# ESS Beam Interlock System Requirements

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www.europeanspallationsource.se
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# Overview

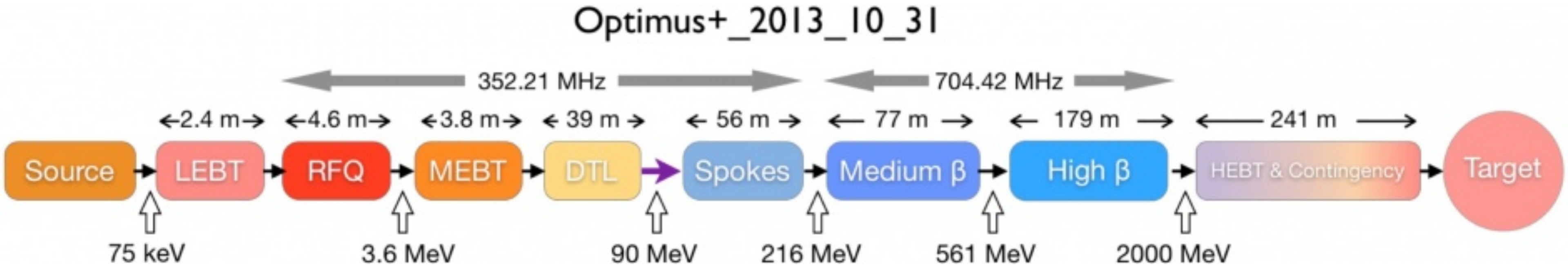
- Introduction to ESS
- Machine Protection at ESS and scope
- Damage potential and related time scales
- Systems and signals connected to the Beam Interlock System
- Actuators and how to stop beam operation
- Requirements for the Beam Interlock System
- Questions

# EUROPEAN SPALLATION SOURCE ESS

## ESS in Lund/Sweden

- 17 European member states
- First Neutrons: 2019
- Full power operation: 2025
- Decommissioning: 2065
- Investment: 1843 M€
- Beam availability 95%

# ESS in Short




Pulsed neutron source, consisting of a 600 m long LINAC, a spallation target and 22 neutron beamlines

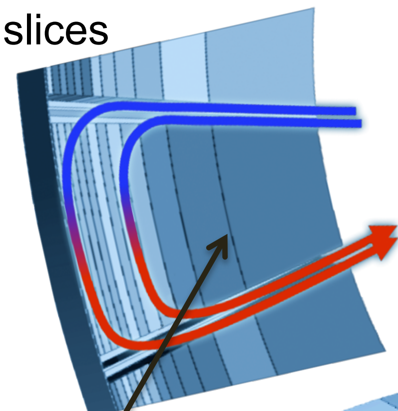
Pulse repetition rate: 14 Hz
Pulse length: 2.86 ms
Proton beam energy: 2 GeV
Peak power per pulse: 125 MW
Average power per pulse: 5 MW

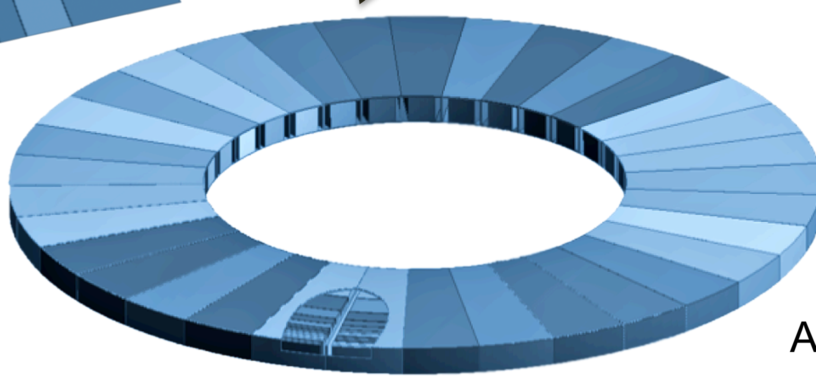
# ESS in Short

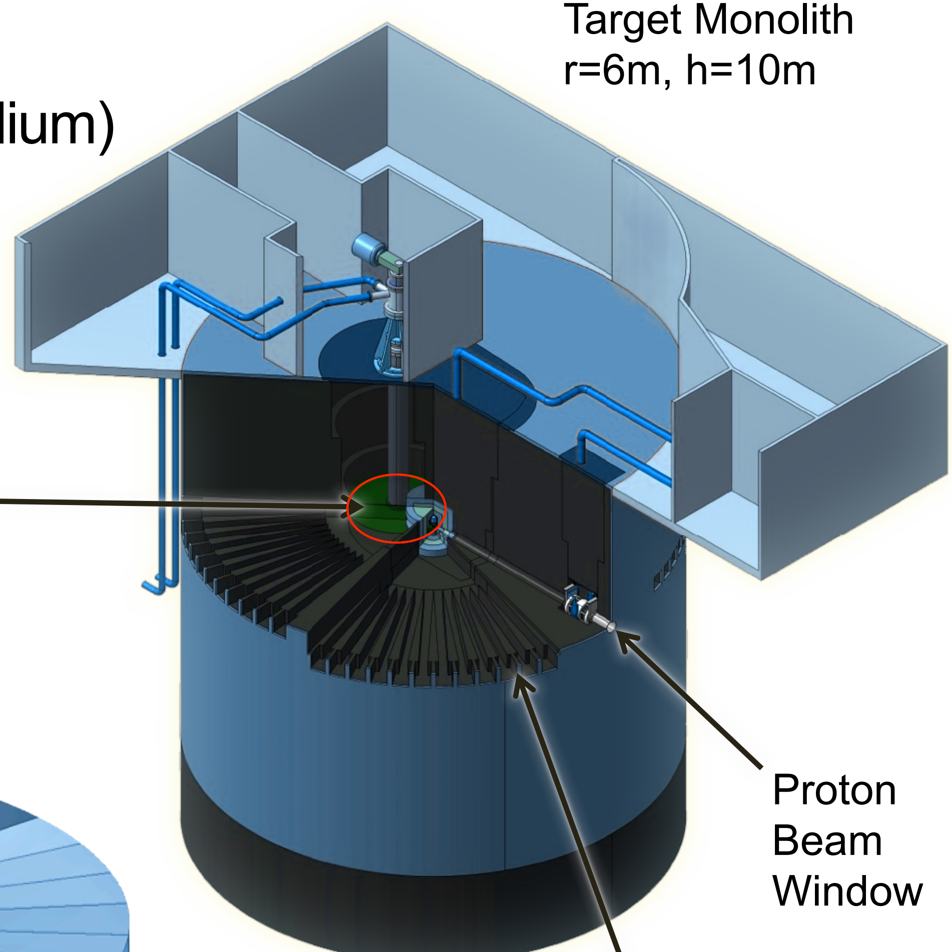
Tungsten target with rotating wheel

33 sectors with cooling channels (Helium)

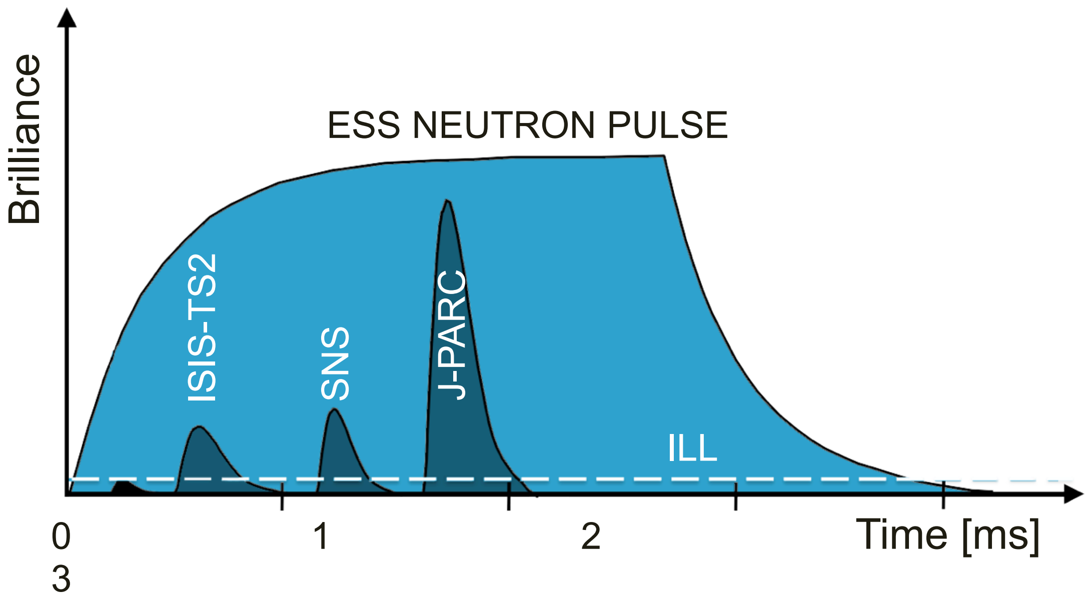
Synchronized to 14 Hz



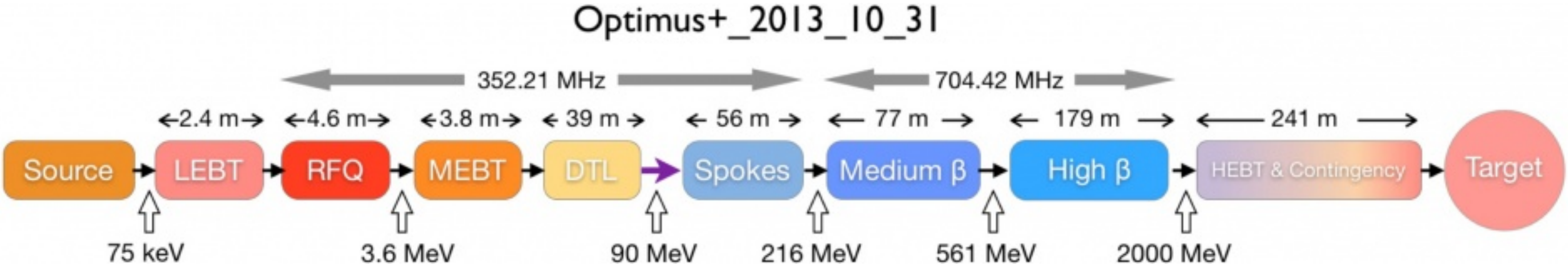



# ESS in Short



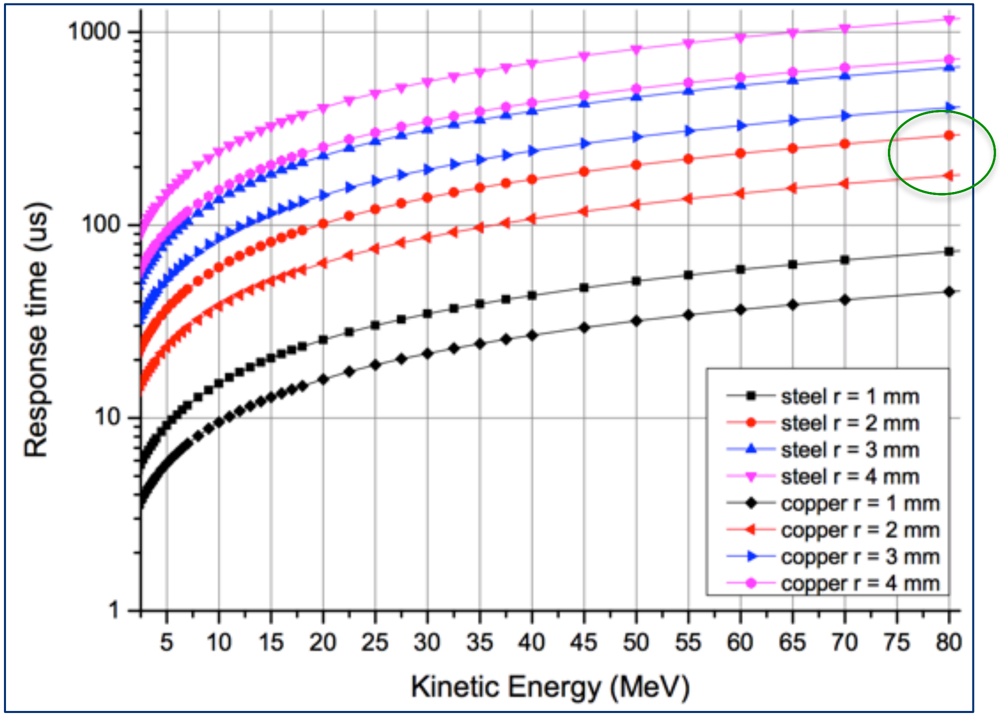

- Long pulses of cold neutrons allow for many different experiments (material-, bio-, nano-science etc.)
- ~ 5000 users per year are expected
- 22 beam lines, not all commissioned on day 1

# Damage Potential and Timescales




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 ....

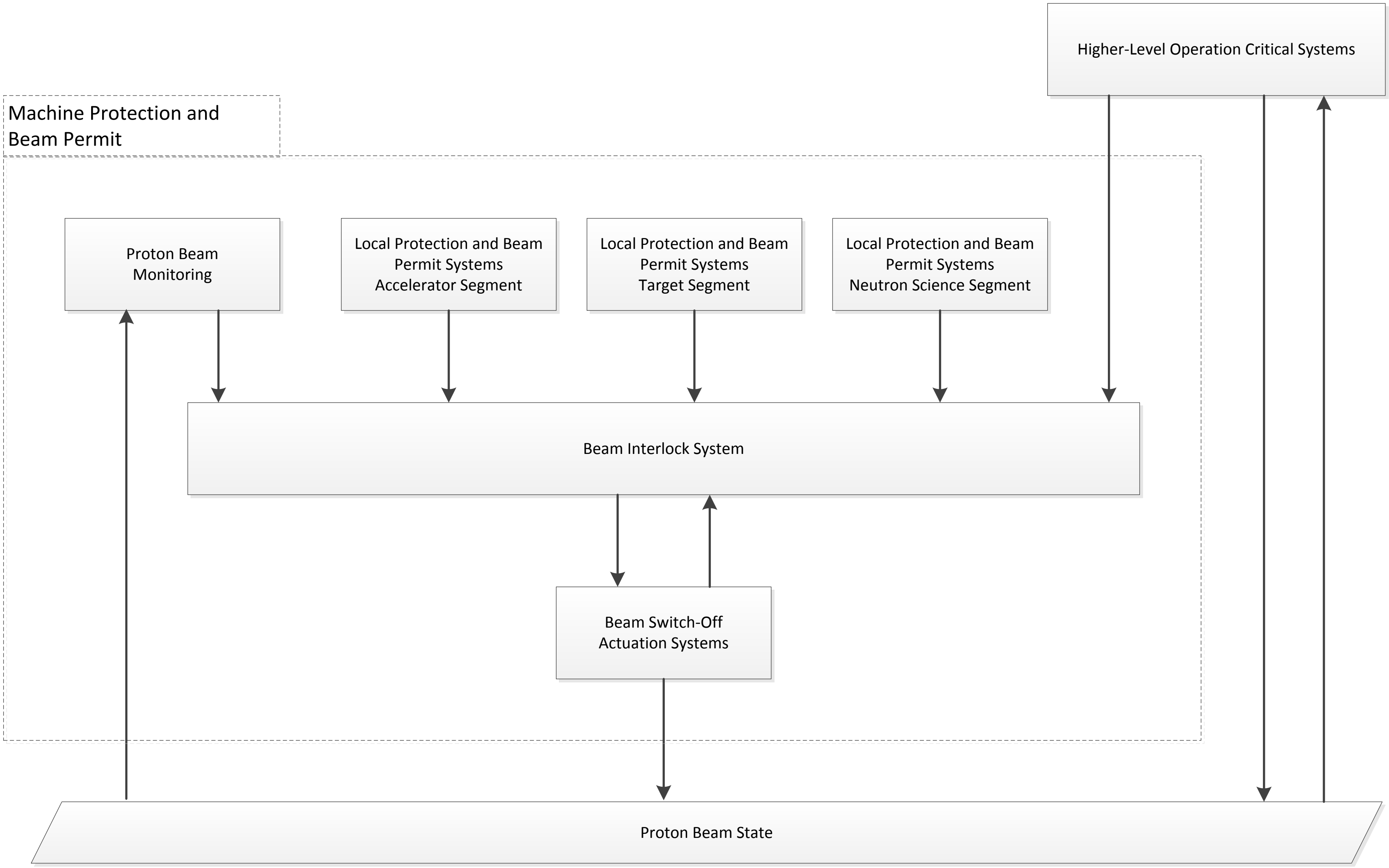


# Scope of Machine Protection at ESS

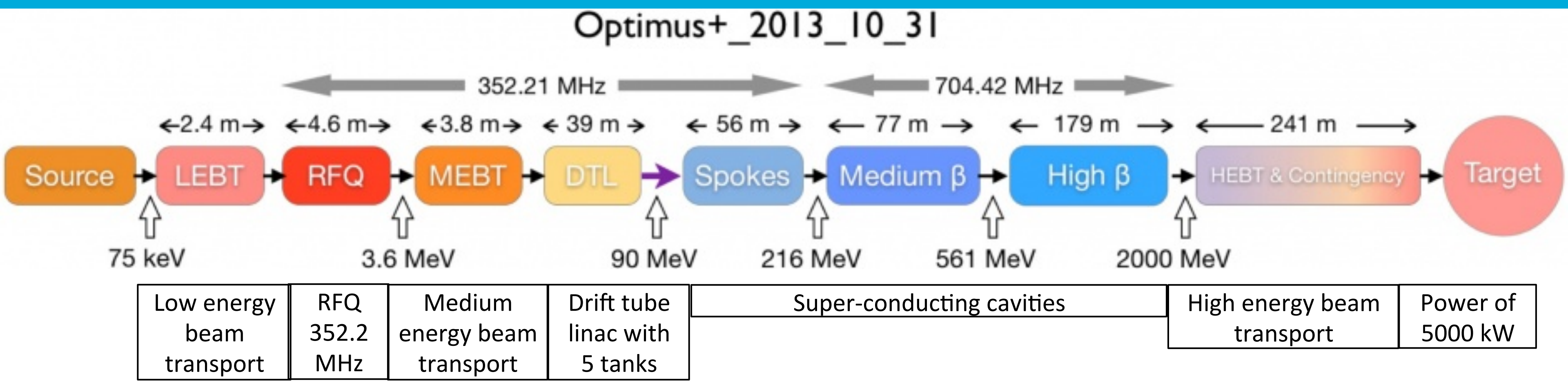
**Machine Protection contributes to operational availability of ESS by:**

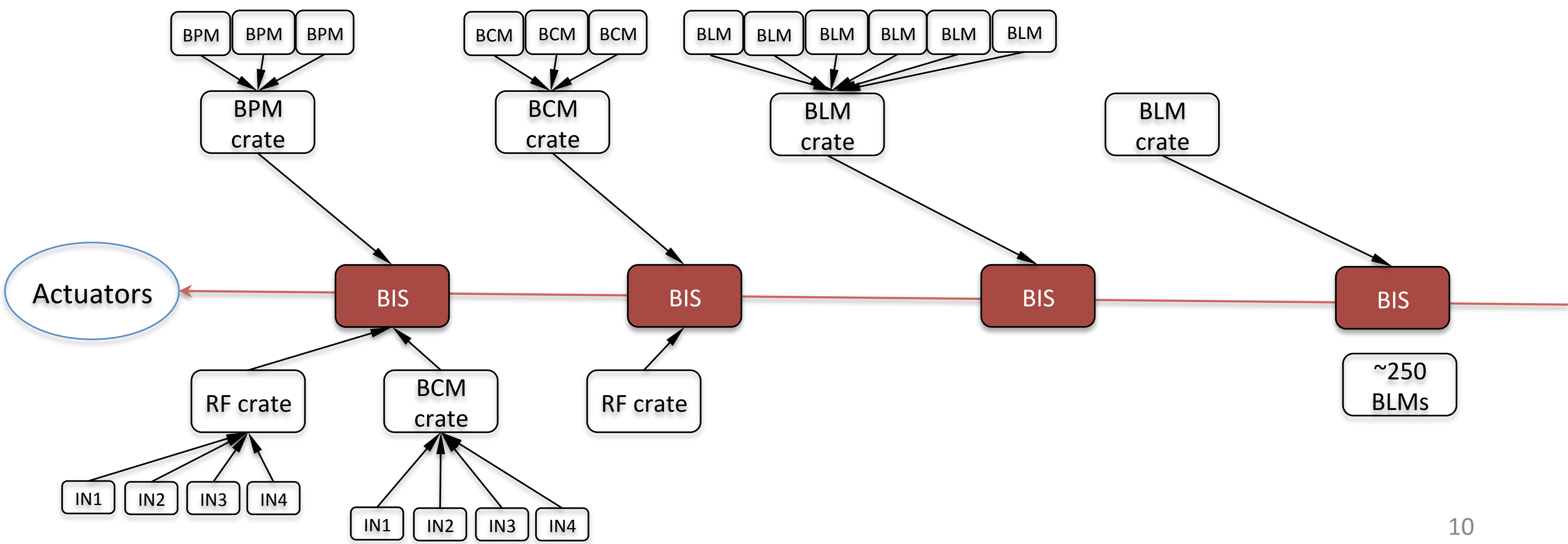
- Protecting equipment from beam induced damage
- Protecting equipment from damage due to a wrong configuration
- Minimising the number of false beam trips leading to unnecessary downtime
- Shortening maintenance times by minimising activation of equipment
- Providing tools for a congruent and consistent failure tracing throughout the machine

# Machine Protection at ESS

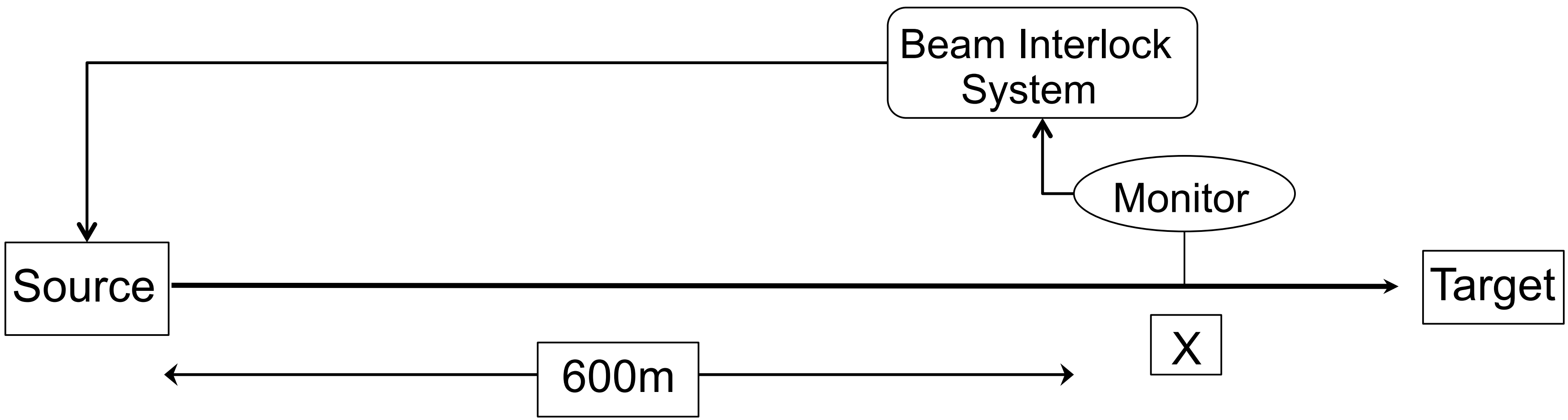


# Beam Interlock System



# Minimum Time Required to Stop Beam




**Beam impact at Position X (shown are estimated time-scales!)**

| | |
|---|---|
| Monitor detects a failure (e.g. beam loss above threshold) | 2 µs |
| Monitor validates failure and informs beam interlock system | 1 µs |
| Beam interlock system records failure and issues beam stop request | 1 µs |
| Signal transmission from Beam Interlock System to Source / Chopper | 2 µs |
| Time to receive stop request at LEBT chopper | <1 µs |
| Time that beam stops at position X/ beam in linac | 3 µs |
| **Sum** | **10 µs** |

# Fast (User) Systems connected to the BIS

1) **Systems for proton beam monitoring:**
   - Beam Current Monitors (BCMs):
     BCM before and after the RFQ & difference,
     BCM after RFQ and after DTL & difference,
     BCM after DTL and after medium beta & difference
     BCM after DTL and after high beta & difference
     BCM after medium beta and before target & difference
     BCM after medium beta and dump line & difference
   - Beam Loss Monitors (BLMs): ~ 250 in cold linac (distributed over 550 m)
   - Beam Position Monitors (BPMs): a few hundreds but its currently foreseen to connect only BPMs in the A2T line to the BIS

2) **RF system:**
   - Status per RF cell derived by local RF protection system

3) **Raster magnet system:**
   - Powering of raster magnets & other signals (tbd)

4) **Timing System** (?)/ interfaces need to be defined

# Fast (User) Systems connected to the BIS

**Questions/issues:**

Its likely to have always fluctuations and higher losses in the beginning of the pulse (due to chopping).

That will have implications on the correctness of BI readings during the first few µs of each pulse.

How can this be compensated for?

Dependency on timing system? Need of an internal counter for BCMs and BLMs?

Does this indicate difficulties for protection during the first few µs? (as its almost impossible to distinguish “bad beam” from “normally fluctuating beam”)

# Slow (User) Systems connected to the BIS

1) **Insert-able devices/interlocks on position**
   - Wire scanners,
   - Collimators,
   - Faraday cups (LEBT, behind RFQ, between DTL and spokes)
   - Beam stops (behind $4^{th}$ cryomodule in medium beta section) (?/tbc)
   - Grids, Slits, EMUs (Emittance measurement units)
   - Iris,
   - Vacuum valves

2) **Vacuum**
   - Status per section,
   - Status/position valves

3) **Magnets**
   - Powering status of magnets (quads, steerers),
   - Status from local magnet protection system(s)

4) **Target Protection System**
   - Wheel position and speed,
   - Temperatures, pressures, flows

# Other (User) Systems connected to the BIS

1) **Status signals**
   - Proton source status
   - Iris status
   - LEBT, MEBT chopper status (incl status of related absorber)
   - MEBT status
   - DTL status
   - Cryogenics status
   - Spokes status
   - Mbeta, Hbeta status
   - Dump line status
   - Target line and target station

2) **Beam off buttons**
   - Control room button
   - Buttons in experimental stations (?)

3) **A2T Line**
   - Bending magnets A2T line ok

# Questions

1) Is it needed to have two different BIS acting on the actuators?
   one PLC based and one FPGA based (to add diverse redundancy)/ how can this be answered? What kind of analysis/consideration will help?
2) Is it worth to consider different BIS requirements for the warm and cold linac? Not only based on the different response time requirements but also based on the fact that we have "only" BCMs for proton beam monitoring in the warm linac?
3) How can we stop beam if the BIS fails?
4) How to propagate operational mode information? Machine modes (beam destination) are implemented in the logic of the truthtables, but not beam modes (pulse length, beam current, etc)
5) Options to operate in a degraded mode (for example slow down from 14Hz to 1Hz repetition rate or from full pulse length to shorter length)

# Actuators

1) Remove RF signal from magnetron of proton source:
   it takes 100 μs until there is no plasma being created anymore
2) Energize electrodes of LEBT chopper and deflect beam into LEBT absorber:
   It takes 300 ns until beam is fully deflected.
   The absorber can withstand two full pulses before being damaged
3) Energize electrodes of MEBT chopper and deflect beam into MEBT absorber:
   It takes 10 ns until beam is fully deflected
   The absorber can withstand 100-300 μs of beam only before being damaged
4) Decrease electrical field of the RFQ:
   It takes 20 μs until field is decreased such that there is no beam being transmitted through the RFQ anymore
5) Other options (not investigated yet):
   Remove field from Solenoids on the LEBT
   Cut 400 V line of Proton source using a contactor like TSS and PSS (back up solution)

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

→ trigger 1) + 2) + 3) simultaneously

# Requirements & Workflow

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Machine Protection Committee (MPC) domain/responsibilities:

(Corresponding to analysis part of IEC61508)

- Approval of concept
- Approval of overall scope
- Coordination of hazard risk analysis
- Approval of overall safety requirements
- Coordination of safety requirements allocation

| | Operations | Accelerator | ICS | Target | CF | NSS | PSS | TSS |
|---|---|---|---|---|---|---|---|---|
| Stakeholder Requirements | - Requirements on work procedures,<br>- Requirements on training for personnel,<br>- Requirements for checklists | - Provide systems suitable for allocated safety functions,<br>- Requirements on development procedures and guidelines<br>- Provide means to stop proton beam operation<br>- Provide means to measure proton beam parameters<br>- Provide means to know the status of all devices that can be inserted into the beam pipe (IN or OUT)<br>.... | - Provide systems suitable for allocated safety functions,<br>- Requirements on development procedures<br>- Requirements on development guidelines<br>- Provide means to interlock sensors & actuators,<br>- Provide technical guidelines | - Provide systems suitable for allocated safety functions,<br>- Requirements on development procedures,<br>- Requirements on development guidelines | | | Provide run permit signal according to MP interface specification (constraint) | Provide run permit signal according to MP interface specification (constraint) |
| System Requirements | | - Proton Source<br>- LEBT chopper<br>- MEBT chopper<br>- BLMs<br>- BCMs<br>- BPMs<br>- Magnets and power supplies<br>- Collimators<br>- Faraday Cups, Wire scanners<br>- Raster magnet system<br>- Dipole bending magnets<br>- Dump line<br>- Vacuum and valves<br>- RF and LLRF.......... | - Beam Interlock System<br>- Post mortem System<br>- Operational mode checker<br>- Development guidelines (software quality)<br>- Technical guidelines (RBAC, usability, implementation, verification)<br>- .... | | | | Specification of signal, cable, connector type | Specification of signal, cable, connector type |

Breakdown Direction

# Requirements & Protection Functions

Preliminary set of systems requirements based on results from a PHA (Preliminary Hazard Analysis) done for all LINAC systems

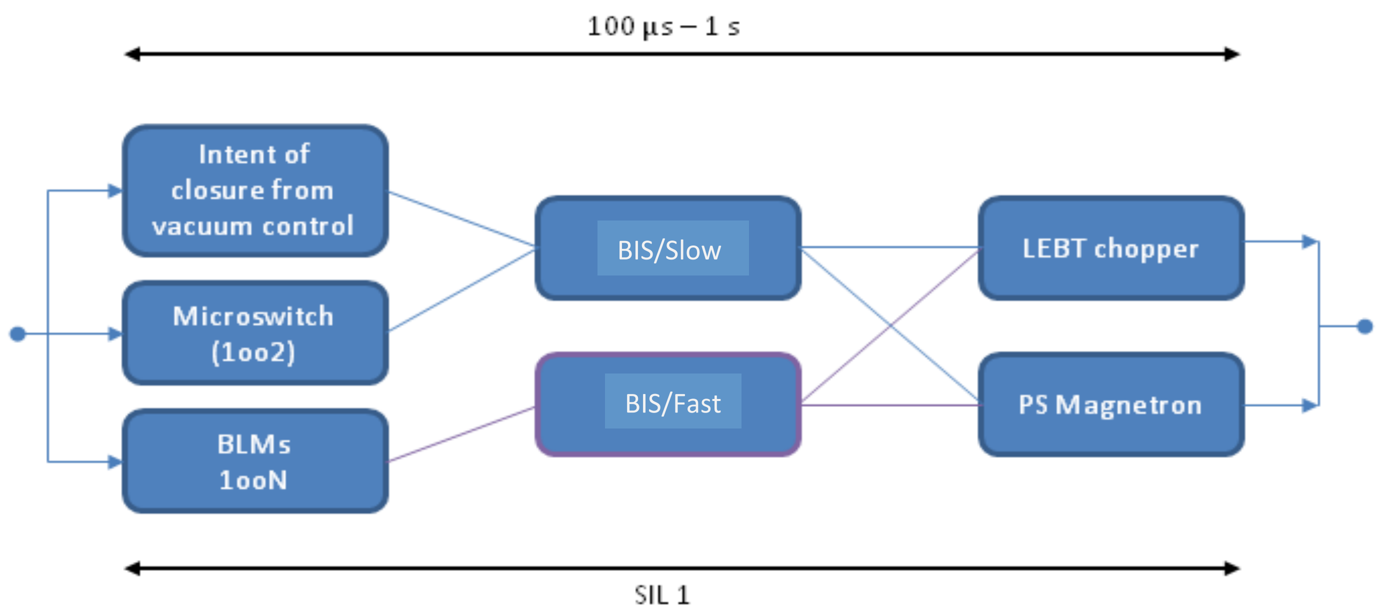
Around 166 protection functions defined for all LINAC systems including a preliminary SIL, response time per protection function, and allocation of SIL quota towards the "user" systems, BIS and the actuators

Some first proposals of how to implement the protection function and how to allocate the SIL towards the "sensor" systems (users), BIS, and actuator systems has been made but needs to be updated according to latest design changes of some LINAC systems

Allocation of SIL to different systems is not obvious and guidelines are required

# Example for Requirements

Example: unintentional closure of a vacuum valve during beam operation due to malfunctioning of valve control system or erroneous operator action or spurious signal of valve closure



# BIS: Hardware

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**Hardware Development for Beam Interlock System (BIS):**

- Interface between sensor systems and BIS
- Processing unit (BIS): PLC and FPGA based
- Interface between BIS and actuator systems
- Cable and connector types to connect the different interfaces with the processing unit (BIS)
- Powering of BIS and interfaces
- UPS for BIS and interfaces
- Interface of BIS to timing system for time stamping
- How to propagate “masking information”?
- Crate types and crate management
- How many in-and output channels per interface and BIS module
- Signal transmission types between interfaces and BIS (optical versus copper, etc.)
- Architecture (dependability analysis)

# BIS: Software and Testing

**Software for Beam Interlock System (BIS):**
How to connect to outside world, several layers (sw FPGA, sw VME, middleware, GUI, databases)
Operator layer (collider, linac, low/high repetition rate)
Middleware (FESA, EPICS)

**Test environment for Beam Interlock System (BIS):**
Test bench for hardware: interfaces, BIS
Test bench for firmware (and masking): BIS (incl. timing system)
Test bench for software: diagnostics on BIS level, software verification
Management of hardware, firmware and software changes: change procedures, verification and validation procedures, tools, tests, requirements, traceability, measurability, etc.

# BIS: Safety Analysis

**Dependability and safety related analysis:**
Sw on FPGA level
Hw of BIS incl. interfaces
Verification of sw, hw
Risk analysis methods
RAMI/Dependability analysis of sw and hw
Event analysis
What standards should be applied for what functions/systems/how consequent?

**Management of safety and mission critical configuration settings & functions:**
Requirements management (traceability, verification, validation, tools, etc.)
Guidelines for management of conf. settings on database level, HMI level, electronics/hw level, sw level, role based access, failure catalogues managements,
Alarm management system
Post mortem system and analysis methods
Early fault detection strategies (preventing foreseeable beam stops)
Issue tracking tools

# Timelines

Start prototyping of BIS components/procurement: 2015 – 2016

Test of BIS prototype with Proton Source: end of 2016

Delivery and installation of BIS in tunnel: Q3 2017

BIS ready for beam commissioning: Q4 of 2017