Machine Protection at ESS

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Overview

1. Overview on the ESS LINAC, Target Station and Neutron Experiments

2. Accidental Beam Losses and Damage Potential of Proton Beam

3. Machine Protection at ESS: scope and concept

4. Summary

ESS LINAC

ESS aims to house the most powerful proton LINAC ever built

Average neutron flux is proportional to average beam power

Average beam power will be: **5 MW**

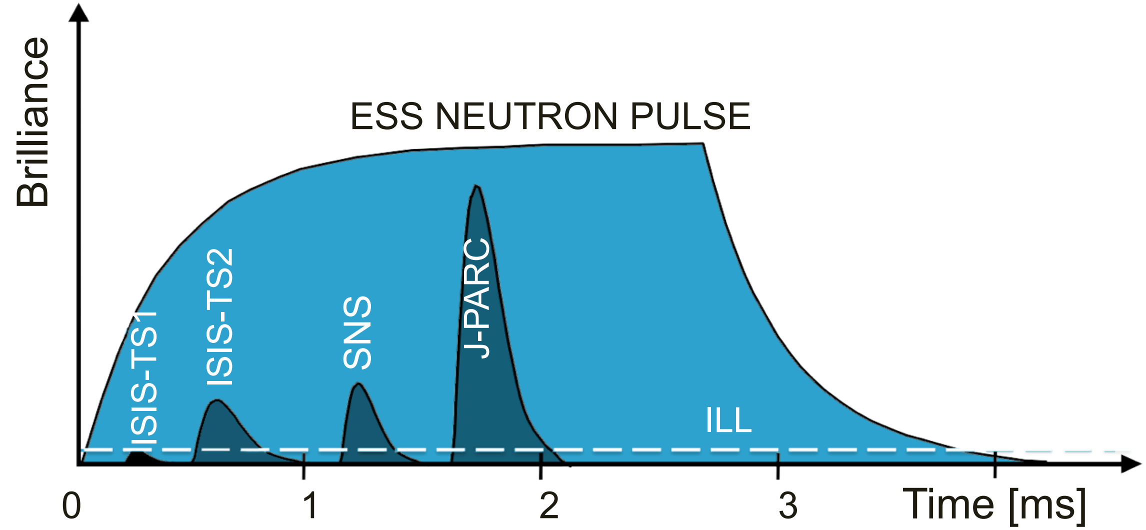
Average beam current: **62.5 mA**

Proton energy per pulse: **360 kJ**

Repetition rate: **14 Hz**

Pulse length: **2.86 ms**

Proton Energy: **2 GeV**

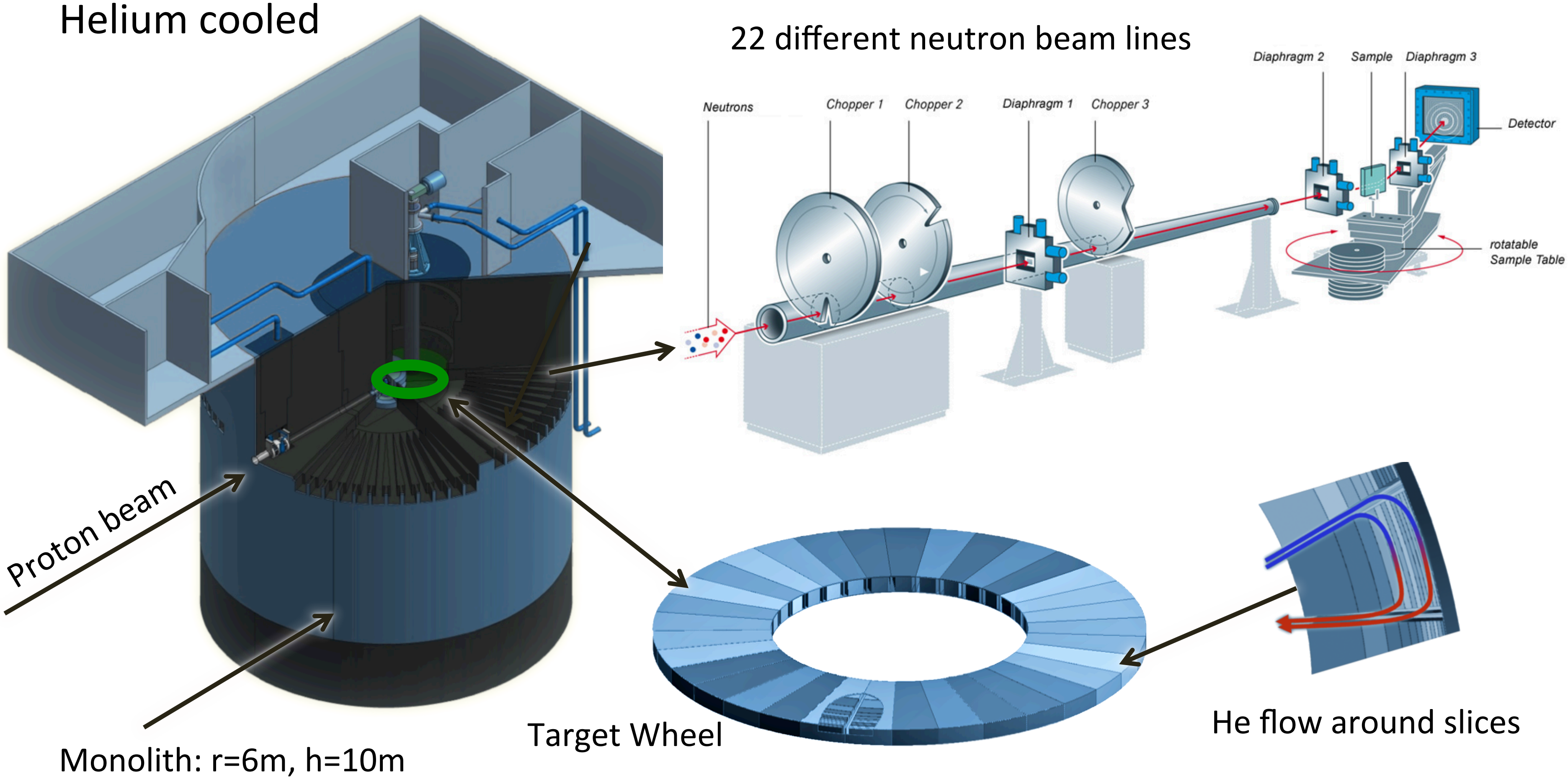


ESS Target and Experimental Stations

Target with rotating tungsten wheel

Synchronized to 14Hz

Helium cooled



Damage Potential of Beam

Relevant parameters to be considered **for heating and** possible **damage to material**:

Momentum of the particle,

Particle **type**,

Energy stored in the beam,

Beam **power**,

Beam **size**,

Beam power/energy density (MJ/mm2, MW/mm2),

Time structure of the beam,

Cooling conditions.

In order to estimate the **order of magnitude for possible damage**:

i) **one MJ** can heat and **melt about 1.5 kg of copper**;

ii) **one MJ** corresponds to the energy stored in about **0.25 kg of TNT**;

iii) **one MW** during one second **corresponds to one MJ**.

Beam Losses and Machine Protection

Continuous beam losses: inherent during operation of accelerators.

Accidental beam losses: transient losses with time scales from ns to many seconds due to a multitude of failure mechanisms.

‘**Machine protection**’ protects equipment from **damage, activation, downtime** due to **accidental beam losses**. Machine protection includes a **large variety of systems**.

Example:

For 1 MW, a loss of 1% corresponds to 10 kW, not to be lost along the beamline to avoid activation of material, heating, etc. If a length of 200 m is assumed, the losses correspond to 50 W/m (1W/m is max. acceptable).

Beam-Induced Accident: Example I

In 2004, during extraction tests in the CERN/SPS extraction line with 450 GeV/c protons, **beam with** an energy of **2 MJ was deflected** with grazing incidence **into a vacuum chamber** after the failure of a septum magnet.

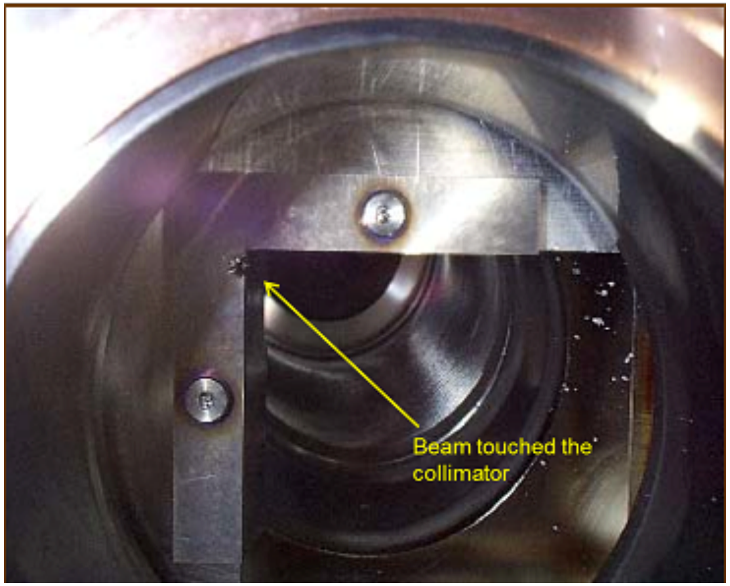
The **vacuum chamber was cut along a length of 25 cm**, with a groove of a length of 70 cm.

Condensed drops of steel are visible on the opposite side of the vacuum chamber.

Vacuum chamber and quadrupole magnet needed to be **replaced**.

Beam-Induced Accident: Example II

Tevatron, Fermilab:
Roman pot (a device that can be moved in the vacuum chamber) **moved into the beam.**



Particle showers generated by the Roman pot **quenched superconducting magnets**.

The **beam** moved by 0.005 mm/turn,
and **touched a collimator jaw** surface after about 300 turns.

The entire beam was lost, mostly on the **collimator** that was **damaged**.

Damage Potential of the ESS Proton Beam

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Assumption

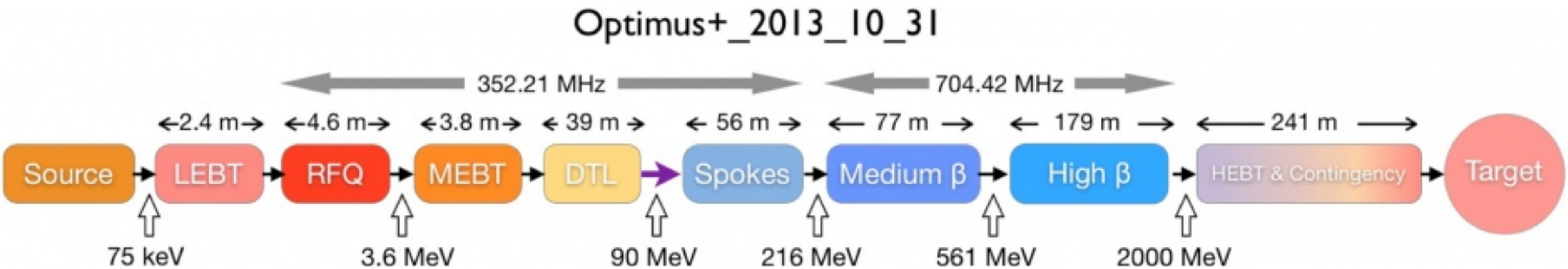
Proton beam impinging perpendicularly on copper or steel (2mm beam size).

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium ß → High ß → HEBT → Target

	LEBT, RFQ	MEBT, DTL	Spokes	Medium ß, High ß, HEBT
Beam Energy in [MeV]	1 - 3.6	3.6 - 90	90 - 216	216 - 2000
Melting Time in [µs]	10 - 20	20 - 200	200 - 400	>400

Damage potential of the beam at low energies (warm LINAC) is very high.

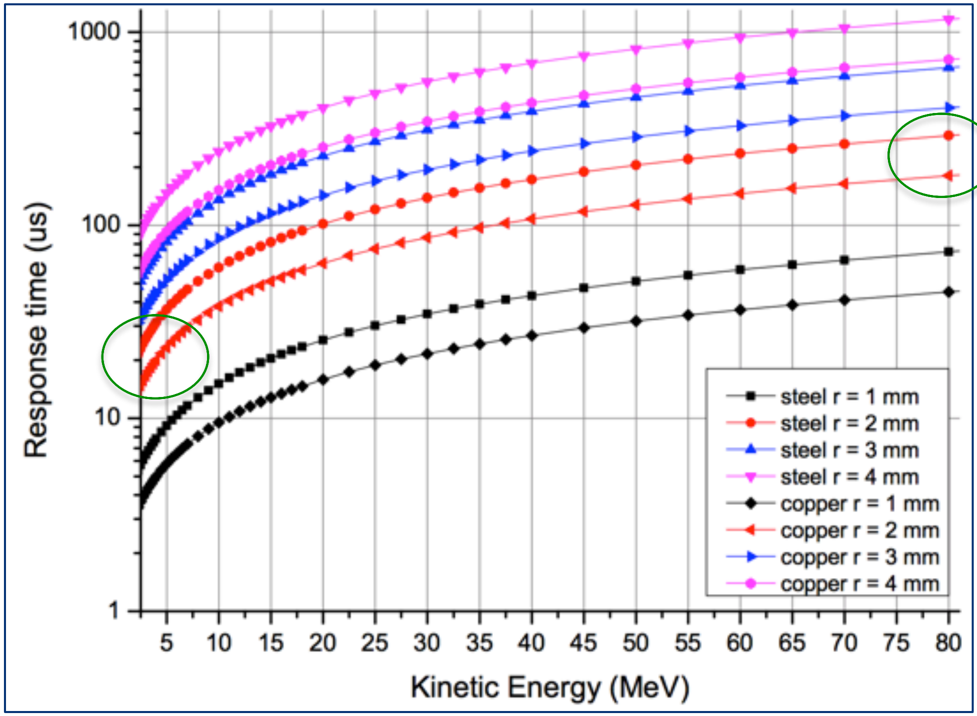
Damage Potential and Timescales for LINAC



After the DTL, the energy of the proton beam is 90 MeV. In case of a beam size of 2 mm radius/and direct impact, melting would start after about 200 µs. Inhibiting beam should be in about 10% of this time.

Examples for required response times to avoid melting of equipment (2mm/10%):

@ 1 MeV: 1 µs
@ 3.6 MeV: 2 µs
@ 90 MeV: 20 µs
@ 216 MeV: 40 µs ....



Scope of Machine Protection at ESS

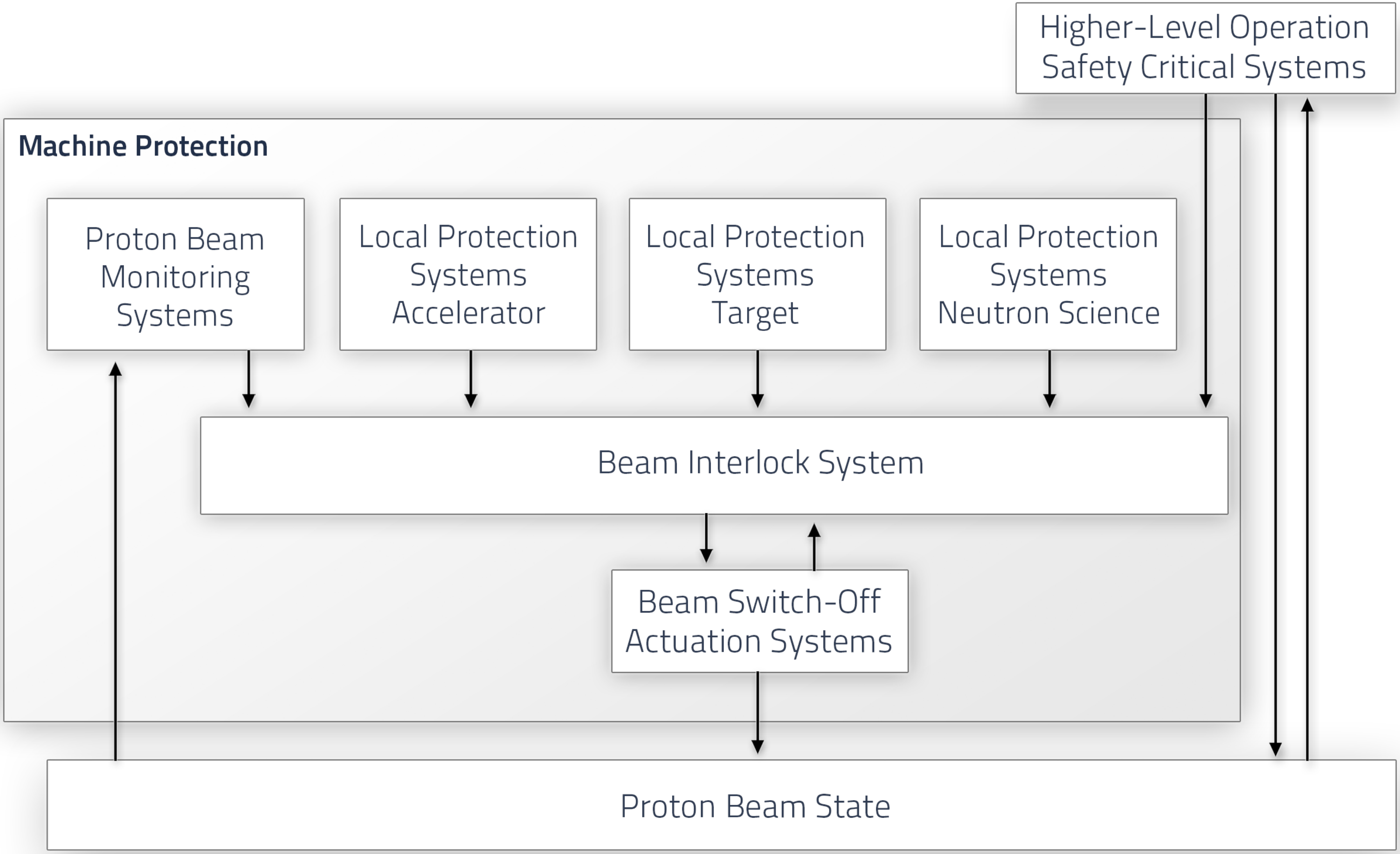
Machine Protection (MP) needs to reliably:

- **protect** the "machine" **from damage**, be it beam-induced or resulting from any other source,
- **protect** the "machine" **from unnecessary beam-induced activation**.

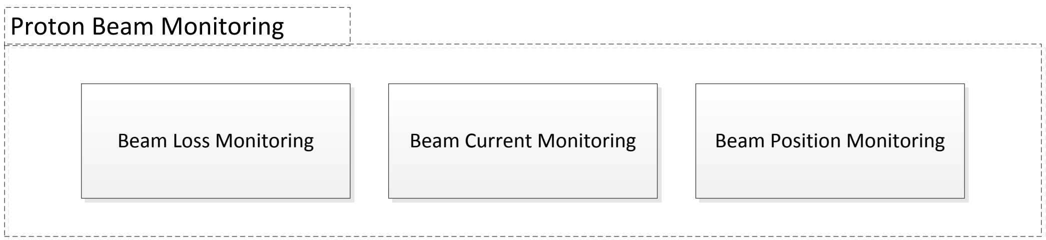
Machine Protection will be implemented in a way to:

- **minimize** unnecessary down-time due to **spurious trips**,
- provide optimal **support** for **failure localization**,
- **support** all **operational modes** of the facility,
- **avoid wrong configuration** of equipment,
- **support** operation in **degraded mode.**

Functional MP Architecture Concept



Local Protection and Beam Monitoring



As the **beam itself is a potential source of damage** and the source for activation, **Machine protection has to make sure that the beam parameters are as they should**.

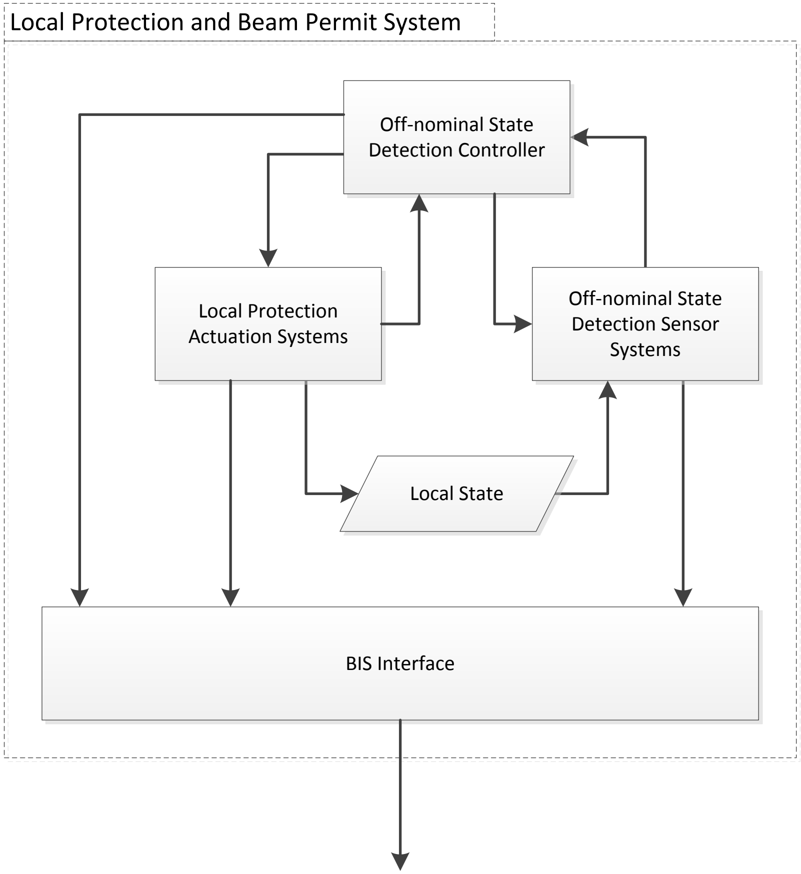
This involves **detecting off-nominal losses, currents, position** and maybe other parameters.

Local Protection Systems and Beam Monitoring will be composed of specialized subsystems. Hence the responsibility to specify those systems must lie with the corresponding expert groups.

Reaching the required availability levels will however only be achievable if some degree of standardization in implementation and documentation is achieved.

Even though documentation does not impact on the function of the systems, it is crucial to allow for a sensible review of the planned implementations and to allow for a realization of optimization potential with respect to availability before going live.

Local Protection and Beam Permit

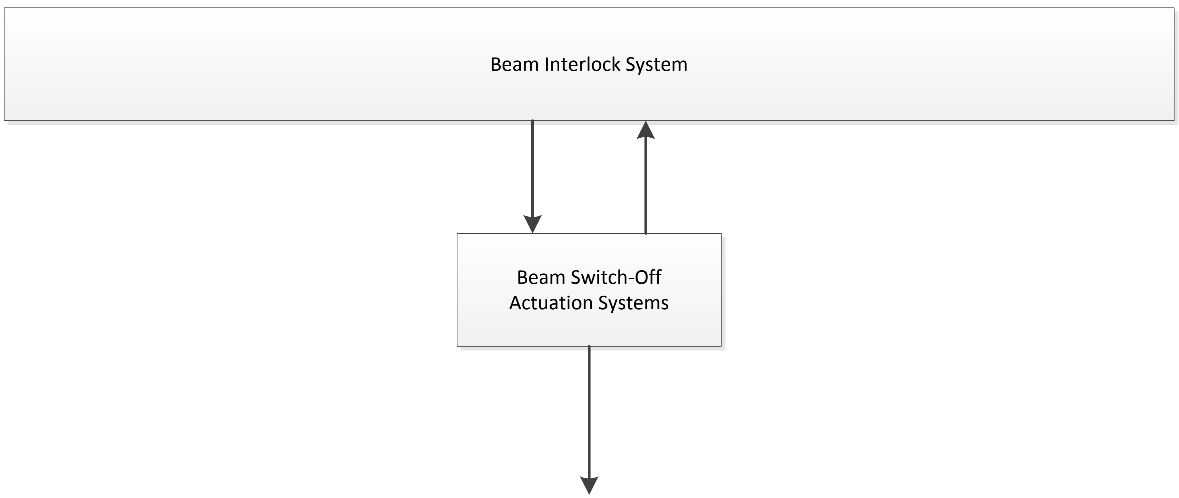


There might be many different concrete designs for Local Protection and Beam Permit Systems, but all of them will fit this generic structure:

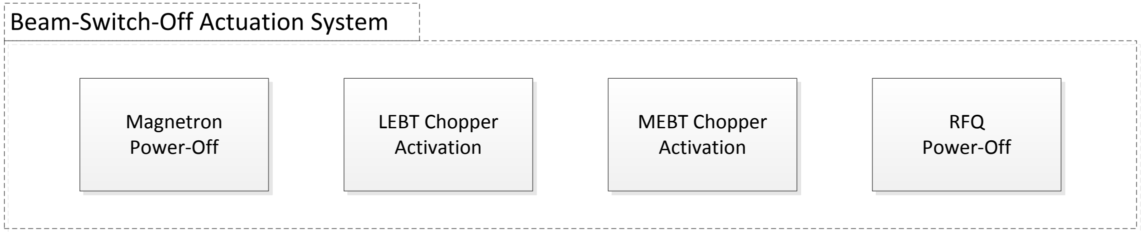
- The Local State is what is being monitored.
- Specific sensors are needed to detect off-nominal states.
- The sensor readings are processed in a controller (this is a functional view).
- Actuation systems are needed to take local protection actions.
- Aggregation of signals is needed as well as propagation of this information to the Beam Interlock System (BIS).

Beam Permit and Beam Switch-Off

The findings of all higher-level and local systems need to be combined into a single BEAM PERMIT. This is the job of the Beam Interlock System.



The beam needs to be switched-off by a reliable actuation system that's fast enough for the purpose.



There are four candidates for reliable (redundant) and fast Beam Switch-Off Actuation.

Actuators for Machine Protection/BIS

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1) Remove RF signal from the **magnetron of proton source**:
   - 100 µs until there is no plasma being created anymore
2) Energize electrodes of **LEBT chopper** and deflect beam into LEBT absorber:
   - 300 ns until beam is fully deflected.
   - **BUT: The absorber cannot withstand full beam power for a long time**
3) Energize electrodes of **MEBT chopper** and deflect beam into MEBT absorber:
   - 10 ns until beam is fully deflected
   - **BUT: The absorber can *only* withstand 100-200 µs of beam before being damaged**

4) Decrease electrical field of the **RFQ**:
   - 20 µs until field is decreased (i.e no beam transmitted & accelerated through the RFQ)
5) Other options (not investigated yet):
   - Remove field from **Solenoids in the LEBT**
   - Cut **400 V line of Proton source** using a contactor like TSS and PSS

None of these mitigation techniques can be used by itself, we have to use a combination

→ trigger 1) + 2) + 3) simultaneously

Operational Mode Concept

The **operational mode concept at ESS** is based on:

- **Machine Modes, defining the "final intended destination" of the proton beam,**
- **Beam Modes, defining the properties of the proton beam.**

Setting an operational mode is clearly a control system job!

→ Machine Protection & Beam Permit systems need to be configurable by the control system.

However, mode confusion could lead to potentially harmful behavior.

→ There is a clear need for some kind of **"operational mode sanity checking".**

This would not only include checking if every protection related system agrees on the same mode, it would also include checking if all those systems have correctly adopted the right configuration related to that mode.

Degraded Mode Operation

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Things will fail.
Some of these things might not be so critical to operation to require an immediate shutdown when they fail.

→ There is a clear need for some kind of a **"masking feature"** at the level of the BIS, but also at the level of the local systems.

It should be possible to force the system to ignore certain inputs (eg when injecting a pilot beam with almost no damage potential, etc). It is however critical to define what should be allowed per operational mode.
And if you define rules, you better check if they are being followed.

→ **Masked signals should be cross-checked to confirm that they are in agreement with the rules defined by the selected operational mode.**

Degraded mode operation includes other features, such as lowering the repetition rate upon detection of specific failures that are not very critical or changing beam current, etc. rather than stopping beam operation.

Configuration Management

There is a third potential source of damage that is closely related to mode confusion and inadequate mode dependent configuration of elements.

This would be the use of elements having a “version” that does not match the system configuration version requirements.

There has to be a clear definition of what versions of what are expected to be there in order to allow operation. And of course, this should be checked.

→ **The version of critical hardware and software configuration items should be checked with respect to system version requirements.**

These last three potential sources of problems might lead to add two functional entities to machine protection and beam permit:

This concept shall include validation as well and not be restricted to Monitoring only

Hardware and Software CI Version Monitoring	Mode and Configuration Monitoring

Summary

Presented scope and concept for ESS Machine Protection.

It is not clear at the moment if the nBLMs are part of Machine Protection or not and if they need to be connected to the Beam Interlock System.

We have not yet defined the protection functions and also not required response times.

However its not unlikely that we will use the nBLMs for MP purposes.
To be prepared its important to foresee the interface to the BIS.

Such interface would be directly integrated on the standard ICS acquisition board but would need to be defined for other non-standard boards

BackUp Slides

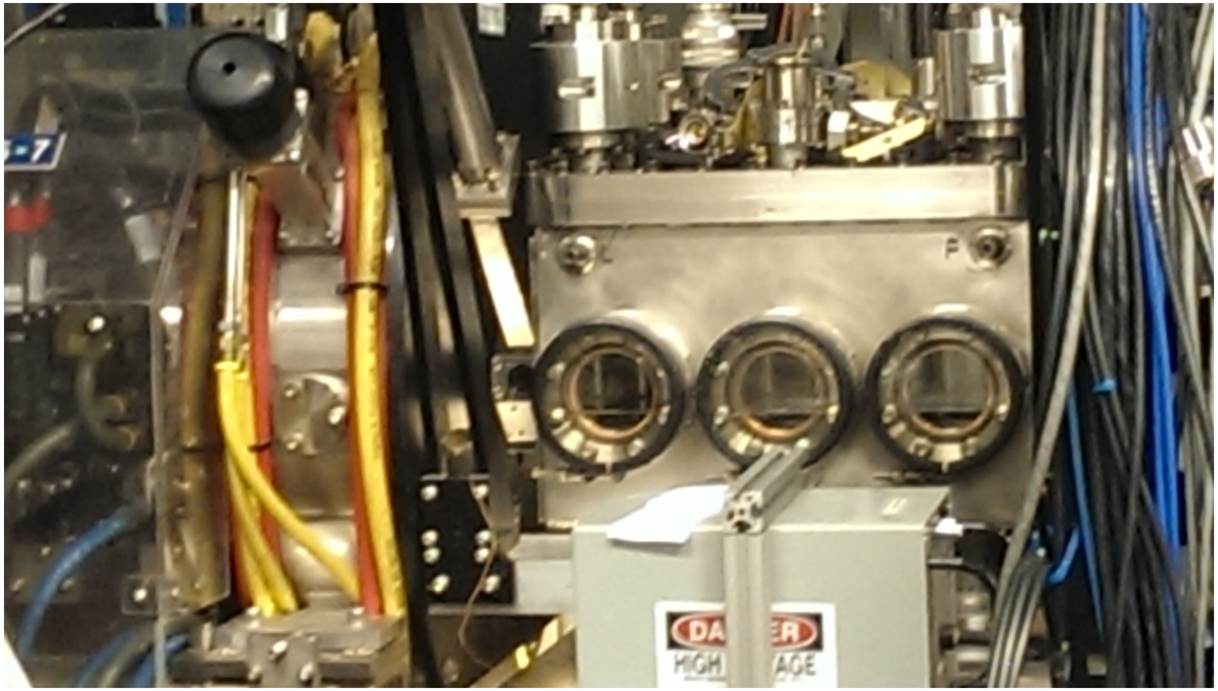
Beam-Loss Induced Damage

Equipment operating at high voltage (RFQ, cavities) can be very sensitive to beam losses (surface quality degradation). Then operation at the same voltage is not possible and probability for arcing is increased.

At SNS, errant beam losses led to a degraded superconducting cavity. Beam current monitors (BCMs) measured **beam losses of a few µs**. After such errant beams, sometimes the cavity gradient needs to be lowered. Conditioning after warm-up helps in most cases, but in one case a **cryo-module had to be exchanged**.

The energy of **beam losses** is about **100 J**. The damage mechanisms are not fully understood; it is assumed that some beam hitting the cavity desorbs gas or particulates (= small particles) creating an environment for arcing.

Another Type of Failures



SNS (2014): Water cooling of the MEBT chopper absorber failed and water entered the MEBT, causing several weeks downtime. Luckily this happened during a maintenance period (ie gate valves were closed and water was “stopped” in the DTL section). The absorber was not interlocked and not periodically checked until this accident happened.

Governance of Machine Protection at ESS

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Machine Protection Committee: Take on responsibility and take decisions

MPC domain/ responsibilities: (Corresponding to analysis part of IEC61508)	Approval of **concept**, overall **scope,** Coordination of **hazard risk analysis,** Approval of overall **machine protection requirements,** Coordination of machine protection **requirements allocation.**

	Operations	Accelerator	Controls	Target	CF	NSS	PSS	TSS
Stakeholder Requirements	- Requirements on work procedures, checklists, training for personnel - …	- Provide systems suitable for allocated machine protection functions - ….	- Provide systems suitable for allocated machine protection functions,	- Provide systems suitable for machine protection functions,	XY, ……	XY, ……	Provide run permit signal according to MP interface specification	Provide run permit signal according to MP interface specification
System Requirements		- Requirements for Proton Source - Requirements for LEBT chopper - ….	- Beam Interlock System - ….				Specification of signal, cable, connector type	Specification of signal, cable, connector type