High-intensity operation: Between Poka-Yoke and Machine Protection

FC2WG, C. Omet, 21.10.2015
SIS100: Main Parameters – a versatile machine

- Circumference: 1083.6 m
  - (5 x length of SIS18)
- Superperiodicity: 6
- Cells per period: 14
- Focusing structure: Doublet
- 108 Dipoles (superferric)
  - 1.9 T, 4 T/s
  - Nominal current: 13.1 kA
- 168 Quadrupoles (superferric)
  - 27.8 T/m
  - Nominal current: 10.5 kA
- Extraction modes:
  - Fast, 1...8 bunches
  - Slow, KO-Extraction up to 10 s
- Acceleration for every ion from protons to uranium (and beyond?)
  - Variable quadrupole powering for $\gamma_{tr}$ shifting or $\gamma_{tr}$-jump

<table>
<thead>
<tr>
<th>Item</th>
<th>RIB ($\text{U}^{28+}$)</th>
<th>CBM ($\text{U}^{92+}$)</th>
<th>Protons for pbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic rigidity @ extr. $B \cdot \rho$ [Tm]</td>
<td>27 ... 64 ... 100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Energy range @ extr. $E$ [GeV/u]</td>
<td>0.4 ... 1.5 ... 2.7</td>
<td>10.7</td>
<td>28.8</td>
</tr>
<tr>
<td>Max. repetition rate $f_{rep}$ [Hz]</td>
<td>0.35 (slow) 0.50 (fast)</td>
<td>0.09</td>
<td>0.4</td>
</tr>
<tr>
<td>Relativistic $\gamma$</td>
<td>... 3.9</td>
<td>12.4</td>
<td>31.9</td>
</tr>
<tr>
<td>Transition energy $\gamma_{tr}$</td>
<td>15.5</td>
<td>14.3</td>
<td>18.3 (45°)</td>
</tr>
<tr>
<td>Tune $\nu_{x,y}$</td>
<td>17.3/17.8 (slow) 18.9/18.8 (fast)</td>
<td>17.3/17.8 (10.4/10.3 (21.8/17.7°))</td>
<td></td>
</tr>
<tr>
<td>Number of ions per cycle $N$</td>
<td>$5 \times 10^{11}$</td>
<td>$1.5 \times 10^{10}$</td>
<td>$2 \times 10^{13}$</td>
</tr>
<tr>
<td>Max. number of ions per second [1/s]</td>
<td>$1.8 \times 10^{11}$ (slow) $2.5 \times 10^{11}$ (fast)</td>
<td>$1.5 \times 10^{9}$</td>
<td>$8 \times 10^{12}$</td>
</tr>
<tr>
<td>Extracted bunch form</td>
<td>1-10 s spill (slow) 10-100 s spill (fast)</td>
<td>Single bunch 70ns (fast)</td>
<td>Single bunch 50ns</td>
</tr>
<tr>
<td>Stored beam energy $E_{beam}$ [kJ]</td>
<td>51.5</td>
<td>6.1</td>
<td>93.0</td>
</tr>
<tr>
<td>Emittance @ inj. $\epsilon_{x,y}$ [mm mrad]</td>
<td>34 x 14</td>
<td>15 x 5</td>
<td>12 x 4</td>
</tr>
<tr>
<td>Emittance @ extr. $\epsilon_{x,y}$ [mm mrad]</td>
<td>1 x 4.0 (slow) 9.6 x 4.0 (fast)</td>
<td>1.0 x 0.7</td>
<td>2.0 x 0.7</td>
</tr>
</tbody>
</table>

Geometrical Acceptance:
3 x maximum emittance

Dynamic Aperture:
3.4 sigma
SIS100: Lattice design criterias

1. Length: 5 x SIS18 length (≈ 1 083.6 m)
2. Reference ion operation: U^{28+}
   - Localize beam ionization losses
   - Control vacuum pressure
3. Secondary ion: Protons
   - Variable $\gamma_t$-optics by multiple quadrupole families
   - Fixed $\gamma_t$-optics utilizing fast $\gamma_t$-jump quadrupoles
4. RF system
   - Room temperature cavities, dispersion free straight sections
   - State-of-the-art bunch manipulations: Bunch merging & compression, Barrier buckets
5. Versatile extraction modes
   - Fast bipolar Kicker system (internal emergency dump)
   - Slow extraction: KO-excited beam, resonant extraction

Images courtesy of M. Konradt / J. Falenski
SIS100: Lattice design

- **Doublet focusing structure**: up to 100% collimation efficiency reachable with focusing order DF
  - First called “storage mode lattice” because many U\(^{29+}\) particles survived one complete turn.
  - **Dipoles act as a charge state separator** when bending angle per cell is chosen correctly.
  - Quadrupoles are stronger than obviously necessary (over-focussing) to assure survival of beam until it reaches the collimator (**which gives other problems → protons**).

- U\(^{29+}\) loss positions are nicely peaked at the position of the collimators

- Dynamic vacuum calculations showed that in spite of the very well controlled losses, a **huge pumping speed** will be required
  - Cold vacuum chambers
  - SC magnets
Risk assessment

- **What to protect?**
  1. **Lives (people)!**
  2. **Health (people)!**
     - e.g. losing the thumb ≅ losing one eye → partial disability
  3. **Environment**
     - Radiation, chemicals,
     - EMC (Electromagnetic Compatibility, not $E=mc^2$)
     - Noises
     - ...
  4. **Machine**
     - Damage of expensive equipment (> 100,000,000 € !)
     - Long-running replacement times / repair times
       - Damage
       - Activation (“1 W/m” → 1 mSv/h after 4 h @ 40 cm after 100 days of operation)
       - Availability

- **Legal necessity**
  - §§ 5, 6 Arbeitsschutzgesetz, § 3 Betriebssicherheitsverordnung
  - § 6 Gefahrstoffverordnung, §§ 89, 90 Betriebsverfassungsgesetz

- **What remains?**
  - **Residual risks** (for radiation protection: ALARA = As Low As Reasonable Achievable)
Hazard and Risk for accelerators

- **Hazard**: a situation that poses a level of threat to the accelerator. Hazards are dormant or potential, with only a theoretical risk of damage. Once a hazard becomes “active”: incident / accident. Consequences and possibility of an incident interact together to create **RISK**, can be quantified:

\[
\text{RISK} = \text{Consequences} \cdot \text{Probability}
\]

**Related to accelerators:**

- Consequences of an uncontrolled beam loss
- Probability of an uncontrolled beam loss
- The higher the **RISK**, the more **Protection** is required
The 2008 LHC accident happened during test runs without beam.

A magnet interconnect was defect and the circuit opened. An electrical arc provoked a He pressure wave damaging ~600 m of LHC, polluting the beam vacuum over more than 2 km.

53 magnets had to be repaired

Over-pressure

Arcing in the interconnection

Magnet displacement

R. Schmidt
2008 SPS run

- Impact on the vacuum chamber of a 400 GeV beam of $3 \times 10^{13}$ protons ($2 \text{ MJ}$).
- Event is due to an insufficient coverage of the SPS MPS (known !).
- Vacuum chamber to atmospheric pressure, downtime ~ 3 days.

Risk = (3 days downtime + dose to workers) x (1 event / 5-10 years)
Incidents happen

Risk = (9 month downtime + dose to workers) x (1 event / 12 years)
Due to a power converter failure, a slow extraction was transformed into a fast extraction.

- Extraction in milliseconds instead of seconds.

As a consequence of the high peak power, a Gold muon conversion target was damaged and radio-isotopes were released into experimental halls.

- Machine protection coupled to personnel protection!

Investigations and protection improvements done, J-PARC restart after ~9 month.

One insufficiently covered failure case had major consequences!
Risk Management Gradient

**Poka-Yoke** 'Mistake Proofing'
- intercepting common mistakes, procedural errors, etc.
- affecting machine performance

Use-cases:
- minimising machine activation (ALARA principle)
- preventing quenches
- investment protection

**Devices:**
- LSA, settings monitoring, ...
- PC, FMCM (?), QPS, FCT, BLMs, ...
- passive absorbers, machine optics, material choices

**Systems:**
- Sequencer & operational procedures
- FAIR (SW) Interlock System
- FAIR-SIS100 Fast Beam Abort Sys. (HW Interlock System)
- FAIR Machine & System Design

**time-scales:**
- 10s of seconds → minutes/hours
- 100 ms
- 50 us
- < turn

R. Steinhagen
**Pokā-Yoke (ポカヨケ) – 'Mistake-Proofing'**

- To avoid (yokeru) inadvertent errors (poka)
- Industrial processes designed to prevent human errors
  - Concept by Shigeo Shingo: 'Toyota Production System' (TPS, aka. 'lean' systems)
- Common mistakes, procedural errors, etc. affecting machine performance
- Real-World Examples:
  - Polarity protection of electrical plugs (e.g. phone, Ethernet cable)
    → SIS18 profile grid connectors
  - Procedures: e.g. ATM machine: need to retrieve card before money is released (↔ prevents missing card)
FAIR Machine Protection Concepts

- Machine & System Design
  - Passive absorbers, machine optics, collimation system, material choices, ...
- Active protection
  - Fast-Beam-Abort System (SIS100 & SIS18, turn → 'ms'-scale)
  - Setup-Beam-Flag (SBF)
    - Beam is safe for playing with, “Pilot beam”
  - Interlock System (slow, '≈100 ms' scale)
  - Beam Transmission Monitoring System
- Procedural protection
  - Beam-Presence-Flag (BPF)
    - no high-intensity beam injection into previously empty machine
  - Management of Critical Settings
  - Poka-Yoke
    - Intensity Ramp-up Concept
      - Don't inject high-intensity beam without having the optics & machine performance checked with lower intensity beams
    - Sequencer (guide/help operation to avoid common mistakes)
Proposal: FAIR Beam Modes – State Diagram

Verification of machine-protection functionality
Minor adjustment of intensity related effects (e.g. \( \Delta Q(\text{intensity}) \))

- **Pilot Beam**:
  - Intensity Ramp-Up
  - Adjust

- **No Beam**
  - cool down + cycling after magnet quench or main PS failure
  - N.B. beam mode = machine mode
  - “handshake”

- **Post-Mortem/Beam Dump**
  - Recovery: No Beam

- **Stable Beams/Production**
  - Here’d be Happiness producing physics beams most settings locked-down

**N.B.**:
1) omitted arrows to 'No Beam'/Pilot Beam' for better visibility (always possible)
2) modes follow existing normal setup routine, initial transition acknowledged by operator, subsequent driven automatically by sequencer

**basic accelerator setup injection \( \rightarrow \) extraction typically with (but not limited to) low setup intensities (SBF=true)**

**normal operational path**
- error/fault case
- low-intensity

R. Steinhagen
Machine protection

- In the past (and present operation of SIS18), devices protect only themselves
  - Caused e.g. by media supply, short circuit, ...
  - Usually instantly power down and
  - generation of an interlock.
- When a device powers down, the result for the machine could be bad
  - Magnets can quench (by beam energy deposition, insufficient cooling, ...),
  - Sensible equipment could be damaged by beam heating
  - S-FMEA (System Failure Modes and Effect Analysis) has to be done.
- Foreseen to protect the machine:
  - Collimation systems (passive protection)
  - Equipment monitoring and beam monitoring
  - Quench detection and protection (QD/QP)
  - Interlock systems
  - Emergency kicker + dump

1. Avoid that a specific failure can happen
2. Detect failure at hardware level and stop beam operation
3. Detect initial consequences of failure with beam instrumentation

How to stop beam operation:
1. Inhibit injection
2. Extract beam into emergency beam dump or
3. Stop beam by beam absorber / collimator
Is activation an issue?

- **Yes!**
  - Components have to be human maintainable, so (uncontrolled!) activation has to be limited.
  - Hands-on-maintenance:
    - Dose rate < 1 mSv/h
    - at a distance of 40 cm
    - after 100 days of operation and 4 hours of downtime.

- Standard assumption for protons: **Uncontrolled** losses have to be < 1 W/m
  - 5…10% protons at 4…28.8 GeV/u
- For heavy ions: < 5 W/m
  - 20% U^{28+} at 200 MeV/u
  - 10% U^{28+} at 2.7 GeV/u
  - Already larger than dynamic vacuum effects allow.

- Controlled losses: Extraction sector S5 is already prepared; components have to be remote / fast serviceable (Magnetic + Electrostatic septa, radiation resistant quadrupoles).
- Halo collimators, Cryo catchers would be more activated.
- Building design has got separate beam and supply areas. The latter would be accessible without any activation problems.
Beam impact on accelerator components

- **SIS100 stored beam energy**
  - Ions: 3.7 ... **51.5 kJ**
    - 11.2 g TNT / 1.5 ml Kerosine (a few drops)
  - Protons: 12.9 ... **93.0 kJ**
    - 20.2 g TNT / 2.7 ml Kerosine (half a tea spoon)

- **Melting/sublimation of acc. components (stainless steel):**
  - SPS event with 450 GeV beam: Vacuum chamber burnt through with 2 MJ beam
  - Experimental **damage limit for protons** ~52 kJ/mm²
    - **SIS100**: with protons: ~1 kJ/mm²
    - PS: ~1 kJ/mm²
  - Bragg peak has to be considered
  - Temperature should not be an issue (details on the next pages)

- **Quench limit of SC cable (Cu/NbTi)**
  - Nuclotron cable: ~1.6 mJ/g [1]
  - Quench recovery time:
    - 10 min at the Serial Test Facility,
    - ~1 h in the SIS100

Is melting an issue? (I)

- **SiS18 beam** onto FRS target
  - Cu, Al und C Targets, 1 mm thick.
  - Graphite → no problems.

- Strong focused $\sigma_x=0.44\, \text{mm}$ $\sigma_y = 0.99\, \text{mm}$, 125 MeV/u, $7\times10^9 \ldots 1\times10^{10} \, \text{U}^{28+}/\text{Spill}$.

- Sometimes, up to 100 shots were necessary to drill a hole.

- Average power was only $\sim 1\, \text{W}$, but peak energy $\sim 3\, \text{kJ/g}$.

- Process: target melts spontaneously but hardens again before next shot (only radiation cooling).

H. Weick
Is melting an issue? (II)

- Take damage limit for protons onto steel (52 kJ/mm² ~ 1 kJ/g)
  - Protons: max. 93 kJ beam energy, **beam spot size** r=0.75 mm
  - Ions: max. 51.5 kJ beam energy, **beam spot size** r=0.56 mm ➔ ignored $dE/dx$
- One should think those spot sizes can not be achieved at maximum energy by optics of the machine:
  - $r_{avg}=3.8$ mm ($2\sigma$) for p $\gamma_1$-shift optics
  - $r_{avg}=5.4$ mm ($2\sigma$) for ion optics
- But when calculating temperature rise analytically:
  \[
  \Delta T = \frac{N \cdot dE/dx}{c \cdot A \cdot \rho}
  \]
  - thin targets, no phase transition
  - no shock waves, no heat transfer or radiation
- Full design beam power for
  - Protons: no problem!
  - **Heavy ions** ($5\times10^{11}$ $\text{U}^{28+}$) are above the limit!
  - But: Before it comes to melting, s.c. magnets will quench already (6 orders of magnitude earlier)

### Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used in</td>
<td>Yoke, He-pipes Chambers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Temp. / K</td>
<td>1,921</td>
</tr>
<tr>
<td>Specific heat $c$ / J/(g*K)</td>
<td>0.49</td>
</tr>
<tr>
<td>Latent melting heat / J/g</td>
<td>270</td>
</tr>
<tr>
<td>Total melting energy density (T=15 K) / J/g</td>
<td>1,204</td>
</tr>
<tr>
<td>Total melting energy density (T=293 K) / J/g</td>
<td>1,068</td>
</tr>
<tr>
<td>Density $\rho$ / kg/m³</td>
<td>7,870</td>
</tr>
<tr>
<td>Proton beam spot radius for melting @15K / mm</td>
<td>0.4</td>
</tr>
<tr>
<td>Max. $\Delta T$ for proton beams with 3.8mm spot radius / K</td>
<td>28</td>
</tr>
<tr>
<td>Uranium beam spot radius for melting @15K / mm</td>
<td>5.6</td>
</tr>
<tr>
<td>Max. $\Delta T$ for Uranium beams with 5.4mm spot radius / K</td>
<td>2,291</td>
</tr>
</tbody>
</table>
1x10^{10} \text{U}^{28+} \text{ are } \text{“not dangerous“} \ \Rightarrow \text{ do not cause instant permanent damage by melting room temperature sections of SIS100...}

Safe beams / pilot beams should contain at maximum half / a quarter of that intensity!
Potential beam damage in SIS100: Slow extraction

- When a
  - full intensity high energy heavy ion beam spirals out
  - in a short time (µs...ms) and
  - hits a small volume (e.g. wires, thin vacuum chambers)
  - especially at room temperature regions,
    - material can melt.

- Unavoidable during slow (KO) extraction: Heavy ions colliding with the electrostatic septum wires are stripped and lost
  - At least ~10% of the beam will hit the wires during slow extraction.
  - W-Re wires day 0 version: 100 µm “thick”, final version: 25 µm thick (thermal / stability issues)
  - Warm (radiation hard) quadrupoles behind the septum.
  - Loss will be controlled (collimator / low desorption rate surface).

- Step width of particles at slow extraction has to be limited to avoid over-heating of the wires
  - Low intensity pilot beams,
  - Phase space tomography,
  - Limiting extraction length at full heavy ion intensity to durations e.g.> 5 s.
  - Active protection with beam loss monitors (BLM’s)
Emergency dump of SIS100

- Part of the active machine protection.
- Emergency dump system:
  - Fast bipolar kicker magnets for extraction,
  - 2.5 m long, internal absorber block below the magnetic septum #3.
- Design:
  - No need for synchronous ramping of beam line to the external dump and “dead time” during ramp up of HEBT switching magnets.
  - Beam dump will happen in ~26 µs after generation of request ➔ fast enough for nearly all processes.
  - Various abort signals will be concentrated in a switch matrix (allows masking of some sources e.g. for low intensity beams). **Incorporation of e.g. experiment aborts is easily possible.**
  - Kicking into a coasting beam will result in up to 25% beam losses (smear out after emergency dump). Have to develop more sophisticated methods (Shut off KO extraction, rebunch, kick?).
- Absorber:
  - Special chamber in lower part of magnetic septum #3
  - 20 cm graphite in front, 225 cm absorber (W, Ta, …)
  - Tilted or saw-tooth surface to smear out Bragg peak in the absorber material (limits temperature rise).
## FLUKA simulations of emergency dump

Simulation assumptions:
- $5.0 \times 10^{11}$ U$^{28+}$, 1.0-2.7 GeV/u
- $2.5 \times 10^{13}$ p, 29.0 GeV/u
- Gaussian beam distribution with $\sigma_{xy} = 3$ mm
- Full beam energy deposited within < 1 $\mu$s

- No melting, but absorber surface has to be inclined (e.g. by 20° which gives a factor of 4 less temperature rise).
- Both maximum and average energy depositions are well below quench limit.
- With W instead of Ta, energy deposition in the SC quadrupole coils drops by another 30%.

### Quench limit

<table>
<thead>
<tr>
<th>Ion</th>
<th>Max. Coil energy deposition / mJ/g</th>
<th>Avg. Coil energy deposition / mJ/g</th>
<th>Quench margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.5 \times 10^{13}$ p, 29 GeV</td>
<td>0.29</td>
<td>0.063</td>
<td>5.5 / 25.4</td>
</tr>
<tr>
<td>$5.0 \times 10^{11}$ U$^{28+}$, 1.0 GeV/u</td>
<td>0.01</td>
<td>0.003</td>
<td>145 / 592</td>
</tr>
<tr>
<td>$5.0 \times 10^{11}$ U$^{28+}$, 2.7 GeV/u</td>
<td>0.10</td>
<td>0.025</td>
<td>16 / 64</td>
</tr>
</tbody>
</table>

Quench limit: $1.6$ mJ/g $\approx 0.2$ mJ/cm$^3$

U$^{28+}$, 2.7 GeV/u
Risk assessment: System-FMEA

- Failure Modes and Effects Analysis (FMEA) on the system level of SIS100
  - Goal: Identify the machine failures in a rational approach,
  - Done according to IEC 61508,
  - Standardized values for personnel safety,
  - Subjective chosen values for machine protection (separately!).
  - Only single errors are accounted for!

- How to get Lambda or MTTF (Mean Time To Failure) values?
  - Experience with existing or similar components/prototypes, ...
    - GSI data,
    - Nuclotron data,
    - LHC data.
  - Calculated (on a per-part basis) according to ISO 13849-1:2008 and MIL Handbook for
    - SCU (Scalable Control Unit):
      $\lambda = 8,626$ FIT
      MTTF (Mean Time To Failure) = 13.2 years
    - Quench detection cards from KIT:
      $\lambda = 1,240$ FIT
      MTTF = 92 years

<table>
<thead>
<tr>
<th>Severity</th>
<th>Meaning for personnel</th>
<th>Meaning for the machine</th>
<th>Examples</th>
</tr>
</thead>
</table>
| S1       | Minor injuries at worst | Short accelerator recovery time MTTR < 2 h | - Target irradiated wrongly
- Magnet quench
- Superficial damage of a beam pipe
- Fuse blown
- Machine activated |
| S2       | Major injuries to one or more persons | Accelerator recovery time MTTR < 1 d | - Target destroyed
- Protective devices (e.g. at septum) burnt through
- Safety valves in He supply or return blown |
| S3       | Loss of a single life | Long shutdown MTTR < 1 a | - Septum wires burnt through
- He safety valves of cryostats blown
- Busbar/cables burnt
- Holes in beam pipes |
| S4       | Multiple loss of life | Catastrophe | - Should never happen! |

$\lambda_{UCL} = \frac{X^2_\alpha \nu}{2T}$ \quad with \quad $\nu = 2f + 1$

1 FIT = 1 Failure in $10^9$ h
Risk assessment: How to define SIL levels?

- When defining a safety function, e.g.: „Dump Magnet Energy when a quench occurs“, how reliable the function has to be?
- S3: Damage so large that downtime >> 1d
- A1: No personnel present when powering S.C. magnets!
- G1: It is possible to prevent the magnet from quenching (e.g. observing temperature)
- W2: Possibility for a quench is >5%, but <25% of operation time
- **SIL3 is necessary for achieving a safe quench detection and dump resistor activation**, \(\text{PFH} < 1 \times 10^{-7}\) failures/h.

- Other example: PSS: “Deny user request to enter restricted area during beam operation.”
- also SIL3, but with \(\text{PFD} < 1 \times 10^{-3}\) failures/demand.

<table>
<thead>
<tr>
<th>Low demand [failure/request]</th>
<th>High demand or continuous request [failure/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average probability of dangerous failure at request of the safety function</td>
<td>Average probability of dangerous failure of the safety function</td>
</tr>
<tr>
<td><strong>SIL / PL</strong></td>
<td><strong>PFD\text{avg. min} \text{ (=)}$$</strong></td>
</tr>
<tr>
<td>4 / e</td>
<td>1,00E-05</td>
</tr>
<tr>
<td>3 / d</td>
<td>1,00E-04</td>
</tr>
<tr>
<td>2 / c</td>
<td>1,00E-03</td>
</tr>
<tr>
<td>1 / b</td>
<td>1,00E-02</td>
</tr>
</tbody>
</table>
Risk assessment:
Magnets, busbars, current leads

- Failures:
  - Quenches
  - Thermal runaways
  - Turn-to-GND short
  - Turn-to-Turn short

- Most severe failures:
  - Quenches (destroys busbars or magnet coils)
  - Dipole:
    - full beam could hit the E-Septum wires in ~1 ms
  - Quadrupole, Chrom. Sextupole, Res. Sextupole, Octupole:
    - beam could hit the Halo collimators, E-Septum wires or external targets / detectors during slow extraction in ~1 ms

- Chosen mitigations:
  - Magnet interleaving Quench Detection (QD)
  - Emergency dump for detected failures (started just before magnet energy dump)
  - Interlocks

- Failsafe behavior:
  - ~99% reduction of risk
    - Already incorporated in hardware design (SIL3 for QD!)
    - Turn-to-Turn shorts only detectable during commissioning and pilot beam operation!
Risk assessment: Power Converters

- Failures:
  - DCCT or control loop causes more or less current than set
  - IGBT shorts
  - Media (cooling water) or sensor failures
  - Primary Voltage supervision sensor failures
  - PE failures (dipoles, quadrupoles, septum 3)

- Most severe failures:
  - Dipole PC: full beam could hit the E-Septum wires in ~1 ms
  - Quadrupole, Chrom. Sextupole, Res. Sextupole, Octupole, Radres. Quadrupoles PC’s: beam could hit the E-Septum wires or external targets / detectors during slow extraction in ~1 ms

- Chosen mitigations:
  - Redundant DCCT in some cases
  - Emergency dump for detected failures (started just before magnet energy dump)
  - Interlock

- Failsafe behavior:
  - ~92% reduction of risk
  - Still (minor) modifications in hardware design necessary
Risk assessment: RF acceleration system

- Failures:
  - LLRF Amplitude control/DAC failure
  - LLRF DDS / Group DDS failure
  - Cavity GAP Arc ignition, shorts
  - Resonance frequency control failure
  - Driver / Power Amplifier failures
  - B2B Transfer unsynchronized
  - Media or sensor failure
  - 50 Ohm Terminator failure

- Most severe failure:
  - Gap arc ignition:
    At least a part of beam will hit cryo collimators (spiraling into it in around 1 ms), happens quite often

- Chosen mitigations:
  - Emergency dump for detected failures
  - Interlock (for media or sensor failures)

- Failsafe behavior
  - ~89% reduction of risk
  - Minor modifications in hardware/software design are necessary
Risk assessment: Injection/Extraction system

- Failures:
  - Single kicker does not fire, voltage deviation
  - Single kicker fires unintentionally
  - E-Septum sparking

- Most severe failures:
  - E-Septum sparking:
    - full beam could hit E-Septum wires
  - Single extraction kicker does not fire / voltage deviation:
    - beam can hit septum or HEBT / detectors / targets

- Chosen mitigations:
  - Emergency dump
    - partial beam loss can not be prevented
      - no warning time
      - up to ~30% beam loss when kicking in coasting beam during slow extraction
  - Low intensity pilot beam for optimizing settings
  - E-Septum has to be actively protected (wire supervision)
  - “Cleaning” of beam which remains after extraction kick onto the emergency dump.

- Failsafe behavior:
  - 89% reduction of risk
  - Further tracking studies will follow to identify and reduce risks
Risk assessment: Global/Local cryogenic system

- Failures:
  - Valve or valve control failure
  - He supply/return line rupture or leak
  - Voltage breaker leakage or rupture
  - Valve bellow rupture
  - Compressor / pressure regulation failure

- Most severe failures:
  - Voltage breaker leakage or rupture: Paschen limit, repair time
  - Valve bellow and He supply/return line rupture: long shutdown for repair
  - Most failures would result in quench, but this is detected by pressure / temperature sensors and QD.

- Chosen mitigations:
  - Pressure readout, Emergency dump (started with magnet energy dump, which is more important) for fast processes
  - Interlock for slow processes
  - QA (Quality Assurance) for all weldings and QD (Voltage tabs) for all interconnections
  - Maintenance plans for valves

- Failsafe behavior:
  - 88% reduction of risk
  - Care has to be taken in design and read-out of insulation vacuum pressure (cold cathode gauges) – some failures have short rise times.
Risk assessment: Control system

- **Hardware, Software and Operators**
- **Failures:**
  - Wrong data delivered to device
  - Timing system does not trigger → all effects possible...
  - Slow extraction efficiency too low
  - Feedback systems (Orbit, TFS, LFS) fail (currently not calculated)
- **Most severe failures:**
  - **Software errors:** full beam could hit anywhere
  - **Physic model errors:** full beam could hit anywhere
  - **Operator** thinks in the wrong direction: full beam could hit anywhere
- **Chosen mitigations:**
  - Low intensity **pilot beam** for verifying optics, physics model and machine settings, **intensity ramp up concept, locking of critical parameters at high intensities**
  - BLM’s, Transmission supervision, Emergency dump
  - Optics check for machine setting parameters, Training for operators
  - Data check (read-back) of machine settings (cyclic every few minutes); Set and Actual Value - window comparison
- **Failsafe behavior**
  - ~99% reduction of risk
  - Human factors still an issue
  - SCU and timing system already designed with very large MTBF

![Graph showing risk assessment results]

- Downtime / h/a
- Events / a

- **Dangerous undetected failures**
- **Dangerous detected failures**

![Graph showing failure intensity factors (FIT)]

- Slow extraction efficiency too low
- Timing System does not trigger
- Wrong CO feedback to steiners
- Wrong data delivered to device

- Downtime / h/a: [Data]
- Events / a: [Data]
Risk assessment: Beam dynamics and others

- Failures:
  - Beam instabilities (difficult to estimate correctly)
  - Beam in kicker gap
  - UHV pressure rise, vacuum leakage, FOD (objects in vacuum chamber – LEP, ESR, SIS18)
  - HEBT / Experiment note ready, EMC, Earthquakes, … (not calculated)

- Most severe failures:
  - Beam instabilities
  - Cold UHV chamber leaks (long downtimes for repair!).

- Chosen mitigations:
  - Emergency dump
  - BLM’s, cryo catcher current readout
  - Robot for searching “UFO”s

- Failsafe behavior:
  - 33% reduction of risk
  - One never knows what high energy / intensity or compressed beams do in real
  - Beam physics studies are ongoing
SIS100 risk assessment: Results

• Most severe (hard to detect at warm and long repair times): cold leaks / defects.

• Heavy ion beam power of SIS100 is high enough to damage sensible equipment (e.g. e-septum).

• All devices are designed self-protecting when internal failures occur, but not necessarily have optimum behavior with respect to the beam. Work is progressing to improve this.

• For emergency dump: Beam losses caused by spurious errors (e.g. power converter problems, RF failures, quenches, ...) as well as dynamically unstable beams can be mitigated effectively by the emergency dump system.

• By failsafe concept, up to 85% of the total failures in time can be detected or mitigated.

• Given 6,000 h operating hours per year, an availability of 66% (3,957 h/a) is currently estimated.
Comparison of SIS100 with CERN PS

for Proton operation:

### Similarities

<table>
<thead>
<tr>
<th></th>
<th>SIS100 ($\gamma_1$-shift settings)</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles per cycle</td>
<td>$2 \times 10^{13}$</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td>Injection energy / GeV</td>
<td>4.0</td>
<td>1.4</td>
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<tr>
<td><strong>Extraction energy / GeV</strong></td>
<td><strong>28.8</strong></td>
<td><strong>20.0</strong></td>
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<tr>
<td>Stored energy Inj. / kJ</td>
<td>12.7</td>
<td>6.8</td>
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<tr>
<td><strong>Stored energy Extr. / kJ</strong></td>
<td><strong>91.1</strong></td>
<td><strong>96.9</strong></td>
</tr>
<tr>
<td>Max. beam radius Inj. / mm</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Max. beam radius Extr. / mm</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Min. beam radius Inj. / mm</td>
<td>3.6</td>
<td>17.7</td>
</tr>
<tr>
<td>Min. beam radius Extr. / mm</td>
<td>1.5</td>
<td>5.6</td>
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</table>

### Differences

<table>
<thead>
<tr>
<th></th>
<th>SIS100</th>
<th>PS</th>
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</thead>
<tbody>
<tr>
<td>Magnet type</td>
<td>SC</td>
<td>NC</td>
</tr>
<tr>
<td>Beam pipe vacuum chamber thickness / mm</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Heavy ion beam energy / kJ</td>
<td>51.5</td>
<td>~7.1</td>
</tr>
</tbody>
</table>

- For p operation, CERN PS and SIS100 similar in energy and spot size (=damage potential); for heavy ions, SIS100 is more dangerous...
- No major accidents in PS due to beam losses
- Spot size in SIS100 even larger with $\gamma_1$-jump settings
- LHC (one beam): 362 MJ => 4 000 times more energy!
After an absorber length of 1 m:
- hardly any primary protons left
- homogeneous energy distribution by secondaries
- Temperature values well below the sublimation/melting points
- Energy deposition values in upper and lower coils identical within 30 %
5 \times 10^{11} \text{ U}^{28+}, 2.7 \text{ GeV/u}
energy deposition in the dump

Graphite dump (20 cm)  Tantalum absorber (225 cm)

distance along z-axis (cm)

projections in YZ plane, averaged over x  view from the top

\sigma_y = 0.3 \text{ cm}

projections in XY plane, averaged over z  view along the beam direction

\sigma_y = 0.6 \text{ cm}