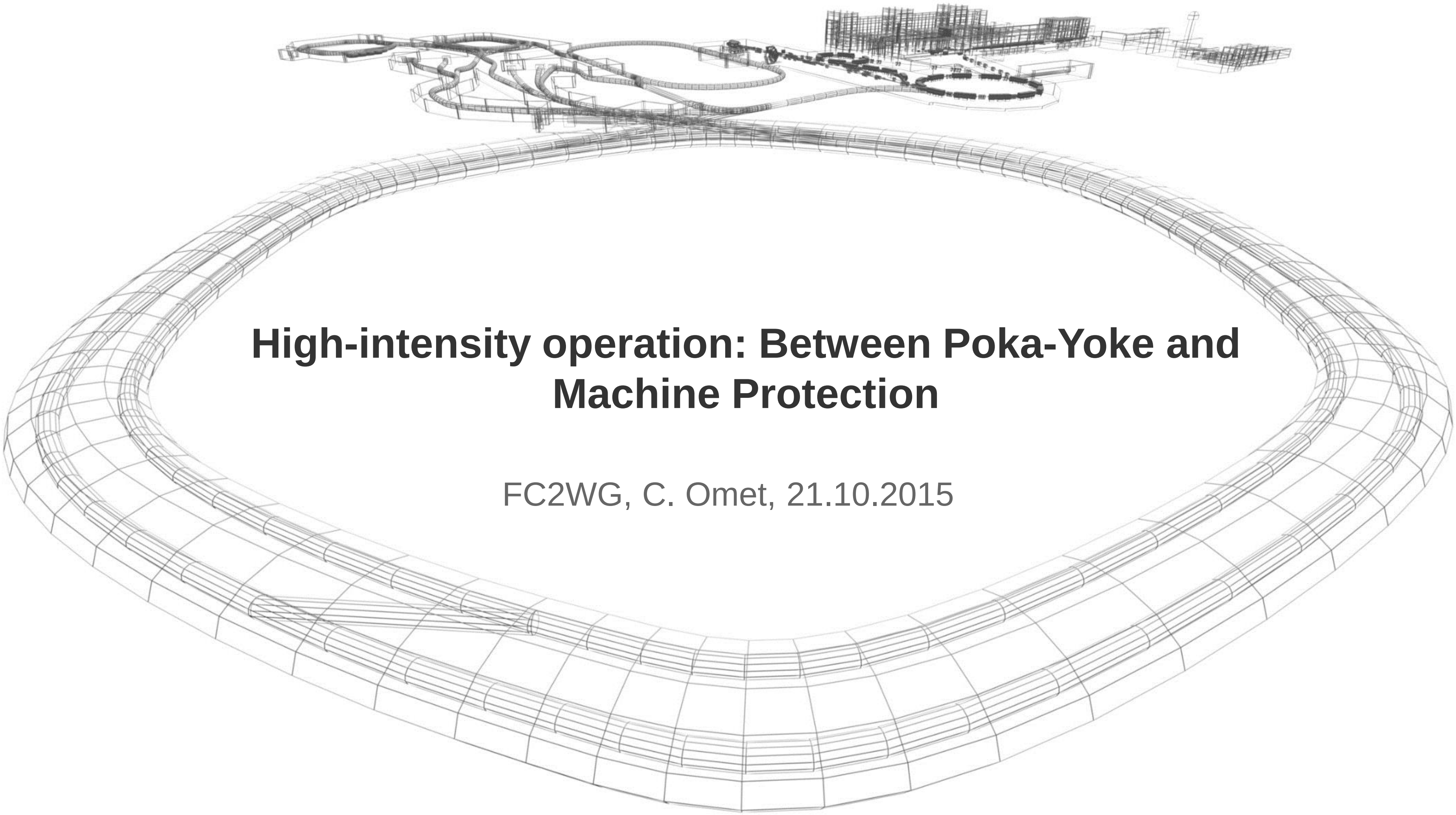
GSI Helmholtzzentrum für Schwerionenforschung GmbH



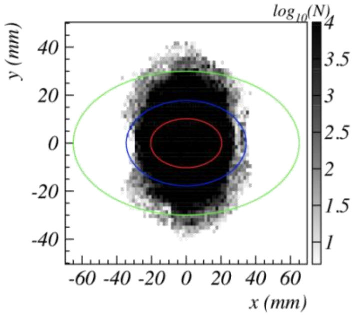
High-intensity operation: Between Poka-Yoke and Machine Protection

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 γ_{tr} shifting or γ_{tr}-jump

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

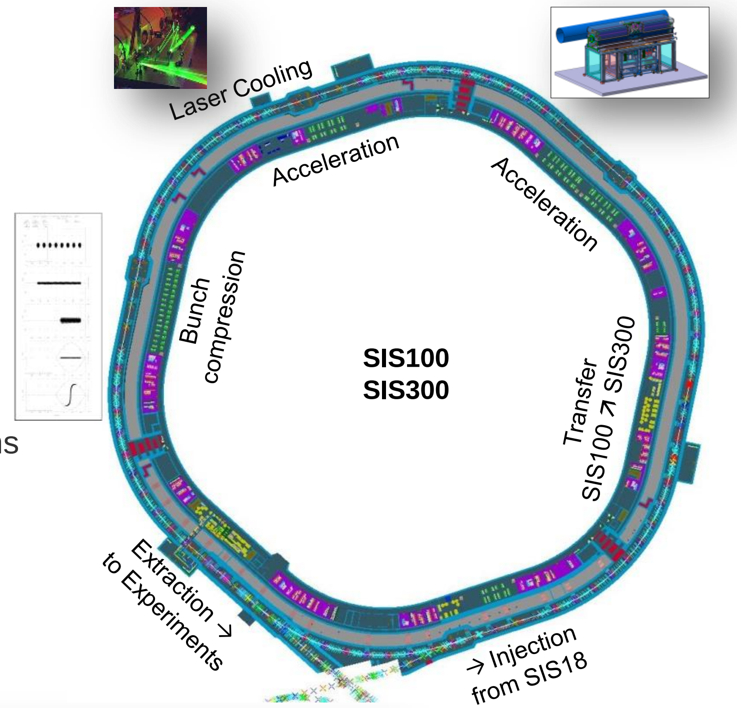


Geometrical Acceptance:
3 x maximum emittance

Dynamic Aperture:
3.4 sigma

SIS100:
Lattice design criterias

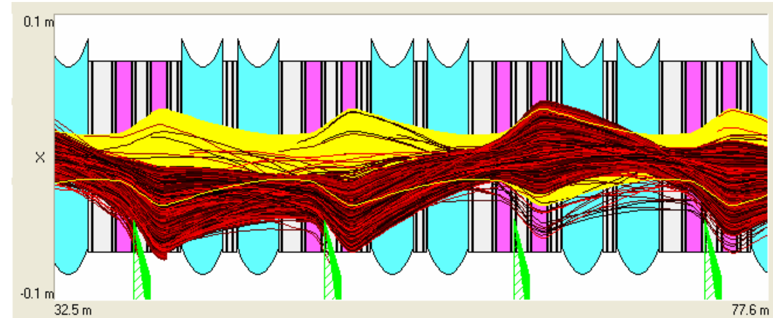
1. Length: 5 x SIS18 length (= 1 083.6 m)
2. Reference ion operation: U^{28+}
   - Localize beam ionization losses
   - Control vacuum pressure
3. Secondary ion: Protons
   - Variable γ_t-optics by multiple quadrupole families
   - Fixed γ_t-optics utilizing fast γ_t-jump quadrupoles
4. RF system
   - 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



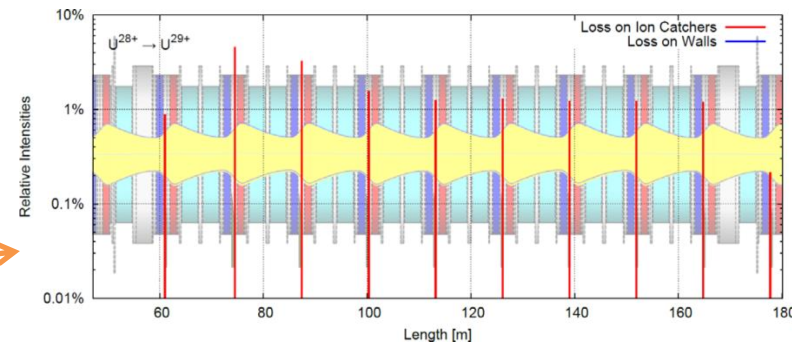
Images courtesy of M. Konradt / J. Falenski

SIS100:
Lattice design

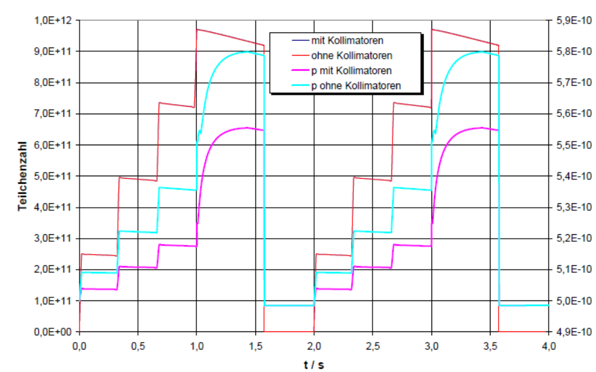
- **Doublet focusing structure**: up to 100% collimation efficience reachable with focusing order DF
  - First called “storage mode lattice” because many U^{29+} particles survived one complete turn.
  - **Dipoles act as a charge state separator** when bending angle per cell is chosen correctly.
  - 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



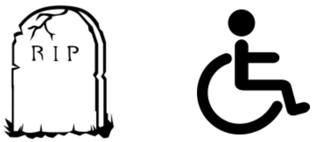
- Dynamic vacuum calculations showed that in spite of the very well controlled losses, a **huge pumping speed** will be required
  - ➢ Cold vacuum chambers
  - ➢ SC magnets



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

This talk



PED

- 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:

RISK = Consequences · 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

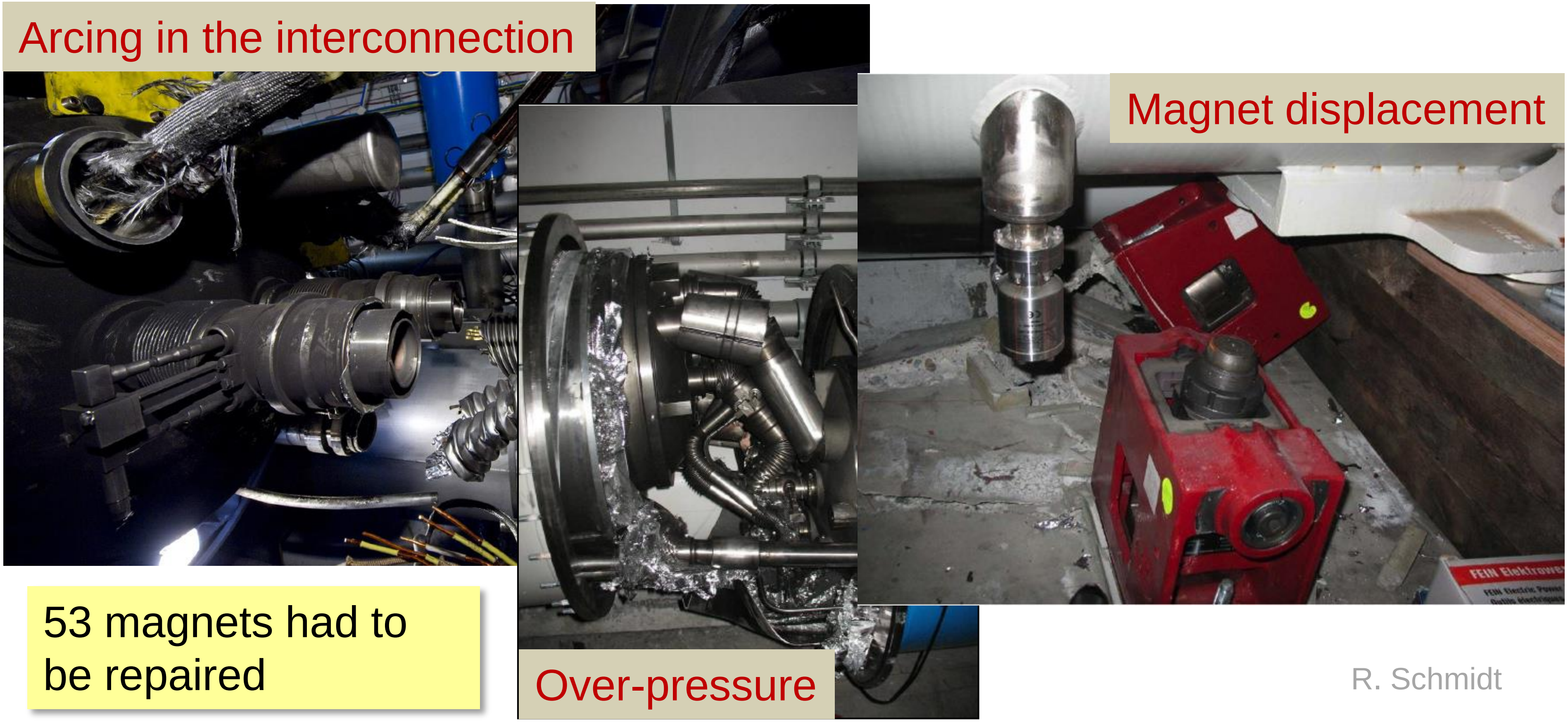
R. Steinhagen

Consequences of a release of 600 MJ at LHC

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.

Arcing in the interconnection



Magnet displacement

53 magnets had to be repaired

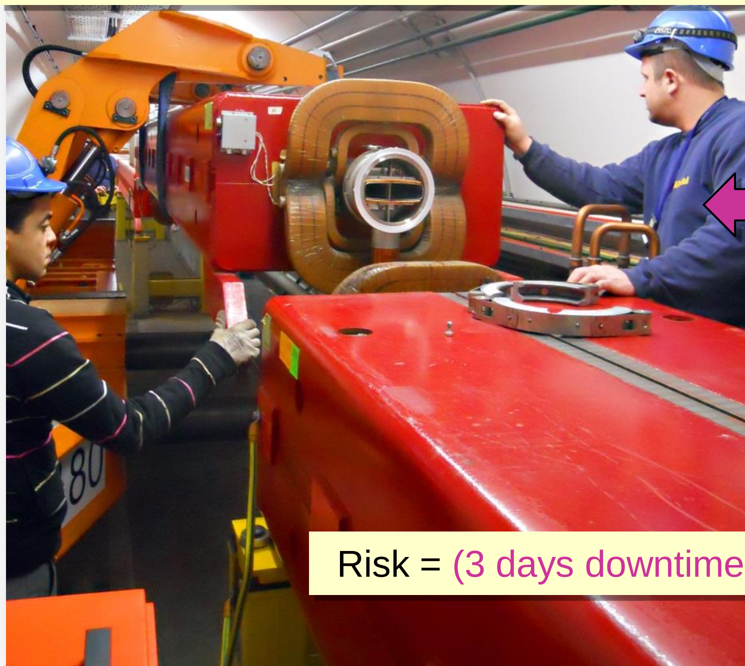
Over-pressure

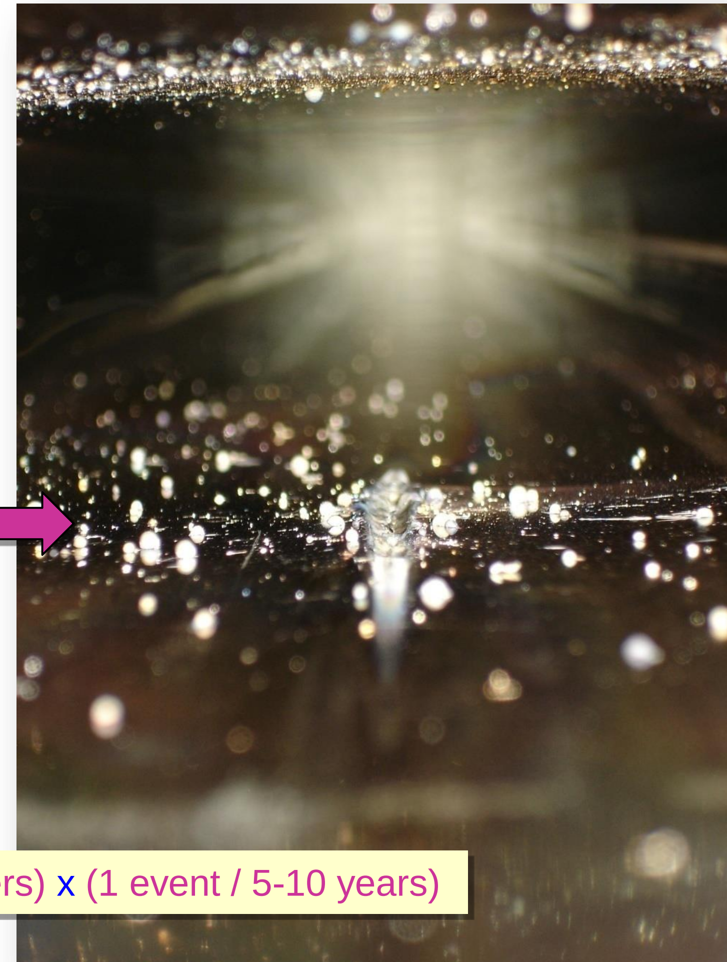
R. Schmidt

Incidents happen

2008 SPS run

- Impact on the vacuum chamber of a 400 GeV beam of 3×10^{13} protons (**2 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)

R. Steinhagen

Incidents happen

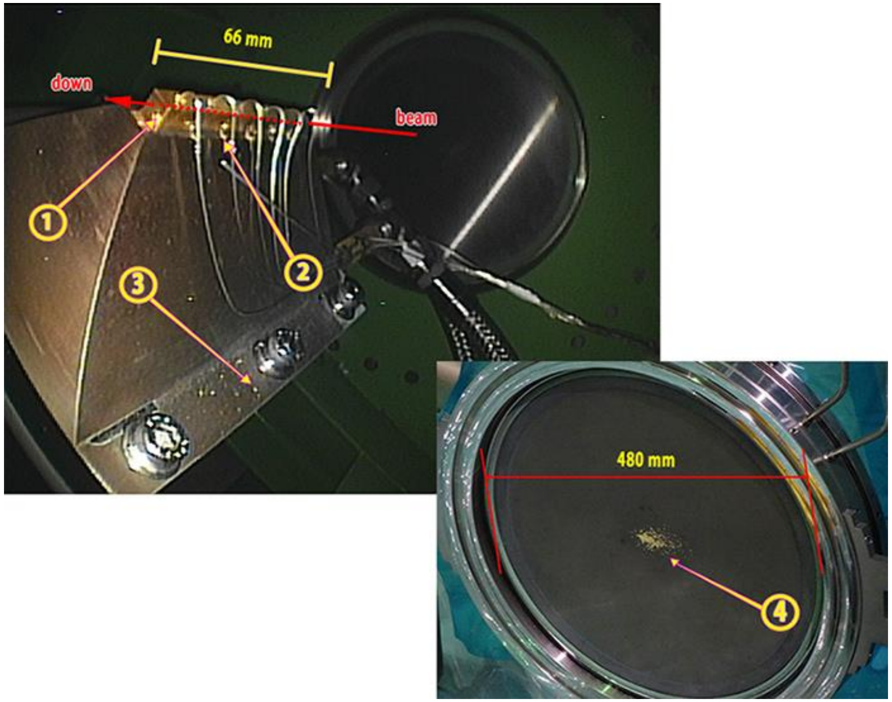
JPARC home page – October 2013

Risk = (9 month downtime + dose to workers) x (1 event / 12 years)

R. Steinhagen

JPARC incident – May 2013

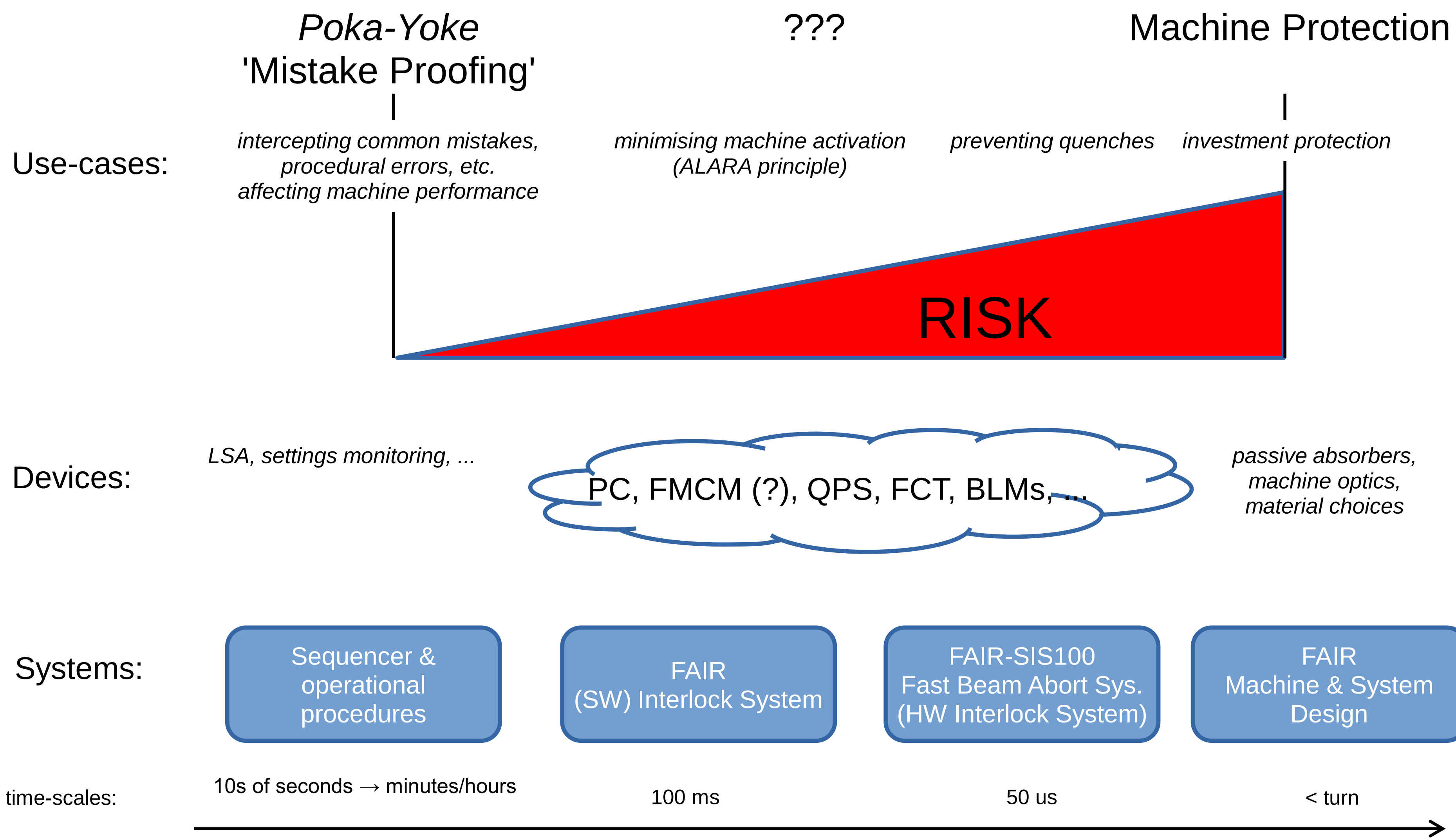
- Due to a power converter failure, a slow extraction was transformed into a fast extraction.
  - *Extraction in milliseconds instead of seconds.*
- As a consequence of the high peak power, a Gold muon conversion target was damaged and radio-isotopes were released into experimental halls.
  - *Machine protection coupled to personnel protection!*
- Investigations and protection improvements done, J-PARC restart after ~9 month.



One insufficiently covered failure case had major consequences !

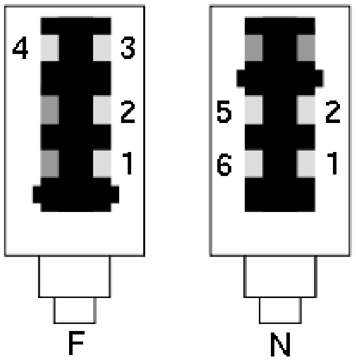
Risk Management Gradient

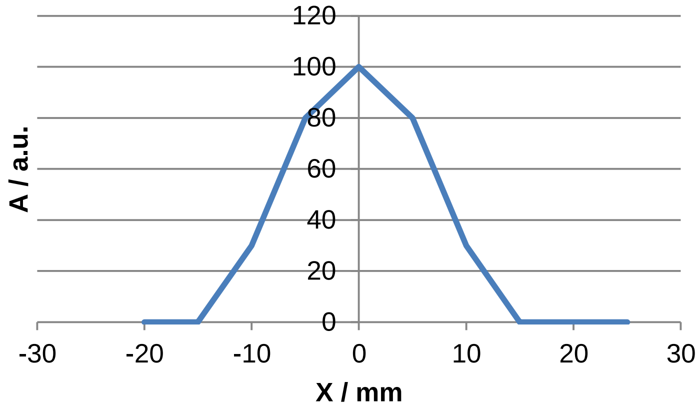
R. Steinhagen



Poka-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)





R. Steinhagen

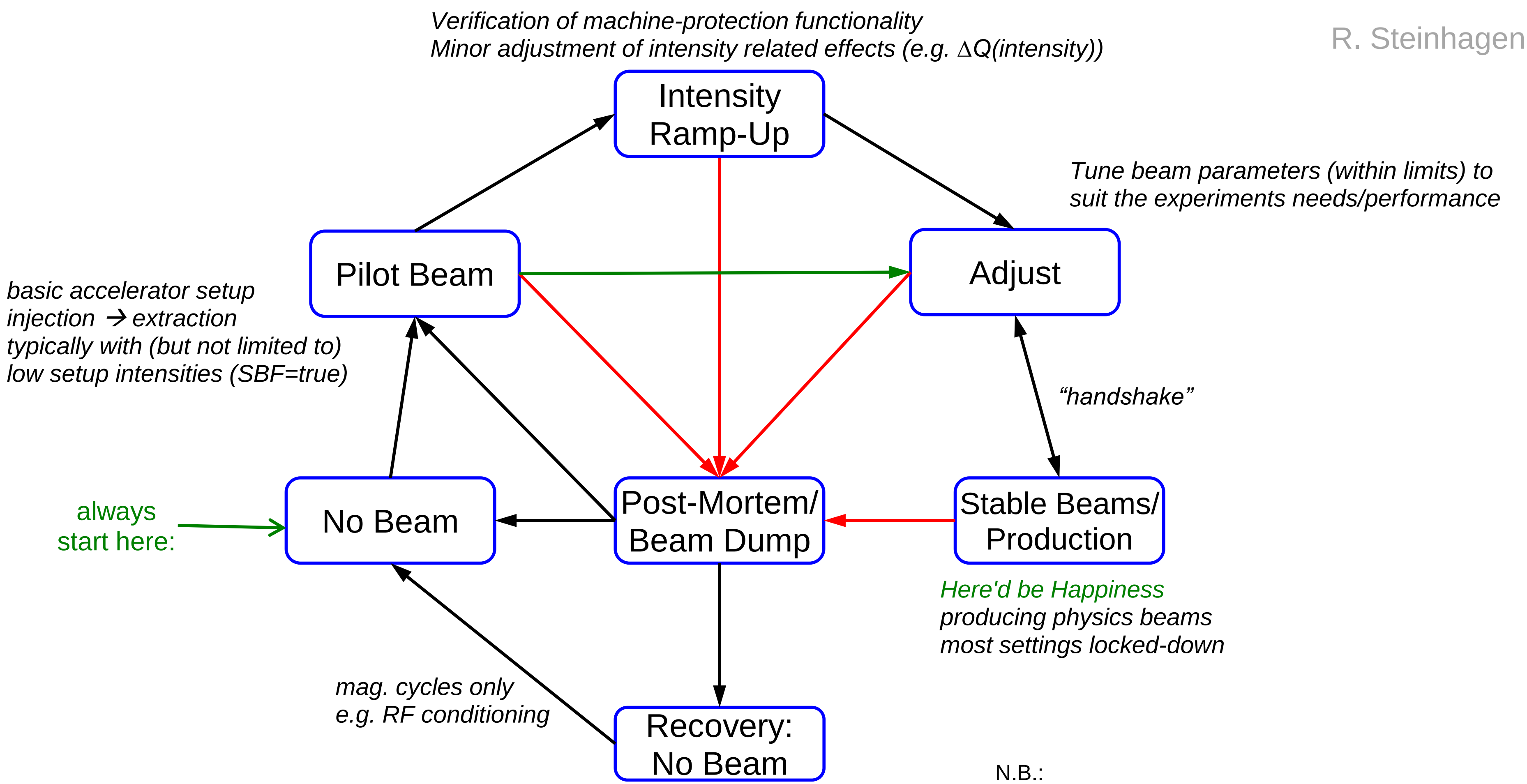
FAIR Machine Protection Concepts

- 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)

R. Steinhagen

Proposal:
FAIR Beam Modes – State Diagram

R. Steinhagen



cool down + cycling after
magnet quench or main PS failure
N.B. beam mode = machine mode

normal operational path
error/fault case
low-intensity

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

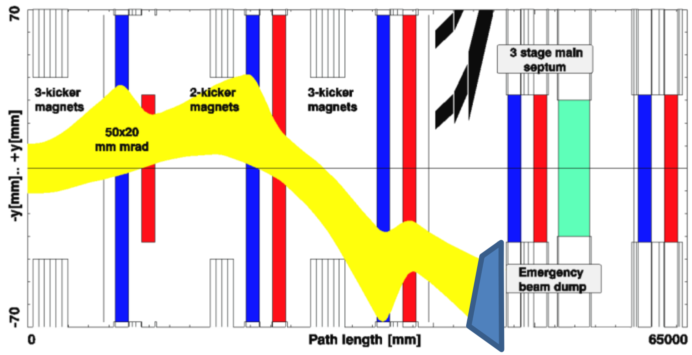
Machine protection

- 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

<u>How to stop beam operation:</u>

1. Inhibit injection
2. Extract beam into emergency beam dump or
3. Stop beam by beam absorber / collimator

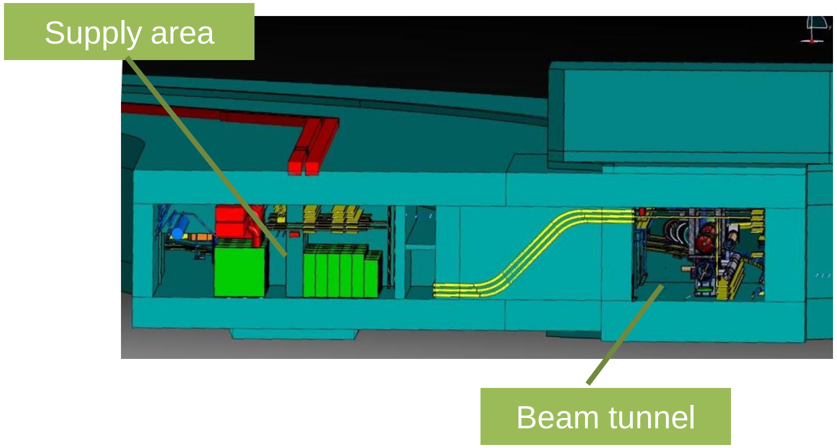


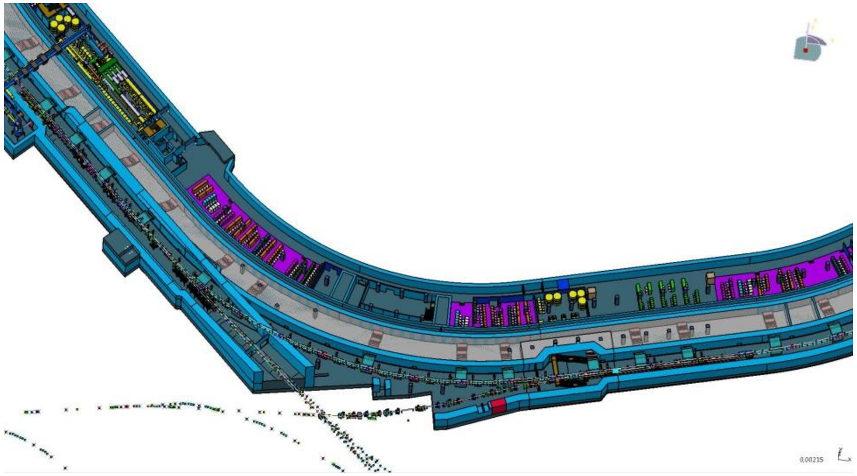
Is activation an issue?

- **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.

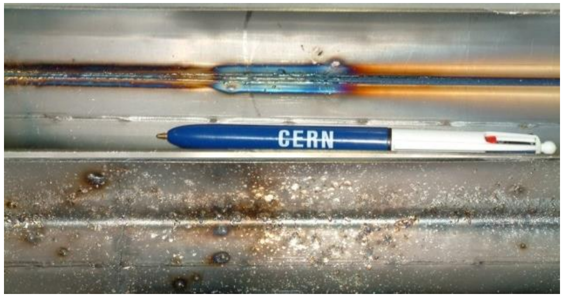
- Controlled losses: Extraction sector S5 is already prepared; components have to be remote / fast serviceable (Magnetic + Electrostatic septa, radiation resistant quadrupoles).
- Halo collimators, Cryo catchers would be more activated.
- Building design has got separate beam and supply areas. The latter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



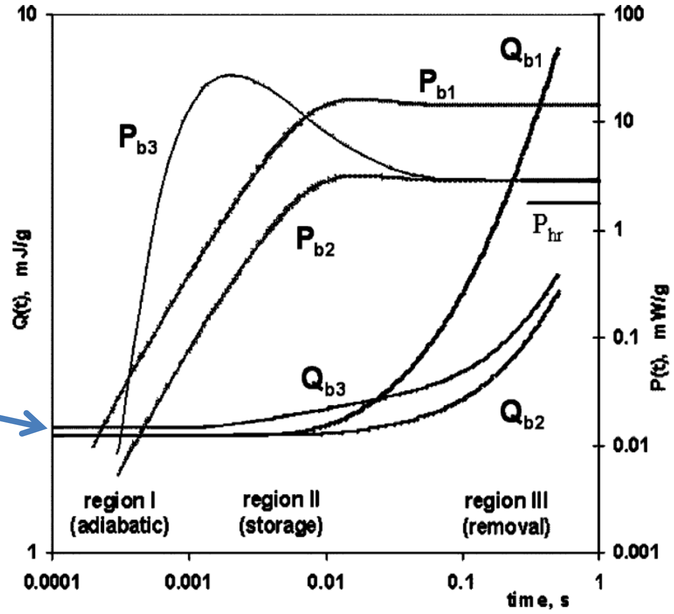


Beam impact on accelerator components

- 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**



Courtesy of R. Schmidt / CERN



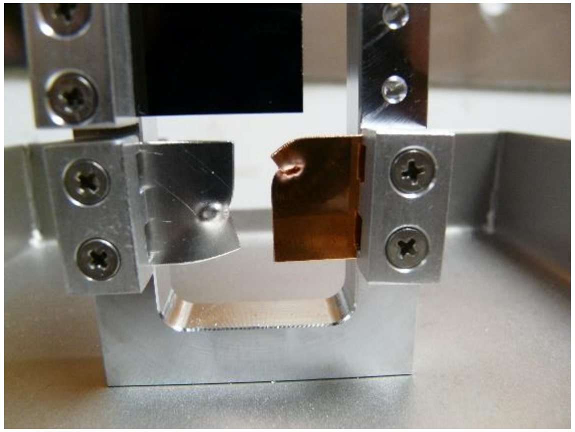
[1]: Some Aspects of Cable Design for Fast Cycling Superconducting Synchrotron Magnetism Khodzhibagiyan, Kovalenko, Fischer, IEEE TOAS Vol. 14, No 2, 2004

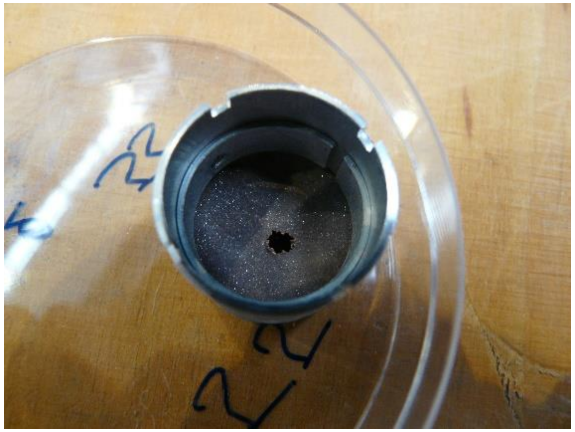
Is melting an issue? (I)

- **SIS18 beam** onto FRS target
  - Cu, Al und C Targets, 1 mm thick.
  - Graphite → no problems.

- Strong focused σ_x=0.44 mm σ_y = 0.99 mm, 125 MeV/u, $7 \times 10^9 \ldots 1 \times 10^{10}$ U^{28+}/ Spill.
- Sometimes, up to 100 shots were necessary to drill a hole.
- Average power was only ~1 W, but peak energy ~3 kJ/g.

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





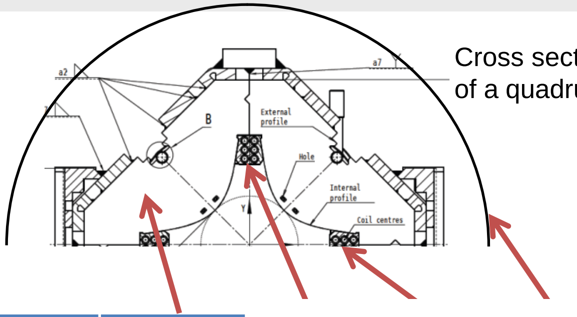
H. Weick

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 (2σ) for p γ_t-shift optics
  - r_{avg}=5.4 mm (2σ) for ion optics
- But when calculating temperature rise analytically:

$$\Delta T = \frac{N \cdot dE/dx}{c \cdot A \cdot \rho}$$

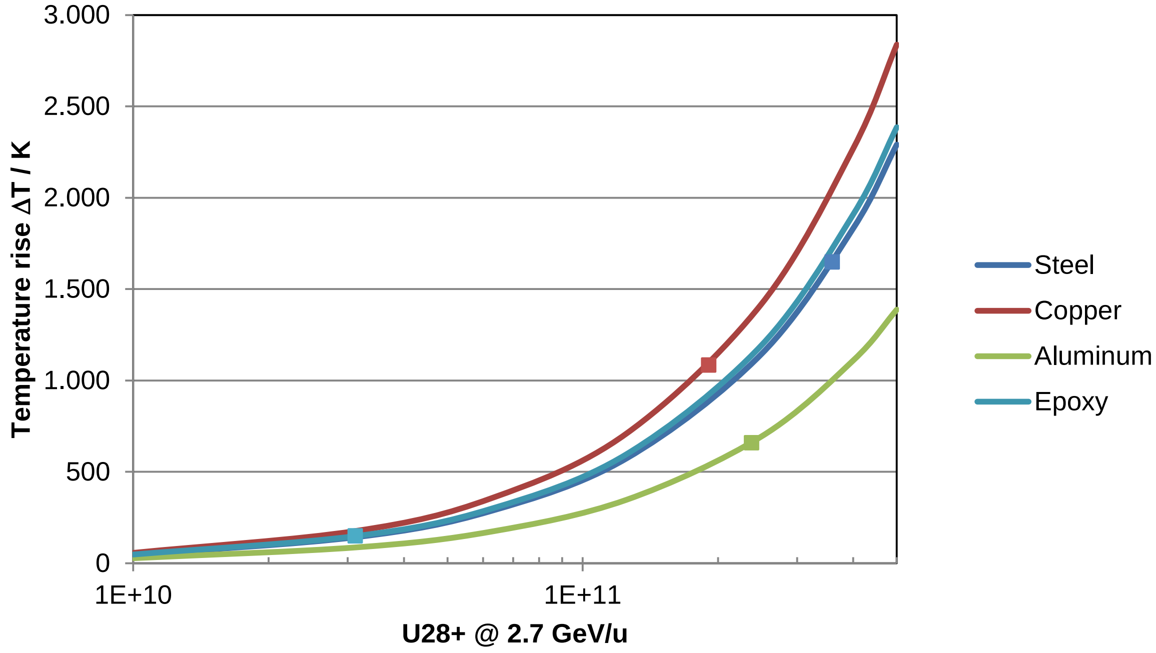
  - thin targets, no phase transition
  - no shock waves, no heat transfer or radiation
- Full design beam power for
  - ✓ Protons: no problem!
  - **Heavy ions (5x10¹¹ U^{28+}) are above the limit!**
  - But: Before it comes to melting, s.c. magnets will quench already (6 orders of magnitude earlier)



Cross section of a quadrupole

Material	Steel
Used in	Yoke, He-pipes Chambers
Melting Temp. / K	**1,921**
Specific heat *c* / J/(g*K)	0.49
Latent melting heat / J/g	270
Total melting energy density (T=15 K) / J/g	**1,204**
Total melting energy density (T=293 K) / J/g	**1,068**
Density *ρ / kg/m³*	7,870
Proton beam spot radius for melting @15K / mm	**0.4**
Max. ΔT for *proton* beams with 3.8mm spot radius / K	**28**
Uranium beam spot radius for melting @15K / mm	**5.6**
Max. ΔT for *Uranium* beams with 5.4mm spot radius / K	**2,291**

Heating of materials by the beam



$$\Delta T = \frac{N \cdot dE/dx}{c \cdot A \cdot \rho}$$

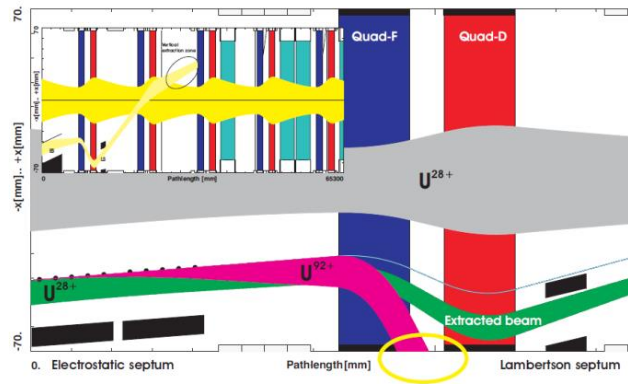
- 1×10^{10} U^{28+} are „not dangerous“ ➔ do not cause instant permanent damage by melting room temperature sections of SIS100...
- Safe beams / pilot beams should contain at maximum half / a quarter of that intensity!

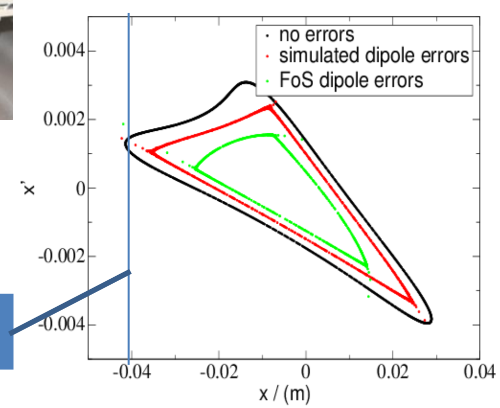
Potential beam damage in SIS100: Slow extraction

- 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)

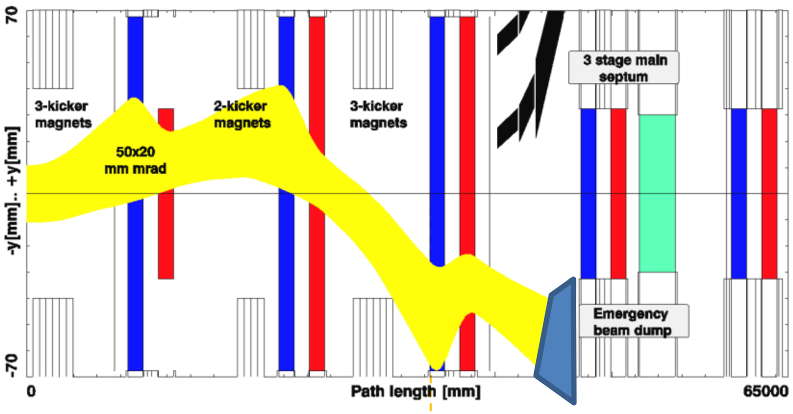


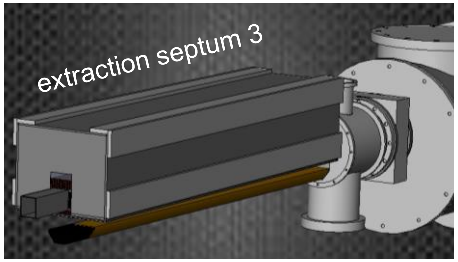


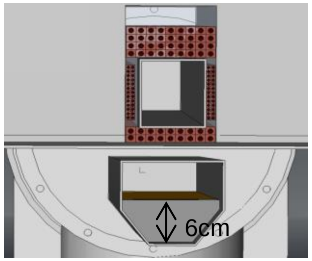
Septum wire position

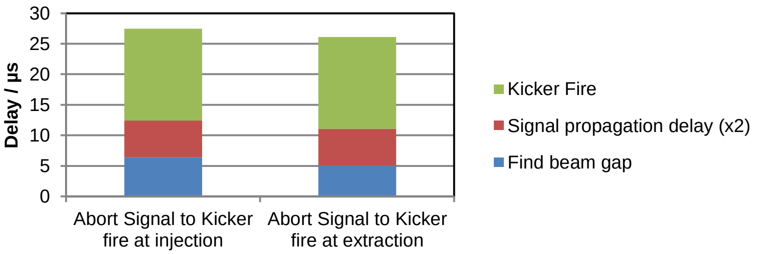
Emergency dump of SIS100

- 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).





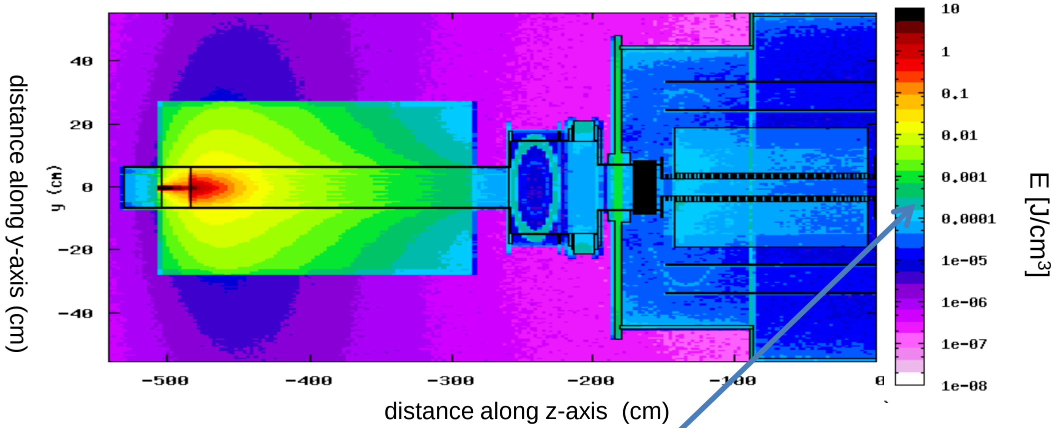




FLUKA simulations of emergency dump

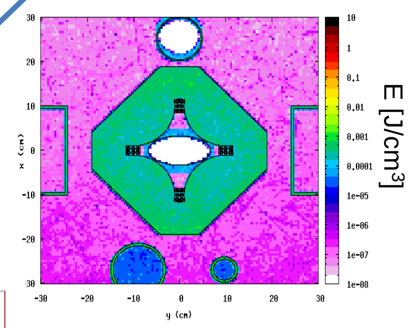
- Simulation assumptions
  - $5.0*10^{11}$ U^{28+}, 1.0-2.7 GeV/u
  - $2.5*10^{13}$ **p**, 29.0 GeV/u
  - Gaussian beam distribution with $\sigma_{x/y}$ = 3 mm
  - Full beam energy deposited within < 1 µs

- ✓ **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%.

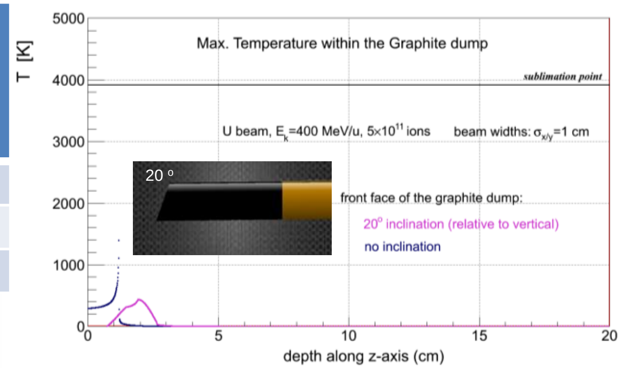


Quench limit 1.6 mJ/g ≈ 0.2 mJ/cm³

U^{28+}, 2.7 GeV/u



Ion	Max. Coil energy deposition / mJ/g	Avg. Coil energy deposition / mJ/g	Quench margin
$2.5x10^{13}$ p, 29 GeV	0.29	0.063	5.5 / 25.4
$5.0x10^{11}$ U^{28+}, 1.0 GeV/u	0.01	0.003	145 / 592
$5.0x10^{11}$ U^{28+}, 2.7 GeV/u	0.10	0.025	16 / 64



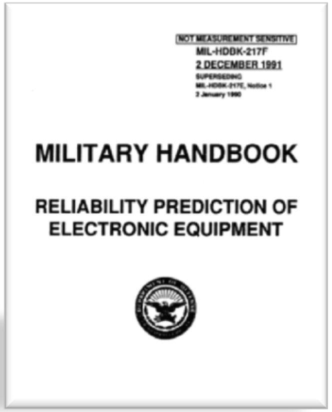
Risk assessment: System-FMEA

- 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.

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

  - 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

Severity	*Meaning for personnel*	Meaning for the machine	Examples
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!

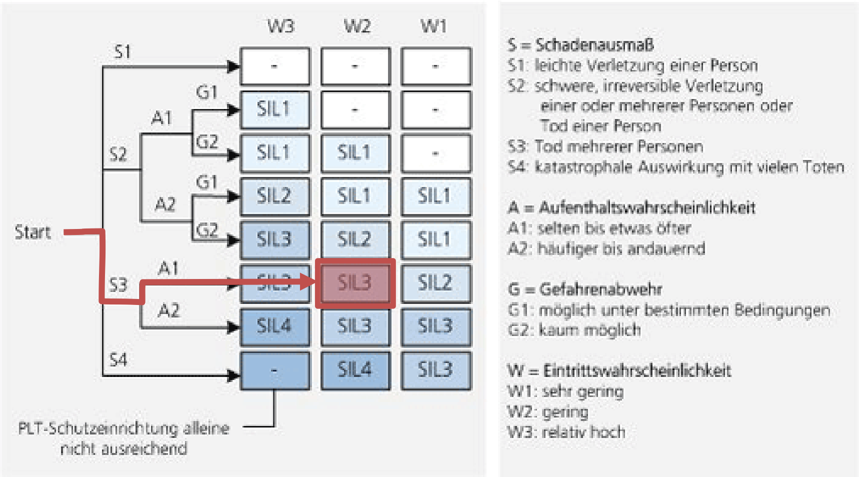

NOT MEASUREMENT SENSITIVE
MIL-HDBK-217F
2 DECEMBER 1991
SUPERSEDING
MILITARY HANDBOOK
RELIABILITY PREDICTION OF ELECTRONIC EQUIPMENT

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**, PFH<$1x10^{-7}$ failures/h.

- Other example: PSS: **“Deny user request to enter restricted area during beam operation.”**
- ➢ also SIL3, but with PFD<$1x10^{-3}$ failures/demand.

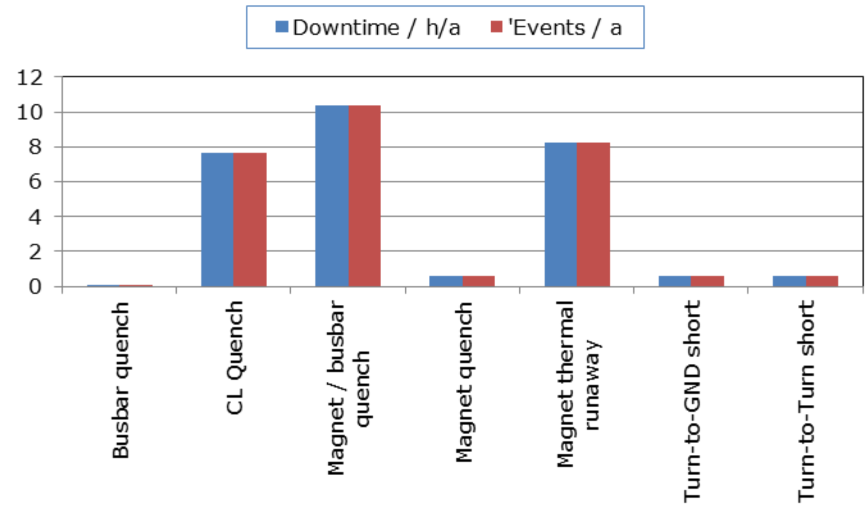


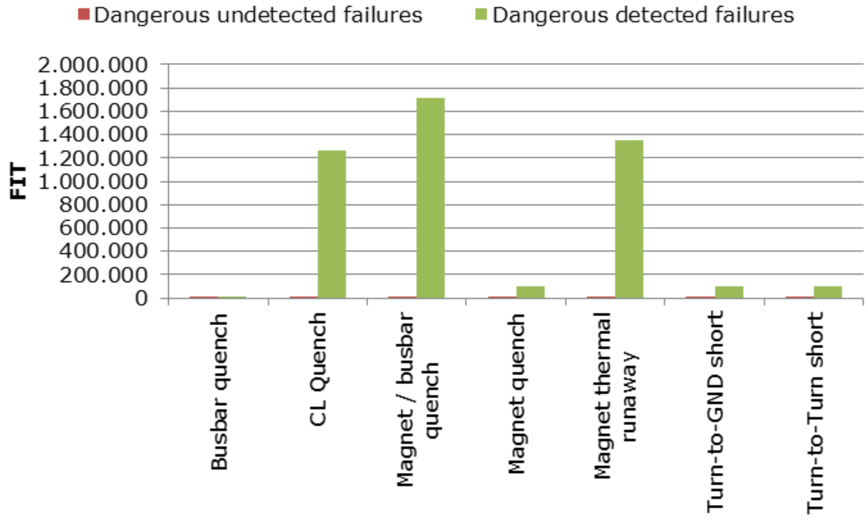
Risk graph

	Low demand [failure/request]		High demand or continuous request [failure/h]	
	Average probability of dangerous failure at request of the safety function		Average probability of dangerous failure of the safety function	
SIL / PL	$PFD_{avg, min}$ (>=)	$PFD_{avg, max}$ (<)	PFH_{min} (>=)	PFH_{max} (<)
4 / e	1,00E-05	1,00E-04	1,00E-09	1,00E-08
3 / d	**1,00E-04**	**1,00E-03**	**1,00E-08**	**1,00E-07**
2 / c	1,00E-03	1,00E-02	1,00E-07	1,00E-06
1 / b	1,00E-02	1,00E-01	1,00E-06	1,00E-05

Risk assessment:
Magnets, busbars, current leads

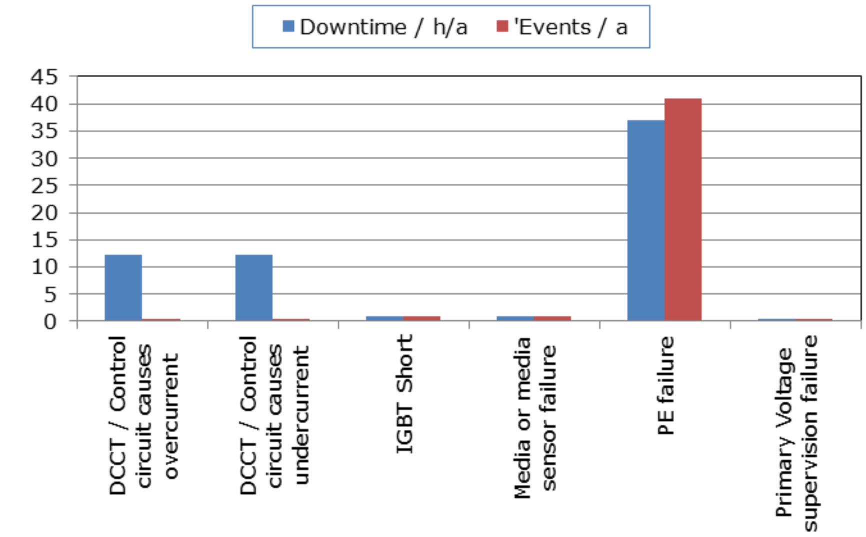
- Failures:
  - Quenches
  - Thermal runaways
  - Turn-to-GND short
  - Turn-to-Turn short
- Most severe failures:
  - Quenches (destroys busbars or magnet coils)
  - **Dipole:**
    full beam could hit the E-Septum wires in ~1 ms
  - **Quadrupole, Chrom. Sextupole, Res. Sextupole, Octupole:**
    beam 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!

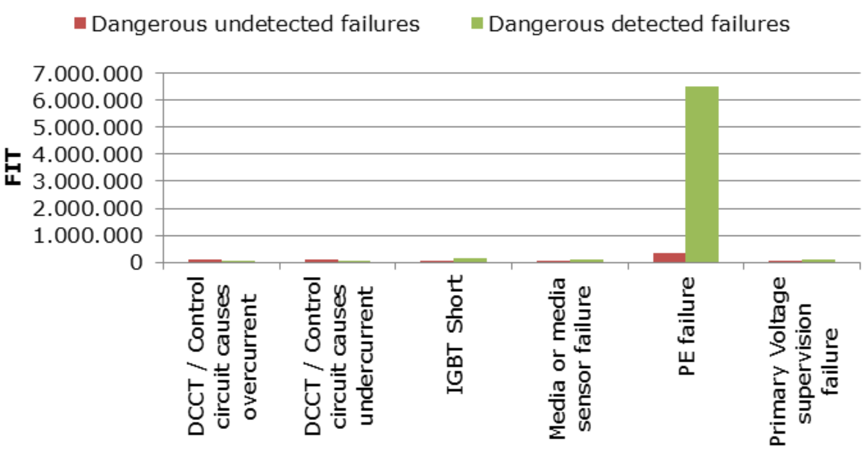




Risk assessment: Power Converters

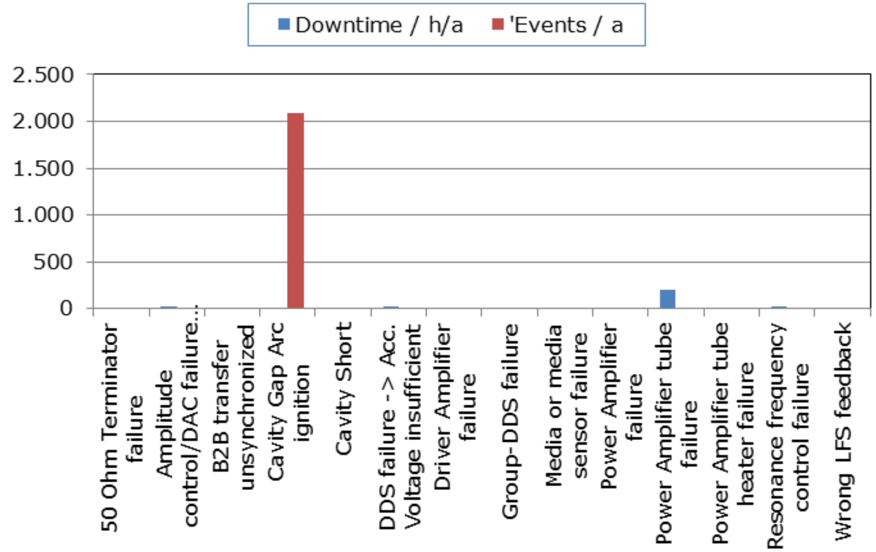
- Failures:
  - DCCT or control loop causes more or less current than set
  - IGBT shorts
  - Media (cooling water) or sensor failures
  - Primary Voltage supervision sensor failures
  - PE failures (dipoles, quadrupoles, septum 3)
- Most severe failures:
  - **Dipole PC:**
    full beam could hit the 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



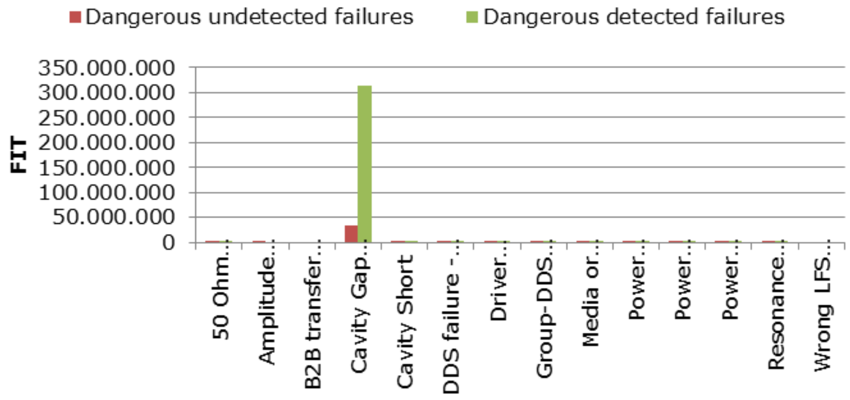


Risk assessment: RF acceleration system

- 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



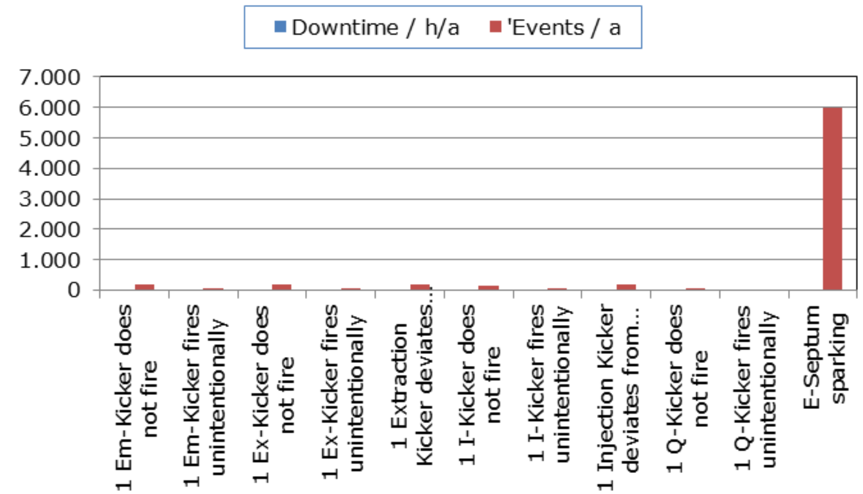
- Most severe failure:
  - **Gap arc ignition:** At least a part of beam will hit cryo collimators (spiraling into it in around 1 ms), happens quite often

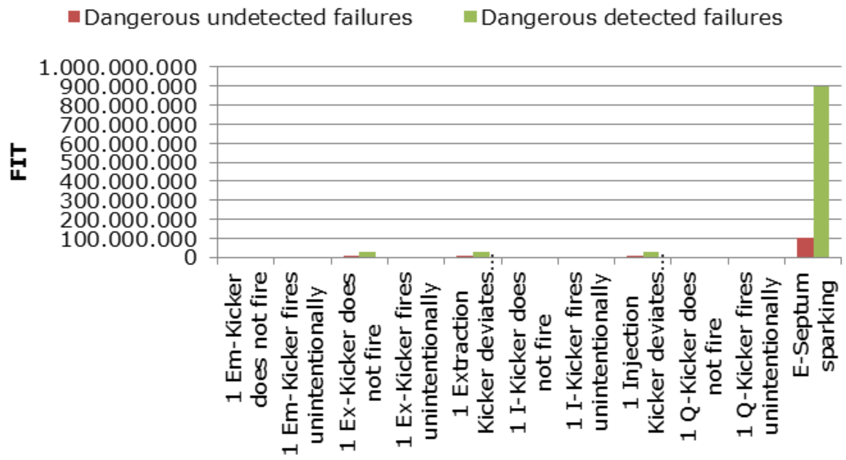


- Chosen mitigations:
  - Emergency dump for detected failures
  - Interlock (for media or sensor failures)
- Failsafe behavior
  - ~89% reduction of risk
  - Minor modifications in hardware/software design are necessary

Risk assessment: Injection/Extraction system

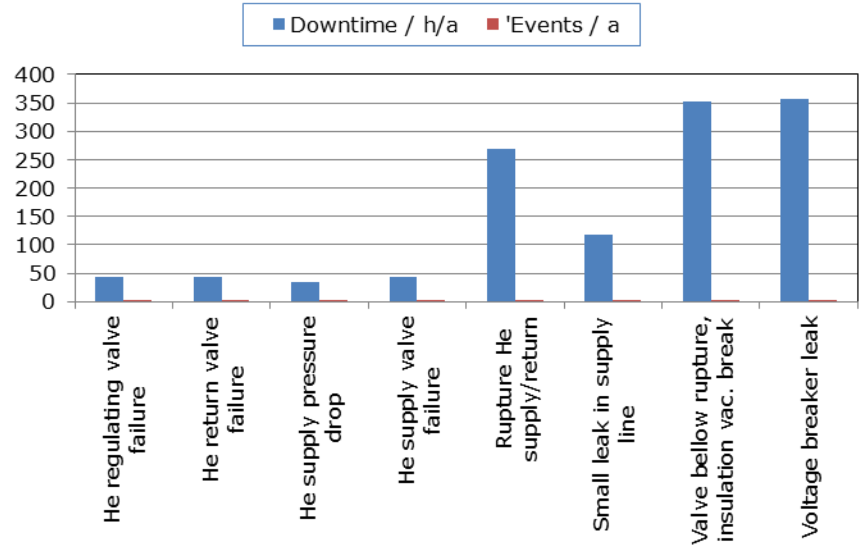
- Failures:
  - Single kicker does not fire, voltage deviation
  - Single kicker fires unintentionally
  - E-Septum sparking
- Most severe failures:
  - **E-Septum sparking:**
    full beam could hit E-Septum wires
  - **Single extraction kicker does not fire / voltage deviation:**
    beam can hit septum 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



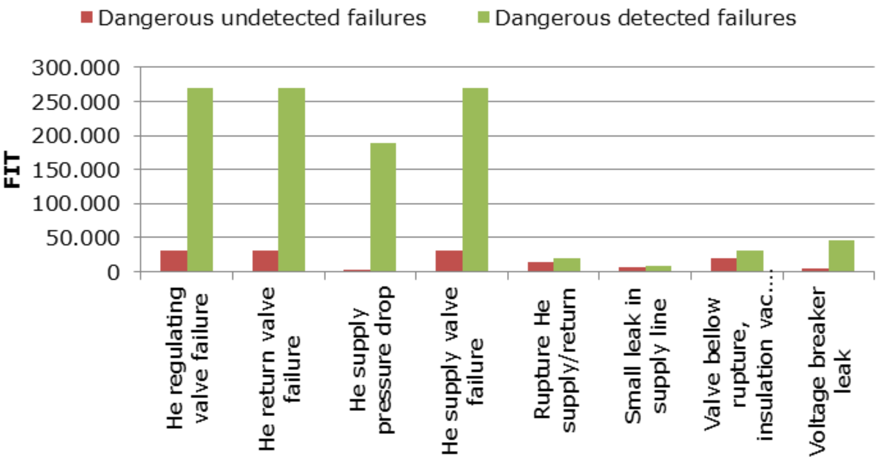


Risk assessment: Global/Local cryogenic system

- 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.

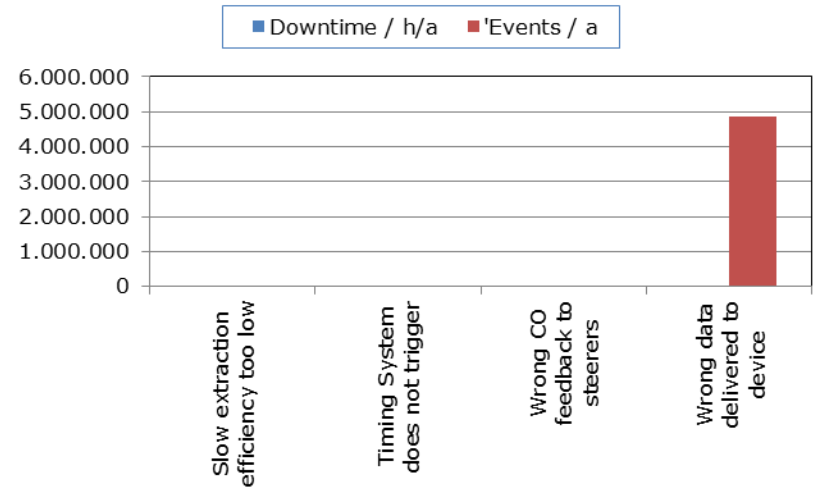


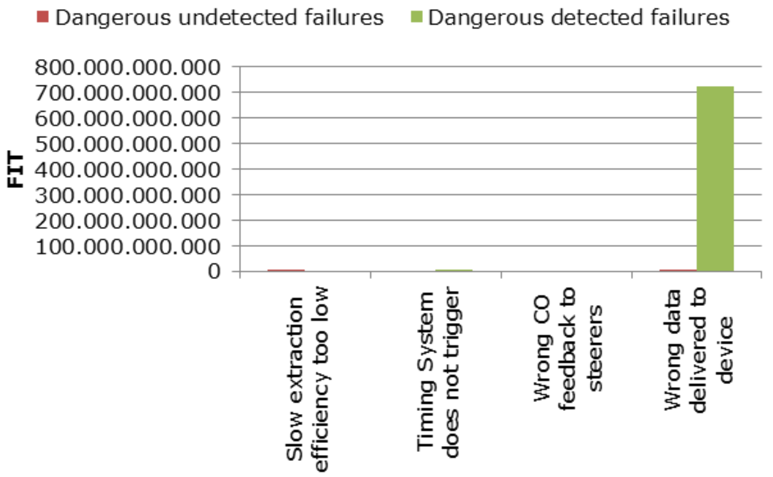
- Chosen mitigations:
  - Pressure readout, Emergency dump (started with magnet energy dump, which is more important) for fast processes
  - Interlock for slow processes
  - QA (Quality Assurance) for all weldings and QD (Voltage tabs) for all interconnections
  - Maintenance plans for valves
- Failsafe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

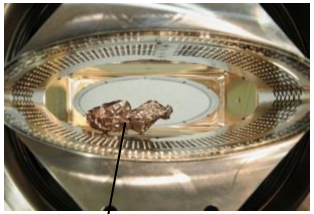
- Hardware, Software and Operators
- Failures:
  - Wrong data delivered to device
  - Timing system does not trigger ➔ all effects possible...
  - Slow extraction efficiency too low
  - Feedback systems (Orbit, TFS, LFS) fail (currently not calculated)
- Most severe failures:
  - **Software errors:** 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



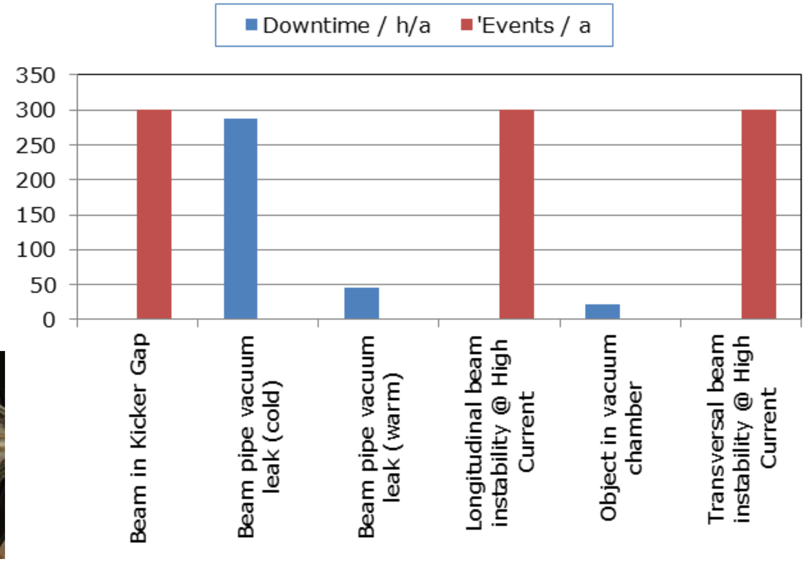


Risk assessment: Beam dynamics and others

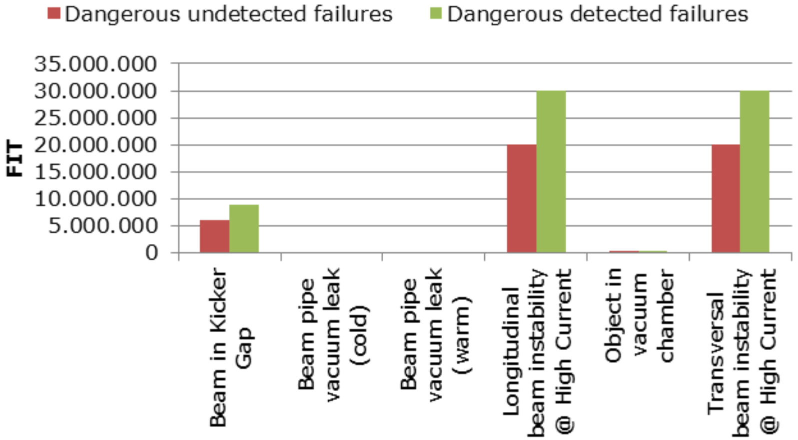
- Failures:
  - Beam instabilities (difficult to estimate correctly)
  - Beam in kicker gap
  - UHV pressure rise, vacuum leakage, FOD (objects in vacuum chamber – LEP, ESR, SIS18)
  - HEBT / Experiment note ready, EMC, Earthquakes, … (not calculated)
- Most severe failures:
  - Beam instabilities
  - Cold UHV chamber leaks (long downtimes for repair!).



SIS18 “UFO“

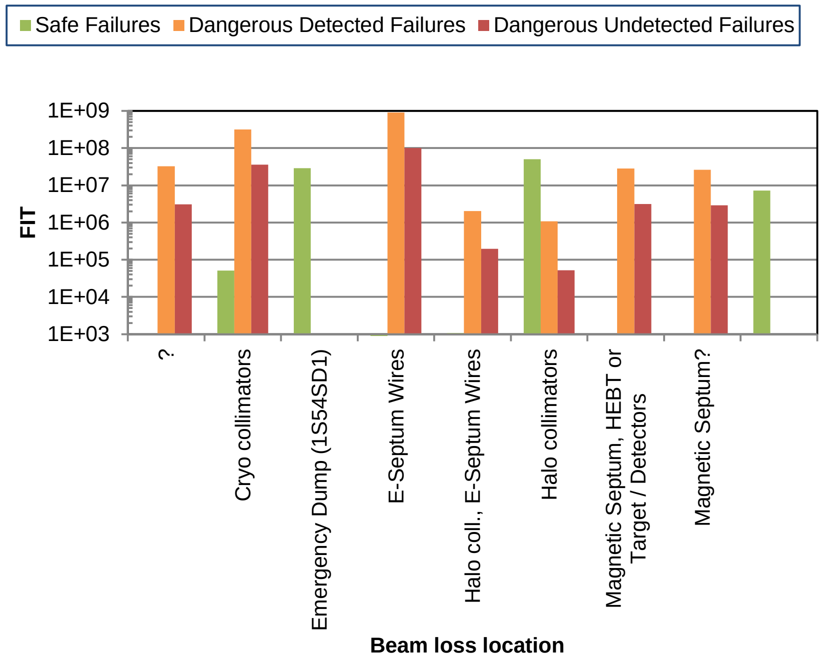


- Chosen mitigations:
  - Emergency dump
  - BLM’s, cryo catcher current readout
  - Robot for searching “UFO”s
- Failsafe behavior:
  - 33% reduction of risk
  - One never knows what high energy / intensity or compressed beams do in real
  - Beam physics studies are ongoing



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:

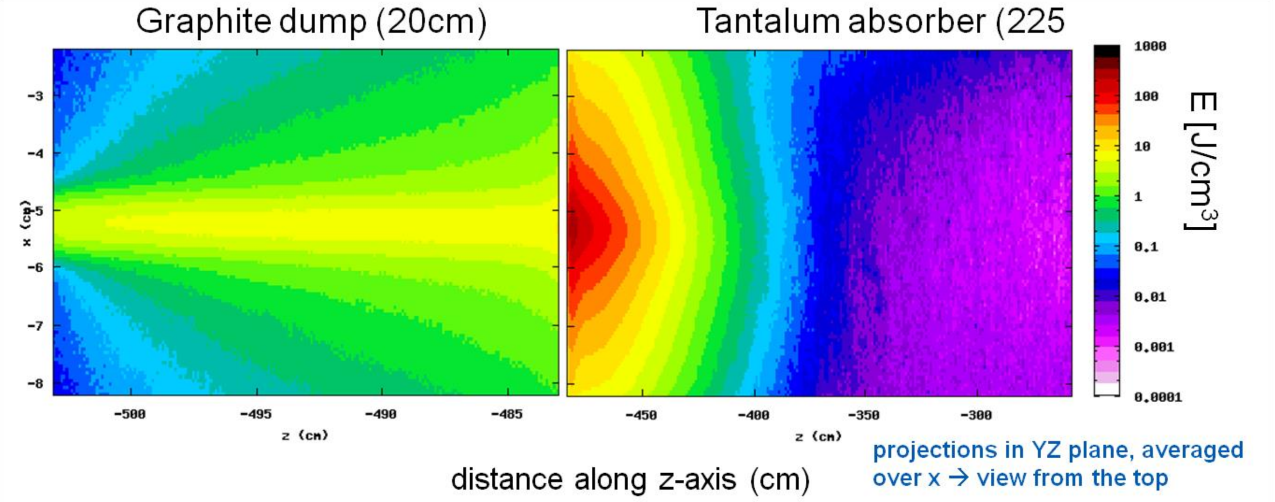
Similarities	SIS100 (γ_t-shift settings)	PS
Particles per cycle	$2*10^{13}$	$3*10^{13}$
Injection energy / GeV	4.0	1.4
Extraction energy / GeV	**28.8**	**20.0**
Stored energy Inj. / kJ	12.7	6.8
Stored energy Extr. / kJ	**91.1**	**96.9**
Max. beam radius Inj. / mm	29	29
Max. beam radius Extr. / mm	12	8
Min. beam radius Inj. / mm	3.6	17.7
Min. beam radius Extr. / mm	1.5	5.6

Differences	SIS100	PS
Magnet type	**SC**	**NC**
Beam pipe vacuum chamber thickness / mm	0.3	1.5
Heavy ion beam energy / kJ	51.5	~7.1

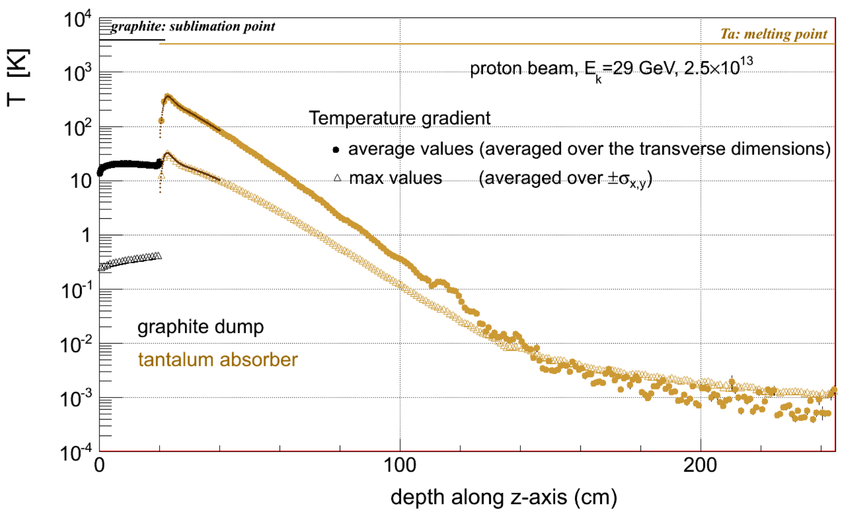
- For p operation, CERN PS and SIS100 similar in energy and spot size (=damage potential); for heavy ions, SIS100 is more dangerous...
- No major accidents in PS due to beam losses
- Spot size in SIS100 even larger with γ_t-jump settings

- LHC (one beam): 362 MJ => 4 000 times more energy!

2.5*10^{13}, 29 GeV Protons
energy deposition in the dump

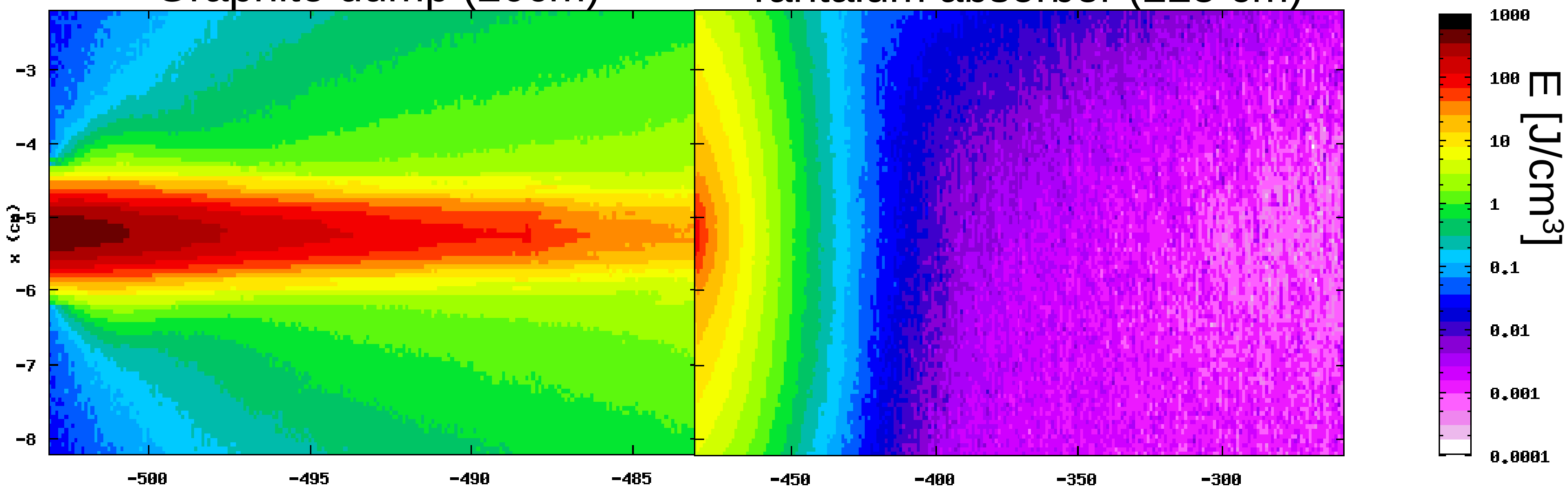


- After an absorber length of 1 m:
  - hardly any primary protons left
  - homogeneous energy distribution by secondaries
- Temperature values well below the sublimation/melting points
- Energy deposition values in upper and lower coils identical within 30 %



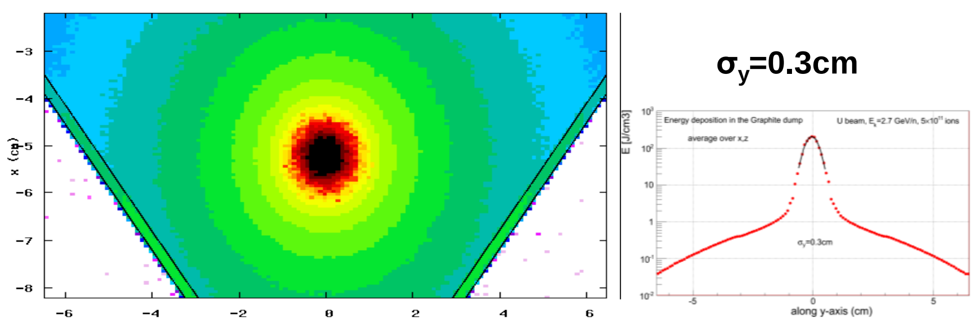
$5*10^{11}$ U^{28+}, 2.7 GeV/u
energy deposition in the dump

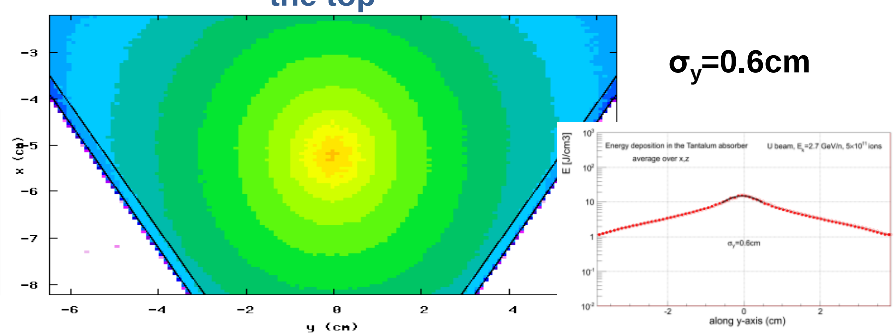
Graphite dump (20cm) Tantalum absorber (225 cm)



distance along z-axis (cm)

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





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