BEAM INTERCEPTING MONITORS

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ABSTRACT

A short introduction on the main phenomena taking place in beam intercepting monitors is followed by the description of luminescent screens, secondary emission foil monitors, wire scanners and gas curtain monitors. Beam scrapers, collimators and stoppers are mentioned briefly.

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1. INTRODUCTION

Beam intercepting monitors are mainly used to measure positions and profiles (from which beam emittances can be deduced), to clean up circulating beams, to set aperture limits, to protect experiments from background and to stop beams.

The phenomena used in these monitors are essentially:
- luminescence,
- secondary emission,
- production of secondaries and Bremsstrahlung,
- ionization of the rest gas or of a gas jet.

The use of the transition radiation will not be dealt with here. Transition radiation monitors are described in Refs. 1 and 2.

The effects on the beam of the intercepting monitors are:
- a beam blow-up,
- an energy loss,
- an absorption in the extreme cases.

The energy loss for hadrons is given in Fig. 1 (Ref. 3) and the energy deposition of electrons in tungsten is given in Fig. 2 (Ref. 7). The first can be calculated with the Bethe-Bloch Formula of which a simplified expression is given below:

\[
\frac{1}{\rho_m} \frac{dE}{dx} \approx 0.31 \frac{Z_m}{A_m} \left[ \frac{Z_i}{\beta_i} \right]^2 \left[ \log \gamma_i^2 \frac{\beta_i^2}{\beta_i^3} - \beta_i^2 - 0.9 \log Z_m + 11 \right] \text{MeV cm}^2/\text{g} \tag{1}
\]

where the subscripts \( i \) refer to the incoming particle and \( m \) to the medium traversed. The other symbols have their usual meaning. The full Bethe-Bloch formula can be found for instance in Ref. 3. Corresponding expressions for electrons and positrons can be found in Ref. 4.

The interaction of electrons with matter can be calculated with the program EGS (Ref. 6). The energy loss can be considered in first approximation to be material independent when the results are expressed wrt the radiation length of the material as in Fig. 2.
Using a gaussian approximation, the projected angular distribution of the scattered beam can be characterized by a standard deviation:

$$\Theta = \frac{14.1 \cdot Z_i}{P_i(\text{GeV/c}) \cdot B_i} \sqrt{\frac{L_m}{L_{\text{rad}}}} \left[ 1 + \frac{1}{9} \log \frac{L_m}{L_{\text{rad}}} \right] \text{mrad}$$  \hspace{1cm} (2)

where $L_{\text{rad}}$ is the radiation length of the material.

The most common materials used in beam monitors are listed together with their radiation lengths in the table below:

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>Be</th>
<th>C</th>
<th>Al</th>
<th>Ti</th>
<th>Fe</th>
<th>Cu</th>
<th>Pb</th>
<th>Ta</th>
<th>W</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{rad}}$ (cm)</td>
<td>35</td>
<td>19</td>
<td>8.9</td>
<td>3.6</td>
<td>1.8</td>
<td>1.4</td>
<td>.56</td>
<td>.41</td>
<td>.35</td>
<td>.34</td>
</tr>
</tbody>
</table>

More data can be found in Refs. 3 and 5.

The effect on the beam is in general acceptable for a single or a few traversals, which means that these monitors are suitable for observations in linacs, in the transfer channels between accelerators, in single-turn operation of circular machines, or that they have to be thin and move fast enough through a circulating beam in order to intercept it only a few times.

The design of the monitors will depend on the type of particle to be observed. As can be seen from Figs. 1 and 2, the energy deposition in matter is quite different between electrons and protons, resulting for instance in longer absorbers for protons than for electrons.

The energy deposition, the light production, the Secondary Emission and the scattering depend on the charge of the incident particle as can be seen in the preceding formulae (1,2).

In electron machines, care has to be taken to minimize the higher order mode losses by providing smooth vacuum chambers for the circulating beams and to take into account the synchrotron radiation generated in bending magnets. The latter can be absorbed in masks if necessary. Considering an initial intensity of photons $I(0)$, the intensity $I(t)$ remaining after the traversal of a thickness $t$ of material is given by:

$$I(t) = I(0) \cdot e^{-\mu t}$$  \hspace{1cm} (3)

where $\mu$ is given in Fig. 3 for some materials. Other data can be found in Refs. 8, 9.
**Fig. 1** - Energy loss rates of protons and α's

**Fig. 2** - Energy deposition of electrons in tungsten

**Fig. 3** - Attenuation coefficients of photons
2. LUMINESCENT SCREENS

When a beam passes through a luminescent screen, part of the deposited energy results in excited electronic states in the material from which a light emission at a defined wavelength will follow. The light emission originates in impurity inclusions, the so-called activators, in most of the materials used. Luminescent screens are used in all accelerators during the running-in periods and when problems occur. They allow a direct observation of the beam position and shape on a TV monitor. They are necessarily single pass monitors.

A typical proton machine monitor is shown in Fig. 4 (Ref. 10). In this design, three different screens can be inserted at 45° in the beam path. The mechanism has a fourth empty position which is used for the free passage of the beam through the monitor. A TV camera observes the light spot generated by the beam passage. This mechanical design is not acceptable for an electron storage ring where the vacuum tank would create unacceptable RF losses. A suitable design is shown in Fig. 5 (Ref. 11). In this design, a so-called "dummy" or "RF chamber" is put in place when the screen is not used and provides, with the help of RF finger contacts, a continuous and smooth enclosure to the circulating beam. The screen and the detector characteristics have to be matched to each other.

There are two main types of detectors: TV tubes with various photocathode types and solid state detectors. Typical sensitivity spectra for a TV tube with a bialkali photocathode and for a silicon CCD (Charge Coupled Device), are given in Figs. 6 and 7. It is clear that a screen emitting light in the blue region will give best results with the first type whereas a screen emitting in the red is well adapted to a CCD device.

For storage rings requiring a good vacuum, the screens have to be bakeable to at least 150°C and be UHV (Ultra High Vacuum) compatible, i.e. non-hygroscopic and non cleaving. The following are typical data for two types of screens which have been used in UHV environments:

<table>
<thead>
<tr>
<th>Material</th>
<th>Activator</th>
<th>λ emission</th>
<th>Detector</th>
<th>Sensitivity</th>
<th>Decay time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li Glass</td>
<td>Ce</td>
<td>400 nm</td>
<td>TV tube</td>
<td>1.10⁸ p/mm²</td>
<td>100 ns</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>Cr</td>
<td>700 nm</td>
<td>CCD</td>
<td>2.10⁵ p/mm²</td>
<td>s</td>
</tr>
</tbody>
</table>

The sensitivity of the monitor can be increased beyond the indicated level by using an intensifier. The sensitivity is a function of the doping level, of the thickness of the screen material and of its transparency.
Fig. 4 - Luminescent screen monitor for proton machines

Fig. 5 - Beam scraper (a), luminescent screen (b) and split-foil monitor (c) for an electron-positron storage ring. Shown in the picture are also the vacuum tank (d) and the "RF chambers" (e)

Fig. 6 - Relative sensitivity of a TV tube with a bialkali photocathode

Fig. 7 - Response curve of a CCD detector
Other scintillators, together with some of their activators, which have been used in accelerators are \( \text{ZrO}_2(\text{MgO}), \text{CsI(Tl)}, \text{NaI(Tl)}, \text{CaF}_2(\text{Eu}), \text{ZnS} \). Except for the first, these materials are less suitable for an UHV environment. Sensitivities of up to 10p/mm\(^2\) have been reported for a CsI screen observed with an intensifier set-up (Ref. 16).

The simplest use of these monitors is to observe the beam-generated light spot on a TV monitor. In general a reference grid is deposited on the screen or superimposed optically on the image (Ref. 11, 12, 13) to get an accurate spatial and dimensional reference. The TV signals can also be recorded on an analog video recorder or on a "frame grabber" digitizer. For the solid state detectors which have a geometrically well defined matrix structure, it is possible to digitize each picture element (pixel) separately thus obtaining the best geometrical resolution. Also due to their good dynamic range, of the order of 1:1000 in single shot operation, it is possible to use them to measure beam profiles. These can be used to display density cross sections, to make projections on a chosen axis, to plot density contours or 3-D representations of the light, i.e. beam density.

CCD devices are for the moment rather new in the field and they are suspected to be more prone to radiation damage in hadron machines than TV tube devices. Due to their small size they can however be protected quite efficiently without excessive amounts of shielding. Furthermore, experiments where a CCD chip has been used directly as a beam detector for protons and oxygen ions have shown that these devices are quite robust (Ref. 15).

The limitations of these monitors are:

- the resolution limited by the thickness of the screen when observed at 45\(^0\), as the screens are not perfectly opaque.
- the beam blow-up: the radiation length of the two mentioned screen types are of the order of 10 and 7 cm and the screens are normally 1 mm thick.
- the sensitivity of the screens to synchrotron radiation if the latter is present.

If the first two limitations have to be overcome together, it is possible to use thin screens (0.1 mm) and to increase the tilting angle from 45 to 60\(^0\) (Ref. 14). If the beam blow-up is not a major problem, then the screen can be placed perpendicularly to the beam and the light spot observed through a mirror placed at 45\(^0\) to the beam and in front of the screen. If, additionally, the screen has to be shielded from the synchrotron radiation from both sides, it is possible to add an absorbing metallic screen on the back of the luminescent screen (Fig. 5), Ref. 11.

If a luminescent screen is too perturbing to the beam, then Secondary Emission (SE) devices should be considered.
3. SECONDARY EMISSION GRIDS

When a beam passes through a foil or a wire a few percent of low energy electrons wrt the incoming particles are emitted from the superficial layers. This charge depletion is proportional to the local density of the beam and can be used to measure a beam density profile.

The production efficiency decreases from low energy to high energy. Given below are some experimental data for protons (Ref. 17).

<table>
<thead>
<tr>
<th>PROTON ENERGY</th>
<th>5 MeV</th>
<th>200 MeV</th>
<th>GeV's</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFICIENCY (%)</td>
<td>20</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

The efficiency changes also with the charge of the incoming particle (1). The secondary emission being a surface phenomenon, the efficiency can be increased by introducing surface irregularities or using porous material, but this will not be acceptable in general in an UHV environment. Efficiencies of 400% have been obtained for 25 MeV electrons by using a 125 μm layer of CsI on an aluminium foil (Ref. 18).

The main problems encountered with these monitors are the small useful signals (pC) generated under a very high source impedance and the collection of unwanted parasitic charges.

The monitors are in general built with the thinnest possible foils to minimize disturbance to the beam. The practical thicknesses used are 20 μm for Al and 7 μm for Ti, resulting in some 0.02% of Lrad introduced in the beam path. Tests have been made with 5 μm aluminium foils. The monitors are either made from individual strips (Fig. 9, Ref. 10) or from foils in which the proper pattern has been etched (Fig. 8, Ref. 19). The strips are mounted on high resistivity insulators (ceramics, stumatite) to minimize leakage of the generated charges to the surroundings.

The monitors should be used in clean environments. If this is not the case, clearing electrodes or at least the possibility to polarize the collecting foils wrt the surroundings must be foreseen. The latter should always be possible. The polarisation can be used to repel the low energy SE electrons, the ions generated in the rest gas or the particles backscattered from an obstacle. The sign of the polarisation voltage is chosen according to the relative importance of the different parasitic signals. Voltages of the order of 300 V are normally used.
Local electronics are used to amplify and shape the signals and to be a low impedance source so that the signals can be transferred over long distances to the digitizing equipment. Analog-to-digital converters of up to 12 bits are generally used (Ref. 19).

The main limitations of these monitors are their resolution due to the finite number and dimension of the strips and the uniformity of the overall gain from channel to channel.

The resolution can be increased in single-shot operation by inclining the grid wrt beam direction (Fig. 10, Ref. 17). A practical limit is an angle of 60°. In a multipulse measurement, the resolution can be increased by displacing the grid between measurements (Ref. 10).

The emittance can be calculated from profiles measured at three monitors separated ideally by 120° in phase space (Ref. 20, 21) or at one monitor where the beam optics are changed accordingly (Ref. 22). One of the measured profiles should be taken at a beam waist.

4. SPLIT-FOIL MONITORS

A Split-Foil (SF) monitor is a secondary emission device made of two adjacent foils which are in general not mounted in the same plane and are moved across the aperture during a measurement: Fig. 11 (Ref. 11). They solve some of the problems mentioned earlier for the SE grids, i.e. the resolution, the uniformity of the gain from strip to strip and the number of channels. Their disadvantages are that they require stable conditions in order to make useful profile measurements and that their results are not easy to interpret.

Their main use is, in fact, to check the stability of beams in transfer channels. In that function, the SF is left at a fixed position and the ratio of the charges collected in the two foils is checked for stability.

All facts mentioned previously for the SE grids apply to the SF's.

5. WIRE SCANNERS

Wire scanners are used to measure beam profiles. The phenomena used are the secondary emission and the production of secondaries or Bremsstrahlung when a wire passes through the beam. Wire scanners are used when the shortcomings of the previous monitors are to be overcome, i.e. the resolution and beam disturbance. They
Fig. 8 - SEM grids

Fig. 9 - SEM matrix

Fig. 10 - Superposed views of a SEM grid with a variable tilt

Fig. 11 - Split-foil monitors
can be used in high repetition rate (above 100 Hz) linacs and transfer channels and on circulating beams.

Wire scanners have two effects on the beam: an emittance blow-up through multiple scattering and an energy loss through collision plus Bremsstrahlung for leptons. These effects will be considered with the fast wire scanners for circulating beams where they are most important. There are essentially two categories of wire scanners:
- the slow ones for linacs and transfer lines,
- the fast ones for circular machines.

In all these monitors it is advisable to take signal leads from both ends of the scanning wire, in order to have always the possibility to check its continuity.

5.1 LINAC AND TRANSFER LINE SLOW WIRE SCANNERS

The speed is chosen to give, in the shortest time, the best resolution compatible with the beam size, for example a speed of 10 mm/s for a 100 Hz linac producing a beam with a σ of 1 mm.

The wire characteristics to be defined are the following:
- the diameter, which has to match the desired resolution and to intercept enough beam to give an acceptable signal-to-noise ratio:
  - 100 to 300 μm are usual for large beams,
  - 7 to 30 μm are used for small beams,
- the material.

Low-Z materials can be chosen when only secondary emission is used. In this case carbon and beryllium are preferred. High-Z materials have to be chosen when large angle secondaries are to be observed. Tungsten is most used in this case.

- the shape of the wire which can be:
  - a single wire for measuring along one direction: Fig. 12 (Ref. 24)
  - a single wire in L-shape for measuring two orthogonal profiles in one movement with SE or secondaries: Fig. 13 (Ref. 25). The wire is then moved at 45° wrt measured directions.
  - two crossed wires for measuring two profiles with the shortest stroke with SE only: Fig. 14 (Ref. 26). The wire is moved as previously.

Three single-wire monitors, rotated by 45° wrt each other, have been used to increase the precision on the emittance measurement for very "flat" beams: Fig. 12 (Ref. 24).
WIRE SCANNERS

Fig. 12 - "Single" wires

Fig. 13 - L-shaped wire

Fig. 14 - Crossed wires

Fig. 15 - Fast pendulum movement.
The resolution of the movement has to match the previous conditions. With stepping motors a resolution of a few \( \mu \text{m} \) is typical (Ref. 24, 32). With DC motors, a resolution of \( 1.10^{-3} \) of the total stroke is usual when using a linear potentiometer as the position transducer and a resolution of a few \( \mu \text{m} \) is reached when using optical linear transducers. The radiation resistance of the latter has to be taken into account.

5.2 FAST WIRE SCANNERS FOR CIRCULAR MACHINES

A compromise has to be found here between the speed for minimum beam interference and the sampling of the measured profile. The wire vibrations are a non-negligible problem. They have to be taken into account when designing the monitor and should be checked on the monitor prototype (Ref. 29, 30).

There are two main types in this category:
- the linear displacement monitors for speeds below about 1 m/s, using pneumatic actuators (Ref. 28) or DC motors (Ref. 29). The position is acquired with linear transducers as mentioned previously.
- The pendulum movement monitors.

Speeds up to 2 m/s with a position resolution of a few \( \mu \text{m} \) have been achieved with stepping motors (Ref. 30). Speeds up to 20 m/s have been achieved with a high torque DC motor incorporated in a servo loop including a potentiometer and a tachymetric generator and controlled by a function generator (Ref. 27).

The wire here is always made with low-Z material, beryllium or carbon, the latter having a higher melting point and being mostly used.

When using secondary emission, enough time between successive counter-rotating bunches in storage rings has to be allowed for, in order to separate the signals in the processing electronics. This is not the case when secondaries or Bremsstrahlung are used, because of the high directivity of the emission.

The interaction between the wire and the beam has to be considered. There will be an emittance blow-up of the beam through multiple scattering (2). If \( T_{\text{rev}} \) is the revolution period of the particles and \( v_w \) the speed of the wire, then the blow-up can be estimated by:

\[
\delta E_y = \beta_y \frac{d^2}{L} \frac{z^2}{\beta_1 \gamma} \frac{1}{T_{\text{rev}} w} \cdot 10^{-4} \text{ m/scan}
\]  (4)
for lepton machines (the expression has to be multiplied by \( \pi \) rad for hadron machines). This blow-up is in general kept below 17.

The particles which will pass through the wire will lose energy through collision. This energy is partly deposited in the wire. For electrons, there is in addition an energy loss through Bremsstrahlung. The average probability to emit a Bremsstrahlung photon around energy \( E_\gamma \) smaller than \( E_\gamma \) is:

\[
P(E_\gamma, E_\gamma) \, dE_\gamma \approx \frac{\pi}{4} \frac{d}{L_{\text{rad}}} \frac{dE_\gamma}{E_\gamma}
\]

The particle will be lost if the energy \( E_\gamma \) is greater than the RF bucket acceptance. This is the dominant loss mechanism in electron machines.

Finally the effect of the beam on the wire has to be considered, i.e. the heating of the wire. To make this evaluation, it is not possible to take simply the collision loss, because part of the energy lost by the beam is escaping with the secondaries. But even the substraction of this escaped energy is not considered to be enough for calculating the temperature of the wire. The best approximation for the time being seems to be a rule of thumb stating that only 25 to 30% of the collision energy loss should be taken for calculating the wire temperature. In this case, the calculated temperature elevation of the wire moving along direction \( x \) will be:

\[
\Delta T_x \approx 30 \times 10^{-2} \frac{N_i}{\sqrt{2\pi} \sigma_y} \frac{1}{C_{pw} \nu_{w} T_{\text{rev}}} \frac{1}{\rho_w} \left[ \frac{dE}{dx} \right]_i
\]

where \( C_{pw} \) is the specific heat and \( \rho_w \) the density of the wire material, \( \sigma_y \) the \( \sigma \) of the beam along the direction \( y \). Values for \( [dE/dx]_i \) can be calculated from Refs. 3 and 4.

5.3 BEAM PROFILE MONITORING

As mentioned earlier, three components are currently used: the secondary emission, the secondaries and the Bremsstrahlung. For the SE, the same comments apply as previously, except that the charges collected are usually much smaller than for grids. The polarization of the wire with a bias voltage should be foreseen in the design. Signal pick-up from the beam should be taken into account when designing the monitor (Ref. 24). Secondaries are normally observed at small angles in the forward direction where they are strongly peaked (Ref. 23). Care has to be taken to shield the detector from background signals arriving along the same direction. Observations
at 90° have given good results with electrons up to 1 GeV. In this case, the separation from background signals is much easier because the acceptance can be well limited to the wire (Ref. 25). The observation is performed with scintillators and photomultipliers. The number of particles observed will depend on the detector acceptance and on the production cross-section which can be found in Ref. 31 for hadrons.

In the case of lepton machines, the use of the high energy Bremsstrahlung photons is expected to give a high dynamic range monitor making it possible to explore the tails down to 1/10^5 of the maximum. The detector has to include a gamma converter. A possible solution is to use a tungsten-silicon sandwich with a remotely adjustable converter to cover the whole dynamic range of the explored beam (Ref. 30). A fourth method, using the heating of the wire, can be mentioned. In this method, the wire is put in a resistance measuring bridge and the change in resistance detected (Ref. 25).

6. GAS CURTAIN MONITORS

These monitors are typical of hadron storage rings. They are large in size (Fig. 17) and of complex design. They are potentially the least perturbing monitors described here.

When a beam passes through a gas, it excites and ionizes molecules. The excited molecules emit light that can be observed directly (Ref. 33). The electrons created by ionization can be accelerated onto a phosphor screen which can be observed with a TV camera. These methods give a transverse profile of the beam but are limited to rather high density beams.

It is possible to increase the sensitivity of the monitor and to get both transverse profiles by having the beam pass through a high density gas jet. The monitor can be considered to be similar in its principle to the luminescent screens seen previously, the gas curtain playing the role of the screen.

Consider a monitor where the beam is observed from above and where the gas jet traverses the beam at 45° along the horizontal axis (Fig. 16). The electrons created outside the jet will give the average horizontal profile of the beam as mentioned previously. The electrons created in the gas jet, which is much more dense than the rest gas, will be generated at a defined vertical position and will hence be representative of the horizontal and of the vertical profile of the beam (Fig. 18). The TV image can be analysed as mentioned earlier to extract the data on both directions. The gas jet has to be as thin as possible and the electrons have to be
**Fig. 16** - Principle of the sodium-jet monitor

**Fig. 17** - View of the sodium-jet monitor in the ISR tunnel

**Fig. 18** - TV display showing an ISR beam with the sodium jet. The longitudinal axis is parallel to the cursor

**Fig. 19** - Carbon disk showing at the left the craters produced by the laser beam
accelerated by an electric field and focused by a magnetic field in order to obtain the best resolution of the monitor.

A high gas density has to be generated to achieve sufficient sensitivity. But this density is limited by the equivalent average pressure increase of the accelerator or storage ring, which will define the beam blow-up. The high density and the low divergence of the jet require a supersonic flow with speeds of a few 1000 m/s. The good quality of the jet and of the vacuum of the ring require a high pumping efficiency of the jet molecules, which influences the choice of the jet molecules or atoms.

Two implementations will be mentioned. The first is the sodium-jet monitor which was used in the CERN ISR (Ref. 34, 35). A continuous sodium jet of 0.7 mm thickness and 64 mm width was created. It had a 0.7 mrad divergence and gave a local pressure of $10^{-7}$ Torr, which has to be compared to the average pressure of $10^{-11}$ Torr over the one km rings. The useful range of the monitor was for beam currents of a few tens of mA up to 50 A. The TV lines were digitized and the results were presented on a screen together with the image (Fig. 18). It was a very useful instrument for observing instantaneously the behaviour of the beams in both planes during the various phases of operation.

The second monitor (Ref. 36) will be implemented in the CERN LEAR machine in the early 1989 shutdown. Due to the small circumference of LEAR (78.5 m), the gas jet will have to be pulsed in order to get the best sensitivity while keeping the average pressure low. The gas jet will be generated by a 15 J laser pulse of 1 ms length, pulsed at a period of at least 2 s and impinging on a carbon disk. The resulting carbon jet will be 1 to 5 mm thick over an 85 mm width and result in a local pressure of $2.10^{-5}$ Torr. The laser will drill little craters in the carbon disk (Fig. 19) which will have to be repositioned regularly in order to present an acceptable surface to the laser pulse and to guarantee a reasonable lifetime to the instrument. The resulting sensitivity should be of $10^8$ to $10^9$ circulating p^-.

7. BEAM SCRAPERS, COLLIMATORS AND BEAM STOPPERS

These devices are destructive and are only mentioned here for the sake of completeness.

Beam scrapers are used to define aperture limits, to eliminate low density beam halos, to control the beam or bunch intensities and to measure beam profiles in conjunction with a beam intensity monitor. In hadron machines, scrapers are usually thin scatterers of high-Z material (Ref. 37), generally tungsten, located at high β points, which create betatron oscillations. In electron machines, where scrapers
are mostly used for bunch equalising purposes, scrapers can be made of low-density blocks of the order of two radiation lengths, in which the particles lose enough energy to escape from the RF bucket. Such a device is depicted in Fig. 5, showing a water-cooled aluminium block of 18 cm length. The block length is a compromise between the energy lost by the beam and the acceptable energy deposition in the block. The particles will be lost in a suitably located downstream aperture limit.

Collimators (Ref. 38, 39, 40, 41) are used in storage rings to protect experiments from particles with large betatron oscillations, from off-momentum particles, or from high energy photons. Their function is to absorb these elements and they are made of high-Z material. Care has to be taken with the particles arriving at the edge of the blocks which are scattered rather than absorbed. This effect needs follow-up collimators, located at odd multiples of 90° in phase-space, in which the scattered particles are then absorbed.

Stoppers are used to absorb beams for safety reasons or to allow tuning of the injection or orbit in a storage ring without upsetting the experiments installed in the crossing areas. The experiment protection function is quite easy to implement in lepton machines where 40 cm copper blocks are sufficient to guarantee less than 10⁻³ of the incoming energy escaping from the block (Ref. 11). This is nearly impossible in hadron machines with realistically dimensioned blocks.

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