Paul Scherrer Institut
Anton Mezger, M. Seidel

Control and protection aspects of the megawatt proton accelerator at PSI
Outline of the presentation

- Facility Overview  [layout, characteristics, beam power]
- Safety philosophy
- Machine protection  [motivation: control beam loss]
- Machine protection requirements
- Protection mechanisms
- Operational tools  [losses visualization, beam centering]
- New challenges  [beam power increase, new project UCN]
- Conclusion
Facility runs now with 2.2 mA, 590 MeV => 1.3 MW

Data for 2009

Average availability = 89.5%
**Facility characteristics**

**Intense 590 MeV, 2.2 mA beam**, to be increased to 3 mA in the future, is only possible by keeping the losses low:

**Losses:**
- Extraction from Injector Cyclotron, injection and extraction from Ring Cyclotron: \(< 0.5 \text{ mA}\) each for 2.2 mA beam
- for the Beam lines: \(< 1\text{nA} / \text{m}\)

**Achieved through:**

**Accelerators:**
- Cyclotrons with **large turn separation** at the extraction in order to keep losses at a minimum (very high acceleration voltage, 1 MV per passage in Ring cyclotron)

**Target E area:**
- 30 % of beam consumed by degrading and shaping => special design to be able to service the components

**And with:**
- Local shielding, Remote handling, shielded flask
Safety Philosophy
Separate protection & safety systems from machine control system:

- Machine protection system
- Personal and radiation safety system
- Patient safety Systems (for the biomedical facility)
- User facility safety systems

This separation of „duties“ is the key for licensing the facility.

All above systems act directly on „beam off“ through several (therefore redundant) mechanism‘s:

- close the first beam stop
- kick the beam away by kicker magnets
- shutdown the ion source, when above actions fail.
Machine protection

[motivation, requirements, devices, mechanisms]
The machine protection system has the duty to prevent from:

1. sudden accidental beam loss (total or large fraction) can be severe and may cause long beam interruptions; with 2.2 mA 10 ms are enough to melt the vacuum chamber.

   ➔ MPS must switch off the beam in less than 5 ms in order to avoid thermal damage.

2. continuous small losses (activation!); should be in $10^{-4}$ range in areas that need frequent access/servicing (cyclotrons).

   ➔ MPS must switch off the beam when the integrated losses become too high.

This demands also an excellent instrumentation with a high dynamic range, observation panels and operator skill.
Machine protection system requirements

- **Highly reliable**, to avoid damage and unnecessary activation
- **Reconfigurable**, since we deal with many modes of operation
- **Consistency check**, for example indicating if the hardwiring between RPS modules is inconsistent.
- **Deterministic**, for answering the “egg or the chicken” problem (example: did a cavity trigger the beam switching off, or was it by another event)
- **Flexible**, the system must be safe, but it should also allow beam development. i.e. special operations with disabled elements and special modes (<150 μA,…)
- **Redundancy** in respect to
  - prepared signals
  - hardwired internal paths
  - actuators stopping the beam
- **Signals generated for the MPS** by devices with local intelligence.

→ System is realized via fast hardware modules (CAMAC and VME) with wired interconnections. Ca. 1500 signals are connected.
Systems used to feed interlock signals into the machine protection interlock system:

- **machine protection from missteered or wrongly transported beam**
  - loss monitoring by ionization chambers
  - Collimators and segmented foils
  - Current monitors measuring transmission
  - Validity windows on the values of power supplies
  - Many other signals like vacuum pressure, valves, water flow, …

- **machine protection to prevent focussed beam at the spallation target**
  - Beam shift into collimator when missing Target (energy change !)
  - Glowing grid observed by camera
  - Validity windows on the values of power supplies
Ionization chambers as beam loss monitors with fixed warning and interlock limits; critical ones also with limits as function of the beam current.

An interlock is generated in case of over limits or outside limits.
Controlling beam loss

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• **machine protection to prevent focussed beam at the spallation target**
  • Beam shift into collimator when missing Target (energy change !)
  • Glowing grid observed by camera
  • Validity windows on the values of power supplies
Collimators with segmented foils of nickel/molybdenum measuring the balance of right and left, up and down scraped beam currents (Target E and SINQ Target regions).

An interlock is generated in case of currents over limits or unbalanced currents.
Controlling beam loss

Systems used to feed interlock signals into the machine protection interlock system:

- **machine protection from missteered or wrongly transported beam**
  - loss monitoring by ionization chambers
  - Collimators and segmented foils
  - Current monitors measuring transmission
  - Validity windows on the values of power supplies
  - Many other signals like vacuum pressure, valves, waterfall, …

- **machine protection to prevent focussed beam at the spallation target**
  - Beam shift into collimator when missing Target (energy change !)
  - Glowing grid observed by camera
  - Validity windows on the values of power supplies
Beam current transmission monitors compare the beam current at different spots for detecting loss of beam, normally 100% of transmission except at the targets (splitted beams are also taken in consideration)

100 % transmission in main cyclotron
100 % transmission in beam pipes, except for splitted beams
97 % transmission of thin target M
70 % transmission of thick target E

An interlock is generated in case of an inappropriate condition
Controlling beam loss

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- **machine protection from missteered or wrongly transported beam**
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  - Collimators and segmented foils
  - Current monitors measuring transmission
  - Validity windows on the values of power supplies
  - Many other signals like vacuum pressure, valves, workflow, …

- **machine protection to prevent focussed beam at the spallation target**
  - Beam shift into collimator when missing Target (energy change !)
  - Glowing grid observed by camera
  - Validity windows on the values of power supplies
Power supply settings with validity window and difference between setpoint and readback values:

These functions are implemented in the logic of the magnet power supply controllers to prevent wrong settings or failures and will generate an interlock signal for the RPS.

- **Bending Magnets**: wrong setting => beam hits the vacuum chamber, but radiation could be shielded by their iron, but no loss monitor could complain

- **Quadrupole Magnets**: wrong setting => beam could get the wrong beam size on Target (especially for the spallation target)
Systems used to feed interlock signals into the machine protection interlock system:

- **machine protection from missteered or wrongly transported beam**
  - loss monitoring by ionization chambers
  - Collimators and segmented foils
  - Current monitors measuring transmission
  - Validity windows on the values of power supplies
  - Many other signals like vacuum pressure, valves, waterflow, …

- **machine protection to prevent focussed beam at the spallation target**
  - Beam shift into collimator when missing Target (energy change !)
  - Glowing grid observed by camera
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Protection of Spallation Target by glowing grid

Tungsten Grid in front of the Target visualised by fiberoptics and camera gives an image of the thermal radiation: The image is digitized in order to detect deviant irradiation conditions in a timely manner.

50 frames /second; 4 frames have to be deviant in order to produce an interlock through the user interlock system.

Deviation is calculated through intensity ratios and absolute maximum values.

By courtesy of K. Thomson
Operational tools

[losses visualization, automated beam steering]
Operational tools

- beam loss monitors ➔ monitoring of losses (loss display).
- phase measurement devices ➔ beam dynamic and tuning tools.
- beam position monitors ➔ automated beam steering.
- feedback tools for stabilizing phases, ion-source, …
- beam dynamics tools (ex. Tomography, Transport, Time – Space structure)

Monitoring the losses:
very important to protect against misbehavior of the beam, but also for an appropriate feedback to the operator for minimizing the losses.

Note: 5 decades logarithmic scale
Automated beam steering (5 Hz) using bpm’s, steering and bending magnets:

- frequent beam trips (30-50 per day) and compensate slow drifts and tuning corrections.
- beam position is current dependent due to changing space charge effects.

- Procedure uses accelerator model and calculates magnet settings through Single Value Decomposition with weighted beam position (gsl_multifit_wlinear from the gnu scientific library)
- Procedure has the ability to record and use magnet settings automatically at small currents for proper ramping up.
New challenges
[beam power increase, new project UCN]
New challenges (higher currents and UCN)

Even higher beam currents, 3 mA means 1.8 MW continuous proton beam

- more beam loading & higher acceleration voltages (new resonators !!)
- Target Collimators upgrade (30% of beam loss !!)

- new collimator required with improved cooling / more even power distribution
- material **GlidCop** (copper-based metal matrix composite alloy) under discussion

target E (d = 4cm)
New challenges (higher currents and UCN)

Beam switching of now 2.2 mA from one beam line to another (Meson & SINQ Targets → UCN Target and back) during 8s every 800s.

Override MPS for 3 milliseconds

1. arm BPM electronics
2. Define pulse length
3. Trigger pulse

Pilot beam pulse of 5 ms the positions in the beam line are measured and a correction of the trajectory is calculated and performed.

Beam in UCN beam line

Timing system produces suppress signal (3 ms) and activates kicker. Beam switches over Collimator.

Timing system produces suppress signal (3 ms) and deactivates kicker. Beam switches back over Collimator.

After delay prepare for next pulse of 5ms or pulse up to 8 seconds
UCN steering procedure

- Trajectory centering control
- Sequencing control
- Beam position measurement
- Sequencing steps
Conclusion
In order to run safely a high intensity beam of over 1 MW (actually 1.3 MW, planned 1.8 MW), several conditions have to be met:

• Facility has to be designed and operated with very low beam losses (10⁻⁴).

• Appropriate protection of the facility against accidental losses using loss detection and a efficient machine protection system.

However sometimes some damage can not be avoided:

• Efficient tools to center the beam and to minimize losses.

As well as ease of access to the facility for servicing and for managing activated components by means of remote handling and shielding boxes.
Acknowledgments

All my colleagues that contributed to this presentation

Thank you for your attention

SLS = Swiss light source

HIPA = high intensity proton accelerator

Infrastructure & personal safety

FEL Project

Inj1 = 72 MeV proton accelerator for low energy experiments and eye melomena treatment

Proscan = 250 MeV proton accelerator for biomedical applications (cancer treatment)

View of the control room at PSI