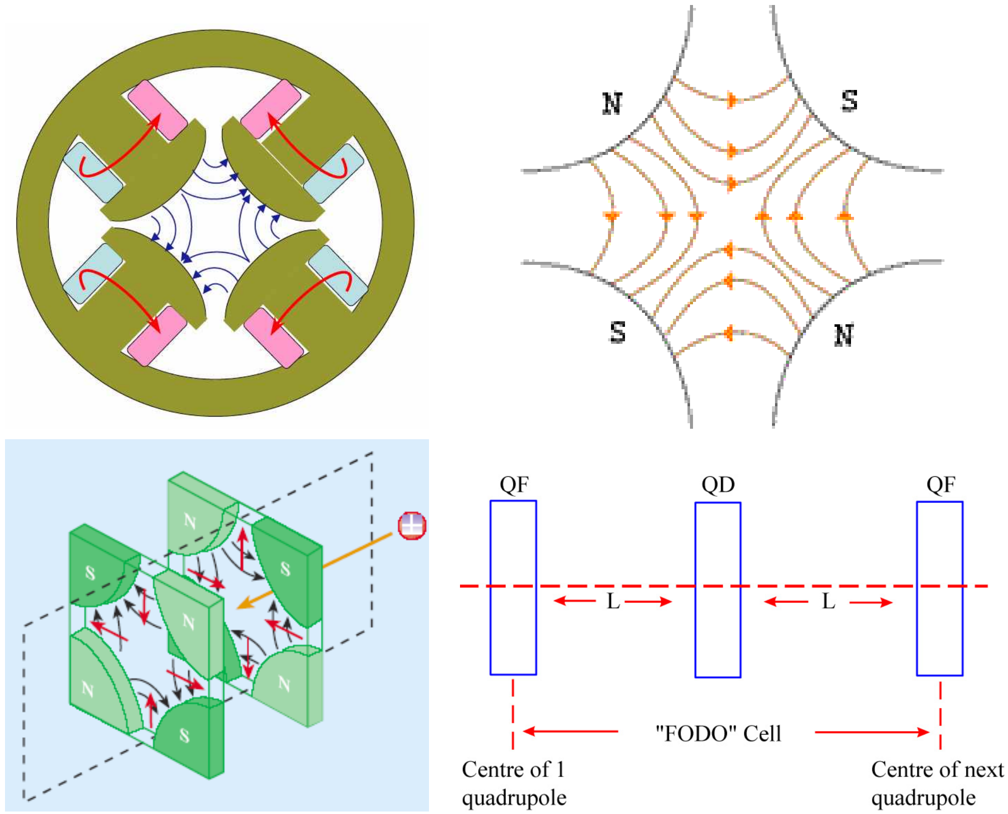


Figure 10: (Top) Examples of quadrupoles with the magnetic field lines. (Bottom left) Arrangement of two consecutive magnets in a FODO cell. (Bottom right) Basic FODO cell layout.

One of the main disadvantage of magnets is that the inductance will resist any change of field resulting in rather slow changes in deflecting power. For applications that require a fast change (on the time scale of a few nanoseconds) it is common to use electric kickers made of two electrodes in which a high voltage pulse is sent. Kickers are often used at the entrance or the exit of rings to be able to inject or extract bunch of particles without disturbing the other particles in the ring.

Lattice

To keep the beam focussed along the full length of the accelerator (either linac or ring) there are usually a large number of magnets. The arrangement of these magnets is called its lattice. Example of lattice are shown on figure 11. The evolution of the beam transverse size as it travels through the lattice is expressed by the "beta-function" (which will be discussed later).

3 Beam dynamics

We will now study what happens to the beams as they are traveling.

3.1 Emittance

Definition of emittance

Seen from the laboratory frame all particles seem to be traveling in the same direction at a very high speed however an observer sitting in the beam's frame would see a very different picture:

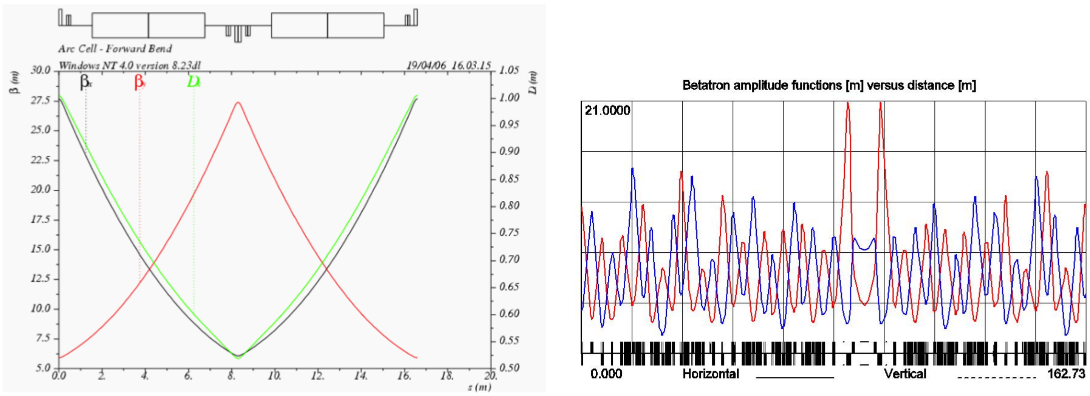


Figure 11: Examples of lattice. (Left) FODO lattice. (Right) More complicated lattice with several FODO elements.

like in any large statistical sample, each particle will have its own motion in the beam frame and the whole bunch can be compared to a gas of electron.

Using an analogy with a perfect gas, we can try to translate the perfect gas law $PV = nRT$ into variables related to the bunch. P is the pressure of a gas, that is a dynamic term, it correspond to the speed of all the molecules. In a particle bunch it corresponds to the speed of the particles in each of the 3 dimensions [b]: $x'_i y'_i z'_i$. V is the volume term, it corresponds to the position of the particles in the 3 dimensions: xyz. n is the number of moles in the gas, normalized by a constant its equivalent to the number of particles in the bunch. R is a constant, for a particle bunch it is conveniently taken either as equal to 1 or π (depending on the convention; for simplicity we will take it equal to 1). T is the temperature of the bunch, let's define an equivalent quantity for a particle bunch and call it emittance, noted ϵ.

We have the relation:

$$\epsilon = \Pi_i x_i x'_i y_i y'_i z_i z'_i$$

This is often written as

$$\epsilon = xx'yy'zz'$$

As the motion and position in the 3 dimensions are not correlated, the emittance can be split into transverse (ϵ_t) and longitudinal (ϵ_l) components:

$$\epsilon_t = xx'yy' \ \epsilon_l = zz'$$

The emittance of a particle beam is a measure of its "temperature".

The perfect gas law tells us that to have a high temperature gas in a small volume large compression forces must be applied. Similarly, a particle beam with a large emittance will be much more difficult to focus to a small volume. As the number of collisions that occur (the luminosity) is inversely proportional to the beam size a higher emittance will lead to less collisions. That is why it is important to build accelerators with low transverse emittance [c].

As outlying particles could dominate the emittance measurement, emittance is often quoted for 90% of the beam (ϵ_{90}) or for the root mean square (RMS) size of the beam (ϵ_{RMS}).

In statistical physics, Liouville's theorem states the volume occupied by a system in phase-space is constant (unless external forces are applied). This appears in the perfect gas law: if you compress the gas, its volume becomes smaller but its pressure increases, the product PV is

[b] We assume that x and y are the transverse dimensions and z is the dimension along the beam propagation axis.

[c] One should be aware that the word "emittance" is often used with the meaning of "transverse emittance" instead of the total emittance in the 3 spatial and 3 momentum dimensions.

conserved. Similarly for a beam of particles the emittance is conserved, and this is true is each dimension separately, that is the products $\Pi_i x_i x'_i$, $\Pi_i y_i y'_i$, $\Pi_i z_i z'_i$ are conserved.

Emittance during beam propagation

It may sound counterintuitive that the product $\Pi_i x_i x'_i$ is conserved when the beam propagate as we know that for a divergent beam x increases while the transverse momentum x' is constant. However this is true, let's look more in details at a propagating beam.

The transverse emittance can be represented by a plot with the x position of each particle on the horizontal axis and the x' momentum of each particle on the vertical axis (see figure 12). When the particles are generated their distribution forms an ellipse in the phase-space plane (whether the ellipse is horizontal, vertical or a circle depends on the beam parameters and the scale chosen for the axis), this is shown on figure 12 (a). As the particles drift (travel) in the accelerator, their x' coordinate does not change, however their x coordinate increases (or decreases) proportionally to their momentum and therefore the ellipse shears (figure 12 b). A thin quadrupole has almost no effect on the position of the particles but it has a strong effect on their transverse momentum: ideally the transverse momentum of the particles should be zero in the middle of a focussing quadrupole (figure 12 c). After the quadrupole the particles drift again but this time starting all with almost the same momentum and different positions, giving an ellipse sheared in the opposite direction (figure 12 d). At some point it will pass again a waist where the particles have a similar momentum but different positions (figure 12 a) and then shear in the other direction (figure 12 b) until the next quadrupole...

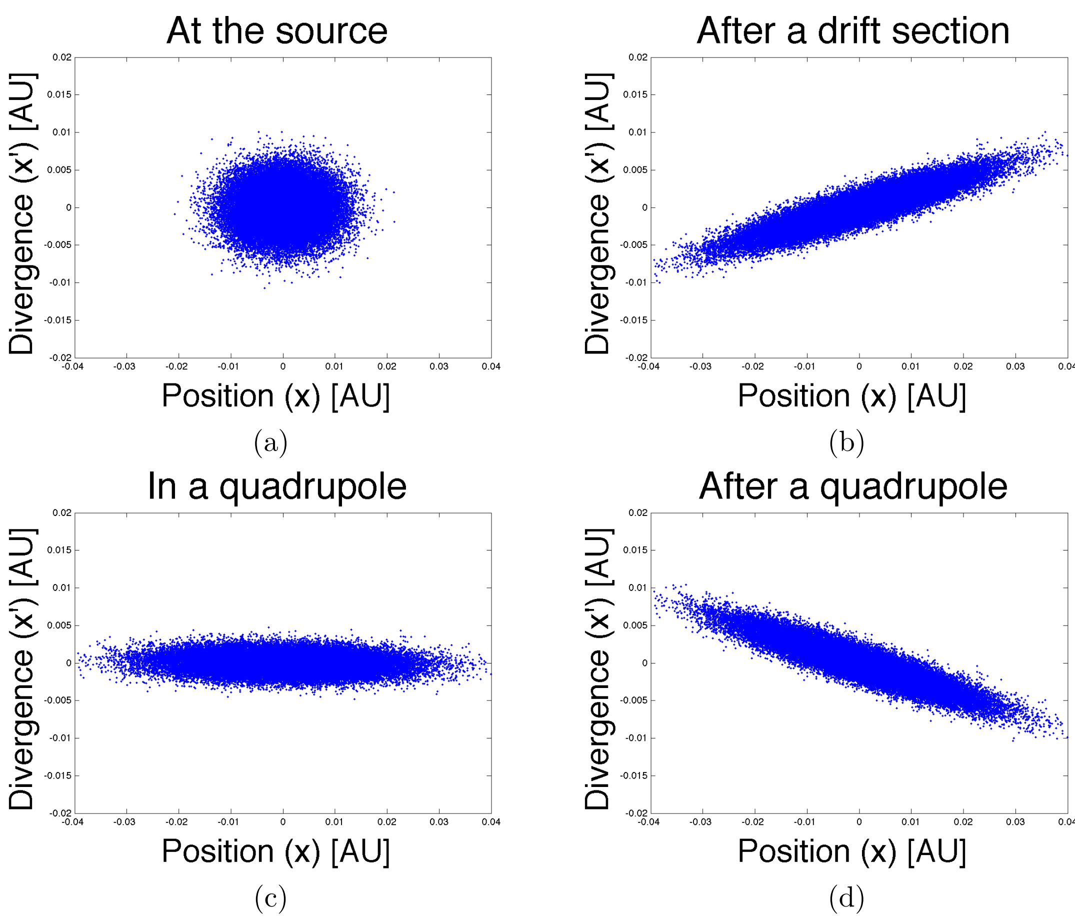


Figure 12: Phase-space (transverse emittance ellipses) along an accelerator: (a) At the source, (b) after a drift section, (c) in a focussing quadrupole and (d) after a focussing quadrupole.

As we can see the shape of the emittance ellipse changes as the beam propagates and therefore the product of the size by the momentum distribution is not constant. However, the surface of the ellipse (product of the half-length of the major axis by the minor axis) does not change. To measure the transverse RMS emittance correctly one has to use the following formula:

$$\epsilon_{RMS,x} = \sqrt{< x^2 >< x'^2 > - < xx' >}$$

where the operator <> denotes the average of a distribution.

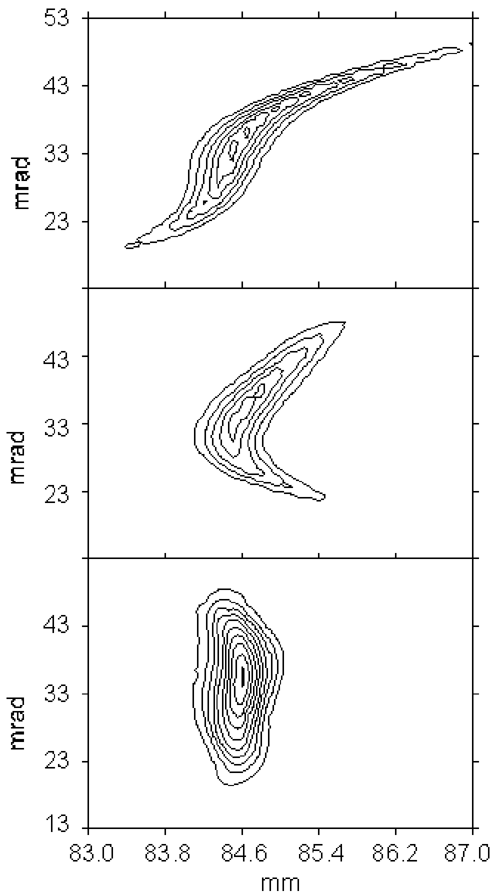


Figure 13: Example of transverse emittance ellipses measurement at Triumf (Canada).

Real beams are more complicated than the ideal picture described above, in particular because it is impossible to build perfect magnets, and therefore the phase-space will be distorted as the beam propagates (see figure 13).

However measuring such ellipse is not always easy as we will see in section 4.4.

In the transverse plane the emittance ($\epsilon_{x,y}$) links the beam size ($\sigma_{x,y}$) to the beta-function ($\beta_{x,y}$) of the lattice by the following relation:

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\epsilon_{x,y}}$$

Acceleration

When a classical beam is accelerated the derivative $\frac{dz}{dt}$ increases whereas $\frac{dx}{dt}$ remains constant (see figure 14). For a relativistic beam on the other hand acceleration becomes equivalent to time dilatation and therefore x' decreases: for an accelerated beam the transverse emittance decreases proportionally to the increase of the relativistic factor γ. The transverse emittance is not constant under an external accelerating force however, the product of the transverse emittance by γ is constant, where can therefore define the normalized transverse emittance ($\epsilon N, t$):

$$\epsilon N, t = \gamma \epsilon_t$$

By opposition to the normalized emittance ϵ_t, the non-normalized emittance is also sometimes called "geometric emittance".

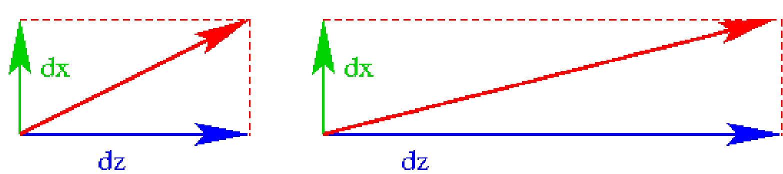


Figure 14: Effect of acceleration on a beam.

Synchrotron radiation

We have seen previously that in a ring particles emit synchrotron radiation due to their trajectory being bent. This radiation is emitted preferably in the plane of the ring (i.e. horizontally). The loss of energy will have to be compensated by further acceleration in the ring and because there is acceleration there will be a reduction of the transverse emittance. In the ring's plane the recoil of the electrons due to the emission of synchrotron radiation photons partly compensate the emittance reduction but not completely. Storing a beam in a ring will therefore lead to an overall reduction of its emittance (down to an equilibrium set by the lattice). This is called damping. In some linear accelerators (such as the SLC at SLAC) dedicated rings called damping rings are used specially for this purpose.

3.2 Wakefield

Any charged object is surrounded by an electromagnetic field. When the object, for example a particle, is traveling this field is mostly behind the object and is called the "wakefield". It can be compared to the wake that can be seen behind a boat moving on water. The wakefield will bounce on conducting surfaces such as beam pipes. It results that the electromagnetic field behind a particle is very complicated. In some cases, injecting a second bunch of particles immediately after a first one may lead to severe disruption of the second bunch. This is a strong limitation on the maximum charge that can be stored in an accelerator (the higher the charge the stronger the wakefield).

3.3 Impedance issues

The wakefield also induces image charges in the beam pipe (see image 15, left). This image current takes power from the beam and dissipates it in the beam pipe by Joule effect (heating), this power is proportional to the impedance of the beam pipe. The smaller the beam pipe the higher the induced charge and thus the higher the energy losses. An asymmetric or irregular beam pipe (from an impedance point of view) will lead to asymmetric losses or to parasitic currents circulating in the accelerator.

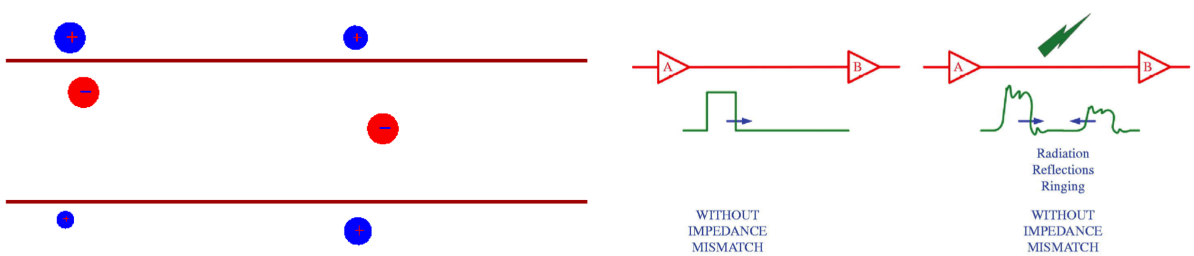


Figure 15: (left) A particle traveling in a beam pipe induces charges on the pipe's walls. (Right) An impedance mismatch in a high-frequency line (such as a particle accelerator) leads to part of the signal being reflected and interfering with subsequent pulses.

Larger beam pipes are not a solution to mitigate this problem as they require magnets with larger aperture and larger vacuum volume, both leading to more expensive (and technologically complicated) solutions.

If the impedance of the beam pipe is mismatched at some point, the same problem will occur than in any other oscillating electrical circuit: part of the signal will be reflected and travel backward, hitting the next pulse or the same pulse on its next turn (see image 15, right).

Therefore in accelerators and in particular in rings it is very important to control very carefully the impedance all along the circumference of the ring.

3.4 Space charge effects and Coulomb scattering

All the particles in a bunch are similar, this means that they have the same electric charge. The Coulomb force is therefore pushing them away from each other. This leads to the bunch "blowing-up". However this phenomena is usually visible only at the early stages of acceleration when the momentum of the particles is low. At higher energy the Coulomb force will also play a role when trying to focus the beam too much: particles will Coulomb scatter onto each other leading either to an emittance growth (Intra-beam scattering) or to the loss of some particles by hard scattering (This is known as the Touschek effect).

Two colliding beams will also exert very strong electromagnetic forces onto each other: this is called the beam-beam effect and it is a strong limitation in circular colliders: the size of the beam at the collision point must not be too small to prevent the beam-beam disruption from destroying the beam.

3.5 Longitudinal dynamics

In a ring the bending strength of the magnets depends on the energy of the particles. In a bunch all particles have almost the same energy but in fact there is a small energy spread (typically a few percent). Particle with more energy than average will be more deflected than the average particle of the bunch and inversely. This means that within a set envelope all particles follow a slightly different trajectory. A parameter called the "momentum compaction factor" gives the relation between the particles energy and the length of the trajectory they travel.

This difference in path length leads in turn to particles not arriving exactly at the same time (position spread) at the RF accelerating cavity and therefore not getting exactly the same acceleration (see figure 16, left).

It is easy to notice that some combinations will be unstable (for example if particles with less energy than average arrive late and therefore receive even less energy). A simple change in the RF setting (change of phase) can switch from a stable to an unstable configuration (figure 16, right). The change in longitudinal position of the particles after one turn in a ring is related to their energy by the momentum compaction factor (α_c). The momentum compaction factor and the phase and amplitude of the RF oscillation in the cavity define together combinations of energy and position (phase) offset that are stable and combinations that are unstable. The stable area is called the RF bucket as shown on figure 16, right. The effect this has on the longitudinal shape of the bunch can be seen on figure 17.

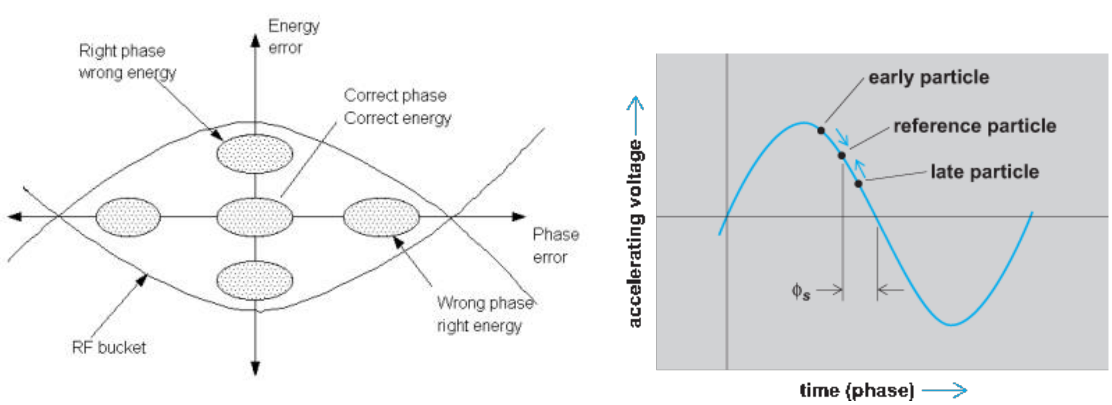
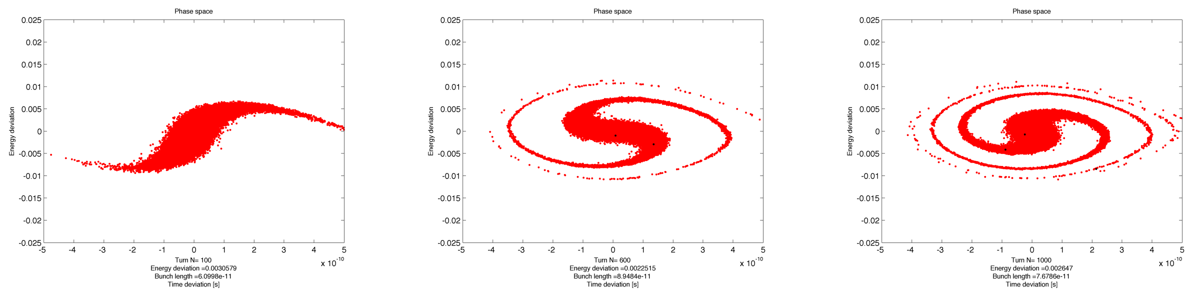


Figure 16: (Left) Properties of the particles in the RF bucket. (Right) Acceleration of particles in a RF accelerating cavity.

3.6 Lifetime

Particle beams do not stay forever in an accelerator. Several processes make that after a few seconds, minutes or hours the beam is no longer suitable for its purpose, the beam must then



100 turns | 600 turns | 1000 turns

Figure 17: Evolution of the longitudinal shape (of a particle bunch after 100, 600 and 1000 turns in an accelerator (Longitudinal position on the horizontal axis, relative energy on the vertical axis).

be discarded and a fresh one injected. Among these limiting factors, there is of courses the particles lost during collisions at the interaction point(s), but there is also intra-beam scattering (soft Coulomb scattering) and Touschek effect (hard Coulomb scattering), interactions with residual ions,...

Instead of dumping the beam advanced accelerators and especially light sources use a technique called "top-up" to inject regularly very small amount of particles on top of the existing bunches to replace losses. This gives users a much more regular filling pattern.

4 Beam diagnostics

Once the particle beam has been produced, one must check during all its lifetime that it behaves as required. This is done by inserting monitoring devices along the beam line. These monitoring devices will use two types of phenomena: either directly the absorption of particles by the detector (destructive monitor) or indirect detection by monitoring the electromagnetic radiation emitted by the bunch. Destructive monitors are often easier to implement or more accurate but they can only be used once at a time along the beam trajectory. All these diagnostics are summarized in table 1 at the end of this section.

4.1 Charge measurement

Faraday cup A Faraday cup is simply a well-insulated piece of copper thick enough to stop the beam. When the beam hits the piece of copper all its charge is transferred to it (provided that the copper is placed at the right electrical potential to also capture all scattered particles). An ammeter located between the piece of copper and the ground will then measure the charge collected by the Faraday cup, that is the charge of the beam.

Beam current monitor We have seen previously that the beam induces image charges in the beam pipe. By inserting a non-conducting gap (see figure 18, left) in the beam pipe and putting an ammeter between the two conducting sections it is possible to measure the charge traveling in the beam pipe, which is equal to the beam charge.

4.2 Position measurement

Screen Particles hitting a material deposit energy. This energy can in turn excite atoms that will emit light when returning to their ground state. This is the principle of (old) phosphorescent TV screens. This principle is used with high purity phosphorescent materials in accelerators to accurately find where the beam is.

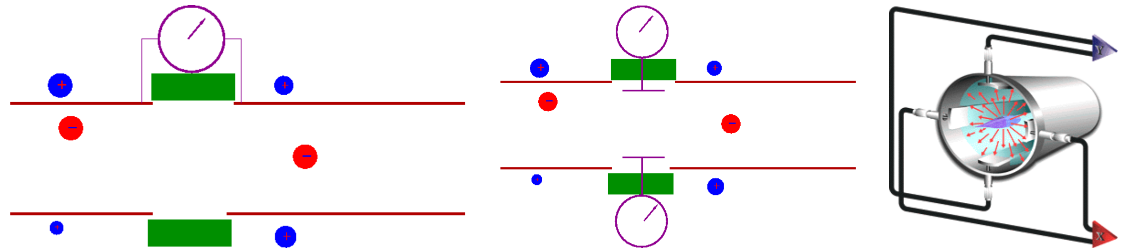


Figure 18: (Left) In a wall current monitor a single monitor measures all the current induced by the particles in the beam pipe. (Center) In a beam position monitor (BPM) four electrodes located around the beam pipe are used to measure the charge induced by the passage of an electron. In each electrode this charge is function of the distance from the electron bunch to the electrode. (Right) The beam position can be deduced by subtracting the signal measured by opposite electrodes.

Beam position monitors The distribution of the charges induced in the beam pipe is proportional to the distance of the beam to the wall in each direction. Therefore by putting small antennas in the 4 directions around the beam pipe and comparing the signal measured on each of them it is possible to measure the beam position without disturbing the beam (see figure 18, center and right).

4.3 Bunch length

The measurement of bunch length is much more difficult and it is still an active field of research. This has become even more important with the latest generation of accelerators (free electron lasers) where bunches must be kept very small to deliver the required performances.

Deflecting cavity A purpose-made RF cavity can be used to give a transverse acceleration to a particle bunch. If the bunch is injected so that the middle of the bunch passes exactly when the field in that cavity becomes 0 the head of the bunch will get a transverse acceleration in one direction and the tail an acceleration exactly in the opposite direction (see figure 19), leading to a bunch rotation from the longitudinal to the transverse plane. A screen located downstream will then image this rotated bunch, giving a measure of the longitudinal profile of the bunch as it was before deflection.

Coherent radiation There are several phenomenon by which a bunch can radiate. If the wavelength of the radiated photon is longer than the bunch length it will trigger coherent emission by all the particles of the bunch. This coherent emission is much stronger than incoherent emission. By detecting the wavelength at which coherent emission occurs one can estimate the length of the bunch. In some cases, such as for example Smith-Purcell radiation, it is even possible to measure the spectrum of the emission, which encodes the Fourier transform of the bunch longitudinal profile.

4.4 Transverse Emittance measurement

We have seen previously that transverse emittance is an important parameter for a collider to deliver the required luminosity. However, transverse emittance is not a direct observable, it is the product of two variables that must be measured (almost) simultaneously.

Pepper-pot A solution to measure (almost) simultaneously the beam position and beam divergence is to send the beam on a “pepper-pot”, that is a set of holes or slits that will let the beam through only at a few places (see figure 20, left).

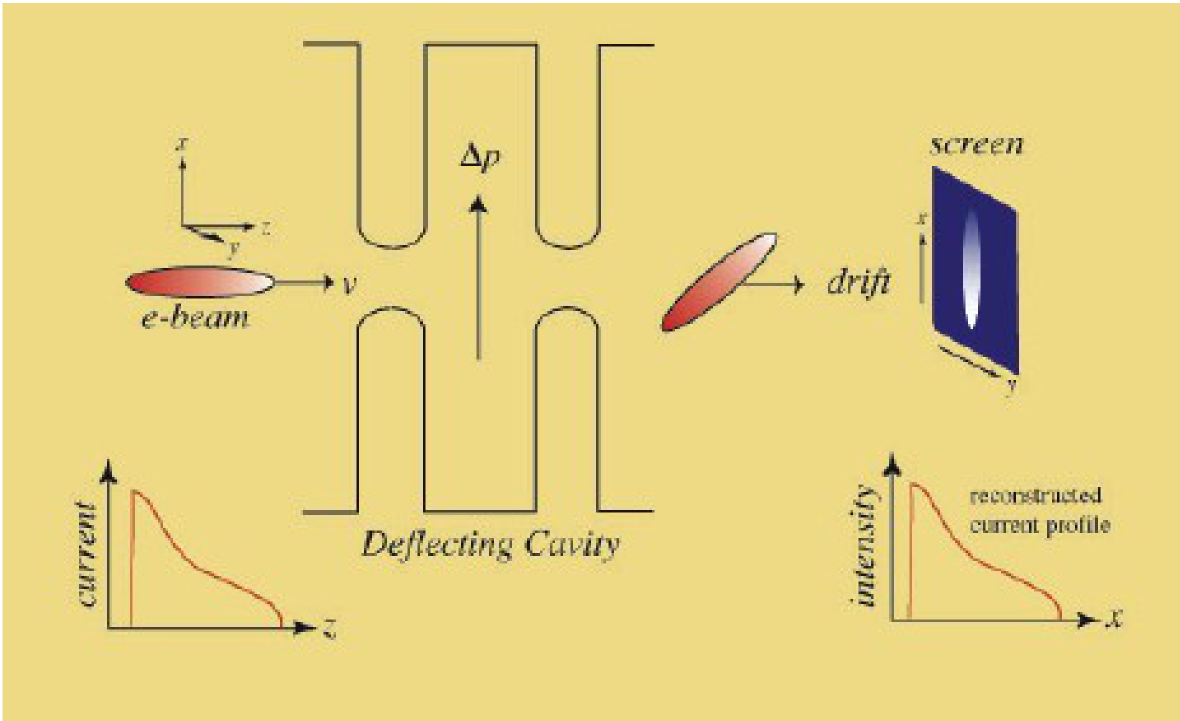


Figure 19: Deflection of an electron bunch in a deflecting cavity to measure its longitudinal profile.)

Looking again at the phase space, the beam will be cut in several beamlets whose position is well defined (the position of the holes; see figure 20, center). After a drift section the beamlets will shear in phase space. This shearing corresponds to their divergence and can be measured on the transverse dimension (horizontal axis on figure 20, right). Hence once can know both the position of the beamlets and their divergence, giving the emittance of the beam.

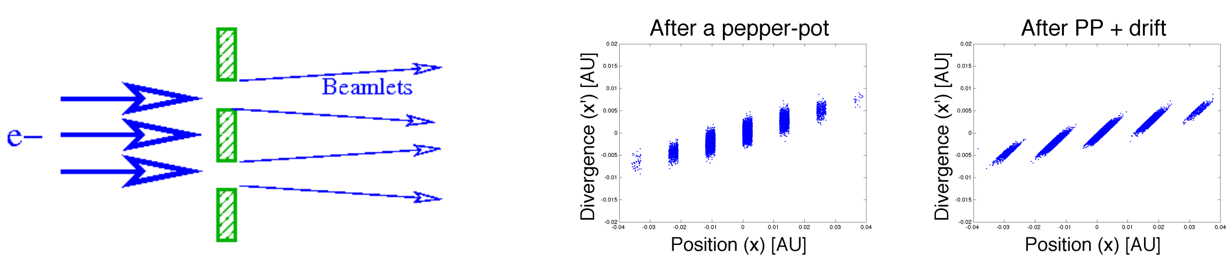


Figure 20: Measurement of the transverse emittance of a particle bunch using pepper-pot: The beam is broken in beamlets of known position (left) and their divergence is measured after some drift (right).

Beam envelope scan The transverse emittance of the beam is related to how easily the beam can be focussed. By measuring how the beam envelope evolves in the field of a quadrupole one can measure how easily this beam is being compressed, giving access to the transverse emittance. Such measurement can be performed by having several screens behind a quadrupole, however this is expensive and often impractical. Instead one can have a single screen and vary the strength of the quadrupole (this is called a quadrupole scan).

Table 1: Beam diagnostics summary table

	Interaction with matter	*Radiation*
Charge	Faraday cup	Beam current monitor
Position	Screen (phosphorescent)	Beam position monitor
Size or shape (transverse)	Screen or wire-scanner (*)	Synchrotron radiation imaging (*) or OTR (*)
Size or shape (longitudinal)	RF deflecting cavity	Coherent radiation detector
Energy		Magnet (spectrometer) (*)
Beam losses	Scintillator (*)	
Transverse emittance	pepper pot or quadrupole scan	

(*) These diagnostics are not discussed in this document.

5 Applications of particle accelerators beyond High Energy Physics

The other presentations given during this school cover in details the applications of particle accelerators in high energy physics. However most accelerators in the world are not in high energy physics labs. We will briefly look at some of the applications of particle accelerators beyond high energy physics.

5.1 Light sources

Most GeV class electron accelerators in the world are used as very intense sources of light.

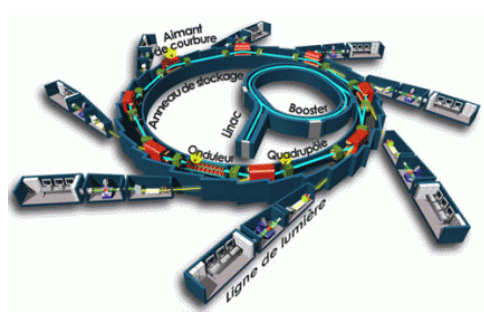


Figure 21: The synchroton SOLEIL.

3rd generation: Synchrotrons In a 3rd generation light source an electron beam with a very low emittance is injected in a storage ring (see figure 21). This storage ring is equipped with special magnets called "ondulators" in which the beam oscillate, enhancing significantly the intensity of the synchrotron radiation emitted (these facility are often called "synchrotrons"). Depending on the magnets configuration this radiation spans from the deep infrared to the soft X-rays. They have been used for a large number of applications such as:

- *Reading a manuscript without opening it!* The dead sea scrolls are very precious manuscript on which parts of the ancient testament are written. These manuscripts found in caves near the dead sea are often too brittle to be unfolded. To read them researchers have exposed them to X-rays tuned to the right wavelength so that they could see in 3D where the ink was on the folded roll. A computer software was then used to "unfold" the manuscript.

- *Heritage studies* X-rays can be used to probe the composition of a material such as a paint. This can be used to study painting techniques and therefore compare artists techniques. X-rays can also reveal hidden details of a painting or of a sculpture.

- *Crystalline structure of chocolate* When chocolate is left in the sun it melts. Once it cools down it has a slightly white color. To understand why this happens a famous candy maker has exposed chocolate samples to an X-ray beam and found that chocolate crystals can take several different configurations depending how it is baked. One of them is unstable and can easily decay to another configuration giving this white color.

- *Protein structures* X-ray diffraction allows to see the structure of all sorts of crystals. This is used for example by pharmaceutical companies to check that the structure of the molecules they are producing matches the sites of the virus they should attack.

Synchrotrons used as 3rd generation light source are now rather common and all large developed countries have built one.

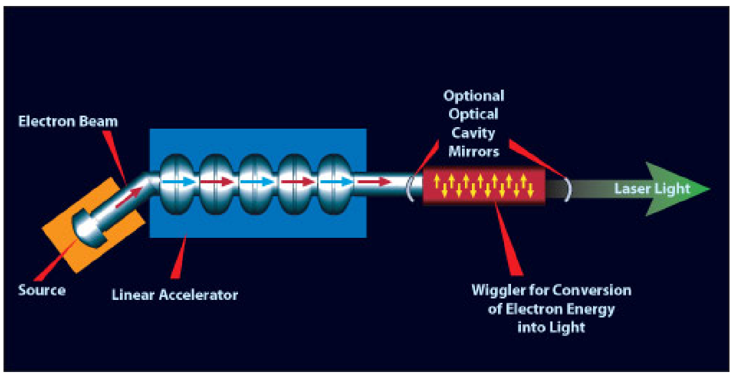


Figure 22: Principle of a Free Electron Laser

4th generation: Free Electron Lasers If the right conditions are met an electron bunch can emit light coherently with a very high intensity. This is done in linac based Free Electron Lasers (FEL) as shown on figure 22. FELs produce very intense very short pulses of light allowing for example to reconstruct how the structure of a protein evolves during a chemical reaction. Although several FELs have been built worldwide these machine remain at the edge of what can be done in accelerator science to achieve good lasing conditions.

Compact X-ray sources Synchrotrons and FELs are expensive to build (in the hundreds millions euros range) and it is therefore difficult to get experimental time on them. Some applications can accept X-rays of lower quality if that means an easier access. Some applications would also benefit of the availability of X-rays elsewhere than at national facilities (eg: some medical applications in hospitals or heritage applications in museums). This has prompted the development of a new class of machines called Compact X-ray sources. These machine use Compton scattering to transfer the energy of the electrons in the ring to laser photons which then become X-rays. This can be done with a low energy electron ring (about 50 MeV) and is cheaper to build than a full synchrotron. However it can only be equipped with one or two X-rays lines instead of several dozens at a 3rd generation light source. The LAL at Orsay is leading the development of one such machine called ThomX.

5.2 Medical accelerators

Most particle accelerators in the world are used for medical purpose. In most developed countries all majors cities have one or more small linear accelerator in a hospital used for cancer treatment by radiotherapy.

Radiotherapy Radiotherapy is used to kill cancer tumors by delivering a high dose of radiation localized on the tumor. This high dose of radiation is produced with a small electron linac producing about 10-50 MeV electrons. These electrons are sent on a metal target where they emit X-rays by bremstrahlung. Unlike the X-rays of a synchrotron the X-rays produced in a medical linac have a poor coherence and a very wide-band spectrum. However this is good enough to deliver high doses of radiations to a tumor. To minimize the impact of radiotherapy

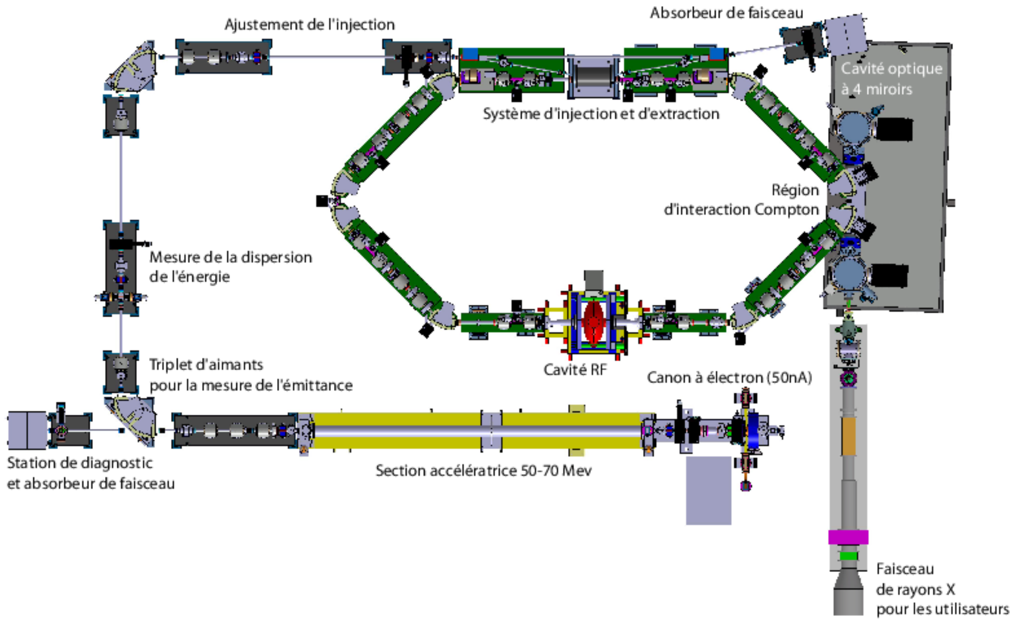


Figure 23: The ThomX compact X-ray source being built at Orsay. The electrons are accelerated in the section shown in yellow and they are then stored in the ring (green). Each time they pass the optical table on the right of the picture they interact with a laser and emit X-rays (toward the bottom of the figure).

on the healthy organs near the tumor, the lethal dose is not delivered at once: the dose is sent from several different direction traversing different organs. As a results the organs around the tumor receive a dose that is high but still acceptable and only the area of the tumor is killed. Accelerators used in radiotherapy are less than 2 meter long. They are often mounted on a rotating structure that allows them to send X-rays from several different directions.

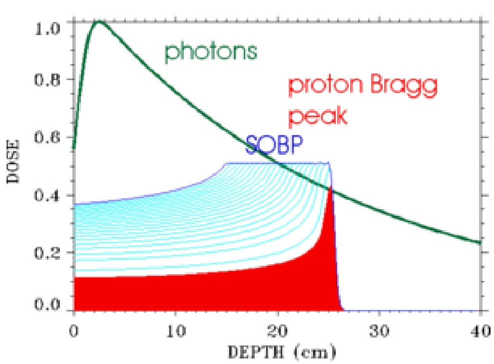


Figure 25: Photons deposit a dose over all the depth of their trajectory whereas protons will deposit most of their energy where they stop (Bragg peak). By varying the energy of the protons it is also possible to spread the depth of the Bragg peak (SOBP - Spread Out Bragg Peak).

Proton therapy For young patients who have not completed their growth, the side effects of radiotherapy may be unacceptable. In that case the radiation dose may be delivered by protons. Protons being heavy they have the advantage that they deliver most of their energy (the radiation dose) where they stop and not in the organs they traverse before (see figure 25). This has the advantage that the doses delivered to other organs is even lower. However this requires a proton accelerator which is much more expensive and complicated to operate than an electron machine, restricting this therapy to cases where it has a clear advantage. There are only a few proton therapy centers in Europe (including one in Orsay).

Heavier ions such as carbon ions may provide an even better contrast between the dose delivered to the tumor and the dose received by the surrounding organs. This is being studied at a few centers in the world.

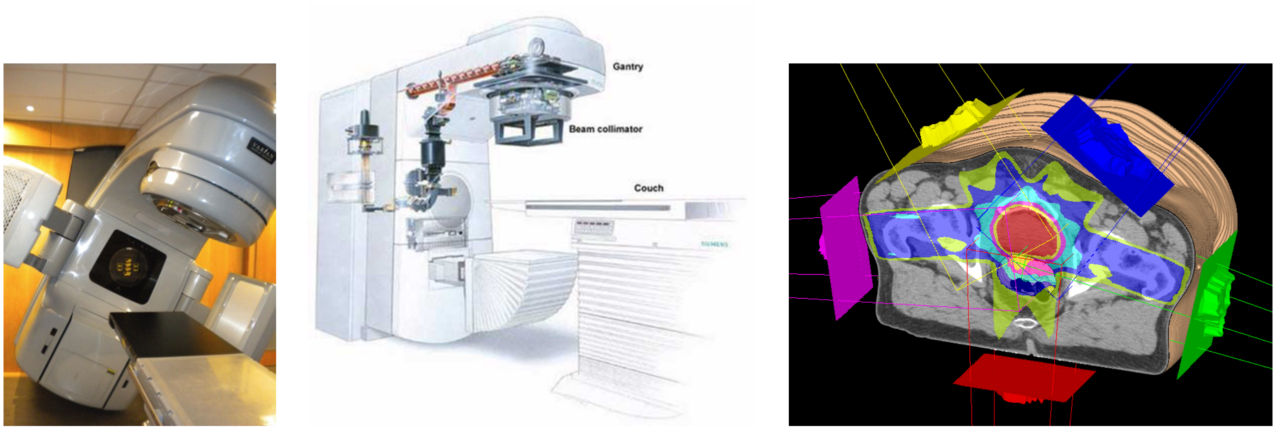


Figure 24: (Left) Photo of a medical linac in an hospital room. (Center) Drawing of a radiotherapy linac. (Right) Dose delivered to various organs when the tumor is attacked from 5 different sides. The highest dose (lethal) is in red at the intersection of the 5 beams. On the path of a single beam the doses are lower (in blue and yellow) and the organs will be able to recover.

Medical isotopes In some treatments doctors need to give the patient a radioactive isotope. This is used for example in Positron Emission Tomography (PET). To minimize the radioactive dose received by the patient and his family the radioactive isotope much be as short lived as possible. This requires the isotope to be produced at or near the hospital. Some of these isotope can be produced by accelerating protons in a cyclotron and sending them on a target of a suitable material. The target is then removed from the accelerator and the required isotopes are chemically extracted and added to a drug.

5.3 Accelerator Mass Spectroscopy and Radiocarbon dating

Accelerator Mass Spectroscopy (AMS) is used to measure the isotopic composition of a sample. In AMS a sample is ionized and the ions are accelerated to a few MeV (typically in a tandem accelerator). Once accelerated the ions are sent through a magnet(spectrometer) in which different isotopes will be bent differently due to their different masses. Faraday cups located behind the spectrometer count the ions giving the isotopic content of the sample.

AMS is the most popular method to find the age of an historic organic sample: it can be used to measure the ratio between carbon-13 (stable) and carbon-14 (radioactive with an half-life of 5568 ± 30 years) in the sample and therefore give the time that has elapsed since its death.

5.4 Neutron sources

Protons sent on a neutron rich target (such as tantalum) will transfer part of their kinetic energy to the neutrons, creating a beam of neutrons. Neutrons can penetrate deeply in matter and reveal some structural details. Typical accelerator driven neutron sources require a proton linac and sometimes a ring to reach an energy of several hundred MeVs or more per proton on target.

5.5 Accelerator Driven System

Accelerator Driven System (ADS) are a concept being studied in which a neutron beam produced by an accelerator is used to burn nuclear waste or subcritical nuclear fuel (unenriched Uranium or Thorium - see figure 26). The principle is similar to that of a neutron source except that the repetition rate must be higher. One of the main challenges of ADS is the thermal fatigue of the nuclear reactor each time the driving accelerator stops. To limit this fatigue very stringent limits are set on the unplanned accelerator stops/failures. These limits are much more stringent that what is commonly achieved with such neutron sources and R&D is ongoing to see how such reliability can be achieved with high redundancy (that is having most components of the accelerator duplicated so that if one fails the other one can take over).

A first prototype is being built in Belgium but more than a decade will be necessary before such accelerator can be used commercially to burn nuclear waste.

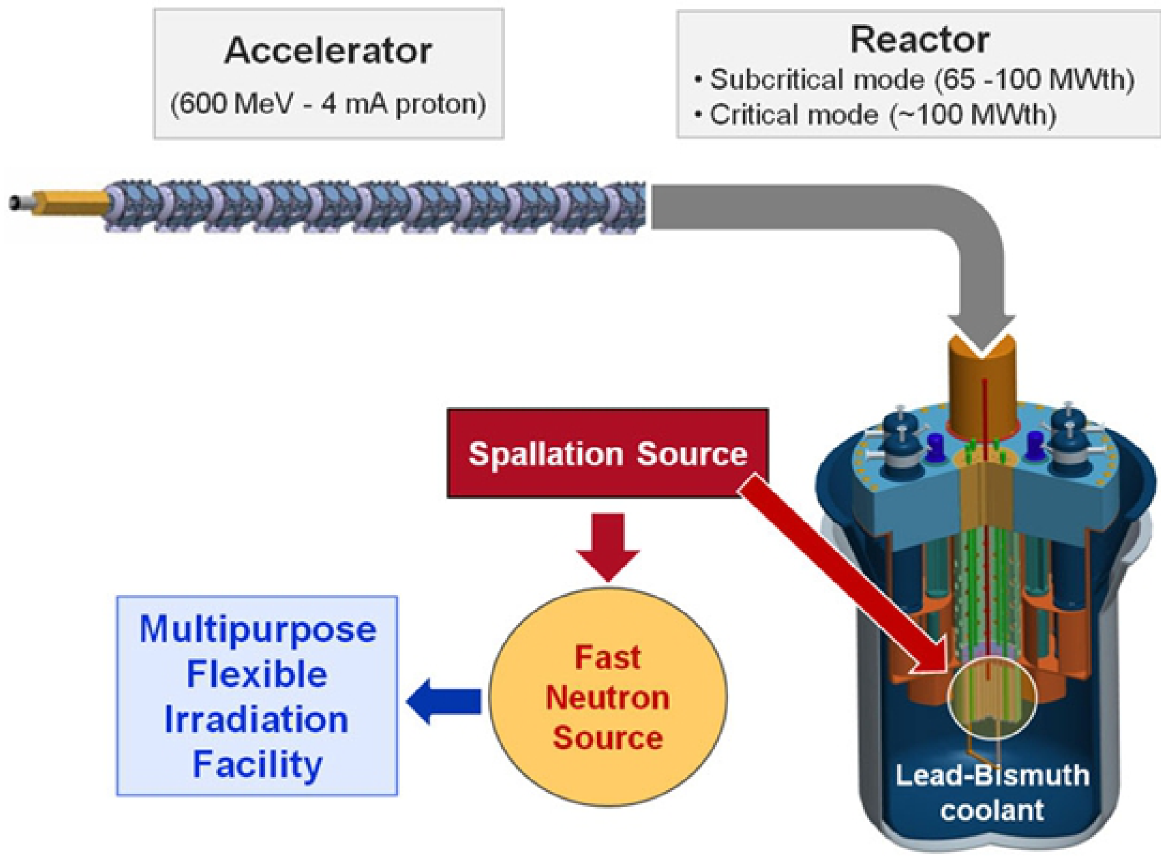


Figure 26: An example of accelerator driven system where an accelerator is used to produce neutrons that trigger nuclear reactions in a sub-critical nuclear fuel assembly.

6 Outlook

Accelerator science is a very wide field with a large number of applications. Designing, constructing and operating an accelerator requires a large number of skills from different parts of physics (electromagnetism, optics, electronics, material science, lasers, ...).

The biggest accelerators such as the LHC or synchrotron light sources are the best known but in fact there are much more smaller accelerators such as medical linacs installed in hospitals.

7 Further readings

Participants to the school are more than welcome to email me if they have questions about accelerators and how they work.

This document is only a short introduction to what happens in particle accelerators. The interested reader is invited to read the following publications:

- "Accelerators for pedestrians" CERN-AB-Note-2007-014.
  Available for free online at http://cdsweb.cern.ch/record/1017689
- An introduction to particle accelerators, Edmund Wilson
- The physics of Particle accelerators, Klaus Wille

And if you want to learn much more:

- Handbook of Accelerator Physics and Engineering, by Alex Chao and Maury Tigner ISBN-10: 9810235003
- Charged Particle Beams, by Stanley Humphries.
  Available for free online at http://www.fieldp.com/cpb/cpb.html
- Principles of Charged Particle Acceleration by Stanley Humphries.
  Available for free online at http://www.fieldp.com/cpa/cpa.html
- LHC Machine, Lyndon Evans and Philip Bryant 2008 JINST 3 S08001 doi:10.1088/1748-0221/3/08/S08001 http://iopscience.iop.org/1748-0221/3/08/S08001

Image credits

- Figure 1 http://people.clarkson.edu/~ekatz/scientists/graaff.html
- Figure 2 and 3 Wikipedia
- Figure 4 Adapted from http://cnx.org/content/m13458/latest/
- Figure 5 Masao Kuriki, ILC school, 2006
- Figure 7 CERN
- Figure 9 DESY
- Figure 13 TRIUMF
- Figure 17 Iryna Chaikovska, LAL, Orsay
- Figure 19 http://pbpl.physics.ucla.edu/Research/Experiments/Beam_Manipulation/Ramped_Electron_Bunch_Experiment/5_Deflecting_Cavity/
- Figure 21 Synchrotron SOLEIL http://www.synchrotron-soleil.fr/
- Figure 22 http://www.lightsources.org/
- Figure 23 LAL
- Figure 24 (left) http://www.myradiotherapy.com/
- Figure 24 (center) http://www.cedars-sinai.edu
- Figure 24 (right) http://www.drrajurao.com
- Figure 25 PSI http://p-therapie.web.psi.ch
- Figure 26 MYRRHA http://myrrha.sckcen.be