MACHINE PROTECTION FOR SINGLE-PASS FELS

L. Fröhlich*, Sincrotrone Trieste, Basovizza, Italy

Abstract

The linacs driving modern single-pass FELs carry electron beams of unprecedented brightness with average powers ranging from few watts to hundreds of kilowatts. The article discusses the scope of machine protection for these accelerators, reviews the parameters of existing and planned facilities, and gives an overview about typical hazards and damage scenarios. As a common problem faced by all single-pass FELs, the effect of radiation-induced demagnetization of permanent magnet undulators is discussed.

INTRODUCTION

The linacs used to drive modern single-pass FELs carry electron beams of unprecedented brightness. These machines are also equipped with unusual amounts of instrumentation that needs to be protected from beam losses. The FEL process itself depends crucially on the precision of the magnetic field inside undulator structures that are prone to demagnetization under radiation exposure. This combination makes machine protection for single-pass FELs much more challenging than for traditional electron linacs.

After introducing the broad scope of the term *machine protection*, this paper reviews the parameters and damage potentials of existing and future FEL facilities. The various hazards connected with electron beam losses are summarized and the effect of radiation-induced demagnetization on the phase error of an FEL undulator is discussed.

SCOPE

The term *machine protection* is often understood as a mere synonym for a system of protective interlocks and beam loss diagnostics. While such active systems play an important role, an effective protection from damage involves many fields of accelerator engineering and physics. To attempt a definition, we may state that *machine protection is the sum of all measures that protect an accelerator and its infrastructure from the beam.* Traditionally, the focus is on the charged particle beam, but the generated photon beam needs to be considered as well, especially due to the unprecedented peak power of X-ray FELs.

From the above definition, we can identify a number of fields connected with machine protection:

Machine protection system: The MPS implements interlocks on components that may interfere with a safe beam transport (e.g. magnets, screens). It monitors the beam with instrumentation that may be generic (BPMs, current monitors) or specifically designed for protection purposes (beam loss monitors, dosimetry systems). When excessive beam losses or other problems are detected, the MPS intervenes according to a mitigation strategy—it might simply inform the operator, reduce the repetition rate, or stop the beam production.

Collimators: Collimators and scrapers are used to limit the extent of the electron bunch (and of possible dark currents) in phase space. In case of trajectory or focusing problems, they should intercept the electron beam before it reaches sensitive components. The electromagnetic cascades originating from the interaction of high energy electrons beams with matter are not easy to contain, so care must be taken to place suitable absorbers.

Shielding: The loss of a small fraction of an electron beam at the GeV level releases a dangerous amount of spontaneous radiation. Even if the average power of the beam is as low as few watts, the radiation can quickly cause temporary or permanent damage to electronics in the vicinity of the beamline. Sustained exposure causes various types of radiation damage like the darkening of optical components. Beam loss can also release sizable quantities of neutrons and activate materials in the process. Depending on the beam power, shielding may therefore be necessary against both electromagnetic dose and neutrons.

Beam physics: A loss-free transport of charge from the injector to the dump requires a good understanding of the optics and of the whole acceleration process. The higher the beam power, the more important it is to have good control over the optics matching and over collective effects that create emittance blowups, tails, or halos.

Robust systems: Every system or software that has a direct or indirect influence on the beam contributes to the protection of the machine by providing a certain level of robustness. Cardinal examples are beam-based feedback systems, low-level radiofrequency (LLRF) systems, or even high-level physics tools for the optimization of the FEL output.

Procedures: Well-defined procedures for typical linac operations like switch-on, change of energy, or ramp to full power contribute to safety and make the machine state more reproducible. Automatization of these procedures can further help to avoid errors.

* lars.froehlich@elettra.trieste.it

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Table 1: Maximum Energy, Bunch Frequency, and Average Beam Power of Selected Existing and Planned FELs. The calculation of the beam power assumes typical parameters for minimum and maximum power operation for each facility.

	E (GeV)	ν (Hz)	P (W)
FERMI@Elettra	1.3	10–50	7–60
SACLA	7	10–60	18–140
LCLS	15	120	8–440
FLASH	1.3	1M–3M pulse	10–22k
European XFEL	17	5M pulse	600k
Berkeley NGLS	2	1M cw	600k
NovoFEL	0.012	5.6M–22M cw	15k–60k
JLab FELs	0.2	75M cw	1M–2M
Future ERLs	5	1.3G cw	500M

EXISTING AND FUTURE FACILITIES

Most of the existing and proposed single-pass FELs are based on normal conducting linacs using S- and C-band accelerating structures. The normal conducting technology permits only a short RF pulse so that, usually, only a single bunch is accelerated per pulse. The beam power is therefore limited by the repetition rate ν of the RF systems of 10–120 Hz. With E denoting the energy per electron, Q the bunch charge and e the elementary charge, the average beam power for single bunch operation is

$$P = \nu Q E / e,$$

so depending on their individual parameters, normal conducting machines transport beams from few watts to more than 400 W (Tab. 1).

Superconducting linacs can sustain the RF pulse considerably longer and hence facilitate the acceleration of long bunch trains with bunch frequencies in the megahertz range, considerably raising the average beam power. FLASH, currently the only working single-pass FEL based on a superconducting linac, has demonstrated the transport of 1800 bunches per pulse at a bunch charge of 3 nC with a repetition rate of 5 Hz, carrying an average power of 22 kW [1, 2]. Future installations aim at an average power of 600 kW, either in pulsed mode like the European XFEL or in continuous-wave (CW) with reduced gradient as in Berkeley's Next Generation Light Source proposal. It is obvious that superconducting linacs, when operated at these power levels, have a serious damage potential.

Table 1 also lists the parameters for FELs based on energy recovery linacs (ERLs)—although these are oscillators instead of single-pass FELs, they are an instructive point of reference for the typical problems associated with high beam powers. The Jefferson Lab FELs, when operated with a bunch frequency of 75 MHz (CW), can carry a nominal electron beam power of more than a megawatt. This means that even the loss of a tiny fraction of the electron beam can cause serious problems including mechanical damage, and consequently machine protection aspects are a fundamental part of the operation of the accelerator. It is a safe assumption that future superconducting single-pass FELs operating in a similar power range will share many of the problems encountered in today's ERLs while adding some of their own.

Table 2: Effects of Beam Loss. The table roughly relates the onset of various damaging effects to the local power deposition caused by a beam loss.

P_{min} (W)	Effects
100 – 1000	Thermal/mechanical damage
10 – 100	Mechanical failure of flange connections
1 – 100	Activation of components
1 – 100	Radiation damage to electronics, optical components, etc.
1 – 10	Excessive cryogenic load, quenches
0.01 – 0.1	Demagnetization of permanent magnets

HAZARDS

The complete or partial loss of the electron beam in a vacuum chamber can cause a number of detrimental effects. The most important ones are summarized in Tab. 2, where the attempt has been made to associate the onset of each effect with the magnitude of the local power deposition. This is to be understood only as a rough indication of the orders of magnitude; obviously, each damage scenario needs to be assessed individually and for special cases very different numbers may be found.

Direct mechanical damage through melting or sublimation depends on power density rather than power; for typical scenarios, however, a substantial power deposition of hundreds of watts or kilowatts is necessary—hence, direct damage is of little concern for normal conducting machines, but needs to be protected against for superconducting ones. Single-bunch damage is not to be expected at typical FEL parameters because of too low charge densities (for the International Linear Collider it has been estimated that a single bunch of 3 nC causes damage when focused to an area below 50 μm^2 [3]).

The deposition of heat can have indirect consequences as well—such as impairing the tightness of a flange connection once the metal starts to cool down after thermal expansion. This, again, is an unlikely scenario for the typical beam powers of normal conducting machines, but is a real danger once the beam power reaches the multi-kilowatt level.

The spontaneous radiation released by beam losses can lead to malfunctions in electronics or to various types of

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radiation damage; the radiation released by a single watt of electron beam is quite destructive to many types of electronics in the vicinity if no proper shielding is in place—obviously, the loss of this amount of power is easily diagnosed in a linac operating at low current, but it only corresponds to a fraction of 10^{-5} of a 100 kW beam. Similar considerations apply to the activation of components; generally, induced radioactivity at electron accelerators is relatively short-lived and substantially lower than at hadron machines, but it can impair the maintainability of components and the accessibility of the beamline.

Superconducting accelerators have a special vulnerability to beam losses because any deposition of heat in the cold mass must be compensated through the cryogenic system with a disproportionate amount of power. Beam losses can also cause superconducting cavities to quench, which in turn creates an immediate instability in the downstream beam transport. Depending on the severity of the quench, it may also be necessary to cut the RF power until the cavity has recovered.

Finally, all working and planned single-pass FELs use undulators based on permanent magnet structures. These magnets are very close to the beam axis and are susceptible to the loss of magnetic field under moderate radiation doses (see e. g. [4–7]). The problem of magnet damage is of particular concern for machine protection at free-electron lasers because

- it is cumulative (even small dose rates can cause a deterioration of the field over longer time scales),
- it is often not possible or at least very expensive to exchange an undulator,
- the undulators represent one of the smallest apertures in the accelerator (the SACLA in-vacuum undulators have a minimum gap of 3.5 mm [8]), and
- the FEL process itself depends on a high precision of the magnetic field.

EFFECT OF DEMAGNETIZATION IN AN UNDULATOR

For a number of reasons, typical beam loss scenarios cause a very inhomogeneous dose deposition along the longitudinal axis of an undulator (see e. g. [9]). The strongest demagnetization is usually to be expected in the first periods at the upstream end of the magnet structure. An extreme example is the U33 undulator from the Petra II lightsource that lost more than 40 % of its magnetic field at the upstream end after 10 years of operation [10].

To illustrate the effect of a partially demagnetized undulator, a single electron can be tracked through the center of a perfect undulator field with a simple 2-dimensional tracking code. At each turning point i of the undulating trajectory (where the transverse velocity is zero), the longitudinal slippage Δz_i between the electron and a photon emitted at the undulator entrance is noted. In this ideal undulator, the

Table 3: Undulator and Electron Beam Parameters for the Phase Error Calculation

Number of periods	66
Period length	3.48 cm
Field amplitude	1.105 T
Electron energy	1.25 GeV
Wavelength (fundamental)	21.7 nm

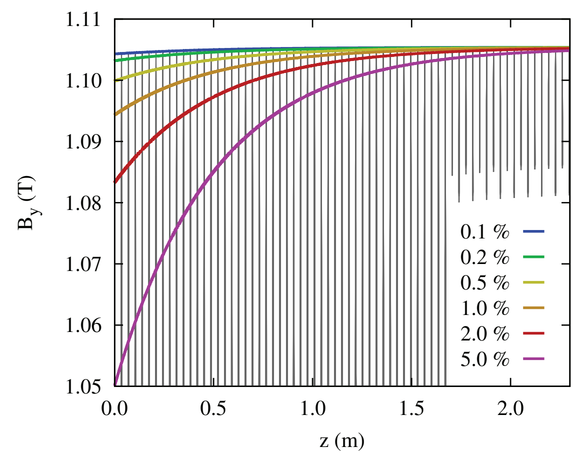

Figure 1: Undulator magnetic field profiles for phase error calculations. Colored lines indicate the tapered field amplitudes, gray lines show the actual oscillating magnetic field.

slippage increases by one radiation wavelength λ_r for each full period of the undulating motion, $\Delta z_{i+2} - \Delta z_i = \lambda_\mathrm{r}$.

If the field amplitude at the undulator entrance is reduced, the electron motion is no longer synchronous with the nominal radiation wavelength—the particle effectively takes a straighter trajectory and therefore gets ahead of where it should be. This asynchronicity can conveniently be expressed as a phase error $\Delta\phi$; at each trajectory turning point i, we define

$$\Delta\phi_i = 360^\circ \cdot \frac{i\,\lambda_r/2 - \Delta z_i}{\lambda_\mathrm{r}} + \phi_0,$$

where the starting phase ϕ_0 can be chosen at will (as by a phase shifter chicane in a real-world FEL).

For a real-world example, a set of parameters for an undulator in the final stage of FERMI@Elettra's FEL-2 has been chosen (Tab. 3). To simulate radiation-induced demagnetization, the ideal undulator field $B_\mathrm{y}(z)$ is then tapered according to

$$B'_\mathrm{y}(z) = B_\mathrm{y}(z) \cdot (1 - d\exp(-z/L))$$

with $L = 0.5$ m and a factor d specifying the relative demagnetization at $z = 0$. The field profiles for values of d between 10^{-3} and $5 \cdot 10^{-2}$ are shown in Fig. 1.

The resulting phase errors are displayed in Fig. 2. For ease of comparison, they have been adjusted (via ϕ_0) to coincide at zero at the exit of the undulator. It can be seen that

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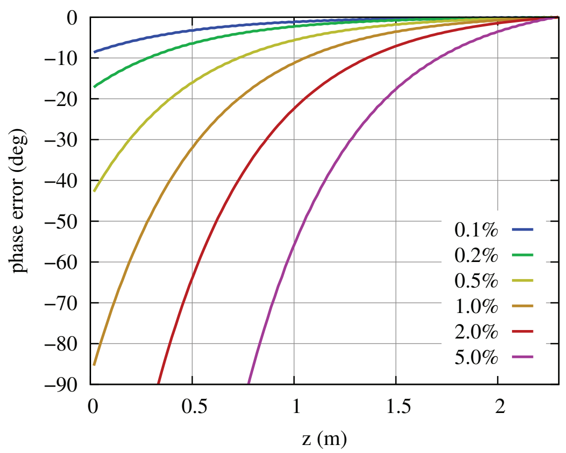

Figure 2: Phase errors for various demagnetization profiles.

the phase errors quickly reach big values: Already at a tapered demagnetization of 1 %, the electron bunch is out of phase by 90° at the undulator entrance. For higher values of d, the electron bunch in the first part of the structure effectively cancels out a part of the radiation through destructive interference. It should be noted that inhomogeneous phase errors like this can not, or only to a small degree, be compensated by adjusting the undulator gap.

Obviously, the effect on the microbunching and on the final output power of the FEL needs to be studied in the context of the whole system of insertion devices and electron beam optics. It is clear, however, that even a small loss of magnetic field can have a big influence on the performance of an undulator.

CONCLUSION

All of today's single-pass FELs share a common set of machine protection problems: the limitation of induced activation, the protection of components from generic radiation damage, and, most importantly, the protection of permanent magnet undulators from demagnetization. The high beam power of superconducting linacs makes all of these problems much more challenging while adding the potential for direct or indirect mechanical damage.

Ultimately, the goal of machine protection is to avoid damage to costly components and to prevent the loss of beam time—one of the most precious resources at any light source. The best approach to this goal is not to reduce machine protection to a mere system of interlocks, but to make safety considerations an integral part of the design and operation of an accelerator.

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