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To promote excellency in patient care and innovative proton treatment

**Therapy Control and Patient Safety**

**Martin Grossmann**

Centre for Proton Therapy, Paul Scherrer Institute, Villigen, Switzerland

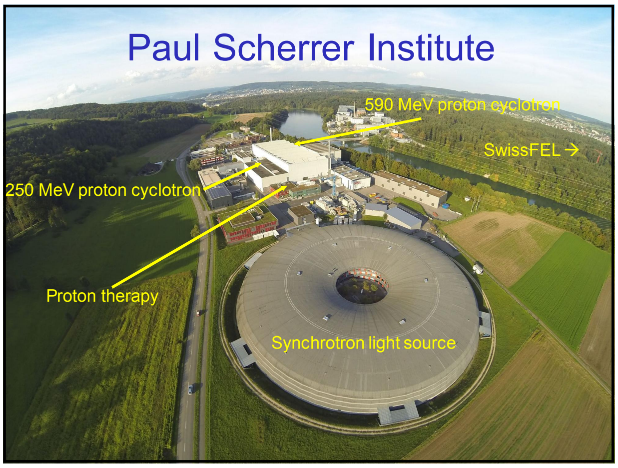


# Overview

- Protontherapy @ PSI
- Controls and Safety
  - Concept
  - Implementation
- Patient Safety System

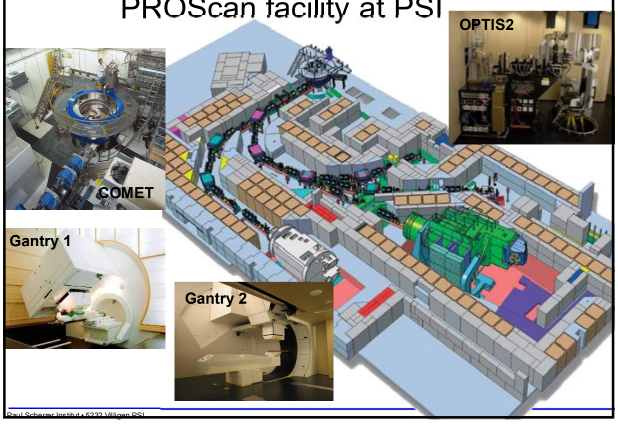


# Paul Scherrer Institute



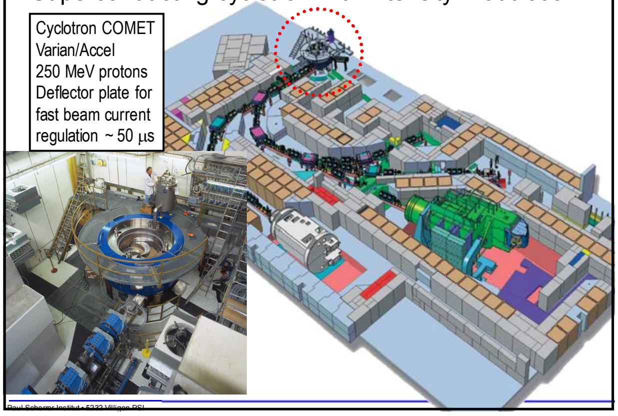



# PROScan facility at PSI



## Superconducting cyclotron with intensity modulation $I$

Cyclotron COMET
Varian/Accel
250 MeV protons
Deflector plate for fast beam current regulation ~ 50 μs

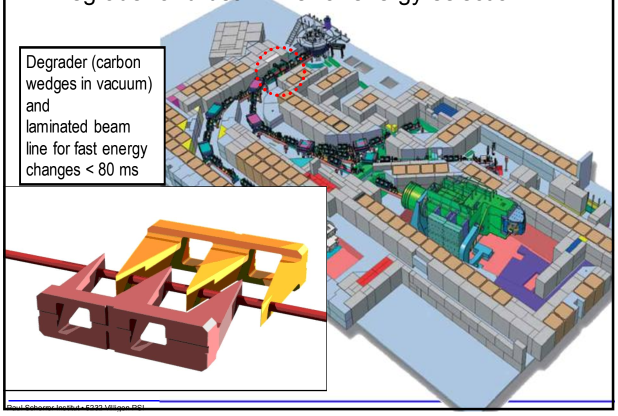






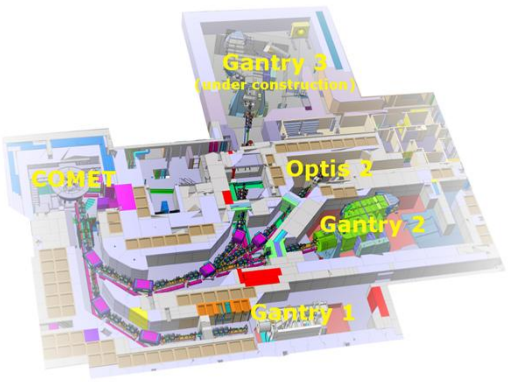
## Degrader and beam line for energy selection $E$

Degrader (carbon wedges in vacuum) and laminated beam line for fast energy changes < 80 ms







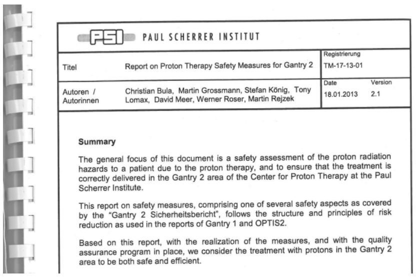







## Controls & safety

## PSI's concept for patient safety



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| | | | |
|---|---|---|---|
| Titel | Report on Proton Therapy Safety Measures for Gantry 2 | Registrierung TM-17-13-01 | |
| Autoren / Autorinnen | Christian Bula, Martin Grossmann, Stefan König, Tony Lomax, David Meer, Werner Roser, Martin Rejzek | Date 18.01.2013 | Version 2.1 |

**Summary**

The general focus of this document is a safety assessment of the proton radiation hazards to a patient due to the proton therapy, and to ensure that the treatment is correctly delivered in the Gantry 2 area of the Center for Proton Therapy at the Paul Scherrer Institute.

This report on safety measures, comprising one of several safety aspects as covered by the "Gantry 2 Sicherheitsbericht", follows the structure and principles of risk reduction as used in the reports of Gantry 1 and OPTIS2.

Based on this report, with the realization of the measures, and with the quality assurance program in place, we consider the treatment with protons in the Gantry 2 area to be both safe and efficient.

- Definition of safety goals
- Description of technical/operational measures



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## #1: NO RADIATION ACCIDENT

- No serious overdose should be delivered to the patient
- Serious: >5% of total prescribed dose (60 Gy), i.e. 3 Gy

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## #2: NO ERROR IN THE DELIVERED DOSE

- No incorrect dose should be delivered
- Prevent errors (hot/cold spots) in dose distribution of >2% of planned field dose

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## #3: NO ERROR IN DOSE POSITION

- The dose must be applied at the correct position
- Prevent errors in a single spot delivery > ± 1mm in lateral direction and depth

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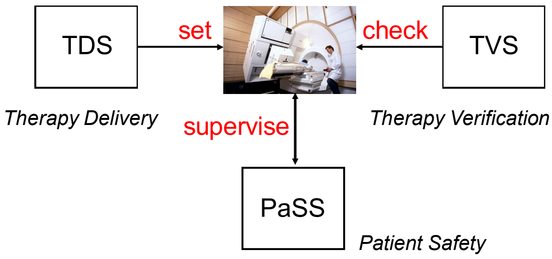
# #4: DELIVERED DOSE AND POSITION MUST BE KNOWN AT ALL TIMES

- If treatment is interrupted, the dose and position already applied must be known in order to allow correct continuation after interruption





# Controls & Safety Concept

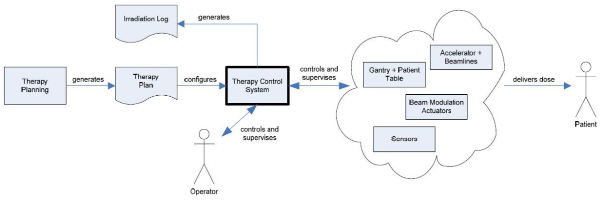







# The Therapy Control System's Task

- The TCS
  - Controls the dose delivery
  - Is configured with the Therapy Plan generated by the Therapy Planning System
  - Controls and supervises the facility equipment to deliver the dose to the patient according to the plan
  - Generates a log of what it finally did with the patient








# The Need for Speed...

- Minimize dead time between spots
  - PSI spot scanning: increase of dead-time by only 1 ms increases the total irradiation time by about 5 %...
- In safety relevant control system design, the speed requirement is normally put behind safety...

BUT

... A perfectly safe but slow scanning control system will be as useless as an unsafe fast one!

# The Need for Speed...

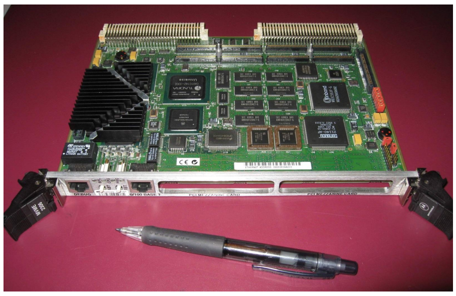
- Our choices for the control systems:
  - The irradiation is controlled by embedded VME systems with Motorola PPC running the VxWorks RTOS
  - Subsystem communication with digital IOs, fast serial links (over optical fibres), reflective memories. Ethernet only when time does not matter
  - Time critical functions directly implemented in custom FPGA or DSP based subsystems
  - Linux PCs as operator workstations





# The Need for Speed...

embedded VME Single Board Computer

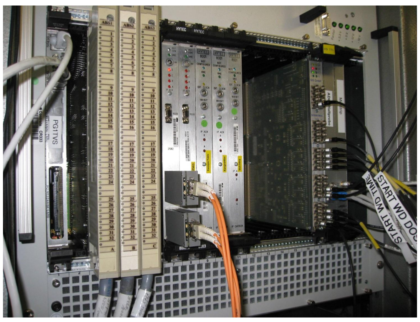






# The Need for Speed...

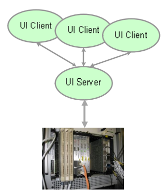
VME crate (TVS)
with connections to sensors, actuators, ...



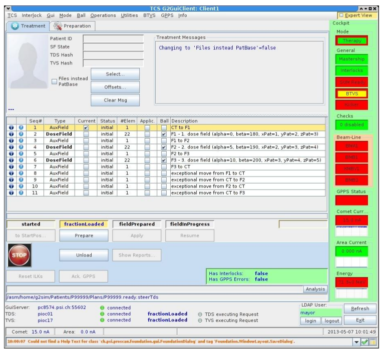




# Graphical User Interface




- client – server application
- implemented in Java





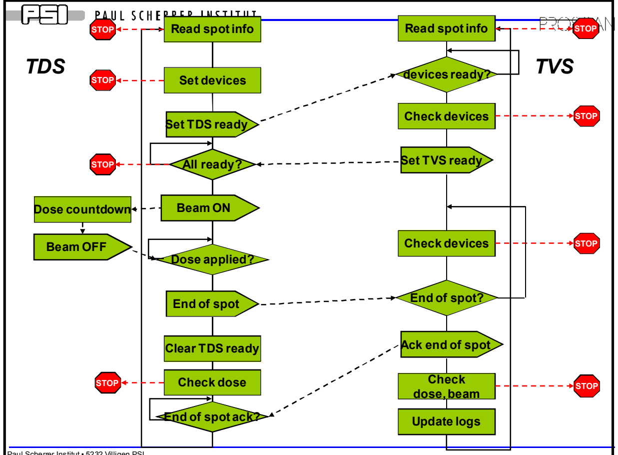


# Spot Scanning Control Loop

- TDS & TVS walk through therapy plan:
  - TDS sets devices, TVS checks devices
  - when all devices ready: beam on!
  - spot termination by dose counter firmware
  - check correct application after each spot
  - write logs
  - proceed to next spot












# Spot Scanning: Operator Tools

**Spot 2035 / P08464_CT0_T0_F0_D45.SCO / WED JAN 07 14:21:18 2009**

| Check ID | time [s] | IST | SOLL | TOL | difference | | result |
|---|---|---|---|---|---|---|---|
| SYNC | 0.000 | 2: subset ready | | | | | |
| Sweeper | 0.000 | -2339 | -2312 | 300 | -27 | -9 % | OK |
| ADG3 | 0.000 | 6971 | 6967 | 348 | 4 | 1 % | OK |
| RangeShifter | 0.000 | 24 | 24 | 0 | 0 | | OK |
| X | 0.002 | -41497 | -41500 | 1000 | 3 | 0 % | OK |
| Y | 0.002 | -112425 | -112499 | 1000 | 74 | 7 % | OK |
| Z | 0.002 | 692562 | 692799 | 1000 | -237 | -24 % | OK |
| A | 0.002 | -89984 | -90000 | 500 | 16 | 3 % | OK |
| B | 0.002 | 93 | 0 | 500 | 93 | 19 % | OK |
| HW Spotnr | 0.002 | 2035 | 2035 | 0 | 0 | | OK |
| SYNC | 0.004 | 3: TVS ready | | | | | |
| SYNC | 0.004 | 4: beam is on | | | | | |
| SYNC | 0.004 | 9: start spot loop (passed 9 times) | | | | | |
| HW Spotnr | 0.004 | 2035 | 2035 | 0 | 0 | | OK |
| Sweeper | 0.004 | -2336 | -2312 | 300 | -24 | -8 % | OK |
| ADG3 | 0.004 | 6971 | 6967 | 348 | 4 | 1 % | OK |
| RangeShifter | 0.004 | 24 | 24 | 0 | 0 | | OK |
| X | 0.004 | -41497 | -41500 | 1000 | 3 | 0 % | OK |
| Y | 0.004 | -112425 | -112499 | 1000 | 74 | 7 % | OK |
| Z | 0.004 | 692562 | 692799 | 1000 | -237 | -24 % | OK |
| A | 0.004 | -89984 | -90000 | 500 | 16 | 3 % | OK |
| B | 0.004 | 93 | 0 | 500 | 93 | 19 % | OK |
| SYNC | 0.004 | 5: beam is off | | | | | |
| SYNC | 0.004 | 6: end of spot from TDS | | | | | |
| Monitor 2 | 0.004 | 366 | 395 | 258 | -29 | -11 % | OK |
| Ratio M1/M2 | 0.004 | 372 | 393 | 60 | -21 | -35 % | OK |
| Monitor 3 | 0.004 | 450 | 490 | 539 | -40 | -7 % | OK |
| U Center | 0.006 | -12246 | -12716 | 1500 | 470 | 31 % | OK |
| U FWHM | 0.006 | 13024 | 13099 | 4000 | -75 | -2 % | OK |
| U Dose | 0.006 | 2009 | 2296 | 3183 | -287 | -9 % | OK |
| T Center | 0.006 | -3381 | -3201 | 1200 | -180 | -15 % | OK |
| T FWHM | 0.006 | 7839 | 8800 | 4000 | -961 | -24 % | OK |
| T Dose | 0.006 | 1816 | 2177 | 3174 | -361 | -11 % | OK |
| WD Dose | 0.006 | 34544 | 34550 | 3455 | -6 | -0 % | OK |
| WD time | 0.006 | 996 | 999 | 299 | -3 | -1 % | OK |
| SYNC | 0.006 | 7: start DoseDataLog | | | | | |
| SYNC | 0.006 | 8: end DoseDataLog | | | | | |

peering into the control loop ...

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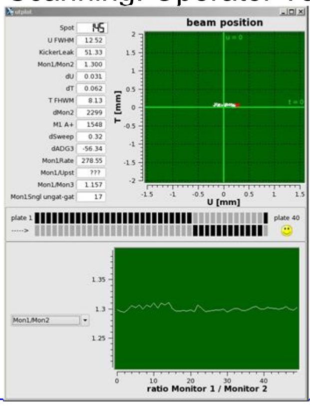
# Spot Scanning: Operator Tools

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# Safe Setting – Redundant Checking – Independent Supervision

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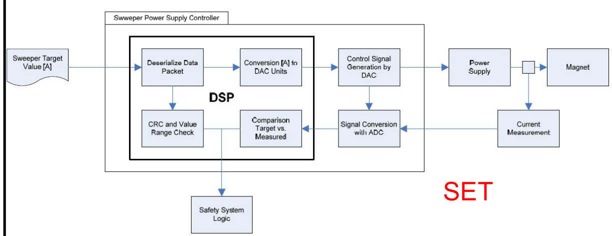
# Example: Sweeper Magnet Control




SET

- The sweeper power supply controller receives target values over an optical link from the TCS, checks data integrity, and controls the power supply for the magnet coils
- At the same time, the current through the coils is measured and compared in realtime with the target value on a DSP inside the controller, without TCS involvment. Any deviation beyond tolerance triggers a safety interlock

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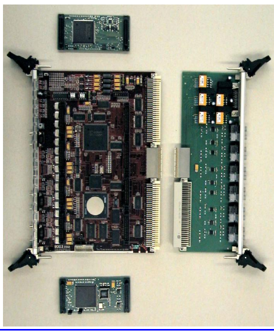
# Magnet Power Supply Control Hardware



- VME board with 4 Industry-Pack Slots and onboard DSP
- Industry-Packs with FPGA implementing communication interface to power supply
- VME transition module with optical transceivers for data transmission to power supply
- Digitally controlled power-supplies (developped by PSI)

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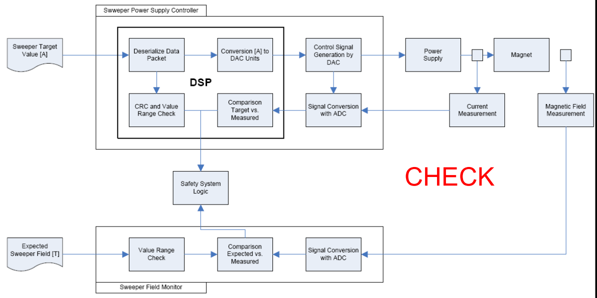
## Magnet Power Supply Control Hardware





## Example: Sweeper Magnet Measurement




- Monitoring channel is measuring the magnetic field with a hall-sensor and triggers an interlock if a deviation beyond tolerance is detected





## Hall Probe used at PSI



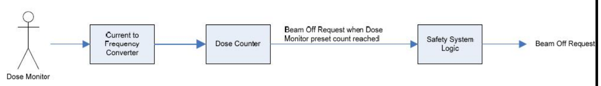


## Actuation and Monitoring: Implementation

| Control Function | TDS Actuation Channel | TVS Monitoring Channel |
|---|---|---|
| Beam Position | Sweeper Magnet controlled by DSP based subsystem. Continuous monitoring of power supply setting and state | Hall sensor measuring sweeper magnetic field monitored by TVS. Ionisation strip chamber measuring beam position at exit of nozzle. Monitored by TVS |
| Beam Tune | Degrader and beamline control through Machine Control System (MCS). MCS implements full actuator supervision | Degrader position and bending magnet hall sensor data continuously monitored by DSP based subsystem |
| Range Modulation | Control of range-shifter with DSP based subsystem. State of single plates measured with optical sensors supervised continuously | Redundant optical sensors for each single plate. Monitored by TVS |
| Patient Position | Patient table and Gantry rotation through the Gantry and Patient Positioning System (GPPS). GPPS implements full actuator supversion as well as collission protection | Absolute position encoders and end-switches monitored by TVS |

# Example: Spot Termination

- General method for dose measurement:
  - Ionisation chambers
  - Current converted to frequency, fed into counter module

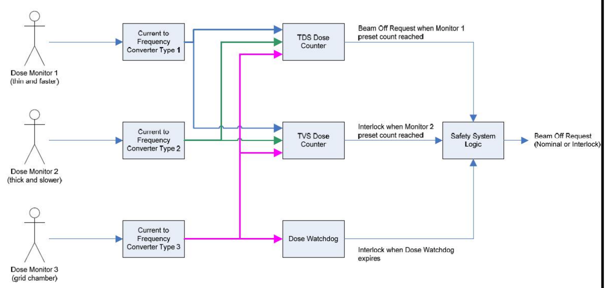



SUPERVISE





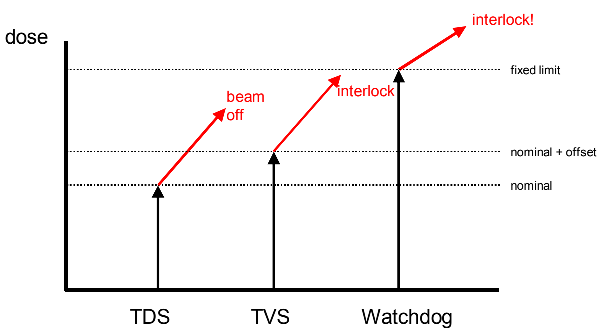
# Example: Spot Termination








# Example: Gantry 1 Spot Termination








# Formal Risk Analysis

- Fault Trees:
  - Start from safety goals
  - Imagine what can go wrong
  - Define measure to reduce associated risks
    - Come up with redundant ways to detect failures and avoid consequences
    - Technical and Operational Measures (TM, OM)
  - Estimate risk before and after applying the measures

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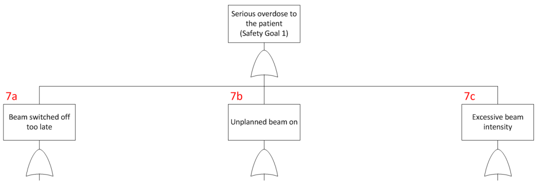
# Example:
## Safety Goal #1 – no serious overdose



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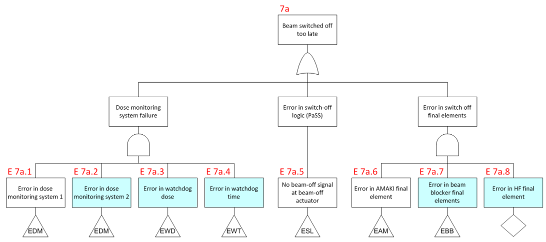
# Example:
## Safety Goal #1 – no serious overdose

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# Example:
## Safety Goal #1 – no serious overdose

**E 7a.1** Error in Dose Monitoring System 1

**TM 7a.1.1** A beam *switch-off* is activated upon saturation of the Monitor.

**TM 7a.1.2** The high-voltage supply to the Monitor is continuously monitored.

**TM 7a.1.3** The monitor units are transmitted together with a heartbeat signal.

**TM 7a.1.4** The dose is measured by two independent monitoring systems, connected to TDS and TVS, respectively.

**TM 7a.1.5** In case a failure of the front-end electronics is detected, an interlock is generated.

**OM 7a.1.1** The gain and offset of the front-end electronics of the Monitor is checked daily.

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# Risk Categorization

## Severity

| Index | Severity | |
|---|---|---|
| 1 | Negligible: | little or no effect |
| 2 | Minor: | minor injury (benefit > harm) |
| 3 | Marginal: | moderate injury (benefit insecure) |
| 4 | Critical: | serious injury (harm > benefit) |
| 5 | Catastrophic: | death(s) or multiple serious injuries |

## Occurence

| Index | Occurrence | | |
|---|---|---|---|
| 1 | Incredible: | < once in 100 years | < 1 / 1'800'000 fields |
| 2 | Improbable: | once in 10 years | 1 / 180'000 fields |
| 3 | Remote: | once per year | 1 / 18'000 fields |
| 4 | Occasional: | once per month | 1 / 1'500 fields |
| 5 | Probable: | once per week | 1 / 350 fields |
| 6 | Frequent: | once per day | 1 / 70 fields |

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# Risk Categorization

| Occurrence | Severity: 1 Negligible | 1 Minor | 3 Marginal | 4 Critical | 5 Catastrophic |
|---|---|---|---|---|---|
| 6 Frequent | C | C | C | C | C |
| 5 Probable | B | C | C | C | C |
| 4 Occasional | A | B | C | C | C |
| 3 Remote | A | B | B | C | C |
| 2 Improbable | A | A | B | B | C |
| 1 Incredible | A | A | A | B | B |

| Risk Index | Acceptance Criteria |
|---|---|
| A | Acceptable without additional actions. |
| B | Acceptable. Risk reduction required if practicable with a reasonable effort (ALARP[15]). |
| C | Unacceptable. Corrective actions must be taken. |





# Risk Evaluation

**E 7a.1 Error in Dose Monitoring System 1**

The Dose Monitoring System 1 regularly terminates the spots with the beam *switch-off* control function. Any error in this system could result in the beam not being switched-off as intended at the end of the spot. The measures described in the following sections, are in place to detect errors in the Dose Monitoring System 1 and to ensure that, following an error, a safe state is regained.

| Risk eval.: | Before measures | $Sev_{np}$ | $Occ_{np}$ | $RI_{np}$ | After measures | $Sev_p$ | $Occ_p$ | $RI_p$ |
|---|---|---|---|---|---|---|---|---|
| | | 3 | 5 | C | | 2 | 1 | A |





# Patient Safety System PaSS

- Elements of (any) safety system:

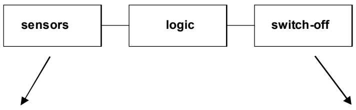
sensors — logic — switch-off





# Elements of a safety system

# Elements of a safety system




beam detectors
Hall-probes (magnetic field)
end switches (beam blocker)
…

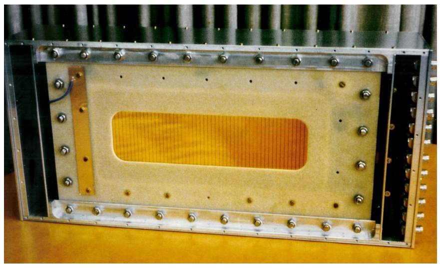
achieve / maintain safe state
= no beam, no mechanical movement

kicker magnet
beam blocker
radio frequency
ion source





# Example: measuring beam position with strip detectors

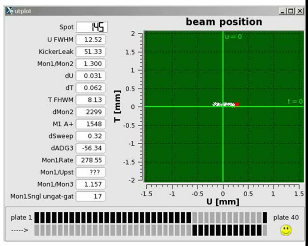






# Measuring beam position

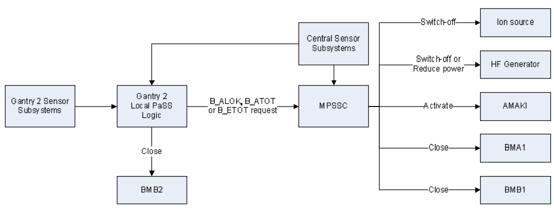
- read out strips after each spot
- determine position and compare with nominal value
- if deviation > tolerance:
  →beam switch-off by PaSS! („interlock“)



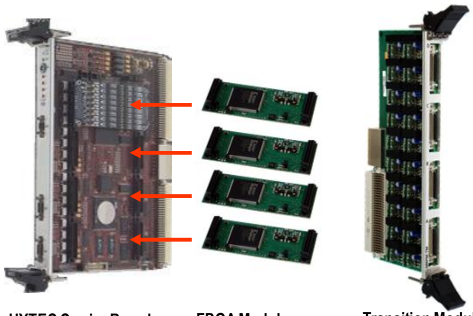





- Local & central final elements
  → local & central logic subsystems



## PSI Safety System Hardware



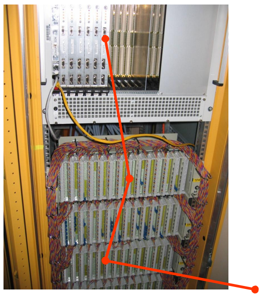
**HYTEC Carrier Board** (Type VICB8003.2) | **FPGA Moduls** (Based on XILINX Spartan-II) | **Transition Module** (Type TILK)





## PSI Safety System Hardware

– Interconnections made via Patch-Pannels
– Possibility to bridge signals by hardware



3-wire current loop interface

To/From Sensor Subsystem / Final Element





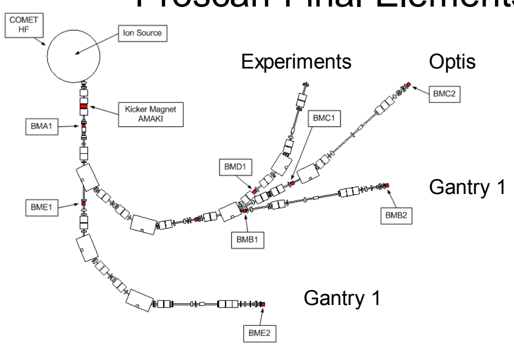
How do we switch off the beam?

(«Final Elements»)



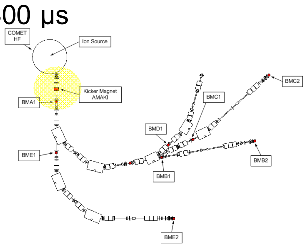


## Proscan Final Elements



# Kicker magnet

- Magnet deflects beam out of axis
- Switch-off in < 300 µs

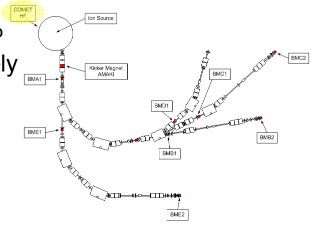







# High Frequency Generator

– 2 Levels:
– Reduce power to 20%
– De-energize completely
– Switch-off in < 400 µs

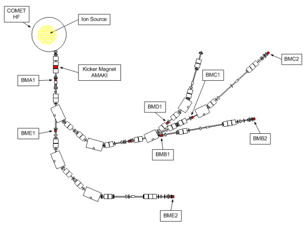







# Ion source

– De-energize ion source
– Switch-off in < 20 ms

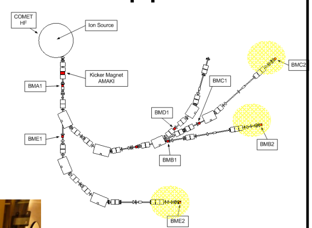


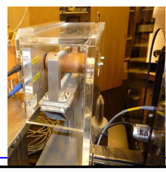





# Fast Mechanical Stoppers

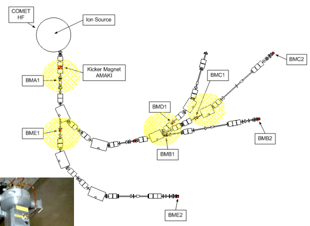
– copper block 5 cm length
– moved by pressured air & mechanical spring
  - Switch-off in < 100 ms



## Slow Mechanical Stoppers

– Graphite blocks up to 25 cm
– moved by pressured air & gravity
– Switch-off in < 1 s








## 3 Interlock-Levels

| Final Element | Control Function | Safety Function | | | PaSS Components |
|---|---|---|---|---|---|
| BMB2 | | ALOK | | | local PaSS |
| AMAKI | beam off | | escalates | | |
| BMB1 | | | ATOT | | MPSSC |
| BMA1 | | | | | |
| HF reduced | | | | escalates | |
| HF off | | | | ETOT | E_OR |
| IQ off | | | | | |





## Recovery of failing beam switch off

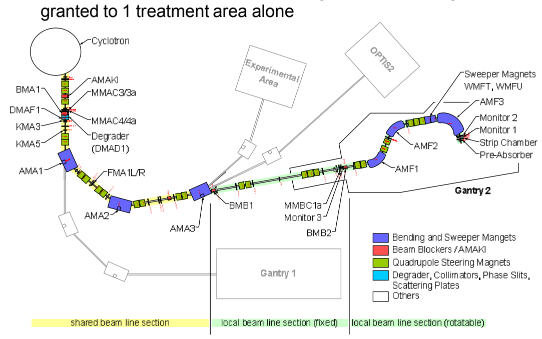
| Paragraph in this report | Failure of final element | Recovered by | Reaction time till next fastest final element reacts | Extra dose delivered using regular settings (60 Gy total dose; 6 Gy/s dose rate) | | Extra dose delivered using hypofractionation (10 Gy total dose; 6 Gy/s dose rate) | Extra dose delivered if beam current excursion by factor 10 (100 → 1'000 nA) |
|---|---|---|---|---|---|---|---|
| | | | ms | Gy | % of total dose (60 Gy) | % of total dose (10 Gy) | % of total dose (60 Gy) |
| 10.4.1.1 | AMAKI | HF reduced | 0.70 | 0.0042 | 0.007 | 0.042 | 0.07 |
| 10.4.1.2 | + HF reduced | HF off | 0.98 | 0.006 | 0.01 | 0.06 | 0.1 |
| 10.4.1.3 | + HF off + IQ off | BMB2 | 60 | 0.36 | 0.6 | 3.6 | 6.0 |
| 10.4.1.4 | + BMB2 | BMB1, BMA1 | 1'000 | 6.0 | 10 | 60 | 100 |

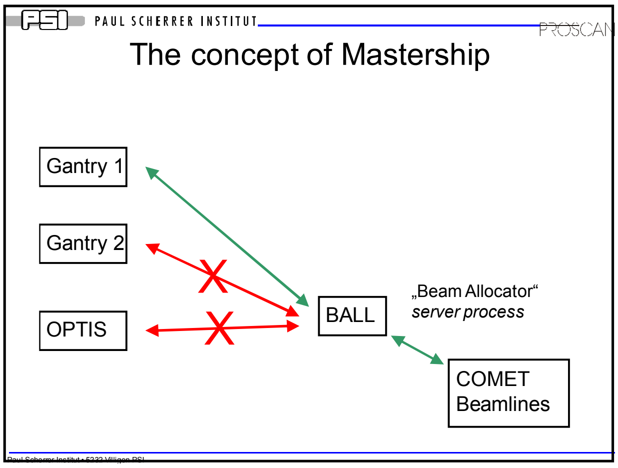


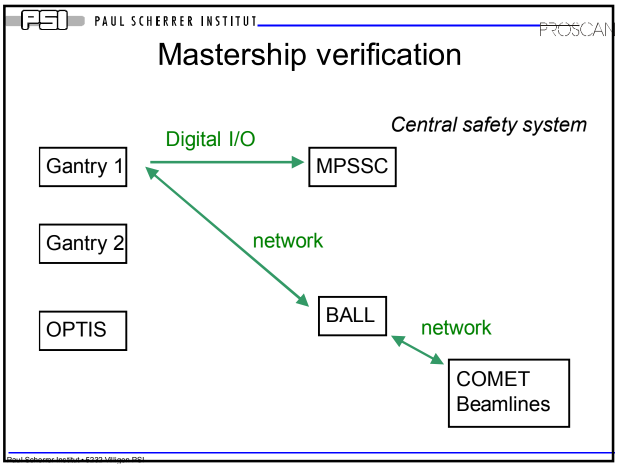


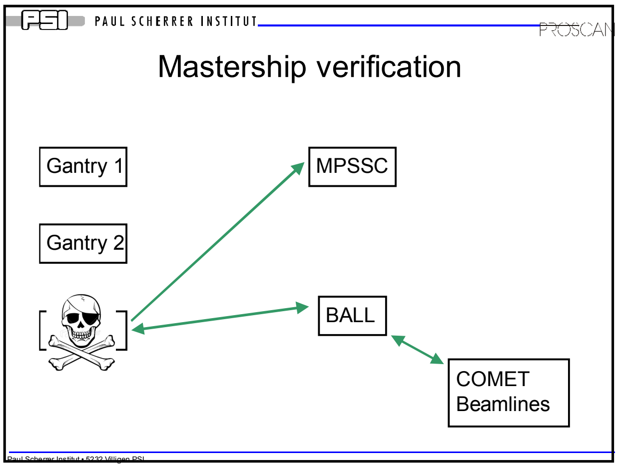
## The concept of Mastership

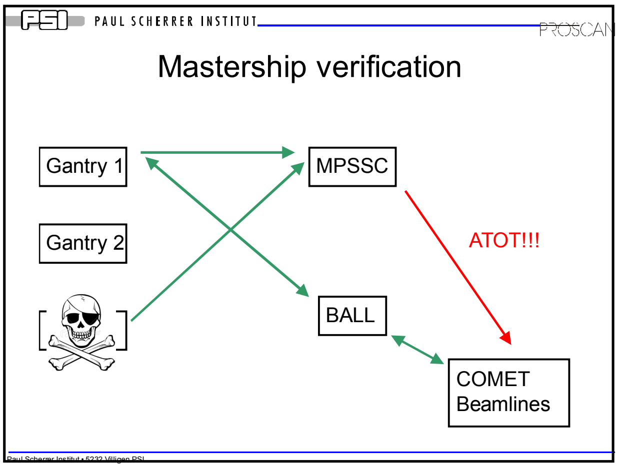
- Control over central components (degrader, kicker magnet, …) granted to 1 treatment area alone




PAUL SCHERRER INSTITUT
PROSCAN
The concept of Mastership
Gantry 1
Gantry 2
OPTIS
BALL
„Beam Allocator“
server process
COMET
Beamlines


PAUL SCHERRER INSTITUT
PROSCAN
Mastership verification
Central safety system
Digital I/O
Gantry 1
MPSSC
Gantry 2
network
OPTIS
BALL
network
COMET
Beamlines


PAUL SCHERRER INSTITUT
PROSCAN
Mastership verification
Gantry 1
MPSSC
Gantry 2
BALL
COMET
Beamlines

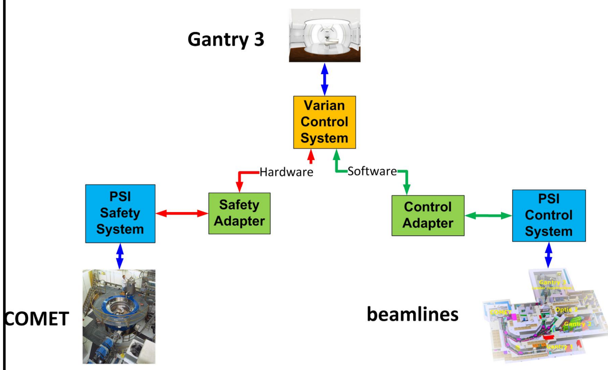

PAUL SCHERRER INSTITUT
PROSCAN
Mastership verification
Gantry 1
MPSSC
Gantry 2
ATOT!!!
BALL
COMET
Beamlines

# Integration of Gantry 3

- Commercial Gantry including Control System
- Still needs access to central elements
  - Setting beam energy & intensity
    → accelerator & beamline control
  - Beam on/off control → Kicker magnet
  - Interlocks → final elements
- Definition & Implementation of Interfaces
  - Software (network) and Hardware



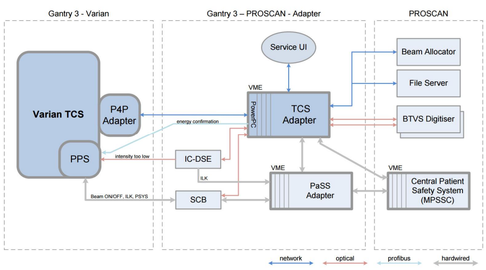









# Control Adapter

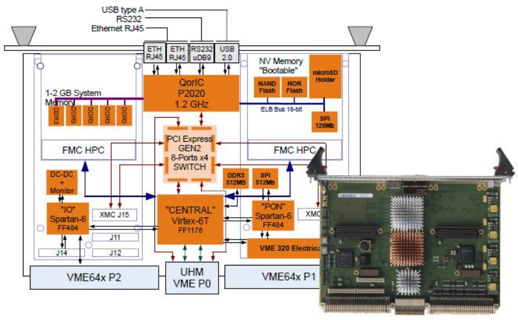




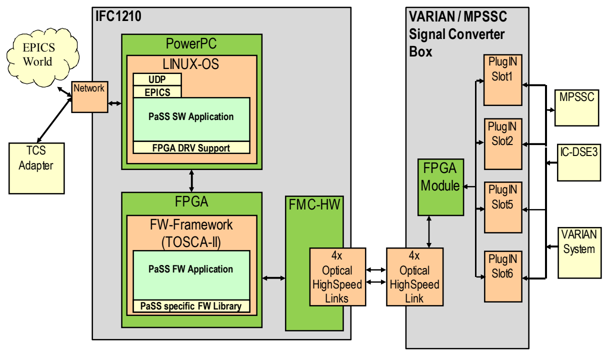



# Safety Adapter

- HW based on IFC1210 (www.ioxos.ch)



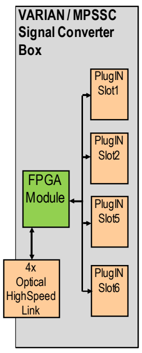
# Safety Adapter



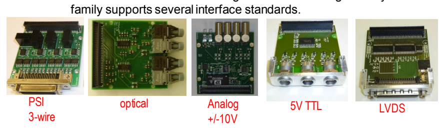





# Signal Converter Box



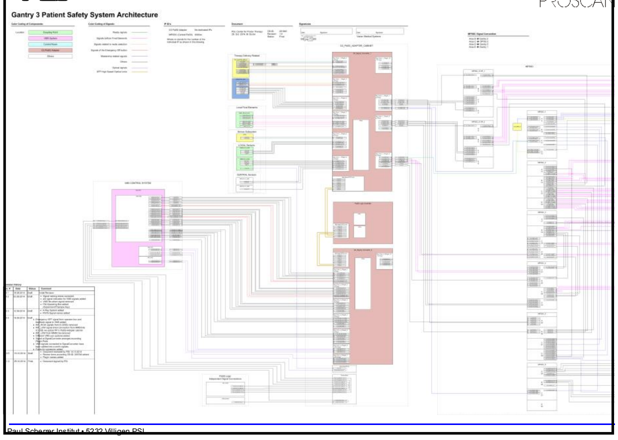

Simple HW box, which fits into 19 inch crate
Interfaces:
- 4x high speed optical links – SFP transceivers
- Interface to FPGA COTS module (e.g. ENCLUSTRA – Like used in G2 – MCCS Project
- 6x interface slots for connecting CPT standard PlugIn family. This family supports several interface standards.




- FPGA design supporting HighSpeed optical link communication and IO communication to PlugIn slots
- Supporting VARIAN interface requires additional development of PlugIn boards
- Complexity: Simple HW design and medium complex FPGA design












If you think
proton therapy controls
is complicated…