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Machine Protection

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Abstract
The protection of accelerator equipment is as old as accelerator technology and was for many years related to high-power equipment. Examples are the protection of powered equipment from overheating (magnets, power converters and high-current cables), of superconducting magnets from damage after a quench and of klystrons. The protection of equipment from beam accidents is more recent. It is related to the increasing beam power of high-power proton accelerators (e.g. ISIS at Rutherford Appleton Laboratory, the Spallation Neutron Source (SNS) at Oak Ridge, the European Spallation Source at Lund (ESS) and the cyclotron at the Paul Scherrer Institute in Switzerland), to the emission of synchrotron light by electron–positron accelerators and free-electron lasers and to the increase of energy stored in the beam (in particular for hadron colliders such as the Large Hadron Collider at CERN, Switzerland). Designing a machine protection system requires an excellent understanding of accelerator physics and operation to anticipate possible failures that could lead to damage. Machine protection includes beam and equipment monitoring, a system to safely stop beam operation (e.g. dumping the beam or stopping the beam at low energy) and an interlock system providing the glue between these systems. The most recent accelerator, the LHC, will operate with about 3×10^{14} protons per beam, corresponding to an energy stored in each beam of 360 MJ. This energy can cause massive damage to accelerator equipment in case of uncontrolled beam loss, and a single accident damaging vital parts of the accelerator could interrupt operation for years. This article provides an overview of the requirements for protection of accelerator equipment and introduces the various protection systems. Examples are mainly from LHC and ESS.

Keywords
Machine protection; interlock system; high-power accelerator; beam loss; accident.

1 Introduction

In general, risks come from energy stored in an accelerator (measured in joules) and power when operating an accelerator (measured in watts). When we are talking about a very powerful accelerator, we need to consider that the power flow needs to be controlled.

Particle accelerators use large amounts of power; large accelerators operate with a few megawatts to many megawatts. The question to be addressed is where does the power go in case of failure? An uncontrolled release of energy or power flow can lead to unwanted consequences, such as damage of equipment and loss of time for operation. There is also the risk of activation of equipment when operating with particle beams in case of beam losses. Handling large amounts of power/energy is an issue in many domains, but a particular challenge for complex systems such as accelerators.

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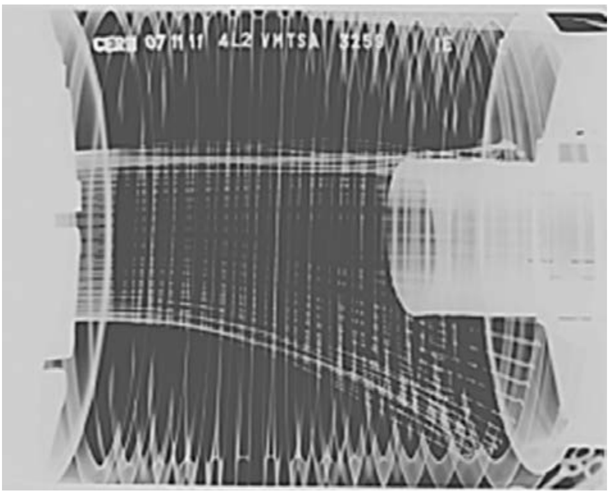

Fig. 1: RF fingers in LHC interconnects; some of them are bent. The metallic coating on the fingers had melted: the temperature had reached more than 800°C [1].

For an accelerator, there are several sources of energy or power that need to be considered.

- The energy stored in the particle beam, e.g. in a synchrotron or storage ring.
- The beam power of a particle beam or in a linac, cyclotron or synchrotron. The beam power is given by the number of particles multiplied with their energy, per unit time.
- The energy stored in superconducting magnets.
- The power required to operate accelerator systems, e.g. magnets, power converters and RF systems.

2 Energy transfer from beam to equipment

There are several mechanisms for energy transfer from the beam to the equipment, one of them by losing particles into the equipment. There will always be particle losses during operation, due to collisions with the residual gas or with a counter-rotating beam, or particle losses at the aperture (e.g. due to emittance growth and other effects). Accidental particle losses can occur due to a large number of possible failure mechanisms.

Another mechanism is energy deposited by electromagnetic interaction between beam and environment (vacuum chamber, RF, beam instrumentation, kicker magnets etc). The deposited power depends on the beam intensity and bunch structure, as well on the impedance seen by the beam. Problems have been frequently observed at accelerators. Figure 1 shows the damage of RF fingers in interconnects at LHC. Due to an incorrect installation of RF fingers, the beam deposited energy into the fingers and they were bent [1].

Energy can also be deposited by the synchrotron radiation emitted by particle beams, in particular in electron or positron accelerators. The power increases with the particle energy to the power of four and can be very high, up to several tens of megawatts. The radiation can be very focused; in particular, radiation from wiggler and undulator magnets can increase the power by orders of magnitude (e.g. for free-electron lasers (FELs)). Normally, this is considered in the design of the accelerator and experiments; however, there are a number of failure scenarios that can lead to accidents (e.g. operating with too high current).

Machine protection is essentially to prevent consequences of accidental beam losses, but other mechanisms for damage should also be addressed.

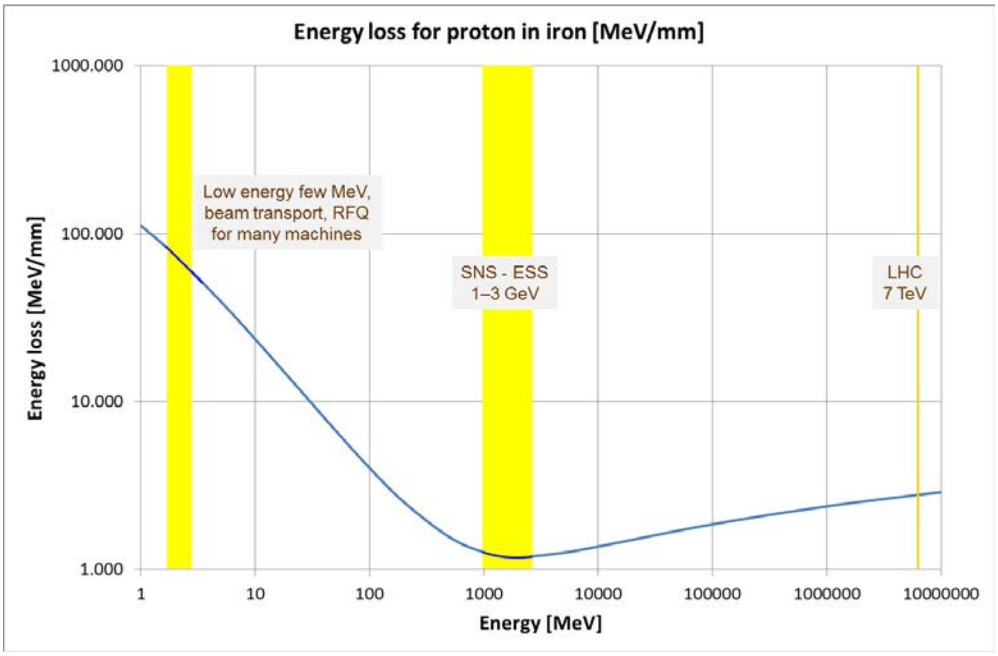

Fig. 2: Energy loss for protons when entering into an iron block, calculated by the Bethe–Bloch equation. Effects of the hadron shower are not included.

2.1 Energy deposition from high-energy particles

Charged particles moving through matter interact with electrons of atoms in the material, exciting or ionizing the atoms. Energy deposition starts when a charged particle enters the material. If the particle energy is high enough, it leads to particle cascades in the material, increasing the deposited energy along the length. The maximum energy deposition can be deep in the material at the maximum of the hadron or electromagnetic shower depending on the particle momentum and material.

To get an idea of the damage potential, the energy loss by ionization at the surface of the target can be estimated using the Bethe–Bloch equation, ignoring particle cascades (see Fig. 2). It is interesting to observe that the energy loss for low-energy particles is very high. For a proton at 7 TeV/c the energy loss at the entrance is much lower, but deeper in the material the energy deposition is dominated by hadron showers with the maximum energy deposition deep in the material.

There is no straightforward expression for the energy deposition of high-energy particles, since this depends on the particle type, momentum, beam parameters and material parameters (atomic number, density and specific heat). Programs such as FLUKA [2], MARS [3] or GEANT4 [4] are being used for the calculation of energy deposition (and subsequent temperature increase) as well for the activation of the material that is exposed.

The following example illustrates the calculation of the beam particles entering a material block or traversing a window.

i) A proton beam travels through a thin window of thickness d.
ii) Assume a beam area of 4 $\sigma_x \times \sigma_y$, with σ_x and σ_y the root-mean-square (r.m.s.) beam sizes assuming Gaussian beams.
iii) Assume a homogeneous beam distribution.

The energy deposition can be calculated; mass and specific heat are known. The temperature can be calculated (rather good approximation), assuming a fast loss and no cooling. With low-energy protons (3 MeV/c) and a beam size of $\sigma_x = \sigma_y = 1$ mm, the following parameters are calculated:

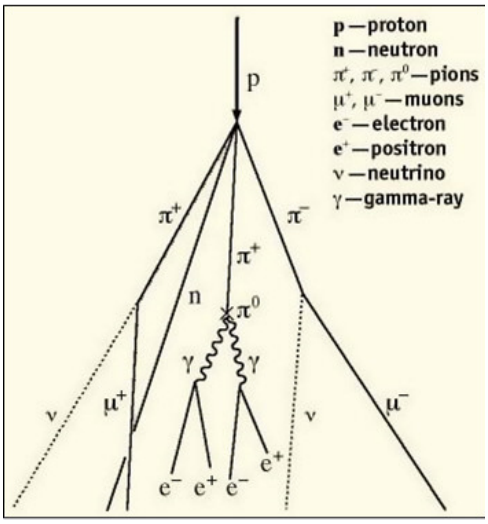

Fig. 3: Illustration of a hadronic shower

i) iron specific heat = 440 J/(kg × K);
ii) iron specific weight = 7860 kg/m^3;
iii) dE/dx = 56.7 MeV/mm;
iv) $N_\mathrm{p} = 1.16 \times 10^{12}$.

The temperature increase in this example for these parameters is 763 K. For high-energy protons the energy deposition by hadronic showers (see Fig. 3) dominates:

i) pions are created when the protons travel through matter;
ii) the decay of pions creates electromagnetic showers;
iii) there is an exponential increase in number of created particles;
iv) the final energy deposition is to a large extent due to the large number of electromagnetic particles;
v) the energy deposition scales roughly with total energy of incident particles;
vi) the maximum of the energy deposition can be deep in the material;
vii) energy deposition is a function of the particle type, its momentum and parameters of the material (atomic number, density and specific heat).

A simple approximation for the temperature increase in material for a 7 TeV/c proton beam impact is given in the following example: for copper, the maximum longitudinal energy deposition for a single 7 TeV/c proton at about 25 cm inside the material is $E_\mathrm{dep} = 1.5 \times 10^{-5}$ J/kg (calculation with FLUKA). The energy required to heat and melt copper is $E = 6.3 \times 10^5$ J/kg. Assuming a pencil beam, the number of particles required to damage (melt) copper is of the order of 10^{10}. For graphite, the number of particles needed to cause damage is about one order of magnitude larger.

2.2 Beam loss and consequences

The energy deposition leads to a temperature increase in the material that can be vaporized, melted, deformed or lose its mechanical properties, depending on the material and the beam impact.

Relevant parameters to be considered for heating and possible damage to material are the momentum of the particle, the particle type, the energy stored in the beam, the beam power, the beam size, the beam power/energy density (MJ/mm^2, MW/mm^2), the time structure of the beam and cooling conditions. In order to estimate the order of magnitude for possible damage:

i) 1 MJ can heat and melt about 1.5 kg of copper;
ii) 1 MJ corresponds to the energy stored in about 0.25 kg of TNT [5];
iii) 1 MW during 1 s corresponds to 1 MJ.

When particles interact with equipment, material can be activated with the subsequent risk for hand-on maintenance. It is considered to be acceptable if beam losses do not exceed, say, 1 W/m (assuming proton beams with high energy, say above some 100 MeV/c). Another principle is 'ALARA': exposure of personnel to radiation should be 'as low as reasonably achievable'. If a further reduction of the beam losses below 1 W/m is reasonably possible, this is recommended in order to minimize exposure of service personnel. Radioactive activation of material is mainly an issue for hadron accelerators; it is less problematic for electron–positron machines.

For accelerators with superconducting magnets there is a specific problem: even with beam loss much below the damage threshold, superconducting magnets can quench (beam loss of mJ to J). In case of a quench, beam operation is interrupted for some time (possibly up to many hours) leading to downtime. In order to avoid beam-induced quenches, beam losses are monitored and the beam is dumped if a predefined threshold is exceeded before a magnet quenches, reducing the downtime since the time to recover from a quench is avoided. The damage threshold is far above the quench threshold; this strategy also protects magnets from beam-induced damage.

Superconducting cavities' performance degradation is observed after beam losses of some 10 J. With higher beam losses, material can vaporize, melt, deform or lose its mechanical properties.

There is some risk of damage to sensitive equipment for an energy deposition of some 10 kJ (beam impact for a short time, say a maximum of a few milliseconds). Risk to damage sensitive equipment exists for less than 1 kJ; risk for damage of any structure for some MJ (depends on beam size).

More refined and complete calculations can be made to determine real-world scenarios on a case-by-case basis, where the distribution of the impacting particles and the details of the material and geometry are important. After the calculation of the temperature increase, the response of the material to beam impact needs to be addressed (deformation, melting etc). Mechanical codes such as ANSYS and hydrodynamic codes such as BIG2 and others can be used.

Beams at very low energy have limited power; however, the energy deposition is very high and can lead to (limited) damage in the case of a beam impact at the initial stage of an accelerator, after the source, in the low-energy beam transport and in the radio-frequency quadrupole (RFQ). This might lead to a long downtime, depending on availability of spares.

There is another risk from beam loss, radiation-induced effects in electronics (single-event effects) that could stop the operation of an accelerator.

3 Accelerators that require protection systems

Not all accelerators require protection systems; in this section we discuss when protection needs to be considered.

– Synchrotrons and storage rings for the acceleration of hadron beams with a large amount of energy stored in the beam. Examples are LHC, RHIC and in the past the TEVATRON and HERA. Other examples are synchrotrons accelerating beams for fixed target experiments or used as injectors for other machines. The energy stored in the beam for different accelerators as well as the energy stored in the LHC magnet system is shown in Fig. 4.
– High-power proton accelerators (e.g. spallation sources) with beam power of some 10 kW to above 1 MW. There is the risk of beam-induced damage and activation. The beam power of existing machines exceeds 1 MW (SNS, PSI cyclotron and in the future JPARC), but also for lower power

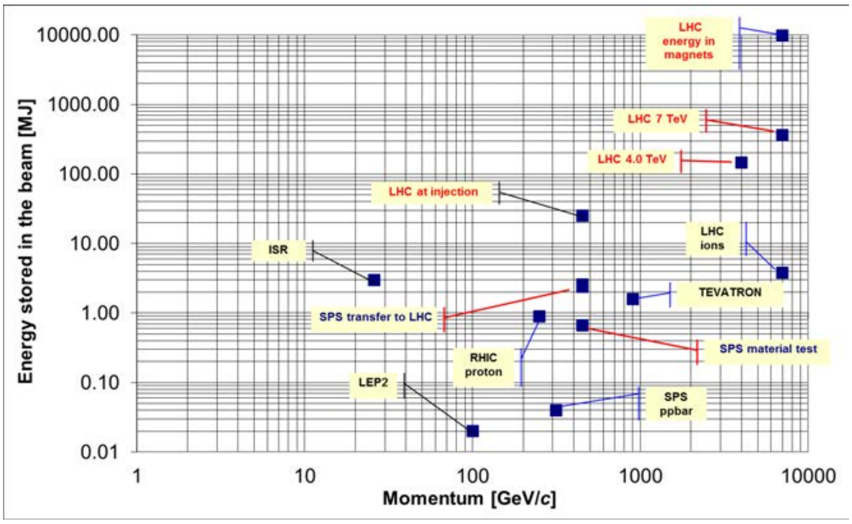

Fig. 4: Energy stored in the beams for different accelerators, and the energy stored in the LHC magnet system

machine protection needs to be considered (ISIS). Several high-power machines are under construction (ESS with a power of 5 MW, IFMIF and MYRRHA are in the project planning phase).

- Synchrotron light sources with high-intensity beams and secondary photon beams. Damage can come from the primary beam but also from the synchrotron radiation.
- Energy-recovery linacs, as an example the Daresbury ERL prototype: one bunch train cannot damage equipment, but in case of beam loss the next train must not leave the (injector) station.
- Linear colliders were expected to operate with very high beam power densities due to small beam size. One beam pulse can lead to damage. After a time interval large enough to allow a substantial change in the beam trajectory (fraction of a second), a pilot beam must be used to prove the integrity [6].
- High average power in linear accelerators: FLASH 90 kW, European XFEL 600 kW, JLab FEL 1.5 MW, ILC 11 MW.
- Medical accelerators: a too high dose to patients needs to be prevented. The techniques for protection are similar.

There is a large interest in the exploitation of high-power hadron accelerators. In spallation sources high-intensity proton beams are accelerated and directed to a target. The protons interact with the target material and spallation neutrons are produced. Other accelerators are using high-intensity proton beams for neutrino production. Rare-isotope beams are produced by accelerating ions (e.g. FRIB is a folded linac to accelerate ions). Accelerator-driven systems (ADSs) are being developed with several projects around the world. A very energetic particle beam is used to stimulate a reaction in a subcritical reactor, which in turn releases enough energy to power the particle accelerator and leaves an energy profit for power generation. Figure 5 shows beam current, beam power and particle momentum for different high-power proton accelerators.

There is a difference between accelerators operating with high-power beams and those with large stored energy. For hadron colliders, the energy stored in the beams can be very high, as has been shown for the LHC. In case of a failure, the energy stored in beam and magnets needs to be safely deposited.

For linear accelerators with high beam power, the beam must be stopped fast at the source in case of a failure causing beam losses. As an example, a continuous beam with a power of 5 MW could deposit the energy of 5 kJ in 1 ms. Even if the beam is stopped at the source, there are still particles present between the source and the location of the beam impact that might damage equipment.

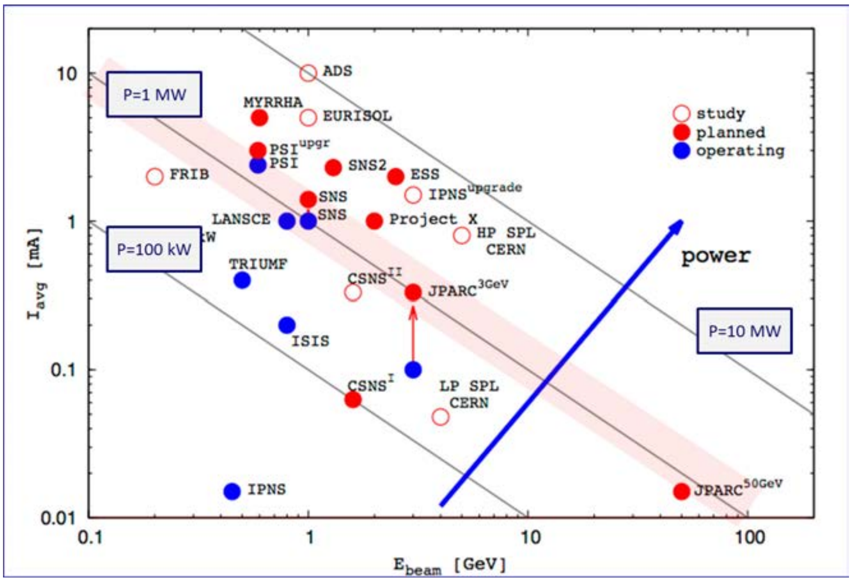

Fig. 5: Current versus particle momentum for high-power proton accelerators around the world

The beam power increases along the accelerating structure proportionally to the particle momentum, which needs to be considered in the estimation of possible damage.

4 Hazard and risk

A ‘hazard’ is a situation that poses a level of threat to the accelerator. Hazards are dormant or potential, with only a theoretical risk of damage. Before designing a protection system, the hazards need to be identified and the risk needs to be quantified. Once a hazard becomes ‘active’ it becomes an incident or accident. Consequences and probability of an incident interact together to create a risk that can be quantified:

$$\text{Risk} = \text{Consequences} \times \text{Probability}. \qquad (1)$$

Related to accelerators, the consequences and the probability of an uncontrolled beam loss need to be estimated to get an idea about the risk. Machine protection systems prevent damage to equipment after a failure, thus reducing the risk to an acceptable value. With increasing risks for hazards, the reliability of the machine protection systems must increase in order to keep the risk at the acceptable value. Machine protection needs to be considered during design, construction and operation of the accelerator.

If a specific failure is considered, the consequences of the failure can be estimated, in terms of damage to equipment (repair requiring investment, e.g. in money), in downtime of the accelerator (e.g. in days) and in radiation dose to personnel accessing equipment (e.g. in mSv).

In the estimation of downtime of the accelerator for repairs the availability of spare parts needs to be considered. If the accelerator was operating with beam, radioactive activation of material must be taken into account. It may be necessary to wait for cool-down of irradiated components to reduce the dose before accessing the equipment.

The second factor entering into the risk is the probability of such a failure happening (e.g. measured in the probability of a failure per year).

For beam operation, a list of all possible failures that could lead to beam loss in equipment should be established. This is not obvious, since there is a nearly infinite number of mechanisms for losing the beam. However, the most likely failure modes and in particular the worst-case failures and their probabilities must be considered.

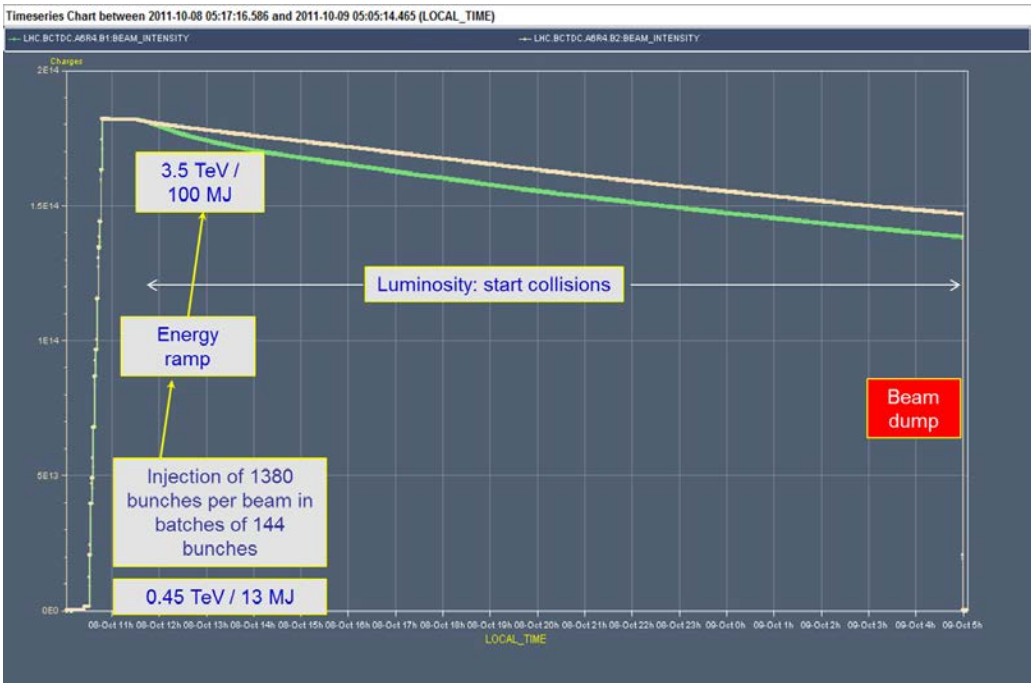

Fig. 6: LHC operation cycle, from injection to beam dump

5 Hazards for a synchrotron: LHC

The LHC is used as an example to discuss hazards for a synchrotron. The operational cycle is shown in Fig. 6. In the LHC, beams are injected at 450 GeV from the SPS, then accelerated to high energy (3.5 GeV and 4 GeV during Run 1 between 2010 and 2012, since 2015 to 6.5 GeV). The beams are then brought into collisions for many hours. At the end of a fill and in case of failure the beams must be extracted by the beam dumping system.

Three different phases during a fill can be identified.

- Injection of the high-intensity beam from the SPS. The energy stored in the injected beam is very high and threatens to cause damage in case of failure.
- When the beams are circulating, there is always the risk of a failure, e.g. a trip of a magnet power converter. Such a trip would change current and magnetic field and particles will be ill-deflected. In this case, the beams need to be safely extracted.
- At the end of a fill or in case of failure, the beams need to be extracted. This is a critical process with a number of hazards.

The general architecture for the essential elements in the machine protection system at LHC is shown in Fig. 7. The LHC has eight sectors and eight insertions; three sectors are related to machine protection: two cleaning insertions with a large number of collimators and one insertion for the beam dumping system. More than 3600 beam loss monitors are installed around the machine. In case of a failure detected by hardware or beam monitors, the beam interlock system transmits a beam dump request to the beam dumping system and the beams are extracted.

The role of the LHC beam dumping system [7] is to safely dispose of the beam when beam operation must be interrupted for any reason. Fifteen fast kicker magnets with a pulse rise time of less than 3 μs deflect the beam by an angle of 280 μrad in the horizontal plane; see Fig. 8. To ensure that all particles are extracted from the LHC without losses, the beam has a particle-free abort gap with a length of 3 μs corresponding to the kicker rise time. The extraction kickers are triggered such that the field increases from zero to the nominal value during this gap when there should be no particles.

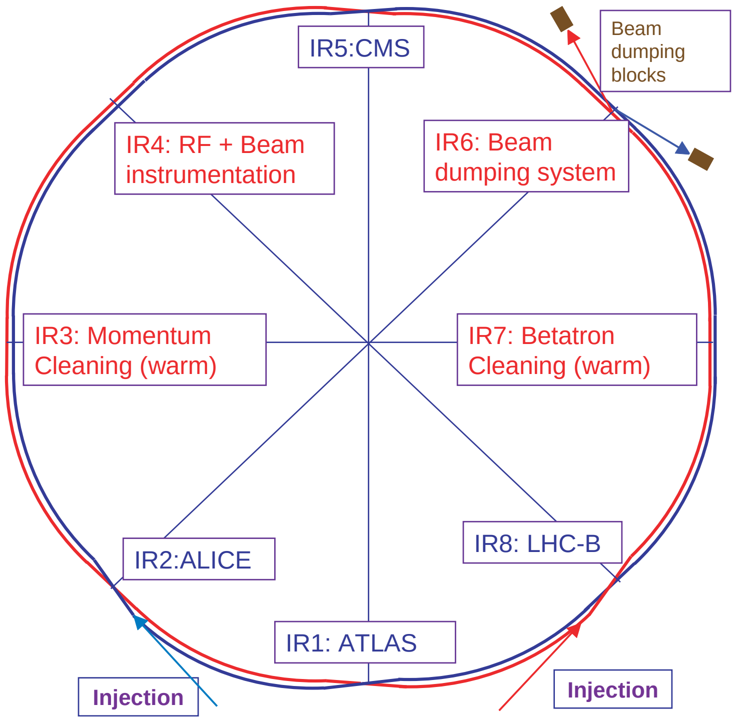

Fig. 7: Layout of LHC with some of the systems for machine protection

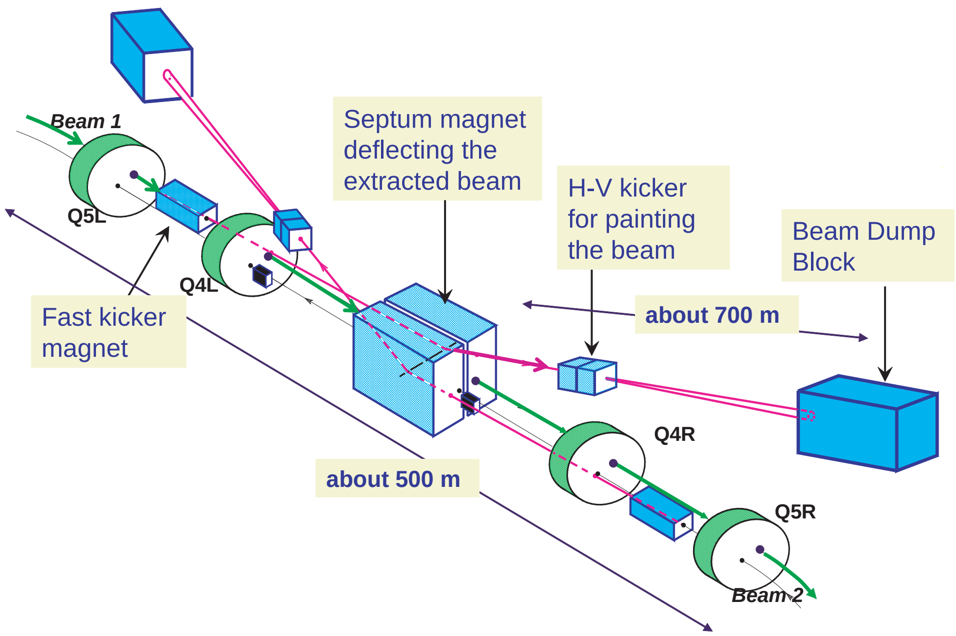

Fig. 8: Layout of the beam dumping systems for both LHC beams (courtesy of M. Gyr)

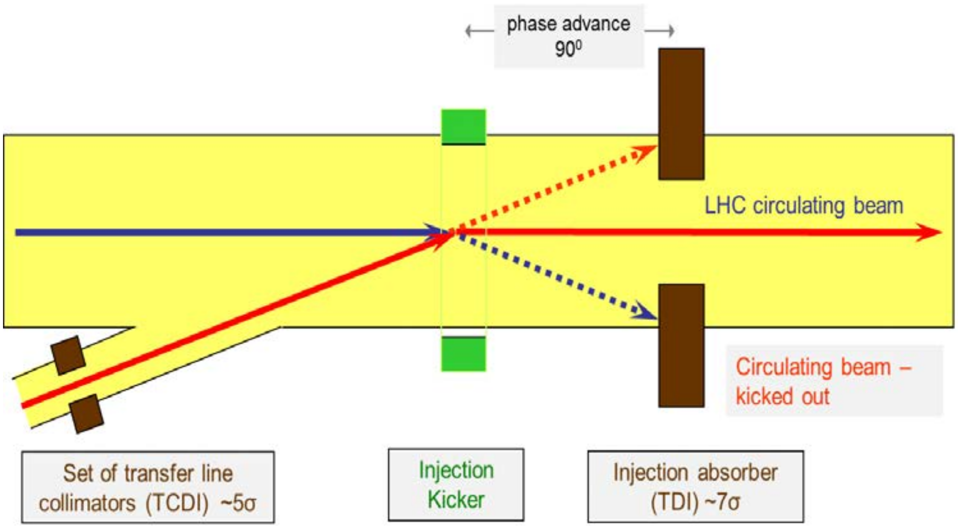

Fig. 9: LHC injection, two failure cases: 1) the injection kicker does not fire to deflect the incoming beam. 2) the injection kicker fires at the wrong time and deflects the circulating beam. In both cases the beam would hit vacuum chamber and equipment. To prevent such accident, the injection absorbers must be correctly positioned to ensure that the beam hits the absorbers for both failure cases.

Downstream of the kickers the beam is deflected vertically by 2.4 mrad towards the beam dump block by 15 septum magnets. A short distance further downstream, 10 diluter kicker magnets are used to paint the bunches in both horizontal and vertical directions to reduce the beam density on the dump block. The beam is transferred through a 700 m long extraction line to increase the transverse r.m.s. beam size from approximately 0.2 to 1.5 mm and to spread the bunches further on the dump block.

The overall shape is produced by the deflection of the extraction and dilution kickers. For nominal beam parameters, the maximum temperature in the beam dump block is expected to be in the order of about 800°C. Access to the dump block becomes difficult since the material will become increasingly activated.

Protection during the injection process is also mandatory. The energy stored in the LHC beam at injection is about one order of magnitude higher than the stored energy at top energy in the beam for other accelerators. An example of a critical failure for the LHC at injection is a failure of the injection kicker. If the kicker does not fire or fires at the wrong time, the incoming beam will not be deflected or the circulating beam will be deflected (see Fig. 9). In both cases, without protection, the beam would hit the vacuum chamber and damage equipment. During the injection process injection collimators are positioned in the vacuum chamber to capture the mis-kicked beam. This type of failure, e.g. a wrong kick of the injection kicker, has happened already several times. Since the injection absorber was always at the correct position there was no damage; however, due to grazing beam incidence superconducting magnets downstream of the injection region quenched.

5.1 Damage potential of a high-energy hadron beam

Beams at very high energy can have a tremendous damage potential for an accelerator such as LHC; damage to metals is expected for about 10^{10} protons. One LHC bunch has about 1.5×10^{11} protons, in total up to 2808 bunches. In case of catastrophic beam loss, the LHC could be possibly damaged beyond repair. The penetration of 2808 bunches (e.g. after a kicker failure) into a metal block such as a magnet has been estimated to be about 20 to 30 m (hydrodynamic beam tunnelling) [8].

In order to estimate the consequences of the beam impacting on a target, the time structure of the beam plays an essential role. Bunches arrive every 25 or 50 ns. The first bunches arrive and deposit their

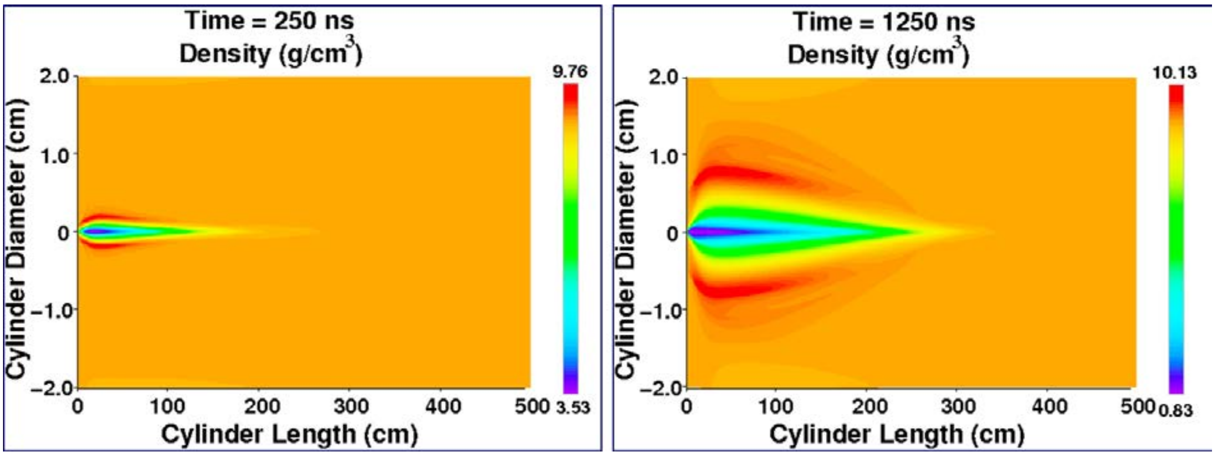

Fig. 10: Density of a copper target after an impact of 250 and 1250 ns for the FCC

energy. This can lead to an increase of the temperature, pressure and finally to a reduction of the target material density. Bunches arriving later travel further into the target since the material density is reduced (predicted also for SSC [9]).

The calculations were performed in the following way. A LHC beam impact on a solid cylindrical target is assumed, with 2808 bunches, each bunch with 1.1×10^{11} protons, a beam size of $\sigma = 0.5$ mm, 25 ns bunch distance, a target length of 6 m and a radius of 5 cm. Various target materials were considered, e.g. graphite with a density of 2.3 g/cm^3.

The energy deposition for a few bunches is calculated with FLUKA. The hydrodynamic code BIG2 uses the 3D energy deposition to calculate temperature, pressure and density of the target. The programs are run iteratively with the FLUKA 3D energy loss data used as input to BIG2, and the BIG2 3D density data used as input for FLUKA. The modified density distribution is used in FLUKA to calculate the energy loss corresponding to this new density distribution. The new energy loss distribution is used in BIG2, which is run for a time step.

For the FCC, a 100 km long accelerator to provide proton collisions at a centimetre energy of 100 TeV was used; calculations were performed for a particle energy of 40 TeV [10]. A copper target with a length of 5 m and a radius of 2 cm was taken. The simulations are very time consuming; this one took about 15 months. The density of the target after 250 ns and 120 ns is shown in Fig. 10; it decreased to 3.5 g/cm^3 after 250 ns beam impact and to 0.83 g/cm^3 after 1250 ns.

Figure 11 shows the density versus depth in the target for the simulation. In the figure, we present the density versus axis at different times during irradiation. Curve ‘a’ represents the time when two bunches have been delivered while later curves are plotted using an interval of 150 ns. We consider 6 g/cm^3 as the reference point on the density curve and calculate the speed with which this point moves towards the right. It is seen that at 800 ns, the depletion front achieves a steady average speed of 1.1×10^6 m/s. The total beam duration considering all 10 600 bunches is 265 µs that leads to a penetration distance of about 290 m. This means that in case of wrong deflection of the beam, the beam and the shower will penetrate through about 290 m of solid copper. If one considers a 50 TeV proton beam, the penetration distance could be up to 350 m.

An experiment was performed at the CERN-SPS HiRadMat facility with a 450 GeV proton beam to validate the simulation technique. Solid copper targets were facially irradiated by the beam and measurements confirmed hydrodynamic tunnelling of the protons and their showers. Simulations have been done by running the energy deposition code FLUKA and the 2D hydrodynamic code, BIG2, iteratively. Very good agreement has been found between the simulations and the experimental results [11] providing confidence in the validity of the studies for the LHC and FCC.

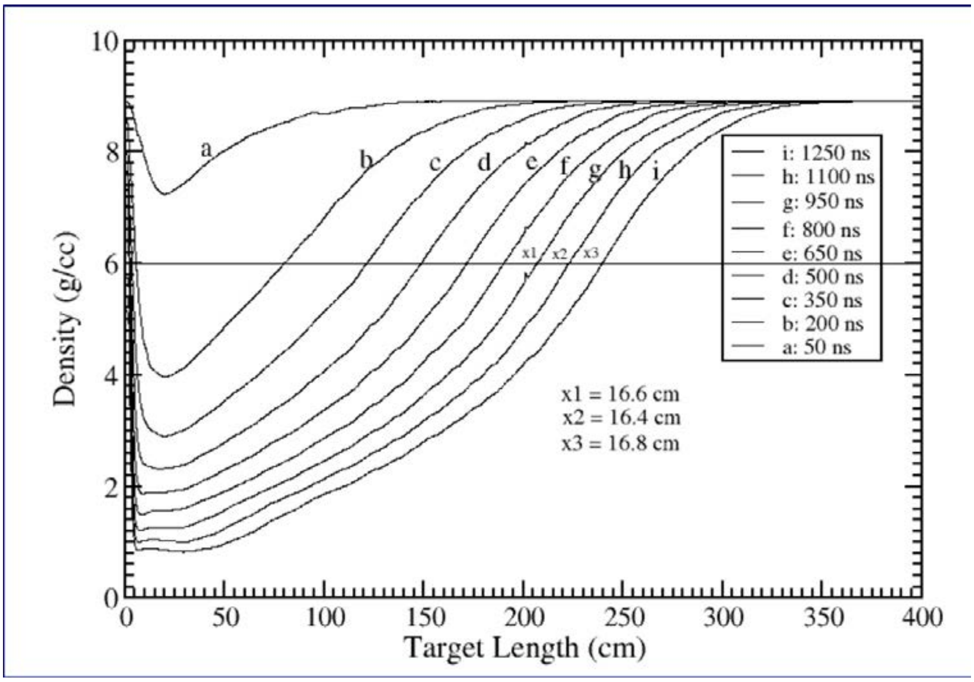

Fig. 11: Density of a copper target after an impact of 250 and 1250 ns

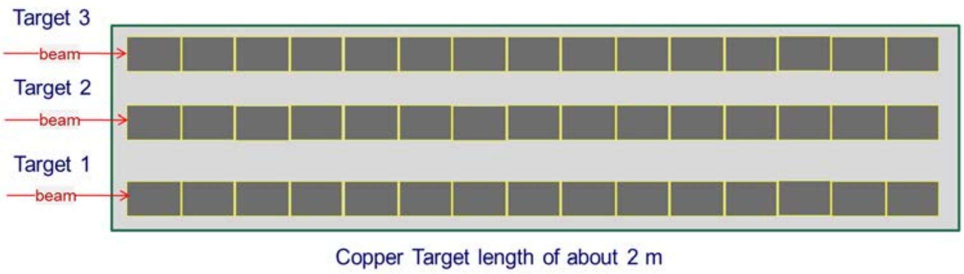

Fig. 12: Layout of the experiment with three different targets

Three targets (see Figs. 12, 13 and 14) were irradiated with bunch trains, each bunch of 50 ns, of different intensities:

- Target 1: 144 bunches, 1.9×10^{11}, $\sigma = 2.0$ mm, no tunnelling expected;
- Target 2: 108 bunches, 1.9×10^{11}, $\sigma = 0.2$ mm, tunnelling expected;
- Target 3: 144 bunches, 1.9×10^{11}, $\sigma = 0.2$ mm, tunnelling expected.

The measured penetration length of the beam and the results from the hydrodynamic simulations using FLUKA and BIG2 were obtained for all targets. Excellent agreement between hydrodynamic simulations and experimental results was found.

6 Protection for a high-intensity proton linac: the European Spallation Source

The European Spallation Source (ESS) being built at Lund, Sweden is designed to accelerate a proton beam with an average power of 5 MW and to direct the protons onto a target. Operation of the ESS will be at a frequency of 14 Hz, with a pulse length of 2.86 ms and a peak power of 125 MW. The layout of the ESS accelerator is shown in Fig. 15.

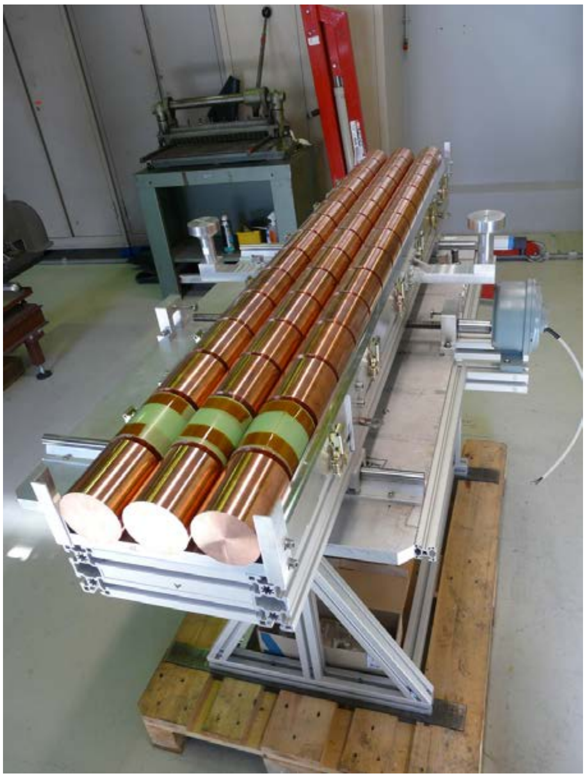

Fig. 13: Picture of the targets before irradiation

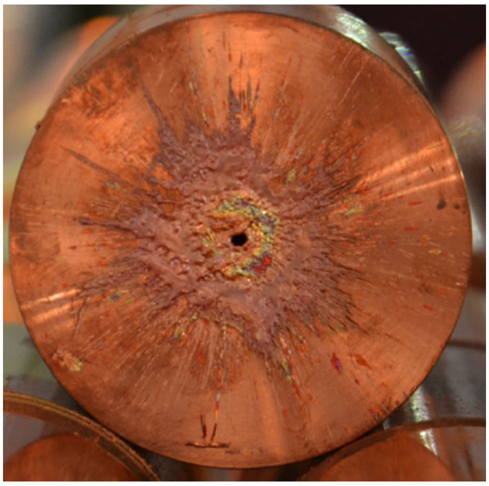

Fig. 14: Picture of the front face of one target block after irradiation

It is assumed that the beam is lost due to a failure after the acceleration section. An example is a trip of the power converter for the vertically deflecting magnets. If the beam loss takes, say, 1 ms, the deposited energy is up to 125 kJ (peak power of 125 MW during 1 ms), for 1 s up to 5 MJ. It is required to inhibit the beam after detecting uncontrolled beam loss as fast as possible. There is some delay between the detection of a failure (e.g. detection of beam losses by a beam loss monitor) and 'beam off'. Figure 16 shows the time to melt copper and steel in the case where the proton beam hits a metal surface between 3 and 80 MeV/c [12]. For example, after the drift tube normal-conducting linac (DTL), the proton energy is 78 MeV/c. In case of a beam size of 2 mm radius, melting would start after a beam impact of about 200 µs. Inhibiting of the beam after a failure is detected should be in about 10% of this time; see [13]).

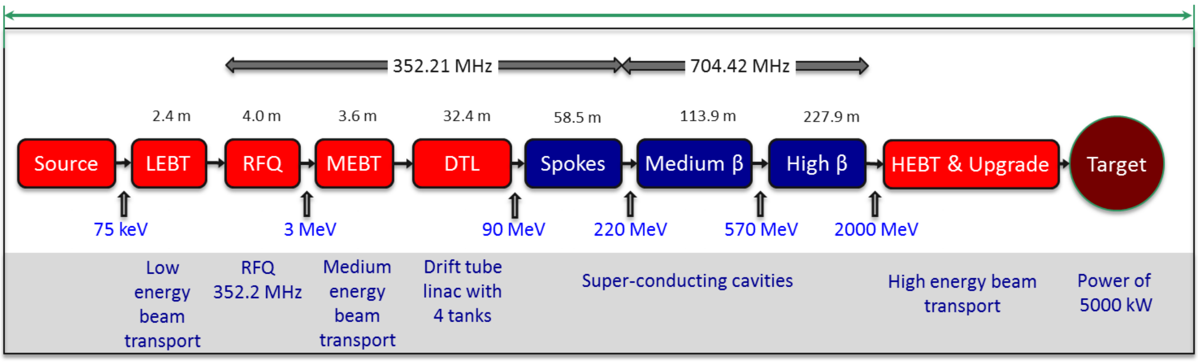

Fig. 15: Layout of the ESS accelerator: the source, low-energy beam transport and RFQ are followed by the medium-energy beam transport. The protons are accelerated by a normal-conducting linac, followed by three sections of superconducting cavities. In the high-energy beam transport line the protons are transported to the target.

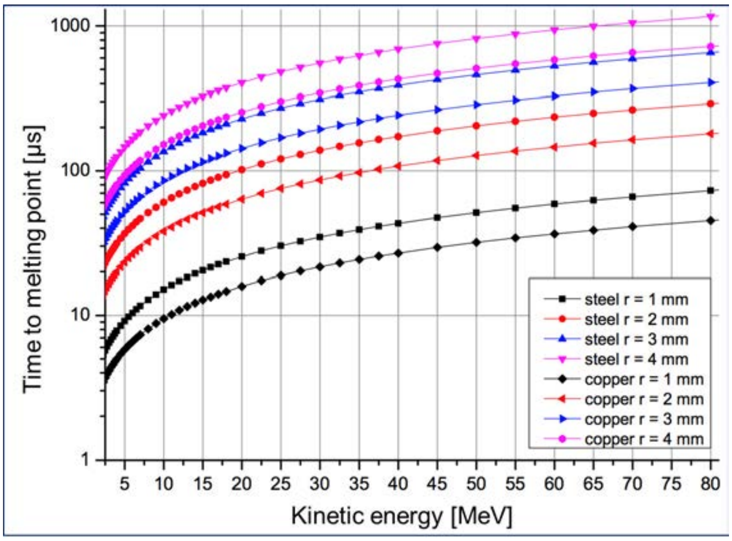

Fig. 16: Time to melt copper and steel, as a function of proton momentum for different beam sizes [12]

The energy stored in the beam at a given moment is relatively small in the low-energy part, in the medium-energy part and in the high-energy part. In case of a failure, the beam needs to be switched off at the source. In between two pulses (about 70 ms), it must be ensured that the parameters of the accelerator allow for correct beam transmission, or do not start the next pulse. If something is wrong and is not detected before the pulse by monitors, the beam must be stopped as soon as possible.

A realistic example for a failure is a trip of the power converter for the bending magnet deflecting the beam vertically Fig. 17. Assume that the power supply for the bend in HEBT-S2 fails and the magnet stops deflecting the beam. A mean time between failures (MTBF) for a power converter of 100 000 hours (15 years) is assumed, already a very good value. If this happens, the beam is not deflected and hits the vacuum chamber. The consequences can be serious; damage of magnet or vacuum pipe, possibly pollution of superconducting cavities.

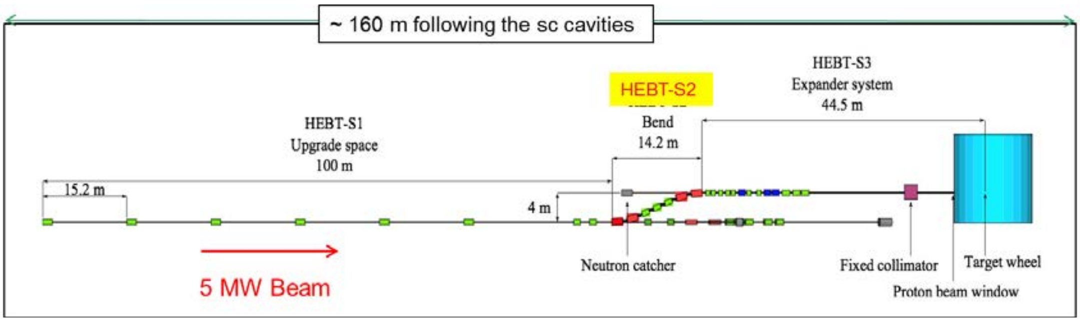

Fig. 17: Illustration of the vertical bending magnet for ESS, deflecting the 5 MW beam into the target plane

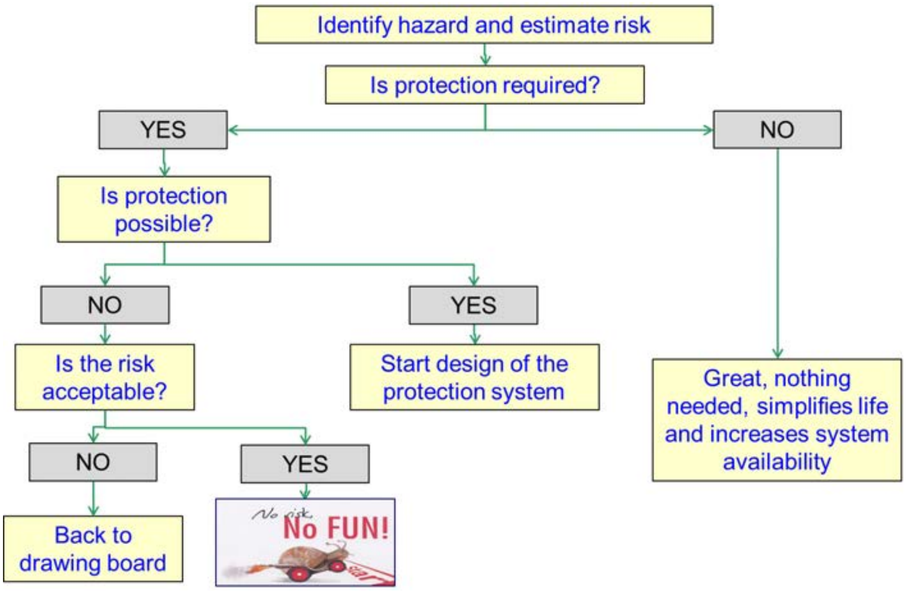

Fig. 18: Analysing if a machine protection system is required

7 Machine protection

7.1 Analysing the need for a machine protection system

The design of a machine protection system requires substantial resources, it can be expensive and it can reduce the availability of the accelerator since it will contribute to false trips. Therefore, it should only be built if absolutely necessary. Figure 18 gives an idea of how to analyse if such a system is required. Different outcomes are possible: there is no need for machine protection or there is a need for machine protection. In some cases protection is not feasible, and the system design must be modified.

7.2 Classification of failures

In the first step different types of failures that can cause beam losses are identified and classified:

- hardware failure (trip of a power converter, magnet quench, AC distribution failure, object in vacuum chamber, vacuum leak, RF trip, kicker magnet misfire etc);
- control failure (wrong data, wrong magnet current function, trigger problem, timing system failure, feedback failure etc);
- operational failures (chromaticity/tune/orbit wrong values etc);
- beam instability (due to too high beam current/bunch current/e-clouds etc).

The most important parameters for a failure are:

- time constant for beam loss after the occurrence of the failure;
- probability of the failure occurring;
- damage potential in case no mitigation is applied.

An accurate understanding of the time constant is required, since this determines the reaction time of the machine protection systems. The risk defined as $\mathrm{risk} = \mathrm{consequences} \times \mathrm{probability}$ is another important input determining the required reliability for the protection systems. For very high risk the protection systems must be extremely reliable.

7.3 Time constant for failures

The time constant for beam loss after a failure varies from nanoseconds to many seconds.

Single-passage beam losses in the accelerator complex have a time constant of a few nanoseconds to some tens of microseconds. In a circular accelerator such losses are related to failures of fast kicker magnets for injection and extraction. If other fast kicker magnets are present, for example for diagnostics, failures of such devices must also be considered. For failures of fast kicker magnets it is not possible to extract the beam or to stop the beam at the source; the particles will travel determined by the electromagnetic field along their path.

Single-passage beam losses are also an issue for any accelerator operating with pulsed beams. In between two pulses, equipment parameters can change (e.g. a magnet power supply can trip). During the following beam pulse, the beam would be mis-steered and can cause damage. This is typically the case for failures in a transfer line between accelerators (e.g. from SPS to LHC) or from an accelerator to a target station (target for secondary particle production or beam dump block). This is also an issue for linear accelerators operating with pulsed beams.

Very fast beam losses with a time constant in the order of 1 ms, e.g. multiturn beam losses in circular accelerators. Such losses can appear due to a large number of possible failures, mostly in the magnet powering system, with a typical time constant of about 1 ms to many seconds.

Fast beam losses with a time constant of 10 ms to seconds, due to many different effects. Beam instabilities in LHC are in general in this time range.

Slow beam losses take many seconds, e.g. due to non-optimized parameters, but also due to a failure.

7.4 Principles for machine protection

There are some principles for machine protection that need to be considered:

i) protect the machine;
ii) protect the beam;
iii) provide the evidence (at CERN, by the so-called post-mortem system).

7.4.1 Protect the machine

The highest priority is clearly to avoid any damage to accelerator equipment.

7.4.2 Protect the beam

The objective is to maximize beam time, but complex protection systems reduce the availability of the machine. The number of 'false' interlocks stopping operation must be minimized. This is a trade-off between protection and operation. A ‘false’ interlock is defined as an interlock that stops operation even though there is no risk (example: a temperature sensor reading a wrong value, therefore switching off the power converter of a magnet and stopping beam operation).

7.4.3 Provide the evidence

If the protection systems stop operation (e.g. dump the beam or inhibit injection), clear diagnostics should be provided [14]. If something goes wrong (leading to damage, but also a near miss), it should be possible to understand the event. This needs synchronized transient recording of all the important parameters in all relevant systems, as well as long-term logging of parameters with reduced frequency (such as 1 Hz). Examples are the current in all magnets, beam position, beam losses and beam intensity. The frequency of transient recording depends on the system and can go from Hz to MHz.

7.5 Active and passive protection

The best strategy is to prevent a specific failure from happening. As an example, fast diagnostic kicker magnets that could deflect the beams into the vacuum chamber wall should only be installed in high-intensity machines if they are indispensable.

7.5.1 Active protection

Failure should be detected as early as possible, with priority at the hardware level. For most failures, this strategy allows stopping beam operation before the beam is affected. This requires monitoring of the hardware (such as state signals, parameters etc). As an example, a trip of a magnet power converter should be detected as early as possible.

It is not always possible to detect failures at the hardware level. The second method is to detect the initial consequences of a failure with beam instrumentation and to stop the beam before equipment is damaged. This requires reliable beam instrumentation.

When a failure is detected, beam operation must be stopped. For synchrotrons and storage rings the beam is extracted by a fast kicker magnet into a beam dump block. Injection must be stopped. For linacs the beam is stopped in the low-energy part of the accelerator by switching off the source, deflecting the low-energy beam by electrostatic plates (‘choppers’) or by switching off the RFQ for proton linacs.

An electronic system (beam interlock system) links the different protection systems. It ensures that the beam is extracted from a synchrotron, injection is stopped, RF acceleration might be stopped (for linacs). The interlock system might include complex logic.

7.5.2 Passive protection

There are failures (e.g. ultra-fast losses) when active protection is not possible. One example is the protection against mis-firing of an injection or extraction kicker magnet. A beam absorber or collimator is required to stop the mis-kicked beam in order to avoid damage. All possible beam trajectories in such case must be considered, and the absorbers must be designed to absorb the beam energy without being damaged. Another example is a fast extraction of a high-intensity beam from a circular accelerator into a transfer line. When the extraction takes place, the parameters of the transfer line must be correctly set since in case of a wrong magnet current the beam could be deflected into the vacuum chamber.

7.6 LHC strategy for machine protection

Machine protection starts with a careful commissioning of the magnet powering system, considering that an energy of about 10 GJ is stored in the superconducting magnets. Magnet protection and powering interlocks must be operational long before starting beam operation. The strategy for LHC machine protection when operating with beam reflects many of the principles that have been discussed above.

i) Definition of aperture by collimators (beam cleaning system).
ii) Early detection of failures of equipment acting on beams generates a beam dump request, possibly before the beam is affected (interlocks for the different hardware system, for LHC essentially the magnet and powering system).
iii) Active monitoring of the beam parameters with beam instruments detecting abnormal beam conditions and generating beam dump requests within a single machine turn (using beam loss and other beam monitors).
iv) Reliable transmission of beam dump requests from a large variety of systems to the beam dumping system by a beam interlock system. An active signal is required for operation; the absence of the signal is considered as a beam dump request and injection inhibit.
v) Reliable operation of the beam dumping system for dump requests or internal faults, safely extracting the beams onto external dump blocks.
vi) Passive protection by beam absorbers and collimators for specific cases of failure.

7.7 Design considerations for protection systems

There are several principles that should be considered in the design of protection systems, although it might not be possible to follow all these principles in all cases.

i) If the protection system does not work, it is better stopping operation rather than continuing and risking damaging equipment.
ii) Fail-safe design: in case of a failure in the protection system, protection functionalities should not be compromised. As an example, if the cable that triggers the extraction kicker of the beam dumping system is disconnected, operation must stop.
iii) Detection of internal faults: the protection system must monitor the internal status. In case of an internal fault, the fault should be reported. If the fault is critical, operation must be stopped.
iv) Remote testing should be an integral part of the design, for example between two runs. This allows verification of the correct status of the system.
v) Critical equipment should be redundant (possibly diverse redundancy, with the same or similar functions executed by different systems).
vi) Critical processes for protection should not rely on complex software running under an operating system and requiring the general computer network.
vii) It should not be possible to remotely change the most critical parameters. If parameters need to be changed, the changes must be controlled and logged and password protection should ensure that only authorized personnel can do the change.
viii) Safety, availability and reliability of the systems should be demonstrated. This is possible by using established methods to analyse critical systems and to predict failure rates.
ix) Operate the protection systems early on before they become critical, to gain experience and to build up confidence. This could be done before beam operation, or during early beam operation when the beam intensity is low.
x) It is inevitable to disable interlocks (e.g. during the early phase of commissioning and for specific tests). Managing interlocks (e.g. disabling) is common practice. Keep track and consider it in the system design. Example for LHC: masking of some interlocks is possible, but only for low-intensity/low-energy beams (‘safe beams’).

Fig. 19: Beam loss monitor at LHC

8 Machine protection subsystems

8.1 Beam loss monitors

Beam loss monitors (BLMs) are used for monitoring beam losses to understand the performance of the accelerator as well as for machine protection. If used for protection, it is important that the monitors cover the entire accelerator and there is no region without BLMs where beam losses can occur.

The monitors should be fast, for LHC down to 40 µs, in order to detect beam losses in time to stop operation. They should be designed such that they can trigger a beam dump and stop operation before very fast beam losses damage equipment. There are about 3600 chambers distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort [15].

For LHC (Fig. 19) and several other accelerators, ionization chambers are used to detect beam losses. The reaction time is down to microseconds; they can have a very large dynamic range exceeding 10^8.

Figure 20 shows the beam losses around LHC during regular luminosity operation. Losses are low in the arcs with the superconducting magnets, higher in the insertions with the experiments due to the debris of the collisions and very high in the betatron cleaning insertions. Figure 21 shows the losses recorded after a beam dump during regular operation. A UFO (unidentified falling object) in the arc between the betatron cleaning insertion and the LHC experiment caused locally an increase of beam losses. The UFO, very likely dust particles getting into the beam (see [16]) causes very fast losses and when the threshold of one BLM is exceeded, the beams are dumped (see Fig. 22).

8.2 Beam cleaning system

The LHC operates with a stored beam with an energy of 360 MJ (nominal parameters). A beam lifetime of 10 min corresponds to a beam loss of 500 kW that should not be lost in superconducting magnets. The strategy to keep beam losses at an acceptable level is as follows:

i) avoid beam losses as far as possible;
ii) define the aperture by collimators;
iii) capture continuous particle losses with collimators at specific locations.

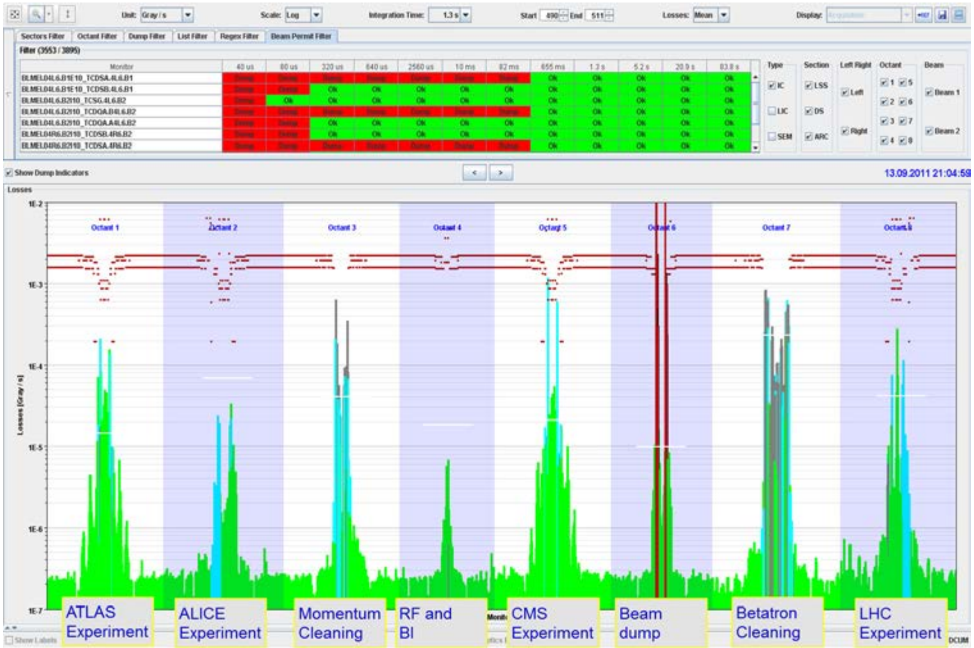

Fig. 20: Regular beam losses during luminosity operation

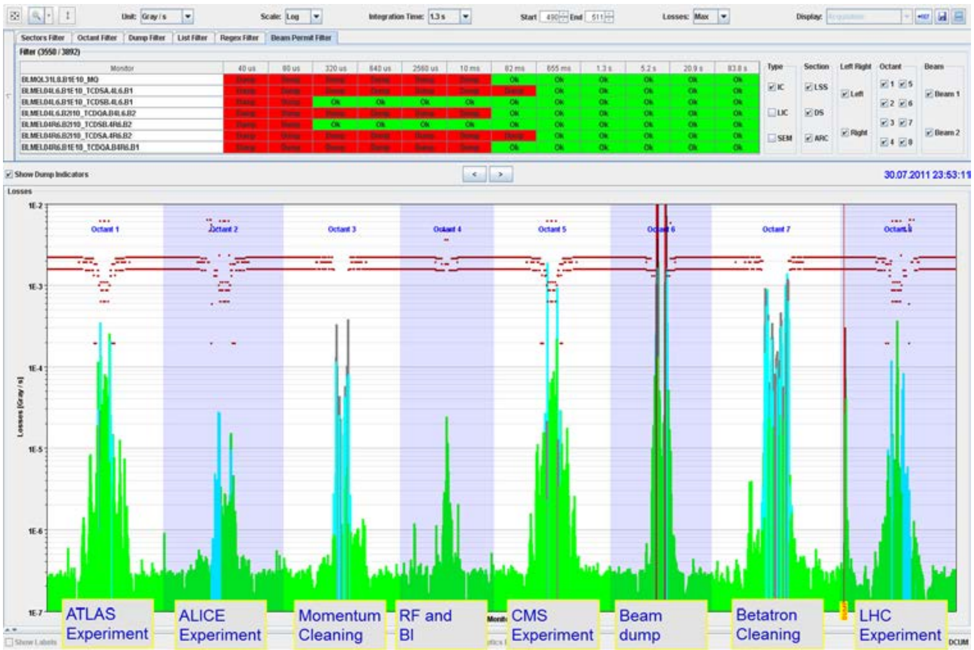

Fig. 21: Beam losses with UFO during luminosity operation

Fig. 22: Time structure of the beam losses caused by a UFO

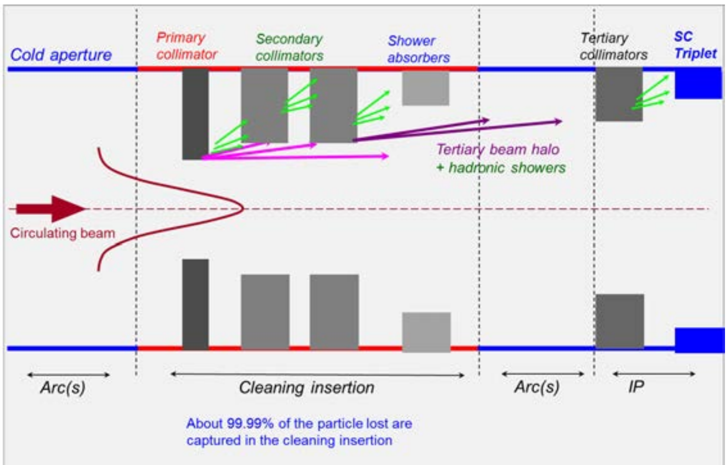

Fig. 23: Illustration of beam cleaning at LHC

A collimation system is a very efficient system to avoid too high beam losses in the accelerator (so-called beam cleaning) [17]. It can be very complex with (massive) material blocks close to the beam installed in an accelerator to capture halo particles. Figure 23 illustrates the LHC beam cleaning system.

The collimation system at LHC reduces the losses by four orders of magnitude and also captures fast accidental beam losses. About 100 collimators are installed in LHC. Figure 24 shows the view of one of the two-sided collimators; it is closed down to 2 mm when operating at 7 TeV/c. Collimators (or beam absorbers) are equally important to capture mis-steered beam.

8.3 Interlock systems

Figure 25 illustrates the interlock systems for LHC. The heart is the beam interlock system that receives beam dump requests from many connected systems. If a beam dump request arrives, a signal is sent to

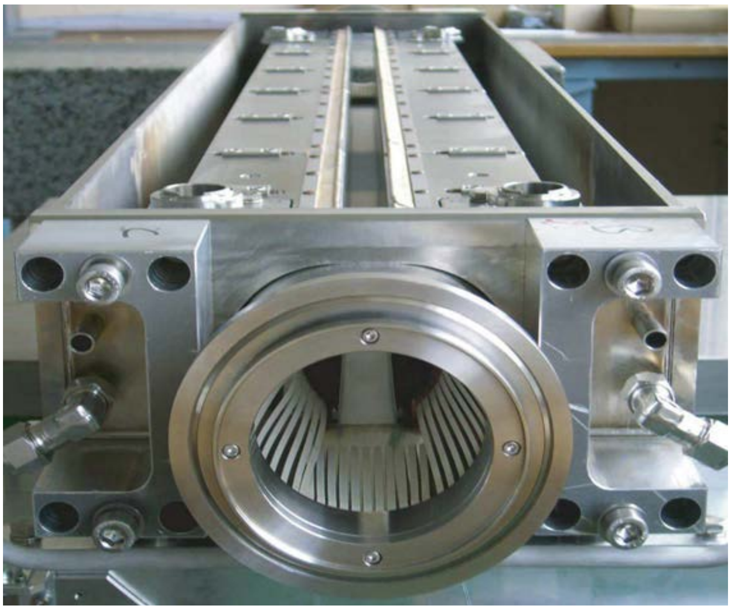

Fig. 24: Collimator at LHC

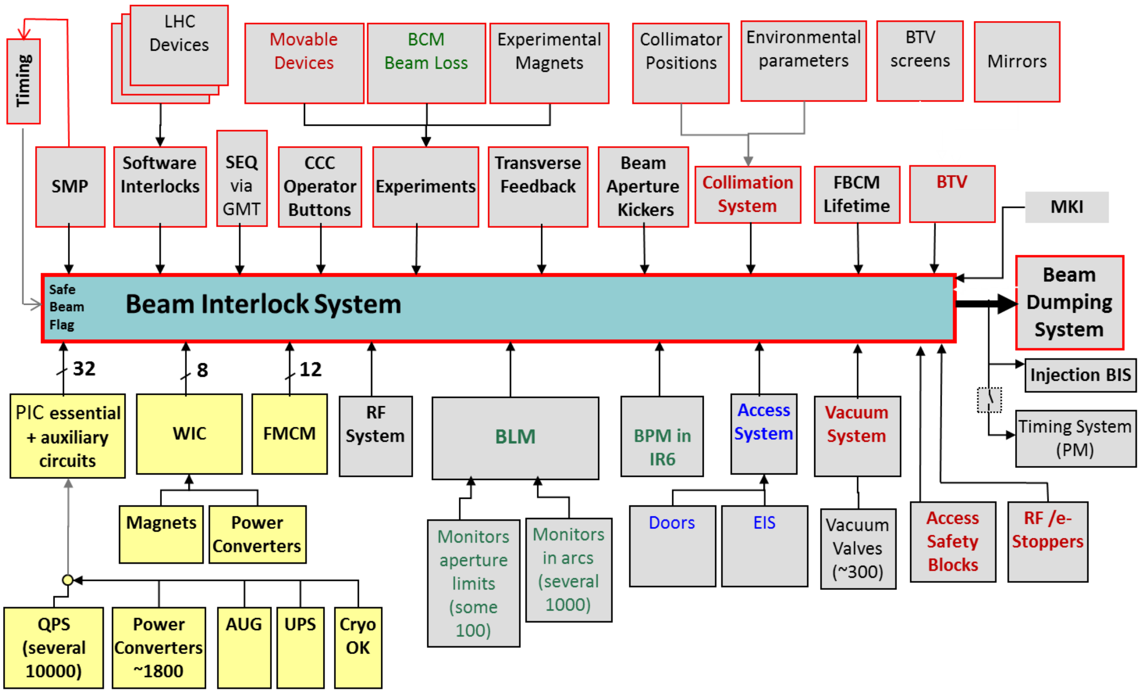

Fig. 25: Beam interlock system at LHC as well as connected systems

the beam dumping system to request the extraction of the beams. At the same time, a signal is sent to the injection system to block injection into LHC as well as extraction of beam from the SPS. A third signal is provided for the timing system that sends out a request to many LHC systems for providing data that were recorded before the beam dump, to understand the reasons for the beam dump (typically beam loss, beam position, beam current, magnet currents etc).

The most complex system of LHC is the superconducting magnets and powering system. The powering interlock system (PIC) ensures communication between systems involved in the powering of the LHC superconducting magnets. This includes power converters, magnet protection system, UPSs (un-interruptible power supplies), emergency stop of electrical supplies (AUG) and the cryogenic system. As an example, in case a magnet quench is detected by the quench protection system (QPS), the power converter must stop. In total, there are several tens of thousands of interlock signals. When a failure is detected that risks stopping the powering of magnets, a beam dump request is sent to the beam interlock system. A second system manages interlocks from the normal-conducting magnets and their power supplies (WIC) that ensures protection of normal-conducting magnets in case of overheating.

The machine interlock system is strictly separated from interlocks for personnel safety such as the personnel access system; however, an interlock from the access system is sent to the beam interlock system.

As shown in Fig. 25, many other systems also provide beam dump requests in case of failure: beam loss monitors, other beam monitors, movable devices and LHC experiments.

9 Conclusions

Machine protection goes far beyond the equipment protection and across many systems. It requires the understanding of many different types of failures that could lead to beam loss. It requires fairly comprehensive understanding of all aspects of the accelerator (accelerator physics, operation, equipment and instrumentation) and touches many aspects of accelerator construction and operation.

Machine protection is becoming increasingly important for future projects, with increased beam power and energy density (W/mm^2 or J/mm^2) and increasingly complex machines.

Protection of equipment, even when operating without beam, must not be forgotten. The largest accident happening at an accelerator was the rupture of a superconducting cable at LHC in 2008 due to the very large energy stored in the superconducting magnet system.

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