Machine Protection for Single-Pass FELs

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What is Machine Protection?

Machine protection is the sum of all measures that protect an accelerator and its infrastructure from the beam.

- **Machine Protection System**
  - Interlock on components (magnets, screens, …)
  - Monitoring of the beam (beam loss monitors, charge monitors, BPMs, …)
  - Mitigation (inform the operator, reduce repetition rate, fire abort kickers, stop beam production, …)

- Collimators, absorbers
- Shielding

- Physics (matching, collective effects, …)
- Robust systems+software (feedbacks, LLRF, controls, …)
- Safe procedures (switch on, change beam energy, ramp to full power, …)
# Average Electron Beam Powers

## Normal conducting
- **FERMI@Elettra**
  - Energy: 1.3 GeV
  - Frequency: 10-50 Hz
  - Power: 7-60 W
- **SACLA**
  - Energy: 7 GeV
  - Frequency: 10-60 Hz
  - Power: 18-140 W
- **LCLS**
  - Energy: 15 GeV
  - Frequency: 120 Hz
  - Power: 8-440 W

## Superconducting
- **FLASH**
  - Energy: 1.3 GeV
  - Frequency: 1-3 MHz pulsed
  - Power: 10 W - 22 kW
- **European XFEL**
  - Energy: 17.5 GeV
  - Frequency: 4.5 MHz pulsed
  - Power: >500 kW
- **Berkeley NGLS**
  - Energy: 2 GeV
  - Frequency: 1 MHz CW
  - Power: 600 kW

## Energy recovery linacs
- **NovoFEL**
  - Energy: 12 MeV
  - Frequency: 5.6-22 MHz CW
  - Power: 15-60 kW
- **Jlab FEL**
  - Energy: 200 MeV
  - Frequency: 75 MHz CW
  - Power: >1 MW
- **Future ERLs**
  - Energy: 5 GeV
  - Frequency: 1.3 GHz CW
  - Power: 500 MW

Photo: Michael J. Linden

Photo: DESY

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### Hazards

<table>
<thead>
<tr>
<th>Local loss power (W)</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 – 1000</td>
<td>Thermal/mechanical damage</td>
</tr>
<tr>
<td>10 – 100</td>
<td>Mechanical failure of flange connections</td>
</tr>
<tr>
<td>1 – 100</td>
<td>Activation of components</td>
</tr>
<tr>
<td>1 – 100</td>
<td>Radiation damage to electronics, optical components, &amp;c.</td>
</tr>
<tr>
<td>1 – 10</td>
<td>Excessive cryogenic load, quenches</td>
</tr>
<tr>
<td>0.01 – 0.1</td>
<td>Demagnetization of permanent magnets</td>
</tr>
</tbody>
</table>
Demagnetization of Permanent Magnets

- FELs rely on precision magnetic fields
- Permanent magnets lose magnetic field under irradiation with high energy electron beams
- Various magnetic materials behave differently

Teruhiko Bizen – “Brief Review of the Approaches to Elucidate the Mechanism of the Radiation-induced Demagnetization” (ERL workshop 2011, Tsukuba, Japan)

Demagnetization of Permanent Magnets

Can demagnetization be compensated by undulator tuning (opening gaps)?

FLUKA beam loss simulation
(FLASH, 1 bunch, 10 Hz)

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Dose Deposition in Undulators

FLASH — Beam loss (1 bunch, 1 nC, 10 Hz)

Absorbed dose rate (Gy/h)

z (m)

Und1 Und2 Und3 Und4 Und5 Und6

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Field Loss of a PETRA-II Undulator

P. Vagin et al., “Commissioning experience with insertion devices at PETRA III”, SR2010, Novosibirsk, Russia.
Demagnetization and Phase Error

Example: FERMI@Elettra FEL-2, second stage radiator
66 periods of 3.48 cm

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• Machine protection should not be just a system of interlocks

• Superconducting FELs can transport dangerously powerful beams

• Permanent magnet undulators need protection