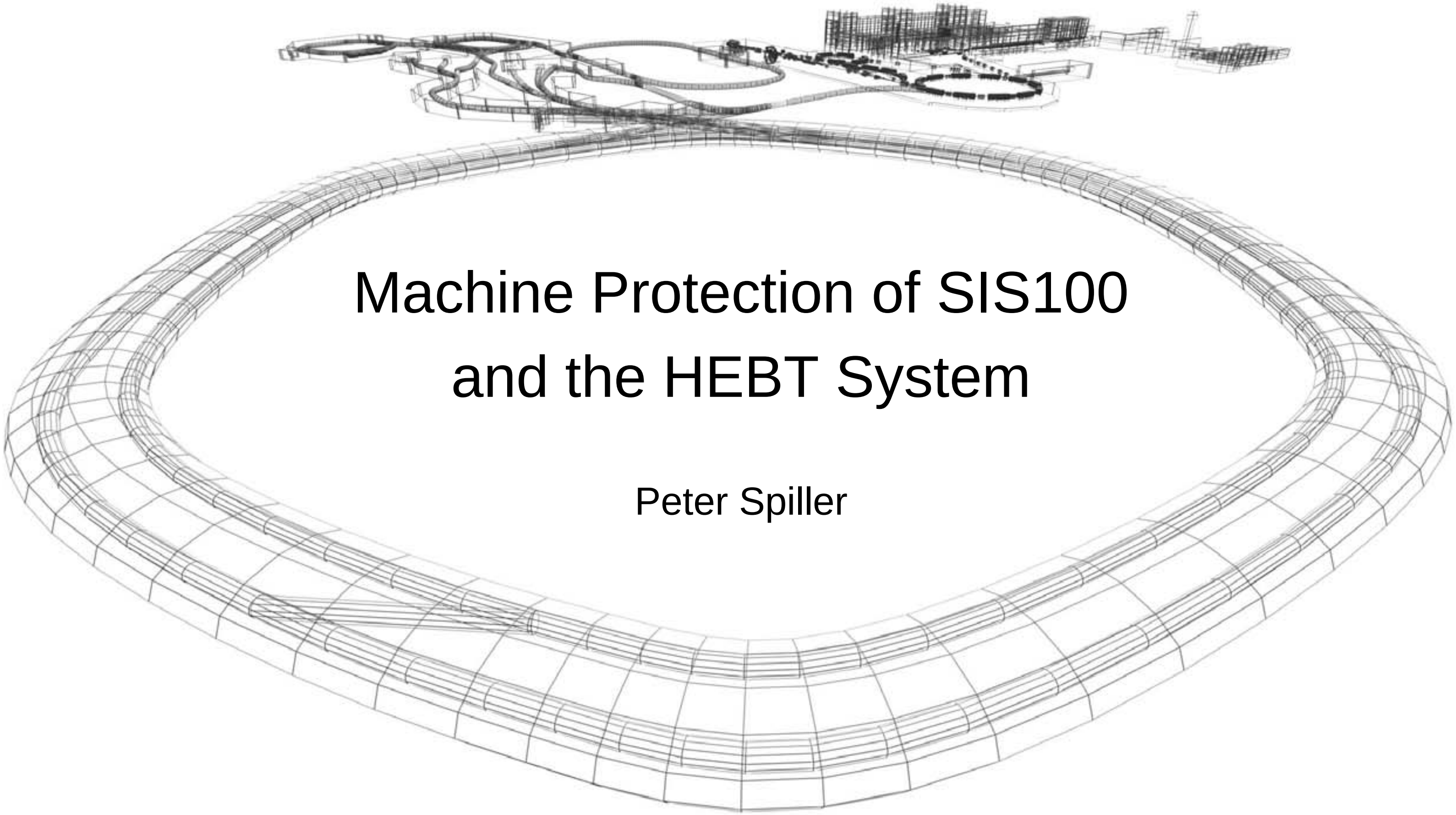
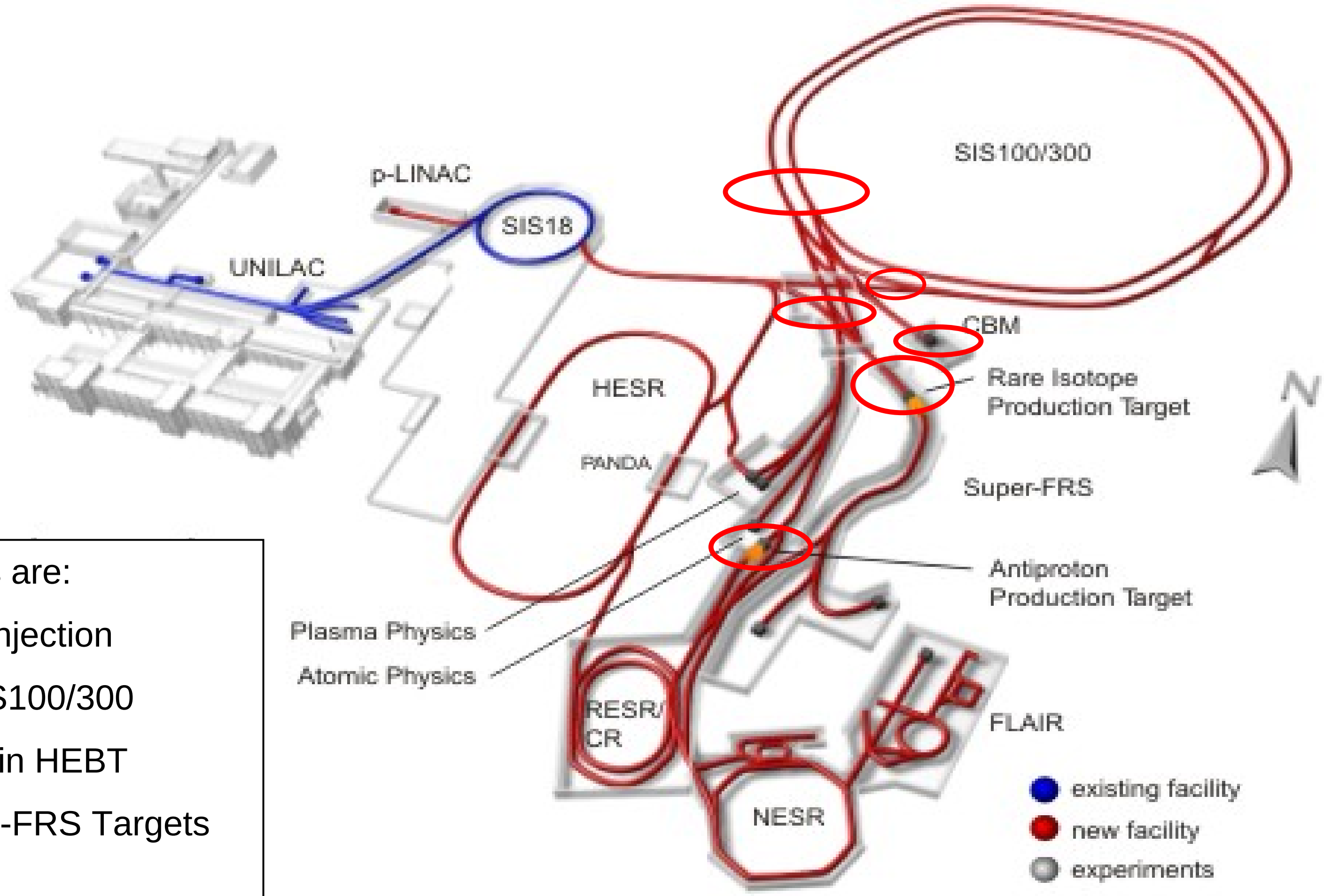
Machine Protection of SIS100 and the HEBT System

Peter Spiller



- Overview
- Principles and General Discussion of Beam Loss and related Issues
- Damage Assessments SIS100 Beam versus LHC Beam
- Beam Loss in SIS100 – Numbers, Positions and Processes
- Collimators
- Beam Dumps
- Accelerator Safety and Interlock Systems

Major Beam Loss Positions in FAIR



The main loss positions are:

- Beam dump SIS100 injection
- Extraction straight SIS100/300
- Machine beam dump in HEBT
- CBM, pbar und Super-FRS Targets

General Remarks

- Acceleration of All ions of the table of elements including rare isotop beams
- Different charge states for one ion species (e.g. U28+ , U73+ and U92+)
- Large variety of different machine cycles
- Fast change of all cycle parameters from cycle to cycle (virtual accelerators)

  (e.g. final energy, number of injections, extraction method or bunch manipulations)
- Large variety of parallel operation modes (mixture of different virtual accelerator in supercycles)
- Difficulties for beam instrumentation:

  Large dynamic range, quantification of measurements (e.g. for BLM), timing, pull-in/pull-out (destructive or non-destructive)
- Potential errors in set value generations and device timing

  (algorithms, parametrizations, hardware limits, consistency, plausibility and preparation times)

General Remarks

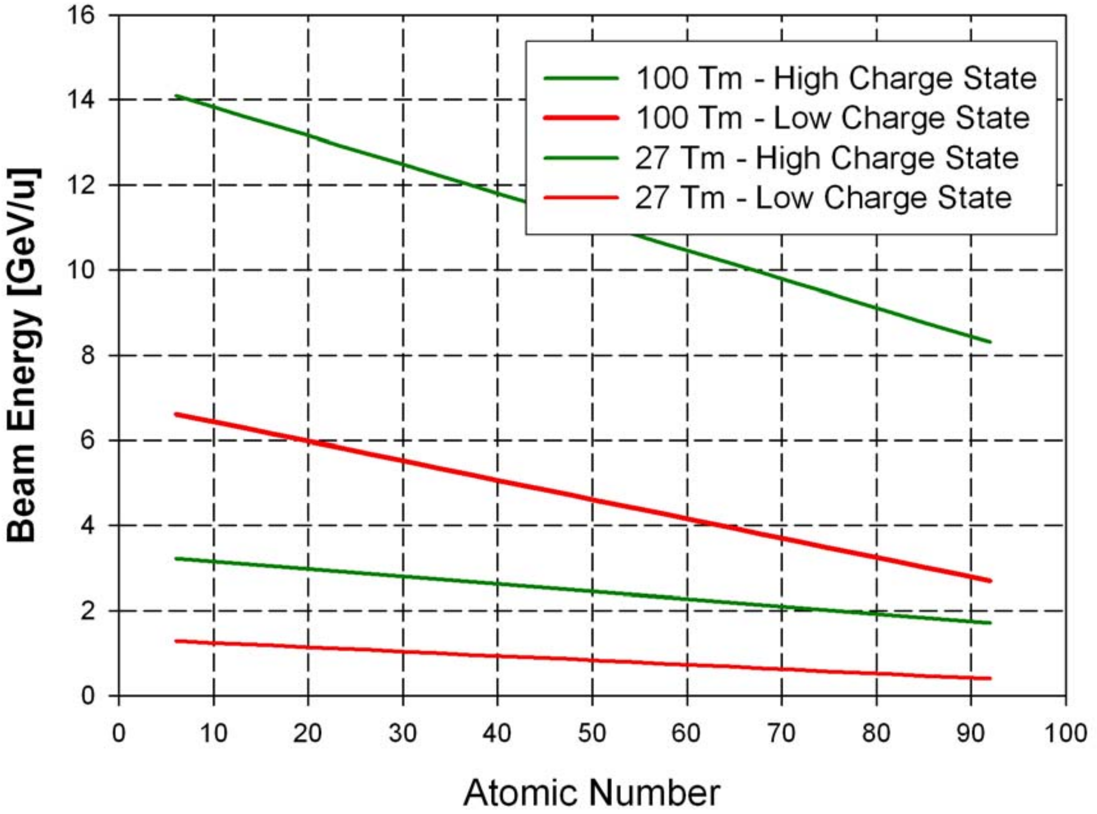
FAIR wide machine synchronisation requires a complex timing system and intelligent supercycle management system

In a failure situation, the different machine cycles must be handeld individually by the accelerator safety systems e.g.

- interruption of a single cycles after beam dumping,
- continuation of a cycle after beam dumping,
- suppression of beam injection with continuation of the cycle
- abort of the supercycle (all virtual machines)
- generation of artificial delays

etc.

Energy Range of SIS100 for Uranium



Extraction energy range of SIS100. The energy range of SIS100 depends on the charge state of the ions. Shown are the upper and lower energies for ions with (e.g. U73+) and without (U28+) transfer channel stripper. Not shown is the energy range of fully ionised ions (e.g. U92+) as can be generated by the stripper system between SIS18 and SIS100.

Beam Loss in Synchrotrons – Principle Discussion

Loss Mechanism	Location	Timescale	Angle	Energy
Tails and Halo due to Resonances, non-linear dynamics etc. (higher order dynamics)	Everywhere but mainly on acceptance limiting devices (in straight sections) (both sides)	Seconds	Envelope angle (<5 mrad) + some μrad	Full Energy Range
Closed orbit distortions, injection losses, tracking errors (1. order dynamics)	Everywhere but mainly on acceptance limiting devices (in straight sections (both sides)	Max. ms (until beam fits into acceptance)	mrad	Injection Energy
RF capture loss	Everywhere but mainly on acceptance limiting devices (in straight sections (both sides)	Max. ms	Envelope angle (<5 mrad) + some μrad	Injection Energy
Losses due to momentum spread jump (during compression)	Mainly in the arcs (both sides)	(~250 μs) max. ¼ Synchrotron osc.	Envelope angle (< 5mrad) + some μrad	Final Energy
Ionization in residual gas	Mainly in the arcs (inner side)	Full cycle and during SE	<25 mrad	Full Energy Range
Ionization and extraction loss in septum wires	behind E-Septum	Spill time	>25 mrad	Final Energy

All, beside two, loss mechanisms drive extremly slow particle growth rates of μm per revolution.

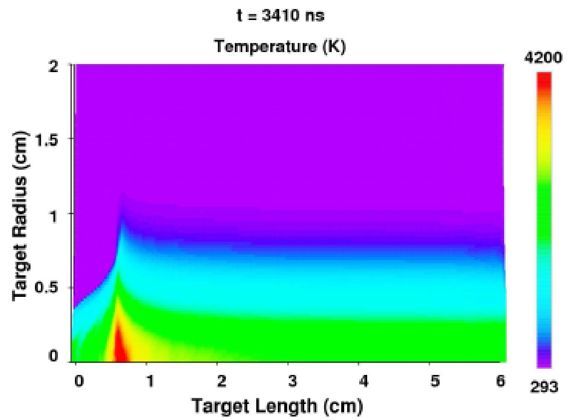
Damage Assesment for the SIS100 and LHC Beam

Table 1: Main Beam Parameters

	LHC	SIS100
Ion Species	Protons	Uranium
Total Number of Particles	$3.2\text{x}10^{14}$	$5\text{x}10^{11}$
Total Number of Bunches	2808	8
Bunch Length (ns)	0.5	190
Bunch Separation (ns)	25	270
Beam Duration (μs)	89	3.4
Particle Energy (TeV)	7	0.6426
Gaussian Profile [σ (mm)]	0.2	3.376
Specific Energy Deposition (kJ/g)	25.0	2.2

Range (final) of LHC beam: 35 m

Range of SIS100 beam: 5.5 cm



Temperature distribution at the end of the pulse.

SIS100 Target Parameters:

Es = 2.2 kJ/g

T_{max} = 4200 K

P_{max} = 12 GPa

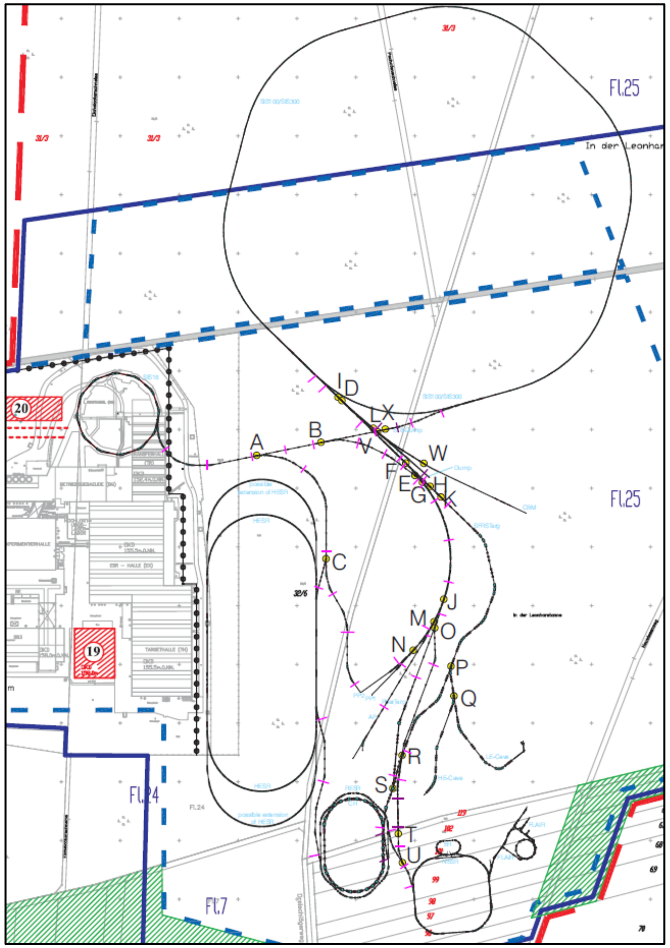
Full perpendicular loss of a SIS100 beam is just at the limit where metal evaporates.

Design Aspects for SIS100 and HEBT

The multiturn injection into SIS18 generates large beam emittances and large beam radii in the order of a few centimeters.

- The design acceptance of SIS100 (Septa) is three times the maximum beam emittance (at minimum energy)
- The design acceptance of the HEBT System is two times the maximum beam emittance (at minimum energy including dispersion)

Beam Position Monitors



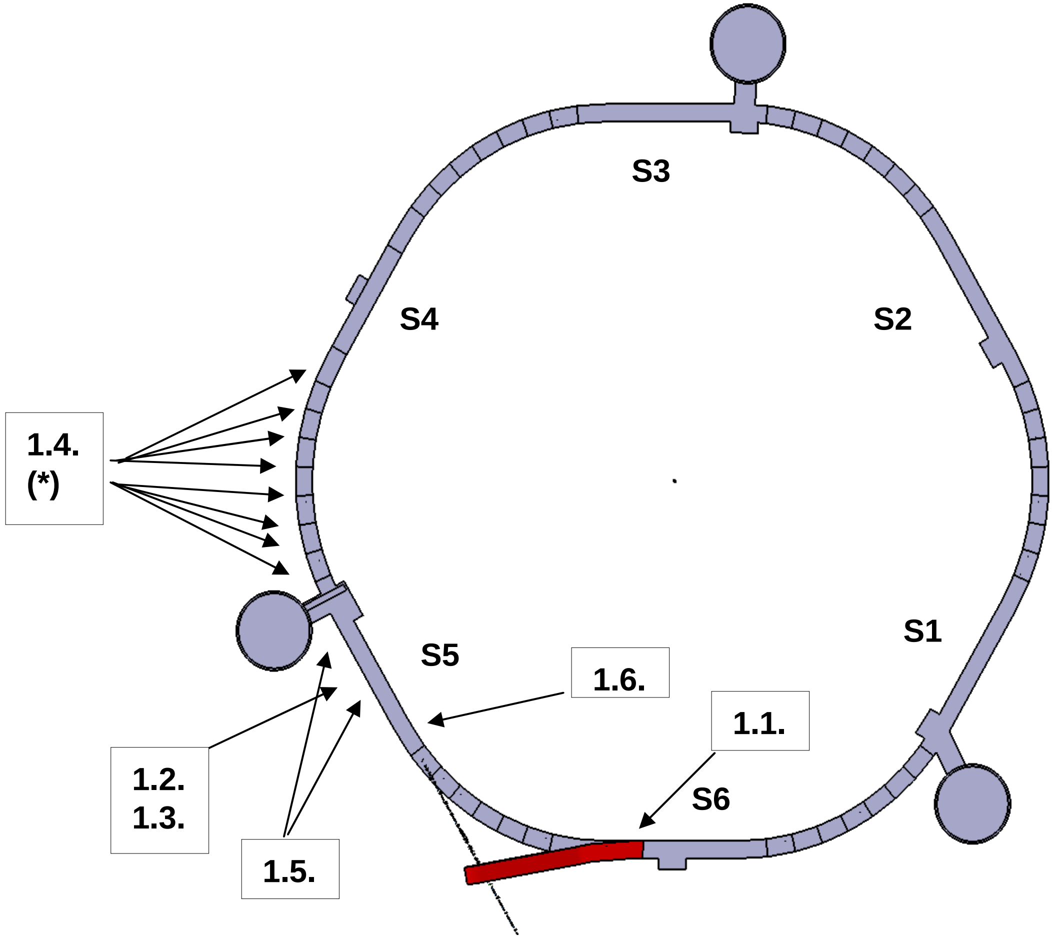
Proposed distribution of BPMs in the HEBT system

- The beam position in SIS100 is measured by 84 BPMs (at an integer tune of about 19)
- The beam position in the HEBT system is measured by 54 BPMs, 65 grids, 39 fluorescene monitors
- Measurement and monitoring of the actual beam position during high current operation and generation of an interlock if the beam exceeds a tolerable deviation.

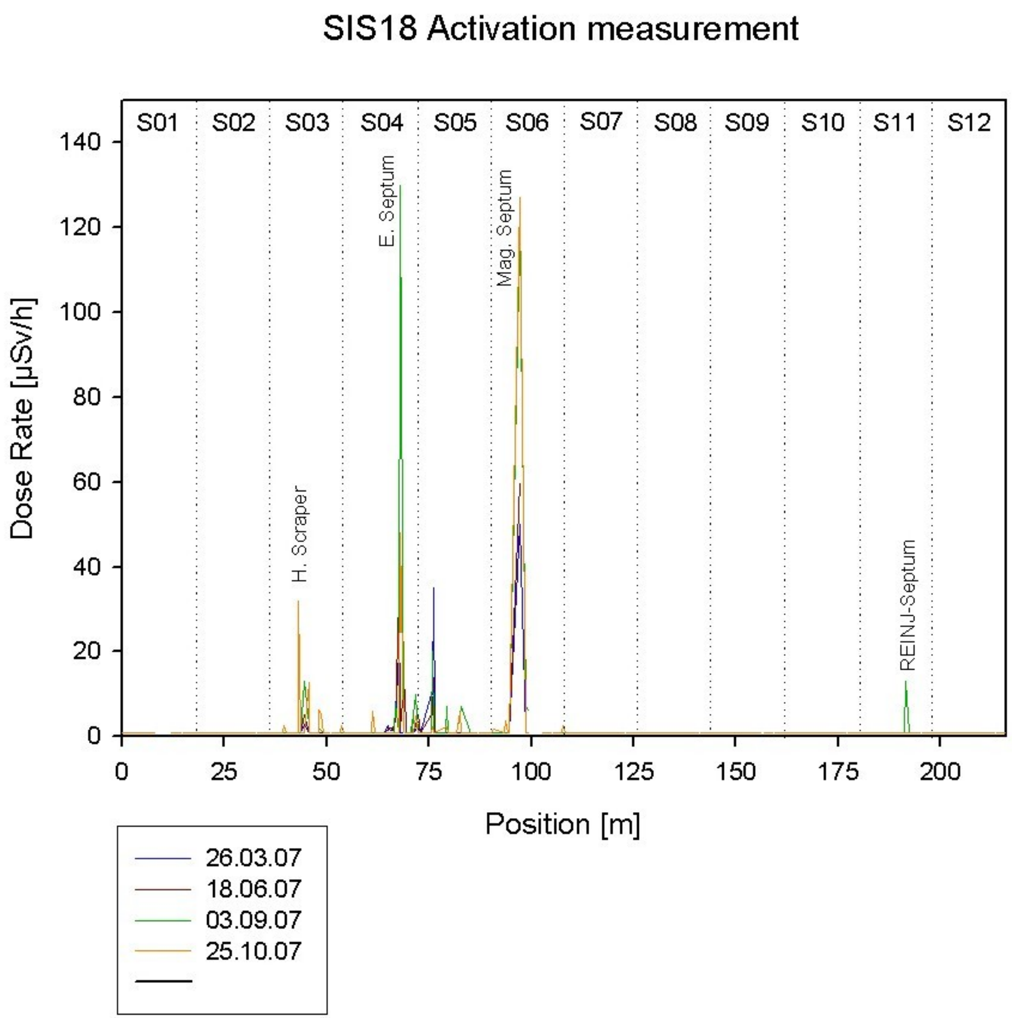
Beam Loss Positions in SIS100

Major „Loss“ Positions in SIS100

- Injection Septum (1.1.)
- Electrostatic extraction septum and one cell behind (1.2.,1.3.)
- Magnetic cepta (1.6.)
- Internal beam dump (1.6.)
- Halo collimators (in extraction straight) (1.5.)
- Ionization loss catchers (in all arcs) (1.4.)



Activation (Beam Loss) Pattern in SIS18



Typical distribution of activation in SIS18 after (the present) operation with highly charged heavy ions.

A similar distribution is expected for SIS100 and SIS300, plus the loss pattern given by ionisation loss.

Reference Cycles

High Intensity Heavy Ion and Proton Cycle

- U^{28+} - High intensity operation in SIS100 up to 2.7 GeV/u with fast and slow extraction
- p – Operation in SIS100 up to 29 GeV with fast extraction

Estimated beam loss numbers are goal values which are

- justified by the machine design
- calculations
- experiences from the existing facilitiy at GSI

The beam loss numbers have been used for the layout of the radiation protection scheme

U^{28+}- cycle in SIS100

(U^{28+} operation up to 100 Tm, $f_{rep=}$0.55 Hz)
Ions after injection: 5.7x10^{11}/ cycle (4x 1.45x10^{11} /SIS18 cycle)

	Loss mechanism	**Max. Relative Losses**	**Max. Absolute Losses /cycle**	**Timescale of loss process**	**Average loss (for exclusive mode, many cycles)**	**Insertion**	**Section (S1...S6)**	**Energy [MeV/u]**
1.1	Injection	2 %	1.2x10^{10}	<4 x 10 μs	6x10^{9}/s (fast extr.)	Injection channel, halo scraper	S6, S5	200
1.2.	Non-linear dynamics	5 %	2.8x10^{10}	1.5 s	1.4x10^{10}/s (fast extr.)	Halo scraper	S5	200
1.3.	Rf capture	2 %	1x10^{10}	(10-30) ms	5.4x10^{9}/s (fast extr.)	Charge scrapers, Halo scraper	Arcs, S5	200
1.4.	Ionization	3 %	1.7x10^{10}	1 s	8x10^{9} /s (fast extr.)	Charge scrapers	Arcs	200-2375
1.5.	Slow extraction (1 s spill assumed)	10 %	4.9x10^{10}	10 s	1.2x10^{10}/s	Quadrupole behind electrostatic septum	S5	<2375
1.5	Fast extraction	2 %	1x10^{10}	4 μs	5x10^{9}/s	Magnetic extr. septum	S5	<2375

p - cycle in SIS100

(p operation up to 100 Tm, f_{rep} =0.5 Hz)
Ions after injection: 2.5×10^{13}

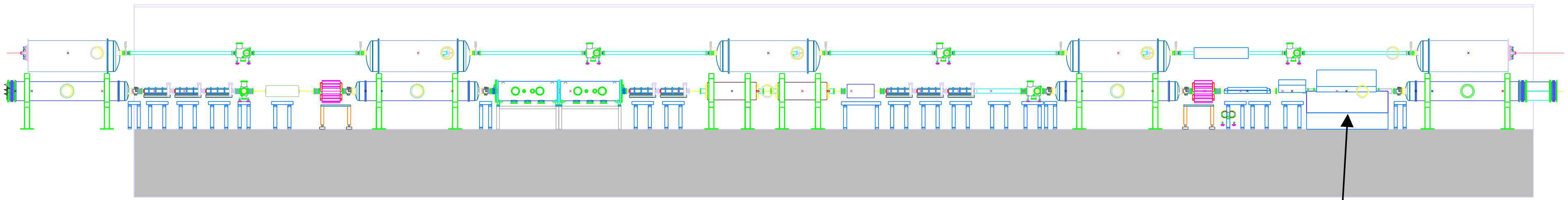
	Loss mechanism	Max. Relative Losses	Max. Absolute Losses	Timescale of loss process	Average Losses (for exclusive mode, many cycles)	Insertion	Section (S1...S6)	Energy [MeV/u]
1.1.	Injection	2 %	5×10^{11}	<1 ms	2.5×10^{11} /s	Injection channel, Halo scraper	S6, S5	2000
1.2.	Non-linear dynamics	3 %	7.4×10^{11}	3 s	3.7×10^{11} /s	Halo scraper	S5	2000
1.3.	Rf capture	3 %	7.1×10^{11}	(10-30) ms	3.6×10^{11} /s	Halo scraper	S5	2000
1.6.	Fast extraction	2 %	4.6×10^{11}	4 µs	2.3×10^{11}	Extraction section, magnetic septa	S5	29 000

Beam Loss at Extraction of SIS100

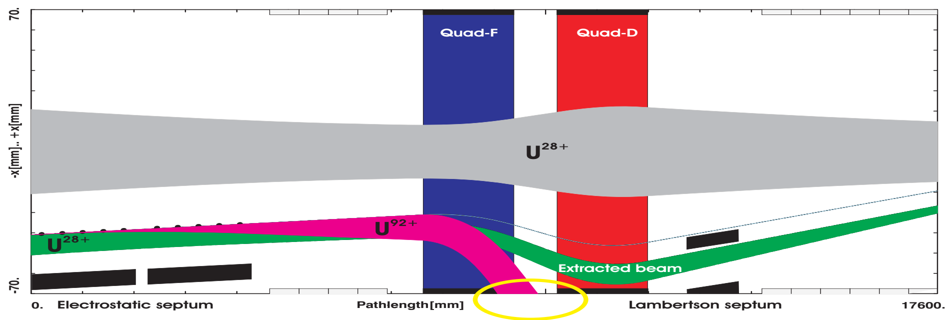
electrostatic septa
source of beam loss

warm quadrupole doublet
main loss position

magnetic extraction septa



Internal beam dump



Loss of stripped U^{28+} ions at slow extraction

Talk by N. Pyka

Beam Loss Issues at Extraction

(Dump) Quadrupole Doublet

- High beam power deposited in the quadrupols following the septa (2-5 kJ)
- One s.c. quadrupole cryomodule is replaced by two warm, radiation hard quadrupole magnets

Electrostatic Septum

- High specific energy deposition of heavy ions (Z^2) heats the septum wires.
- Large temperature increase during slow extraction
- Restrictions in the minimum spill duration at maximum intensities
- Temperature measurement of the wires for spill abort considered

Talk by N. Pyka

Collimator Systems

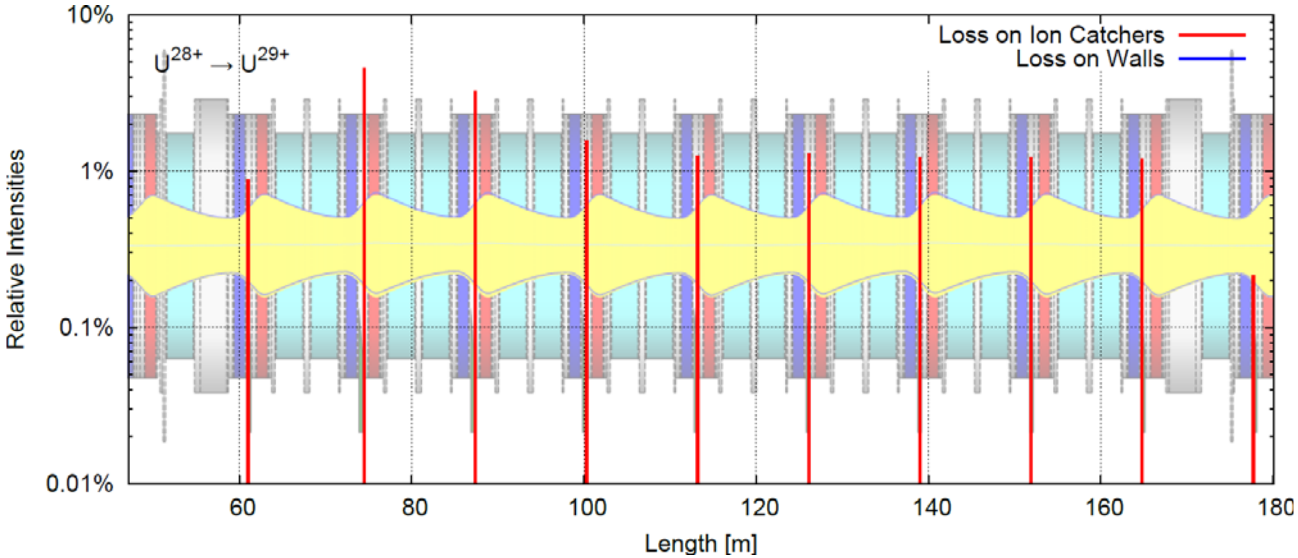
SIS100

- 66 Cryo catchers (under design) for ionization beam loss
- Halo collimator (under study-COLMAT) for beam loss by nonlinear dynamics
- Off-momentum collimator for off momentum particles during ramping and compression (e.g. Rf system failures, insufficient bucket area, extrem momenta at compression) (covered by the cryo catcher system ?)

HEBT

- Halo collimators for CBM/HADES to cut off lateral tails (studied)

Ionization Beam Loss in SIS100

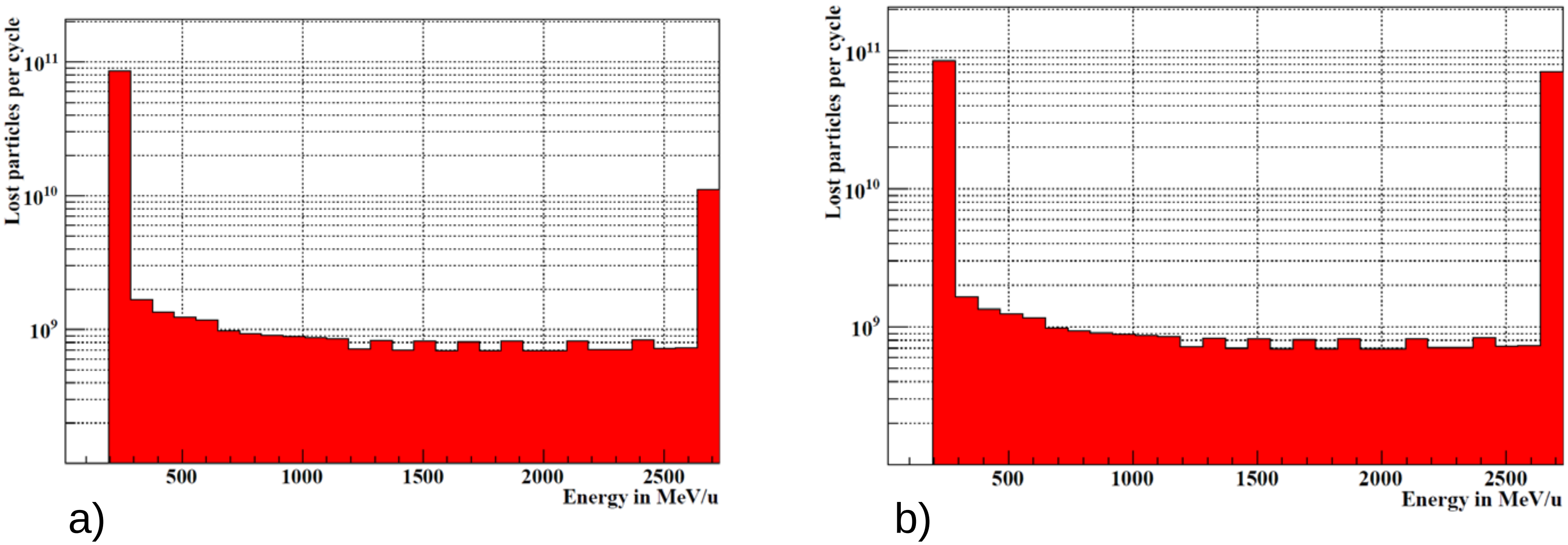


Peaked loss distribution for ionised U^{28+}-ions (operation up to 100 Tm) along one arc of SIS100 with the horizontal envelopes and magnet apertures.

In each arc, ionisation loss occurs after the first and then after each second dipole magnet. From the loss distribution it follows that roughly 50 % of the losses in the charge scrapers occur in the first and second scraper, the rest is distributed in the six charge scrapers (downstream) in between the quadrupoles. For U**28+** the efficiency is about 95 %, with decreasing charge state the efficiency goes down (losses on the quadrupoles) but the cross section and thereby the number of lost ions, too.

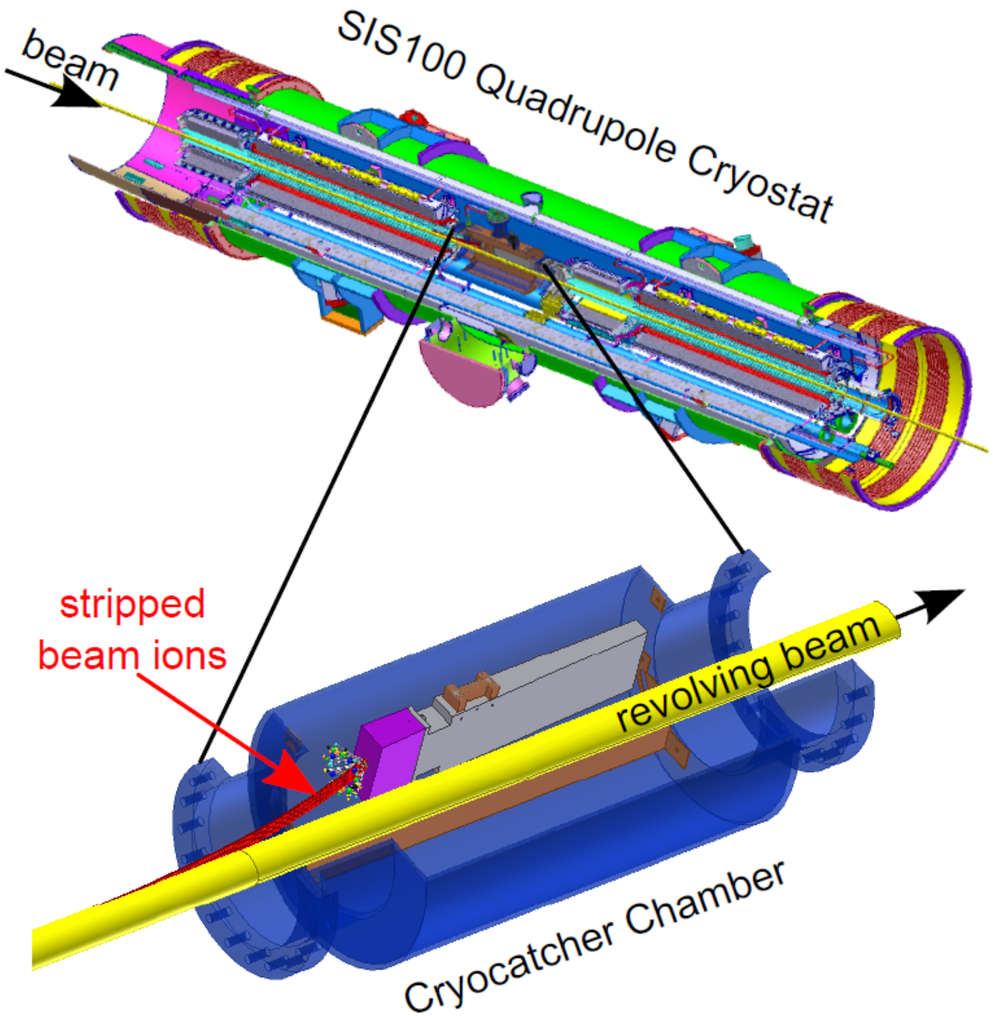
The machine design aims for a limited residual gas pressure dynamics and associated ionization beam loss.

Ionization Beam Loss in SIS100



Beam loss by ionisation (example for high initial systematic loss) during one SIS100 cycle with a) fast- and b) slow extraction (to 2.7 GeV/u) as a function of the actual energy. As indicated, most of the ionisation beam loss appears during the long injection plateau at injection energy and during extraction at extraction energy.

Cryo-Catcher for Ionization Beam Loss



60 cryo-collimators foreseen in the SIS100 arcs for the suppression and control of desorption gases

Collaboration between GSI and CERN in the frame of EU FP7 COLMAT

GSI: Work package leader

The beam current on the catchers will be measured and used to generate an interlock and beam abort signal (in case of a vacuum instability)

Talk by L. Bozyk

Halo Collimator

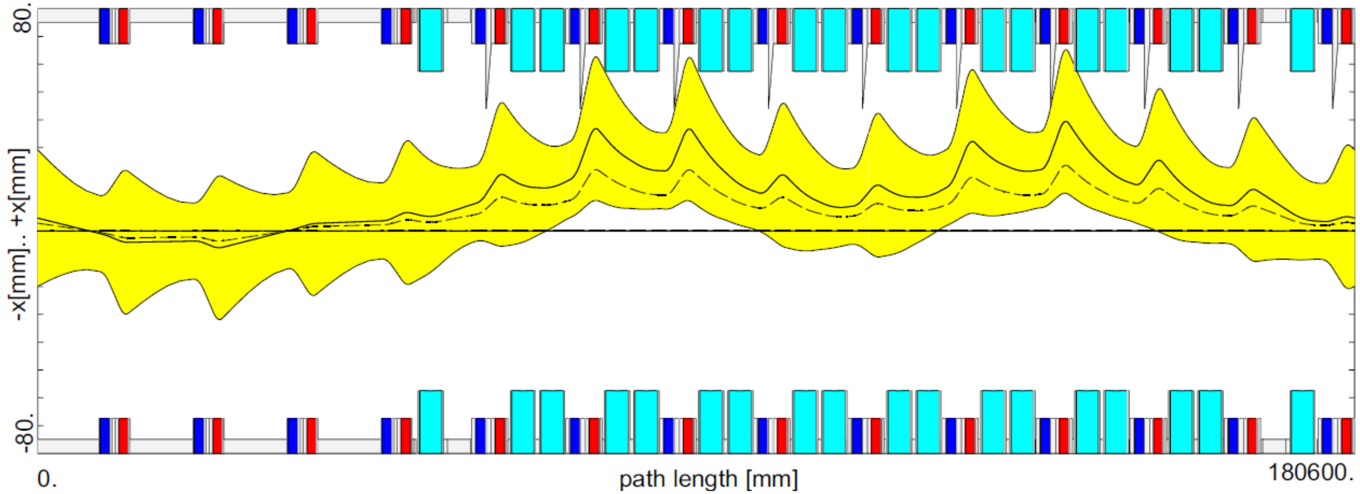
- Halo collimator shall dump particles after reaching a certain amplitude due to e.g. nonlinear dynamics (resonances etc.)
- The halo collimator will be studied and developed in the frame of EU FP7-COLMAT
- Difficult and unique problem due to the charge exchange of intermediate charged beam ions and the large variety of beams
- Energy loss based, multiple stage collimation and dumping does not work here
- Problem: The slow lateral velocity (amplitude gain) in comparison with the fast longitudinal motion (revolution) leads always to a surface scattering problem rather than a perpendicular impact

Options:

- Full stripping of ions (up to the equilibrium charge state) in a „thick“ foil in front of the warm extraction quadrupoles and dumping in the same way as the extraction losses
- Partially stripping by a precise thickness thin foil (may be not possible) and dumping behind dispersive elements

Off-Momentum Collimation (Detection)

- Cryo-catchers in the arc may be used for off-momentum collimation as well
- Rf failures or insufficient bucket area during ramping leads to radial beam motion
- Scraping beam loss due to radial motion is more dangerous than full perpendicular impact
- The beam current on the cryo-catcher will be used to generate an interlock system for beam abort

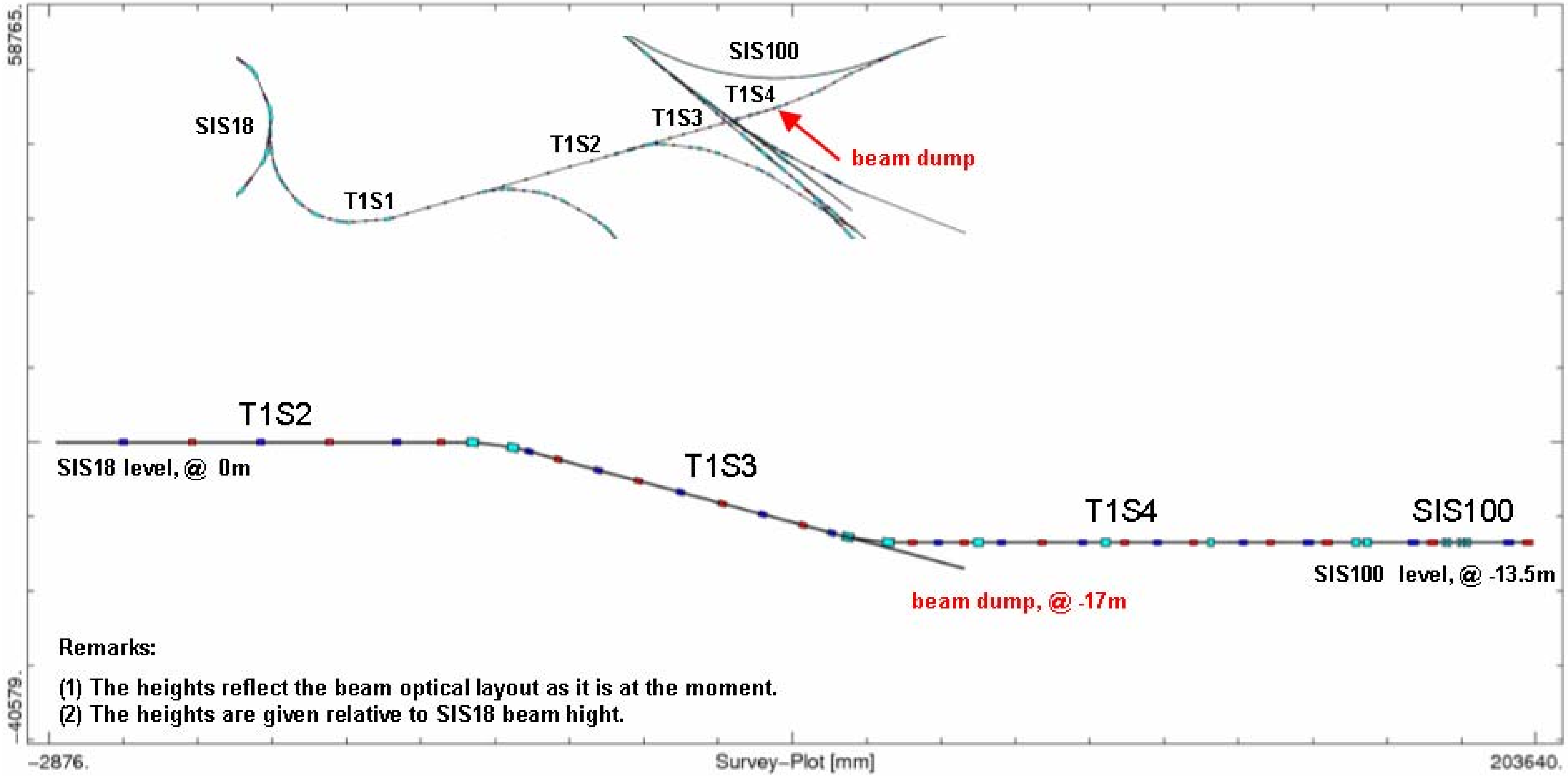


Beam Dumps

Beam dumps for set value generation are foreseen in front of SIS100 and on an intermediate underground level in the extraction line of SIS100/300. They used st full intensity but with reduced repetition rate. An (internal) emergency beam dump is foreseen integrated into the SIS100/300 lattice for single events. The position of the internal beam dump is opposite to the magnetic extraction septa.

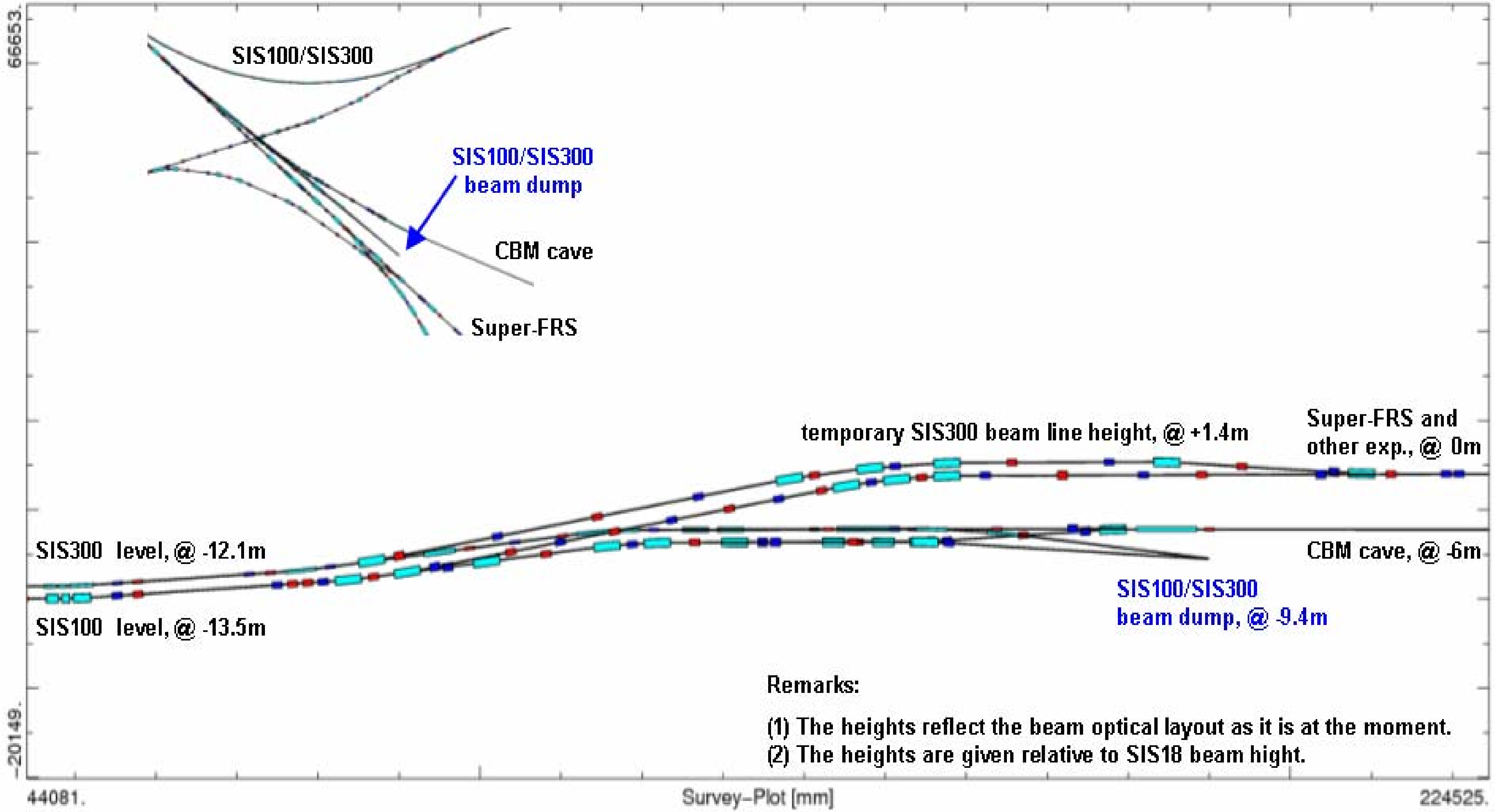
- SIS18-SIS100 Charge separator dumps
- SIS100 Injection dump
- SIS100 Internal emergency dump
- SIS300 Internal emergency dump
- SIS100/300 Machine setting dump
- Halo Dump in CBM/HADES beam lines

SIS100 Injection Dump



Beam dump in front of SIS100 on underground level -17 m.

SIS100/300 Machine Setting Dump



Dump for SIS100/300 machine setting and optimization on underground level -9.4 m.

Accelerator Safety and Control Systems

Beam Monitoring

Beam Position Monitors
Beam position monitoring via BPMs (in SIS100/300 and also in HEBT)
(e.g. for RF failures during ramping) – Tolerance band for beam position

to avoid beam loss and low transmission

Beam Collimators Current Measurement
Collimator/catcher current measurement (ionization beam loss, vacuum Instability)

Particles hitting and being lost on beam collimators in SIS-18/100/300 shall be detected. Appropriate data acquisition systems provide measured data to operation.

Beam Transmission

Transmission (Beam Loss) Monitoring

- Beam loss control by beam loss monitors (at acceptance limiting devices)

The transmission of beam intensities or particle counts within machines and across the GSI/FAIR Beam Production Chains must be monitored and documented. A transmission monitoring system will be implemented within the control system. Transmission data will be processed and appropriate rules and transmission thresholds could be used to generate warnings and potentially block Beam Production Chain execution if configured to do so. Nevertheless, this system is not defined and characterized as a safety system.

Low Transmission (Beam Loss) Protection System

Beam intensity signals by several beam detection systems will be monitored at several stations and transmission levels are computed on hardware layer. Upon intolerable transmission levels a signal will be generated as an input to other systems (e.g. Master Timing generator to stop beam execution). Example: "Strahlstromüberwachung" in UNILAC.

Set-Values

Reference Value (Tolerance Band) Monitoring

This is not a system but a function implemented within the SCU front-end equipment controllers. This function constantly monitors the read values of equipment and compares them with the appropriate reference value. Upon a violation outside of a tolerance band a signal will be raised. The signal can be used for different safety systems (dumping system, beam disable, send a warning, etc.).

Setting Management of Safety Critical Equipment

- Plausibiliy check of generated device ramp data (e.g. in agreement with device specifications but ion optical or beam dynamics nonsense)

- Safety critical settings (e.g. protection system thresholds, etc.) must be protected from intentional and unintentional change operators and non-system specialists. Instead only the responsible equipment specialist must be able to apply changes to safety critical systems. A sophisticated access rights management and documentation of changes applied will be implemented in the control system.

Quench Detection and Protection

Quench Detection

This system detects a quench in a superconducting magnet and generates a signal that shall be handled by other systems (e.g. Quench Protection).

Quench Protection

Triggered by a signal from the Quench Detection system, superconducting circuits will be protected by extracting the stored energy in dump resistors in order to avoid uncontrolled release of energy which leads to damage of equipment. The function will be implemented in the appropriate power converter systems.

Beam Dumping System (SIS100/300)

If an unacceptable failure or situation in SIS-100/300 occurs, the beam must be dumped as fast as possible to avoid potential damage. Triggered by signals that will be derived from appropriate detection systems (e.g. quench detection, tolerance violation, equipment failure, etc.) the kicker system has to be fired.

Protection of Beam Inserts

Lockig of drives and manipulators at high current operation (e.g. profile grids)

In high-intensity operation, certain equipment (e.g. profile grids, etc.) must not be inserted into the beam path in order to avoid damage. This function guarantees that (a) equipment cannot be moved into the beamline in high intensity operation and (b) that if equipment is in the beam path, pre-defined intensity cannot be exceeded by appropriate measures (e.g. at UNILAC shortening of chopper window).

Beam Interlock System

Device and equipment errors

The Beam Interlock System is a technical system within the accelerator control system. It collects and aggregates all relevant equipment states (incl. equipment master interlock states) and processes them. Defined by a dynamically and configurable interlock matrix, the beam interlock system generates, enable or disable signals for the execution of Virtual Accelerators or Beam Production Chains.

Post Mortem Diagnostics

This is not a system but a function. All relevant equipment with data acquisition capability has to be designed in a way for continuous data acquisition in a dedicated post mortem buffer and freeze these data upon a Post Mortem event on the General Machine Timing system. The function is usually implemented in the appropriate equipment controllers. Data will be collected by the control system and made available for in-depth analysis of the triggering condition.

Pressure Interlocks

- Residual gas pressure thresholds (especially in certain devices (e.g. septa)
- Cryostat insulation residual gas pressure interlock

Coupling to other Control and Safety Systems

- Coupling of radiation protection equipment („BIOREM“ alert) to accelerator control system
- Coupling of status informations of the cryogenic plant to the accelerator control system

- Several feed back systems (radial position, closed orbit, fast trans. feed back etc.)

For machine setting:

- Safe operation mode with reduced and controled intensity
- Default measurement cycles for quality assurance

- Detailed requirements must be worked out
- Device property lists must be created
- Wish list must be checked with respect to the need at commissing and the capacity of the available manpower