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Beam Loss Consequences

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Abstract
A summary of beam loss types and their effects is presented.

Keywords
Beam–machine interaction; particle shower calculation; radiation effects.

1 Beam losses

The operation of any particle accelerator features some kinds of relevant beam losses. These can take place at devices meant to intercept the beam, such as targets, dumps, stoppers, collimators, and stripping foils. At the design stage, one must consider both regular and accidental impacts. The latter ones are uncontrolled and may be due to magnet failures at injection or extraction, for instance kicker misfiring or electron beam missteering during top-off injection. As a consequence, the impact conditions become extremely severe, in terms of intensity (i.e., number of impacting particles) or brilliance (i.e., intensity per unit area). In this way, a collimator, instead of intercepting the beam halo at a controlled rate, is directly hit by a few bunches. Moreover, any device on the beam path, as the foreseen beam dilution pattern is lost, is subject to too-small spot sizes that are potentially harmful.

One must also routinely deal with diffused losses, throughout the beamline of both linear and circular machines. Linacs are concerned by several loss mechanisms [1]. Lepton rings are especially affected by synchrotron radiation and gas bremsstrahlung, while in hadron rings nuclear reactions between beam particles and residual gas nuclei are an important source of secondary showers, whose amount scales with the gas density and the beam current.

Colliders are exposed to debris regularly produced at the interaction points, proportionally with the delivered luminosity. Typically, its most energetic component, travelling close to the primary beam, escapes the detector and impinges on the accelerator elements, e.g. the final focus quadrupoles.

Furthermore, the beam trajectory may cross unexpected obstacles, represented by dust particles drifting inside the vacuum chamber or by flawed aperture restrictions. The mass thickness of the object and the fraction of current traversing it determine the loss strength.

2 Consequences

Any of the aforementioned beam loss types is the onset of a secondary particle cascade, whose amplitude depends on the primary particle energy. The scenarios span from low-energy beam absorption within the material surface layers, by ionization, to combined hadronic and electromagnetic shower development over hundreds of metres of machine elements, as for instance in the large hadron collider (LHC). In such a broad context, many different physical processes are involved and their microscopic description, as integrated in multipurpose Monte Carlo codes, allows the calculation of relevant macroscopic quantities and, therefore, the evaluation of loss consequences.

Among these, applying to distinct time-scales, one can list the following.

- *Heating.* This is a short-term effect, owing to the total power deposited in the material by the impinging radiation. It calls for cooling measures when needed.
- *Thermal shock.* Remaining in the short-term domain, the material can undergo rupture, depending on the peak power density and on its spatial distribution.

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- *Quenching*. Far below its damage threshold, a superconducting material loses its ability to conduct electricity without resistance as it warms above a critical temperature, owing to the level and profile of energy deposition density induced by the radiation impact.
- *Single-event effects in electronic devices*. These range from bit upsets perturbing device functionality to destructive burn-outs. Their probability of occurrence is proportional to the time integrated high energy hadron fluence. In addition to these stochastic events, the steady accumulation of defects can ultimately lead to device failure, which can be anticipated on the basis of the expected ionizing and non-ionizing dose (with the latter generally quantified in terms of silicon 1 MeV equivalent neutron fluence).
- *Deterioration*. The long-term degradation of critical properties of organic materials (typically insulators) is related to the accumulated peak dose, while for inorganic materials the reference quantities are neutron fluence and displacements per atom in the hottest spots.
- *Oxidation, radiolysis, ozone production*. Determination of the impact of these chemical effects is based on the assessment of energy deposition. Knowing the power absorbed in an air volume, one can, for instance, calculate the resulting ozone concentration, as a function of the ventilation time.
- *Gas production*. A variety of residual nuclei is generated by nuclear reactions and their abundance can be naturally estimated in the simulation of the beam–machine interaction. Among these, one can distinguish (in addition to the radioactive species featured in one of the next items) those leading to gas build-up—typically hydrogen and helium—which in a solid material contributes to embrittlement and swelling.
- *Radiation in public spaces and shielding requirements*. For radiation protection purposes, depending on the aspects to be considered, particle fluence in a given location is transformed into effective dose or ambient dose equivalent (both expressed in sieverts) by means of respective sets of conversion coefficients, which are a function of particle type and energy. The prompt dose equivalent outside a radiation facility, reflecting the applicable radiation level in a public space during normal or accidental operation of the facility, is the quantity to reduce to below acceptable limits through a suitable shielding design.
- *Equipment and air activation, radioactive waste production, access limitations*. Radionuclide generation is responsible for delayed emissions during beam absence that limit access and intervention possibilities as well as equipment handling, including waste disposal. Induced activation is characterized by isotope activities and spatial distribution of residual dose rate after relevant cooling times.
- *Tumour cell destruction*. Particle beams are routinely used in cancer radiotherapy. They are intended to maximize the dose delivery to the tumour mass and to spare as much as possible the healthy tissue. When moving from conventional treatment with photons to hadron therapy, the calculation of biological dose, taking into account the biological effectiveness of the radiation, becomes a key ingredient.

Beside these effects, the radiation development following a beam loss occurrence also allows it to be detected and quantified by suitably located monitors. Ionization chambers, such as the LHC beam loss monitors [2], provide an online observation and play a central role in the machine protection system, triggering beam aborting if the recorded signals exceed predefined thresholds. Their charge collection is proportional to the energy deposition in the sensitive gas volume, which can be simulated and thus represent a compelling benchmark for calculation validation. Another example is given by detectors measuring hadron fluence, thanks to the single-event effect principle previously indicated [3]. Again in the hadron therapy context, treatment monitoring opportunities are offered by the detection of prompt photons or charged particles from nuclear reactions, as well as by positron emission tomography exploiting the tissue activation, namely the production of β^+ emitters.

It should be noted that only the full description of the particle shower initiated by the beam loss can shed light on the actual link between a peripheral monitor signal and the quantity that matters for the accelerator operation or design, such as the peak energy density in a beam intercepting device or in a magnet coil, or even the dose distribution delivered to a patient.

For a more extended discussion of the radiation effects here outlined and of the physical processes behind them, the reader is referred to Ref. [4].

References

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