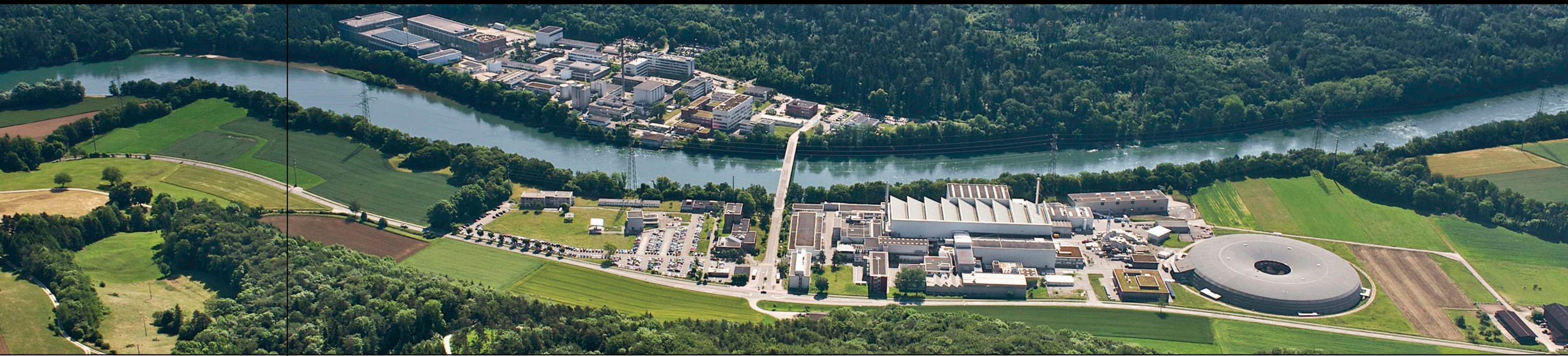
PAUL SCHERRER INSTITUT



To promote excellency in patient care and innovative proton treatment

Therapy Control and Patient Safety

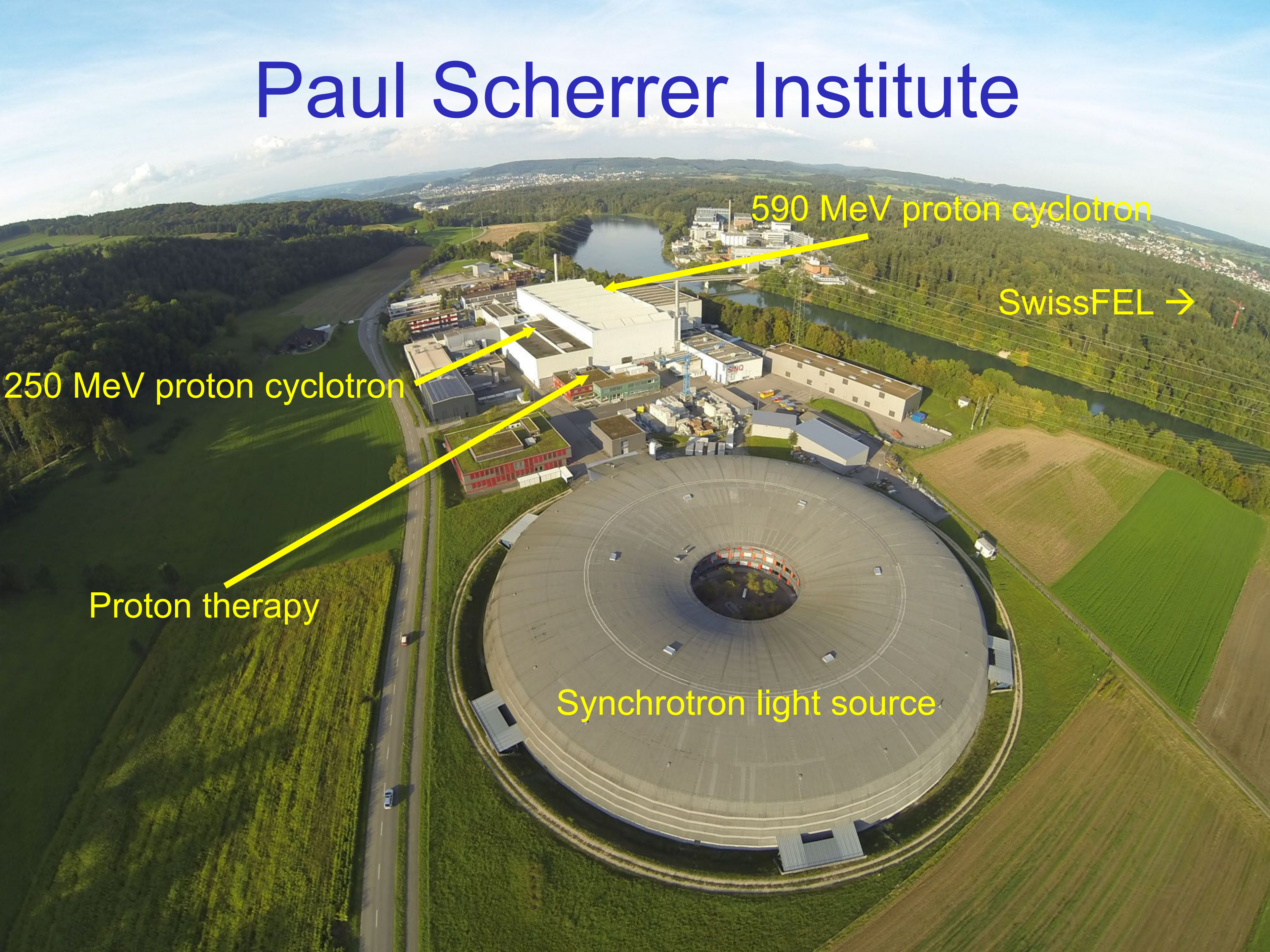
Martin Grossmann

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

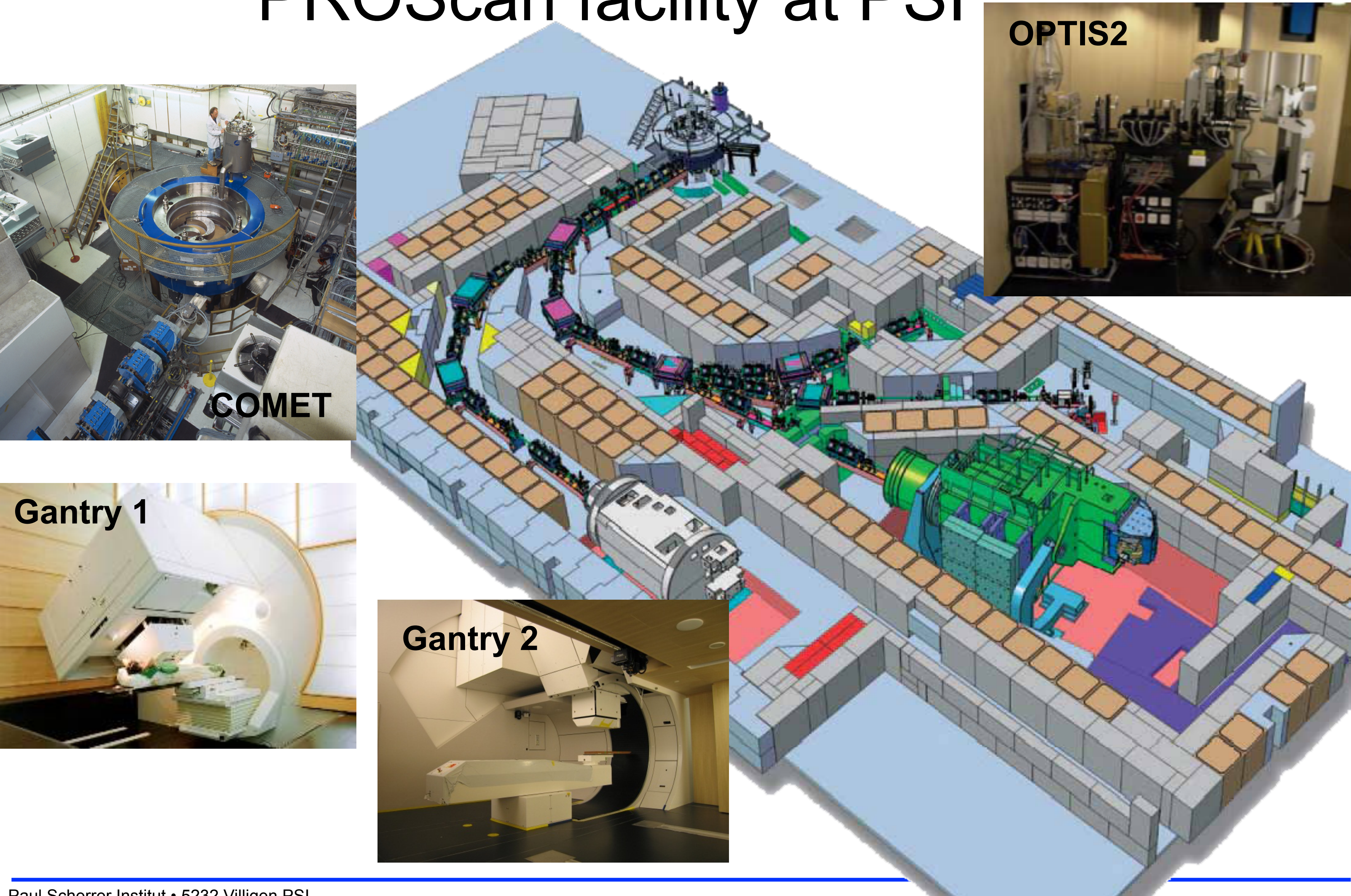
Overview

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

Paul Scherrer Institute

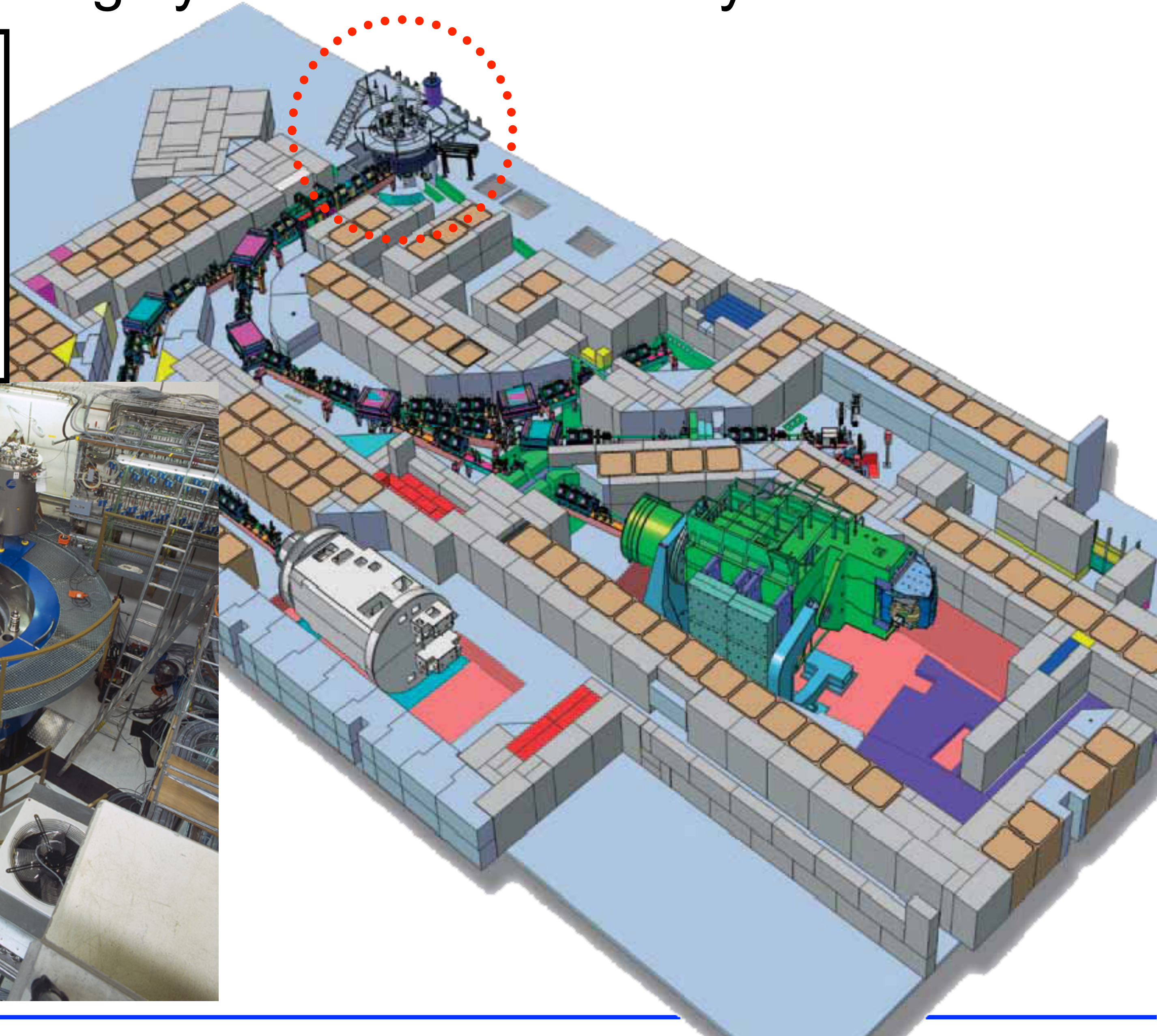


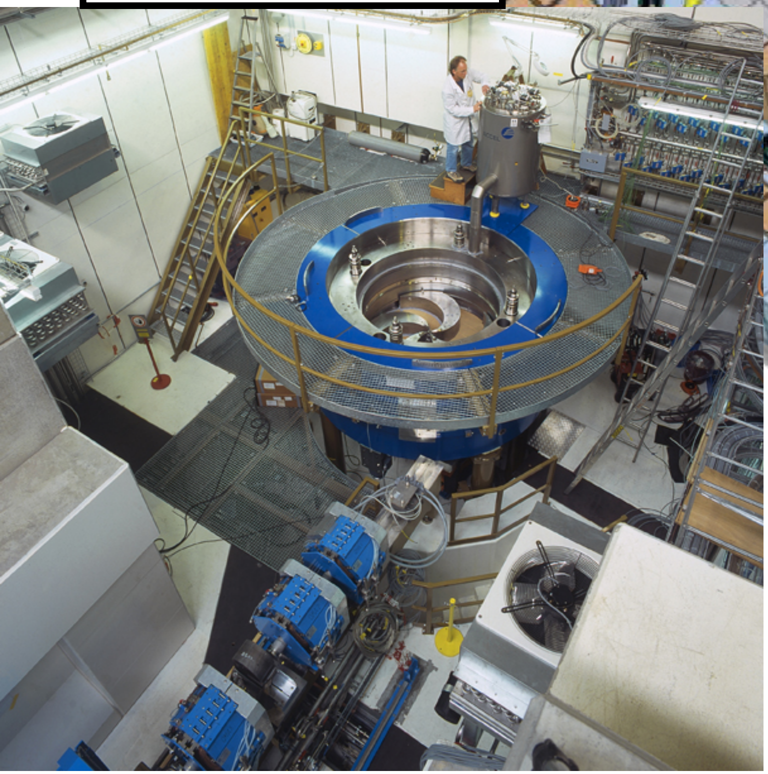
PROScan facility at PSI



Superconducting cyclotron with intensity modulation I

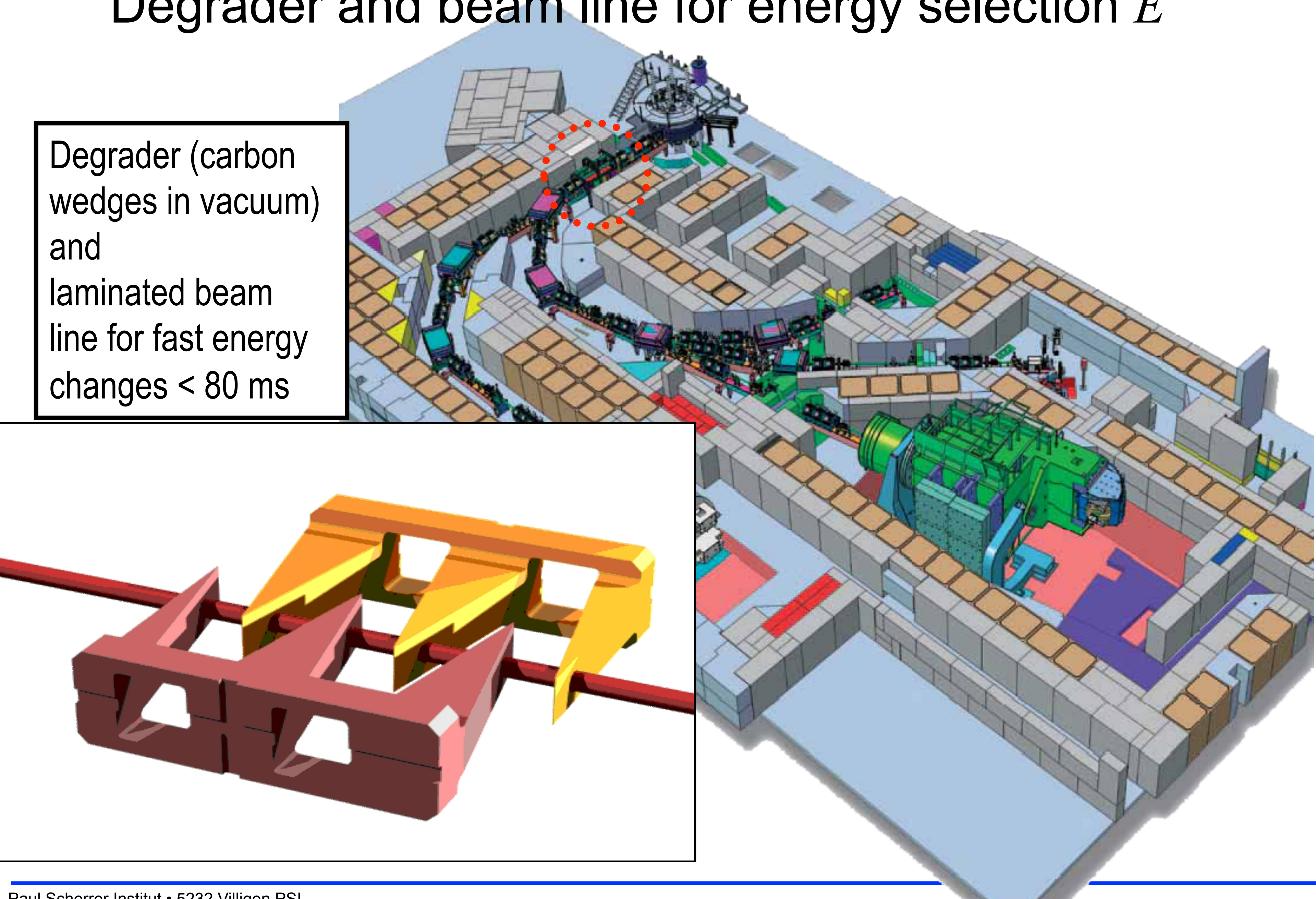
Cyclotron COMET
Varian/Accel
250 MeV protons
Deflector plate for
fast beam current
regulation ~ 50 μs

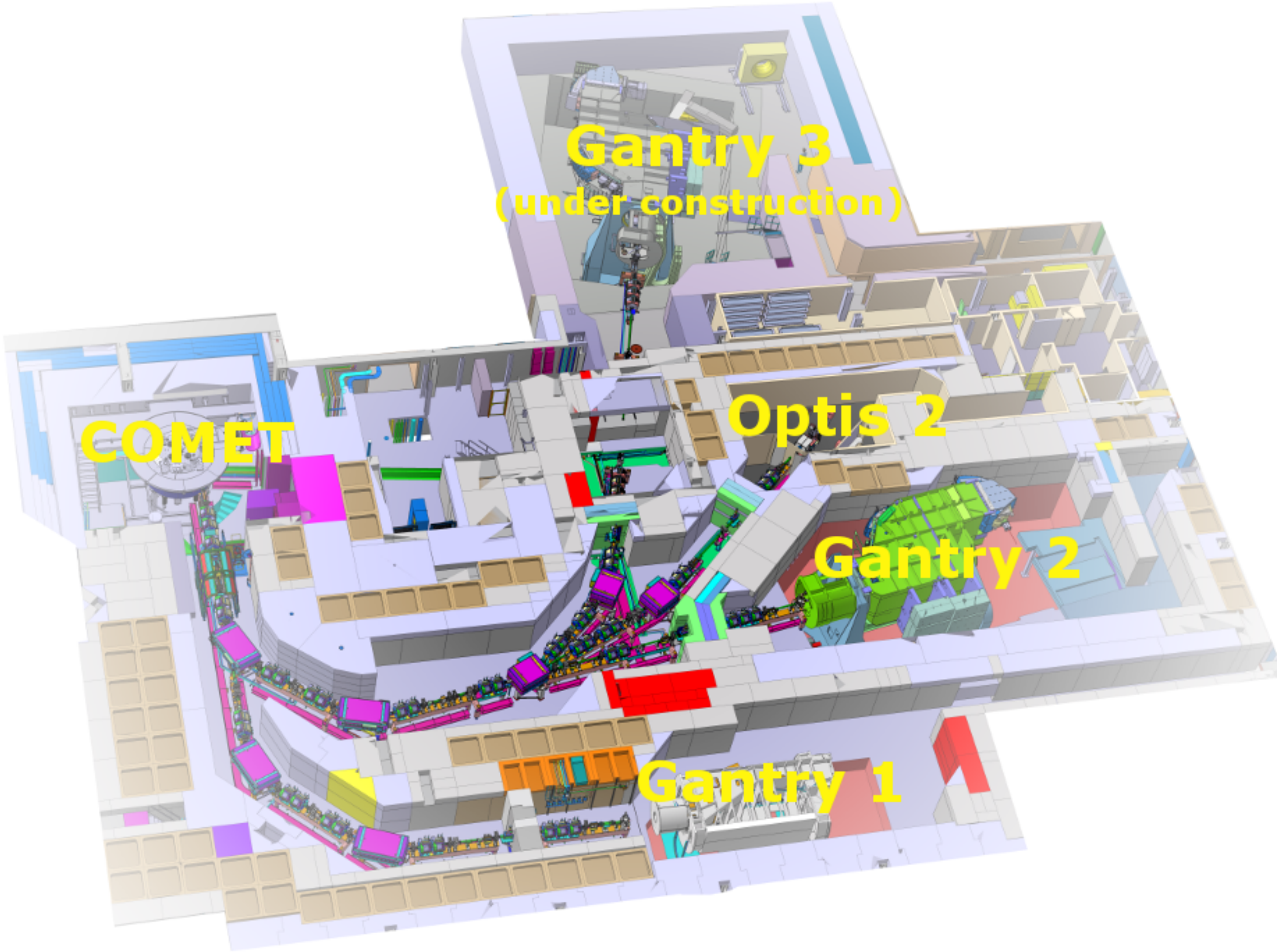




Degrader and beam line for energy selection E

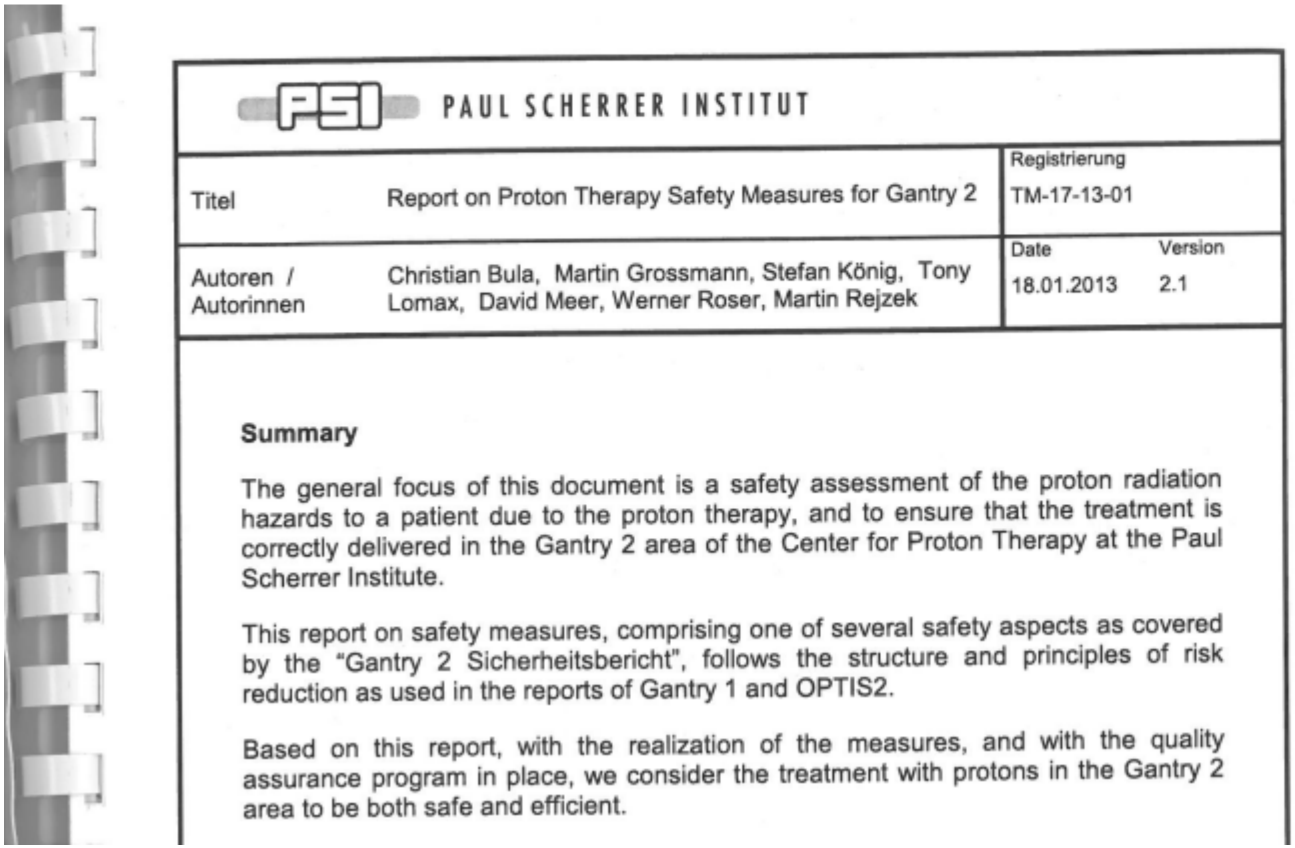
Degrader (carbon wedges in vacuum) and laminated beam line for fast energy changes < 80 ms




Gantry 3
(under construction)
COMET
Optis 2
Gantry 2
Gantry 1

Controls & safety

PSI's concept for patient safety



PAUL SCHERRER INSTITUT

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

#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

#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

#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

#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

TDS — set →

← check — TVS

Therapy Delivery

supervise ↕

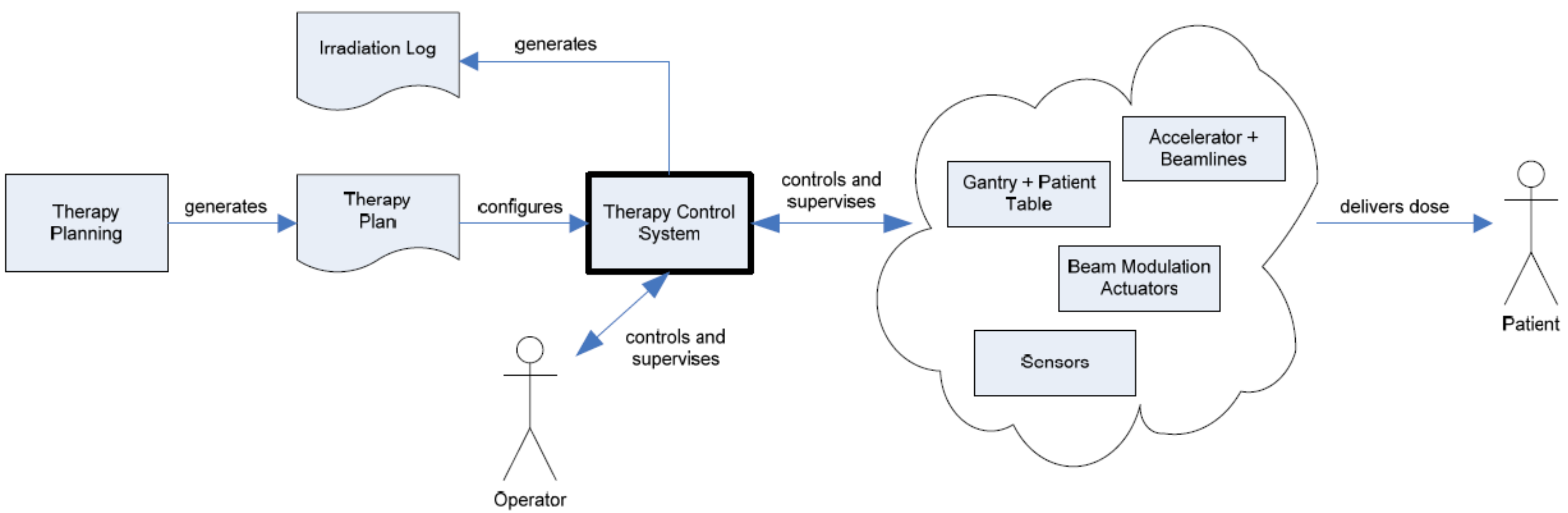
Therapy Verification

PaSS

Patient Safety

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

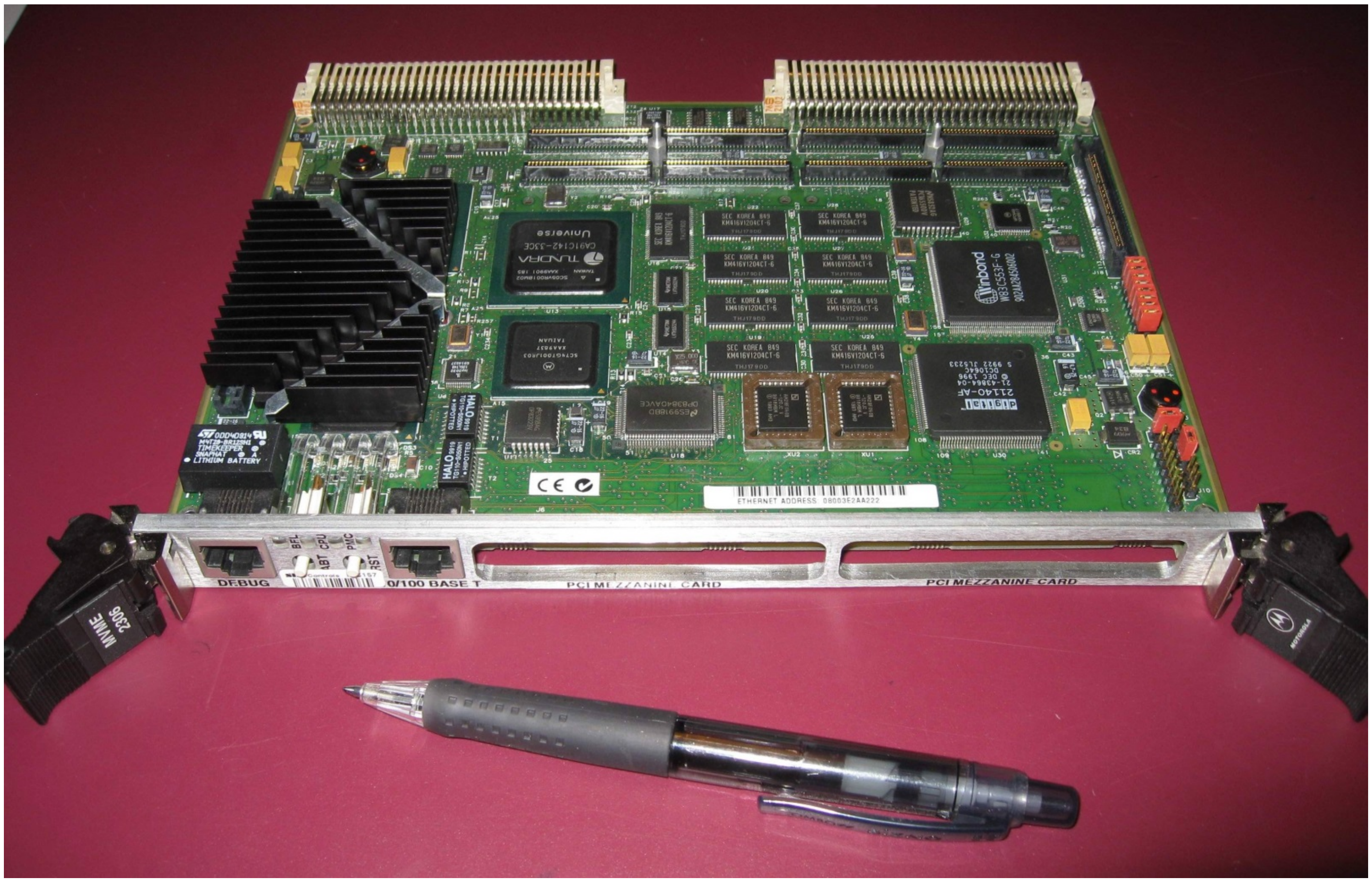
... A perfectly safe but slow scanning control system will be as useless as an unsafe fast one!

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

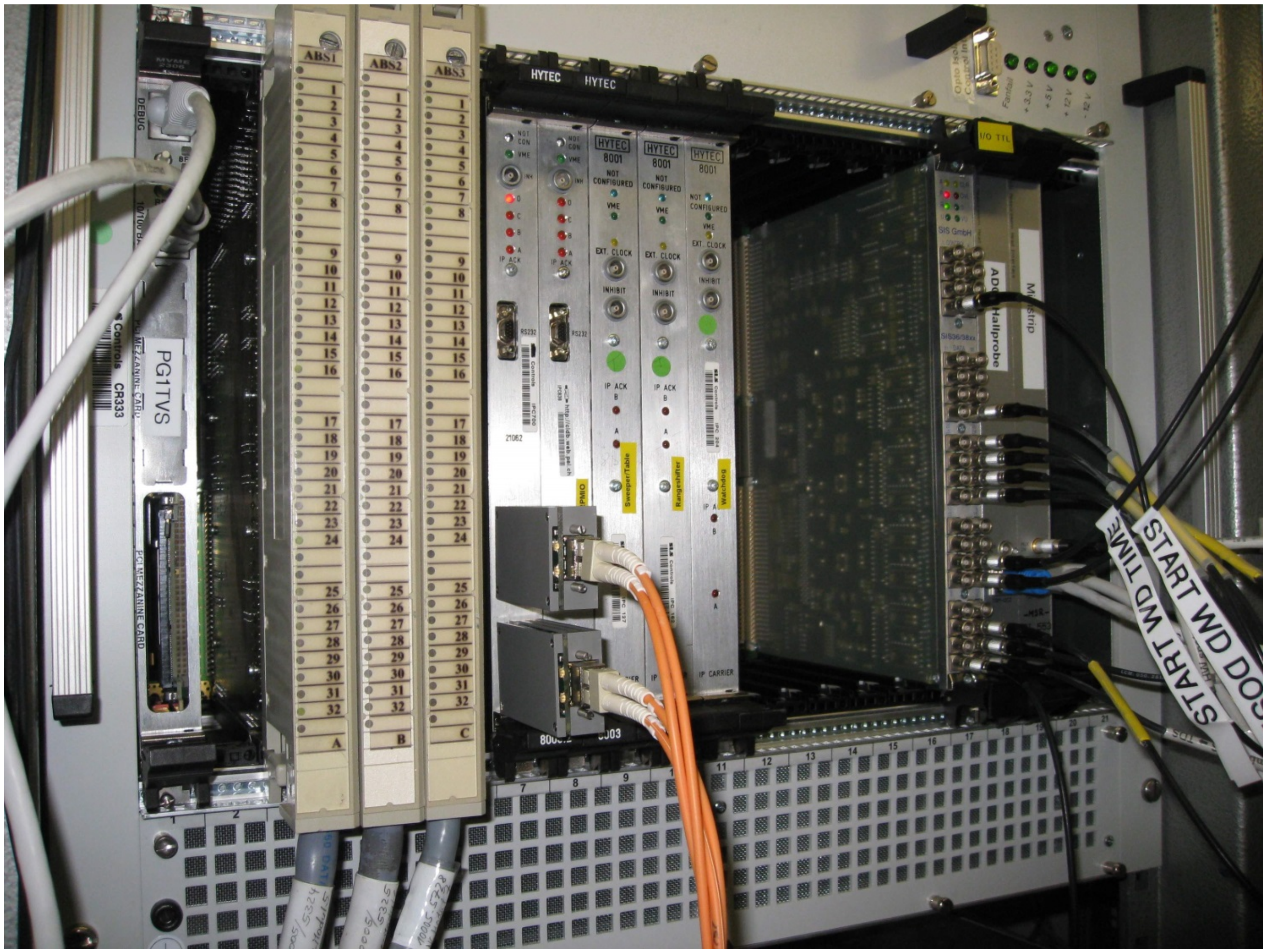
The Need for Speed...

embedded VME Single Board Computer

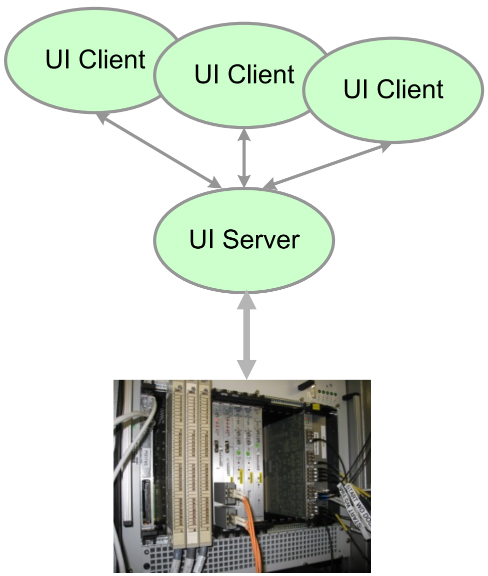


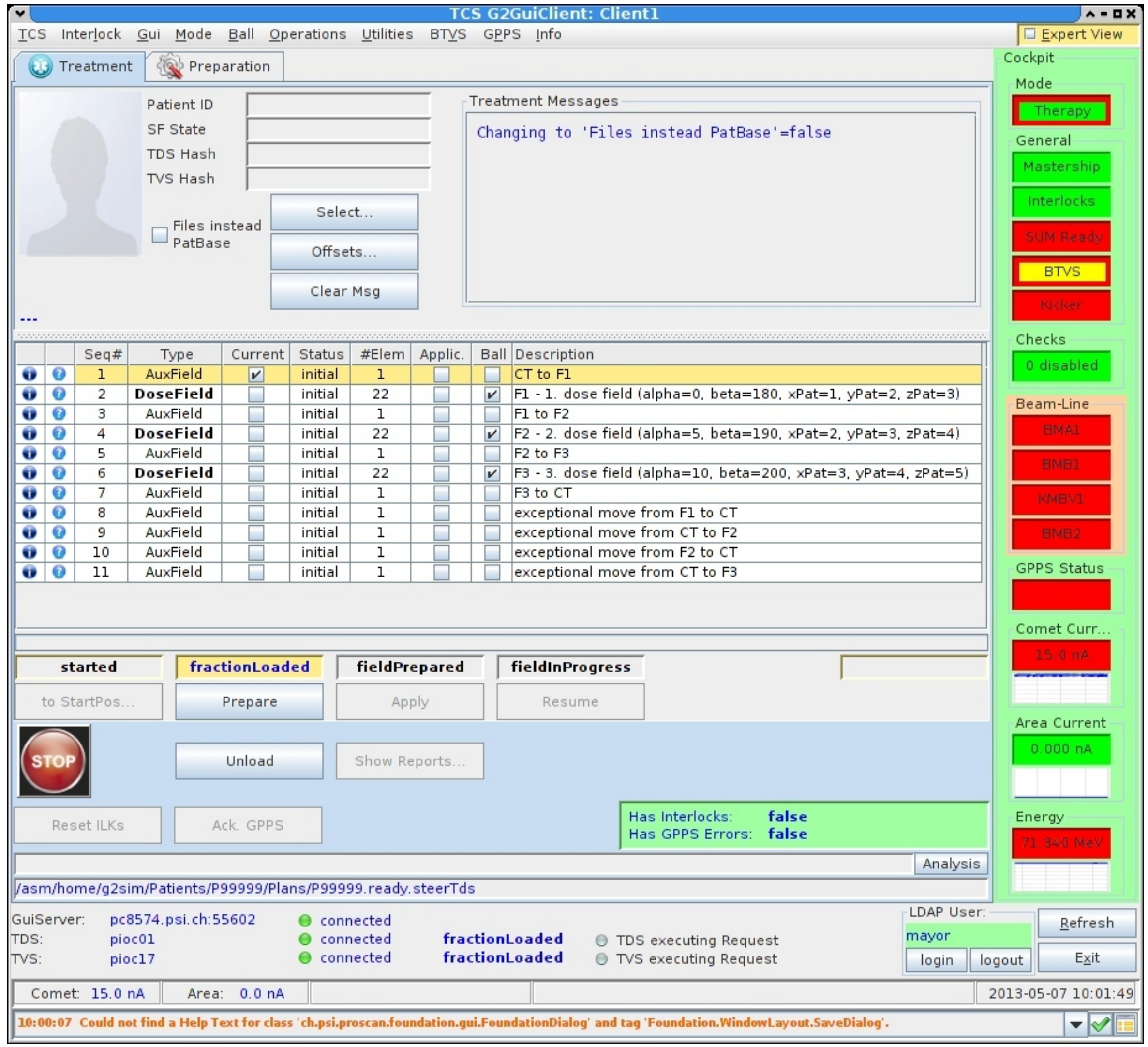
The Need for Speed...

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



Graphical User Interface

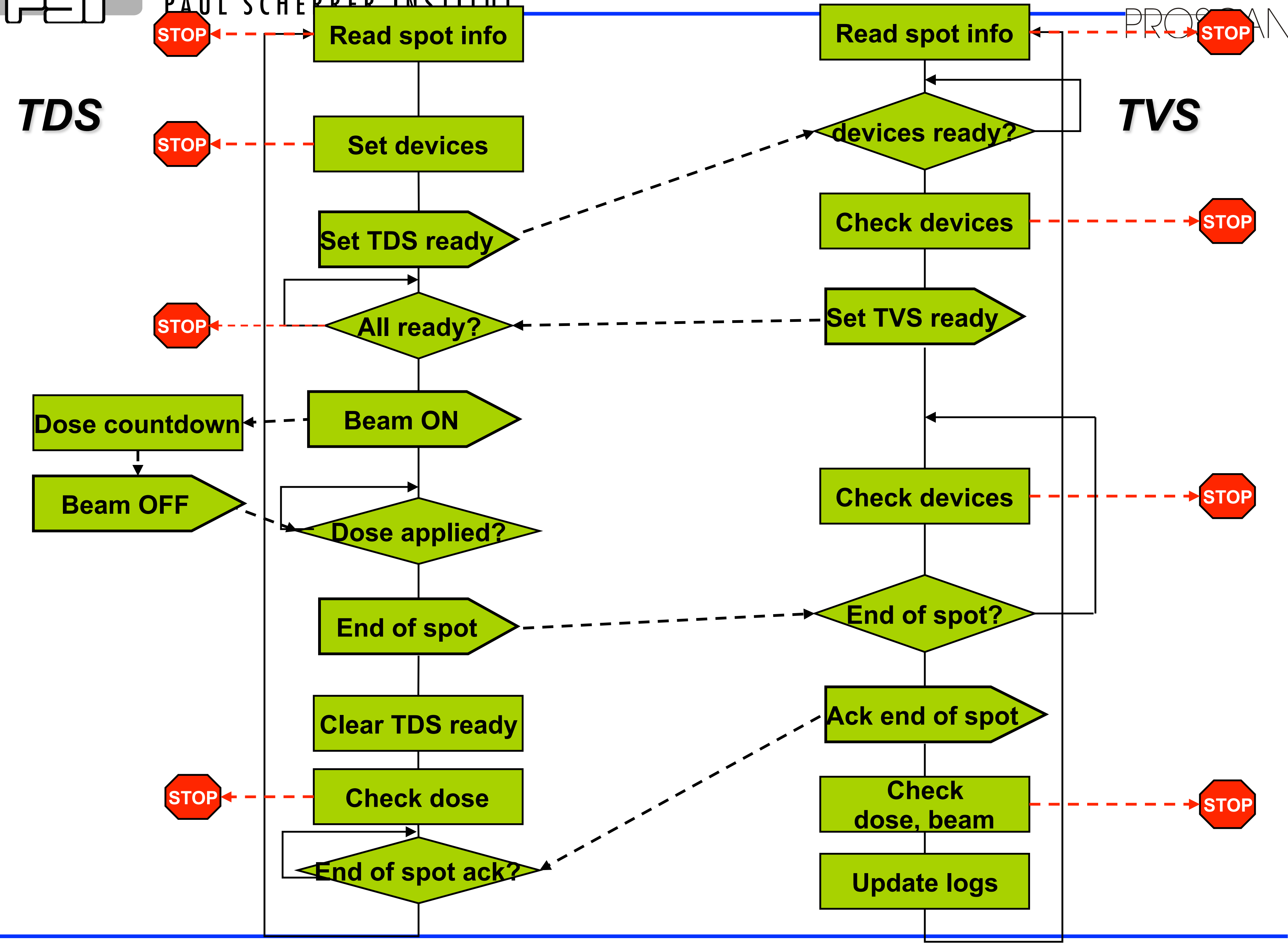




- client – server application
- implemented in Java

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


TDS
TVS
Read spot info
Set devices
Set TDS ready
All ready?
Beam ON
Dose countdown
Beam OFF
Dose applied?
End of spot
Clear TDS ready
Check dose
End of spot ack?
Read spot info
devices ready?
Check devices
Set TVS ready
Check devices
End of spot?
Ack end of spot
Check
dose, beam
Update logs
STOP

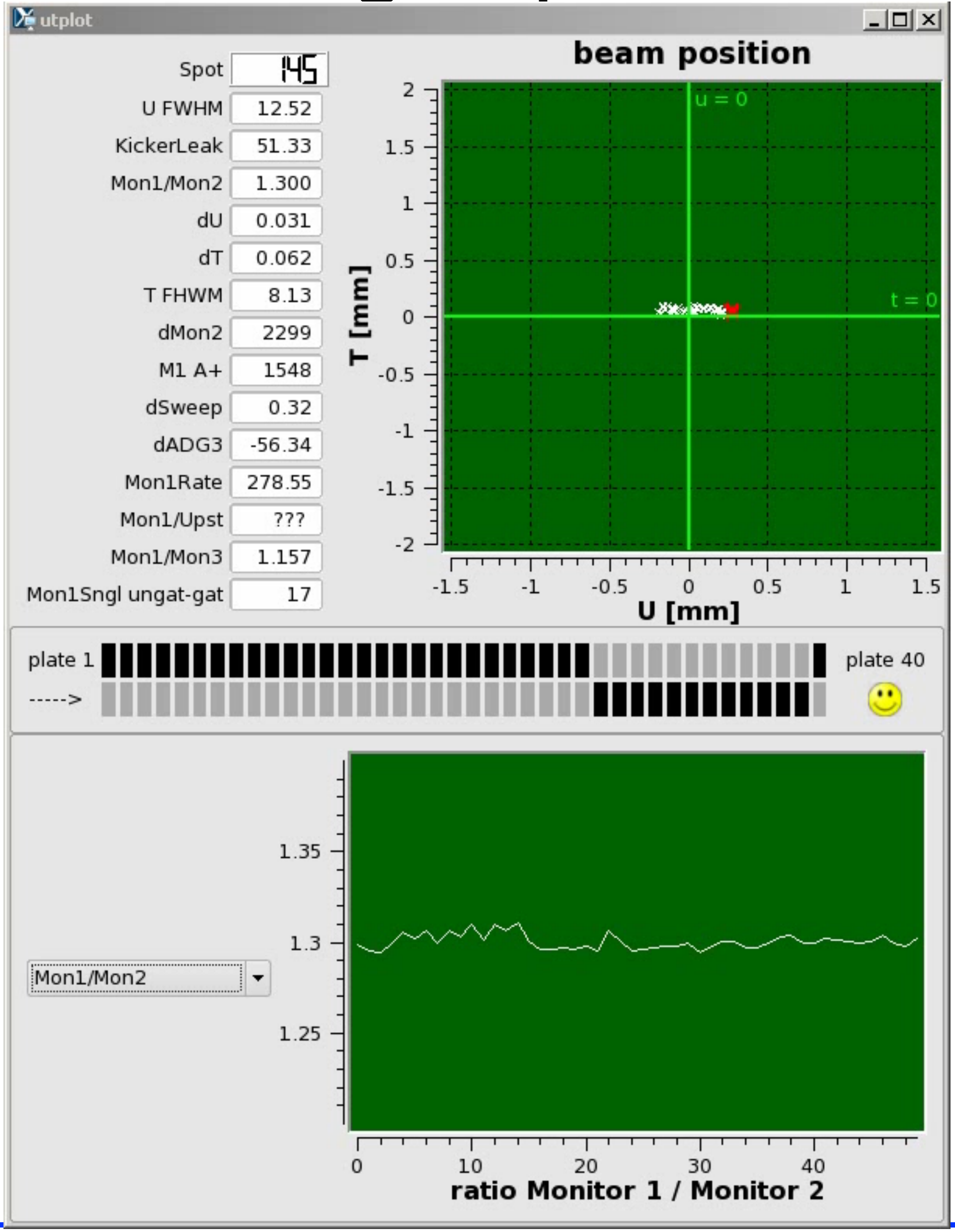
Spot Scanning: Operator Tools

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					

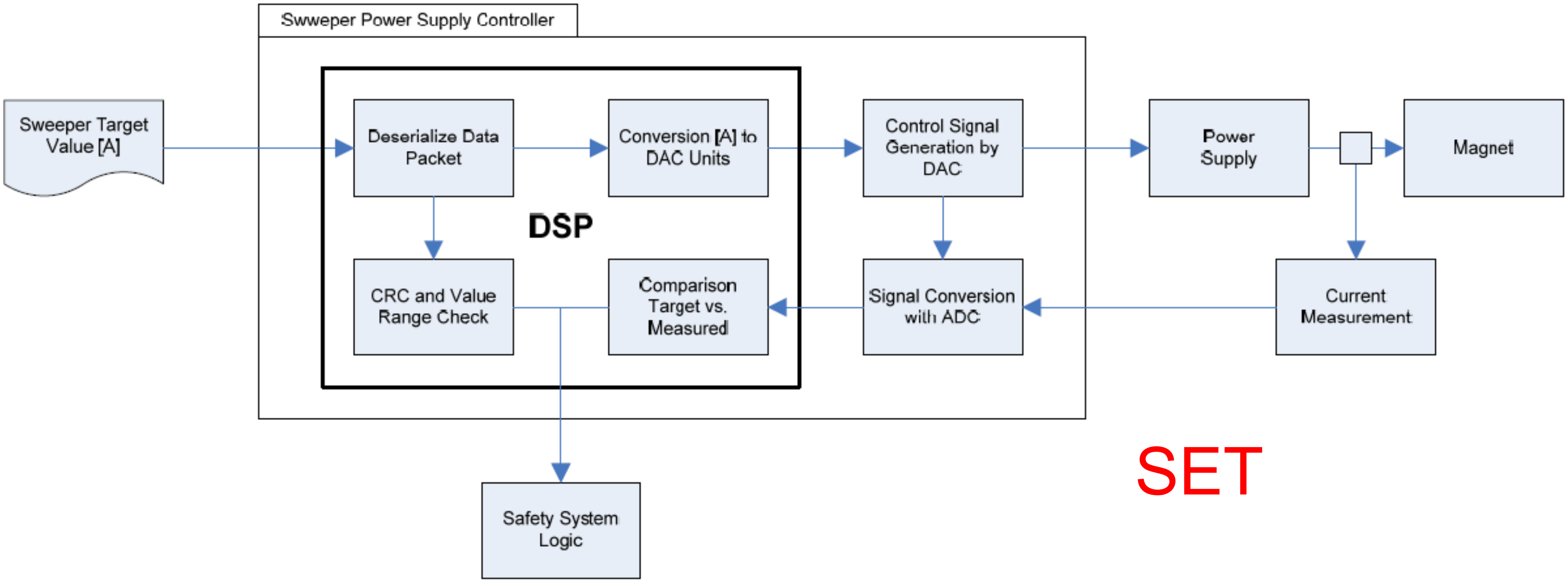
peering into the control loop ...

Spot Scanning: Operator Tools



Safe Setting – Redundant Checking – Independent Supervision

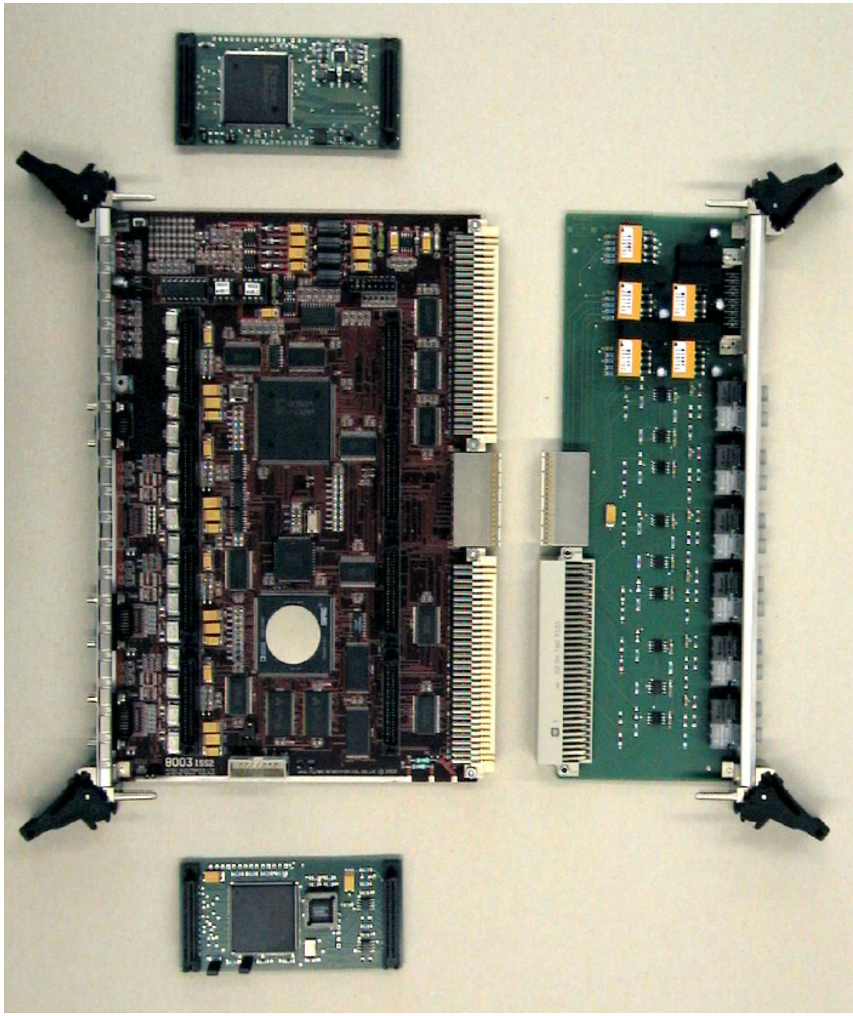
Example: Sweeper Magnet Control



SET

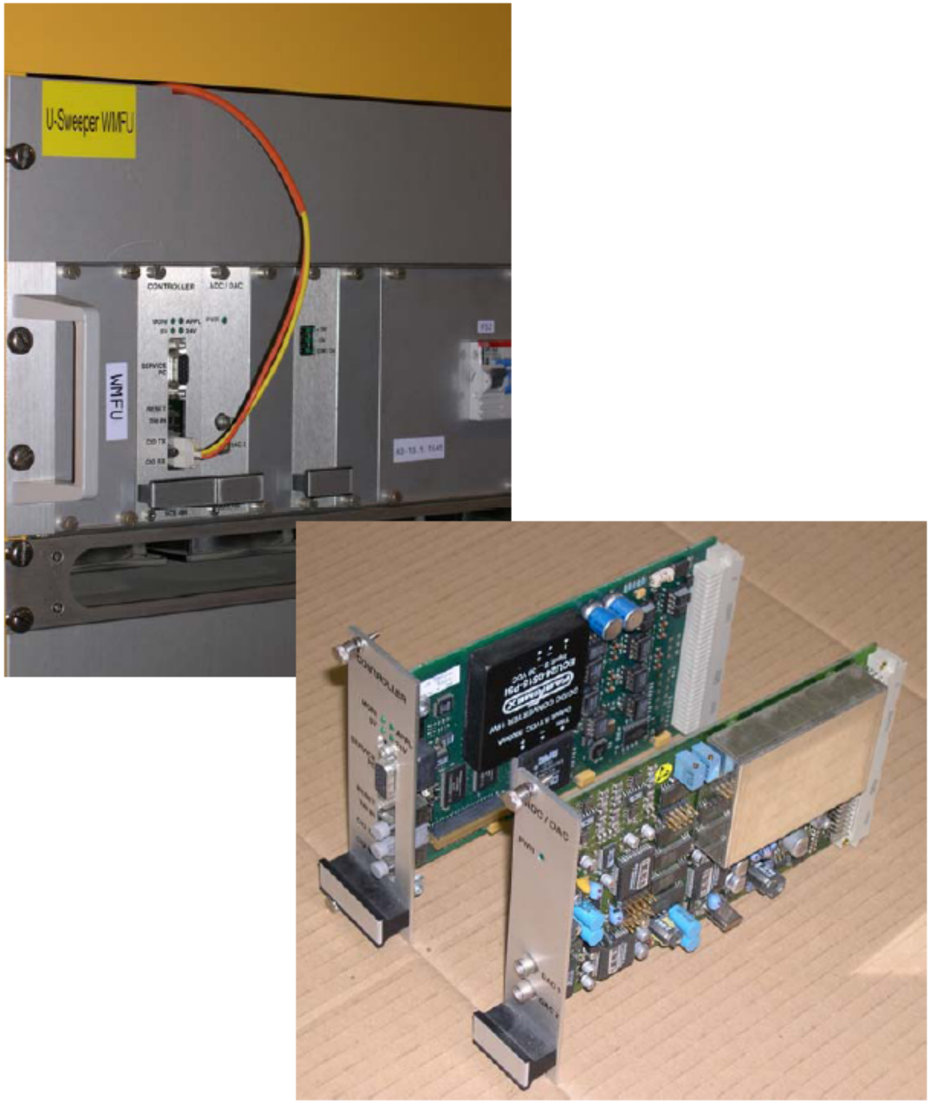
- The sweeper power supply controller receives target values over an optical link from the TCS, checks data integrity, and controls the power supply for the magnet coils
- At the same time, the current through the coils is measured and compared in realtime with the target value on a DSP inside the controller,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

Magnet Power Supply Control Hardware

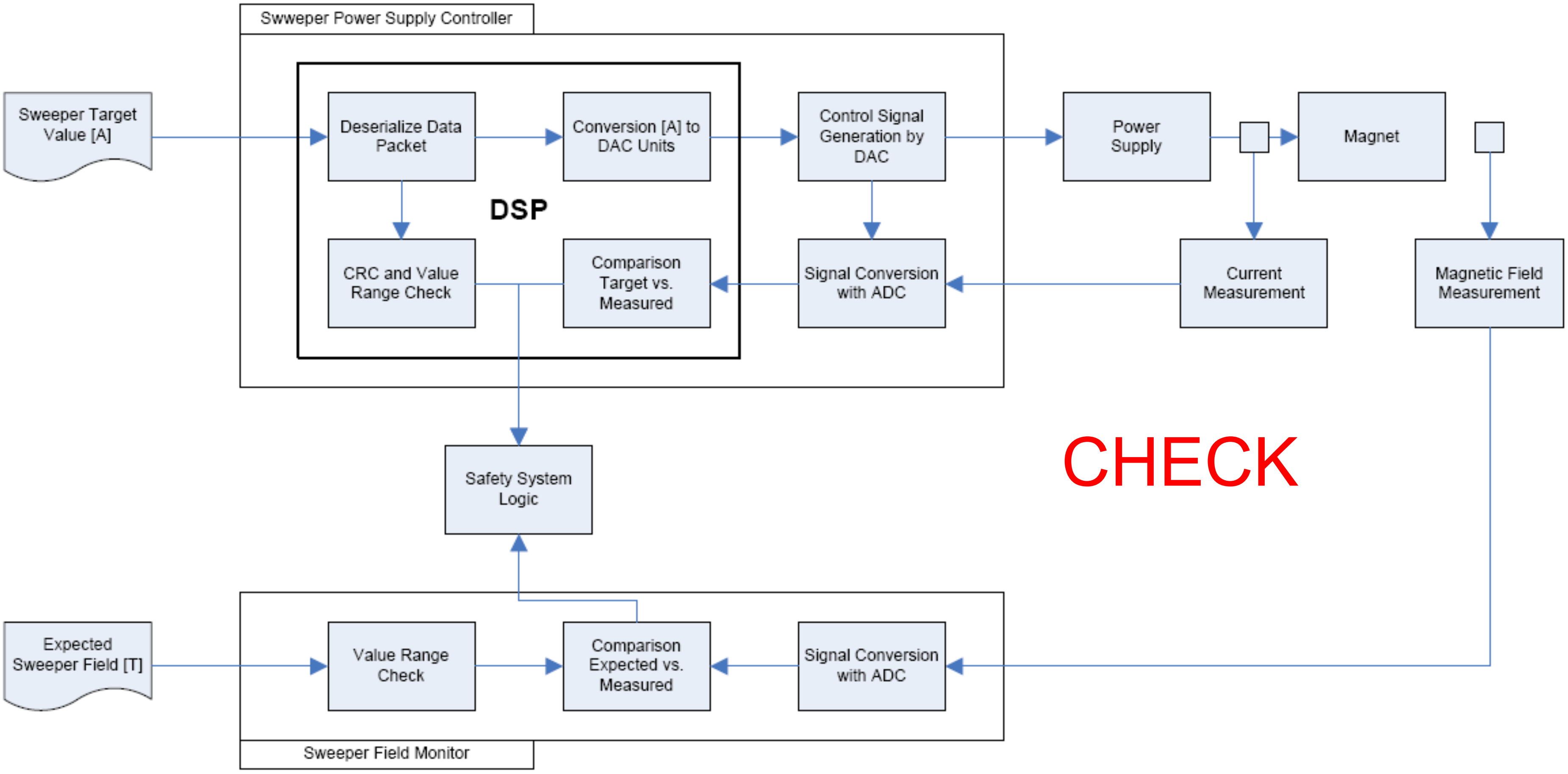


- VME board with 4 Industry-Pack Slots and onboard DSP
- Industry-Packs with FPGA implementing communication interface to power supply
- VME transition module with optical transceivers for data transmission to power supply
- Digitally controlled power-supplies (developped by PSI)

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

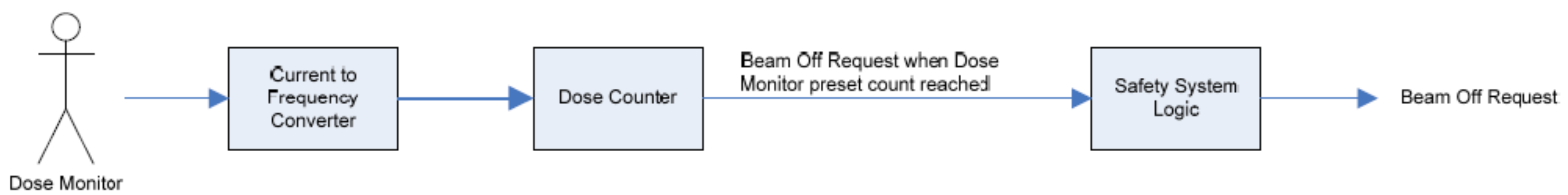
Hall Probe used at PSI

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

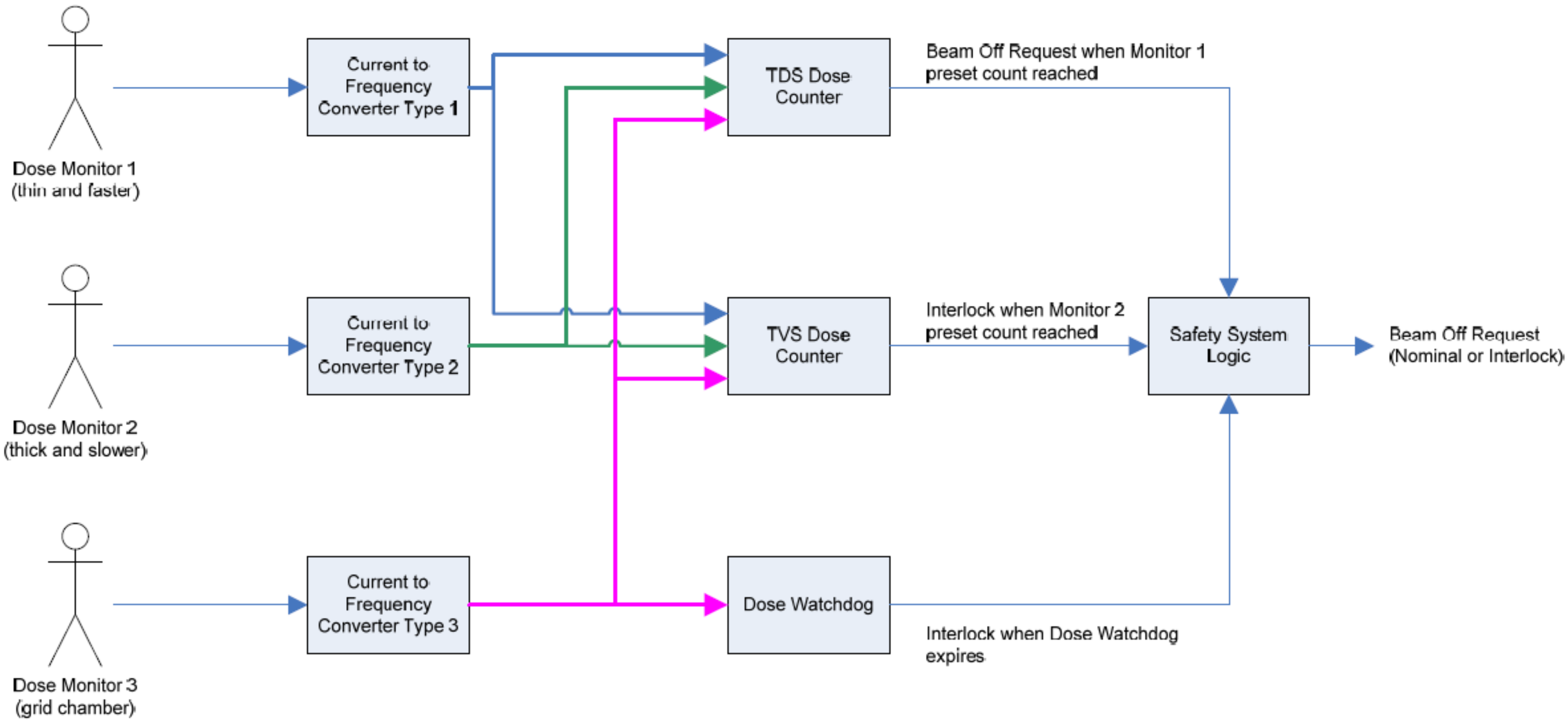
Example: Spot Termination

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

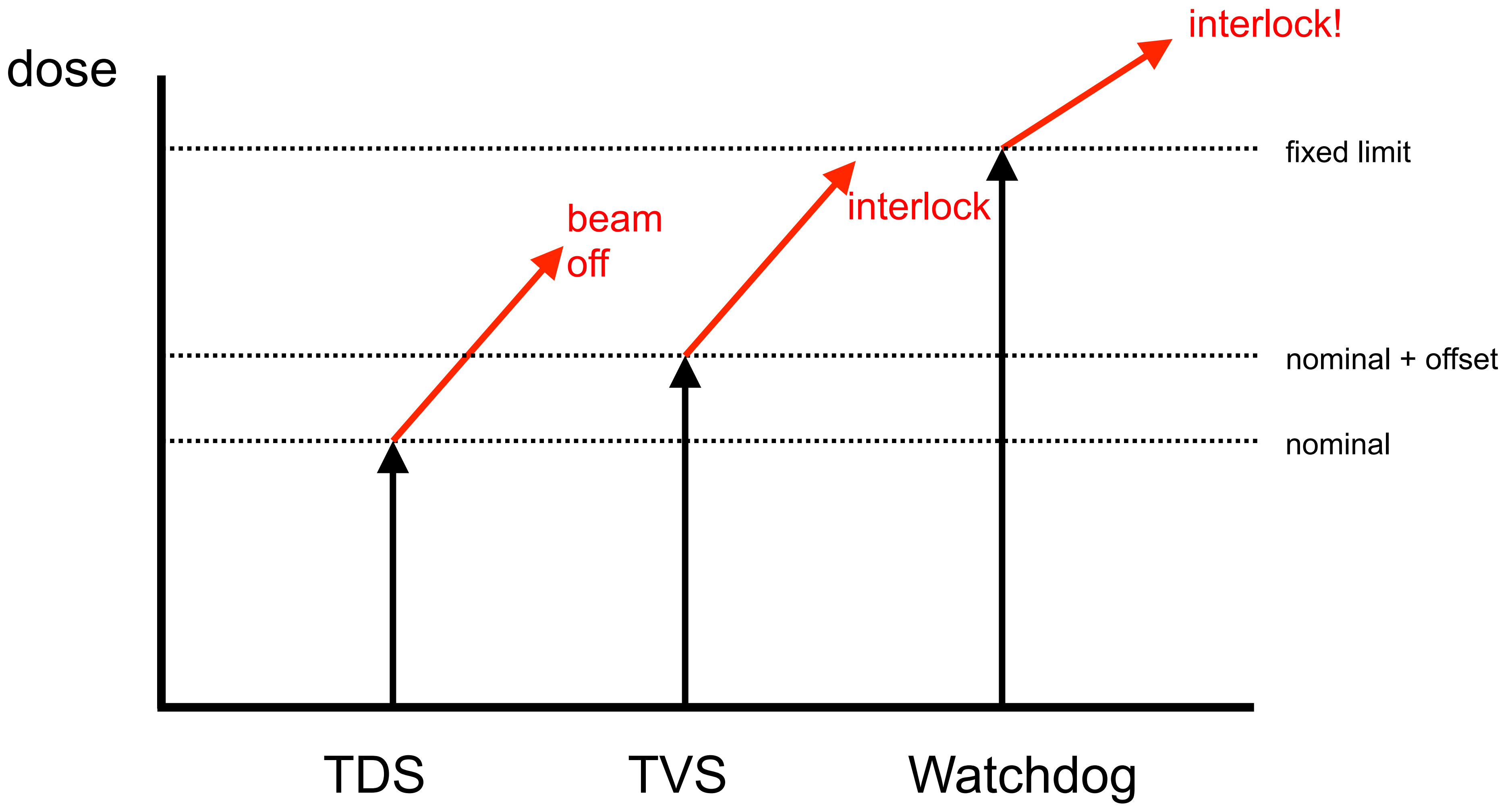


SUPERVISE

Example: Spot Termination



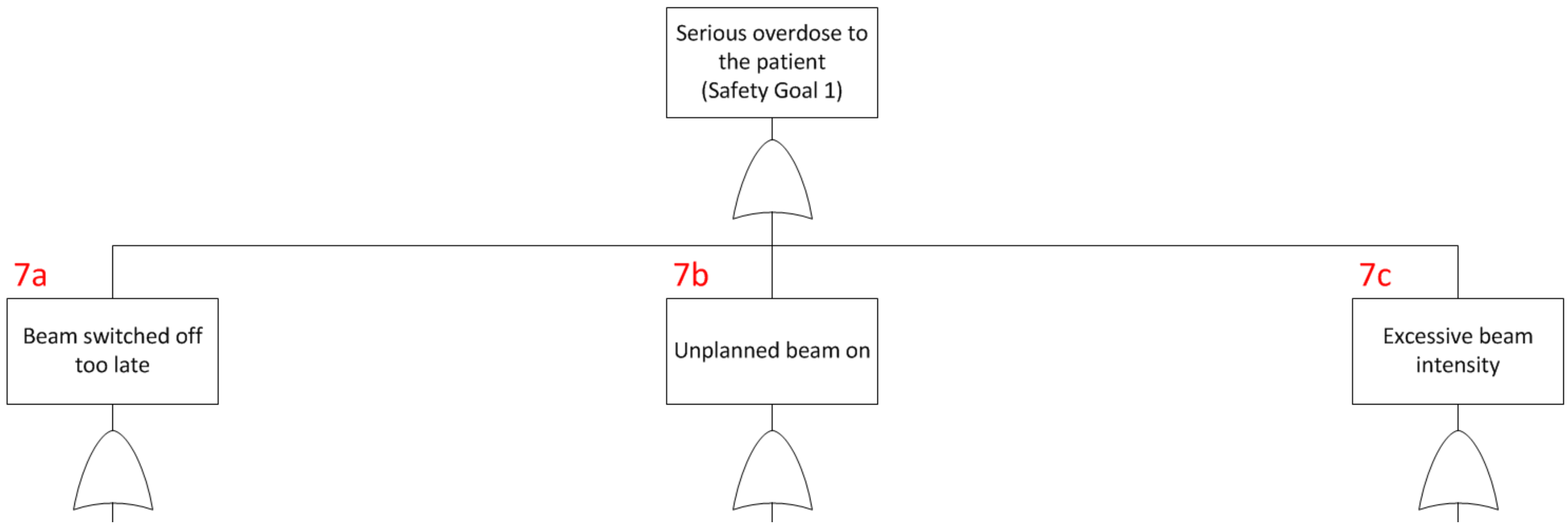
Example: Gantry 1 Spot Termination



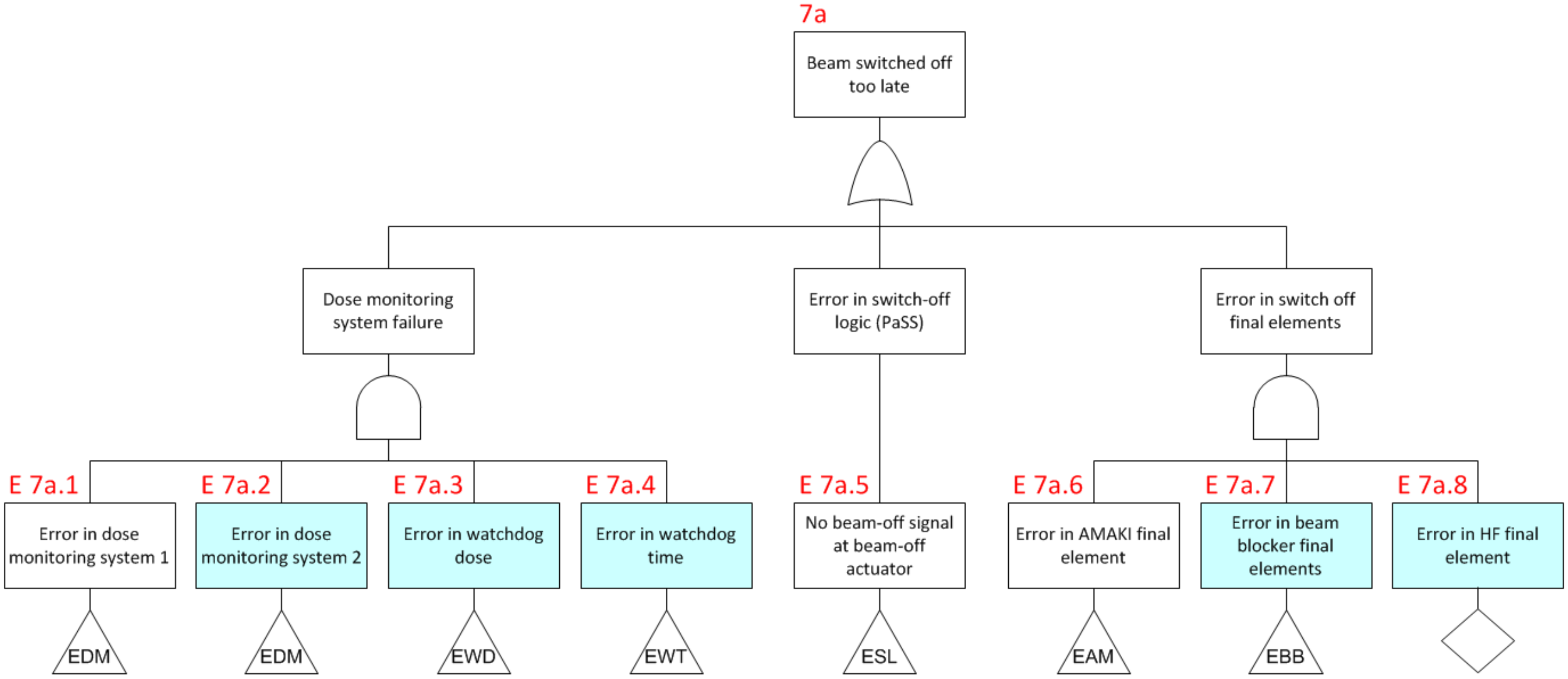
Formal Risk Analysis

- 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

Example:
Safety Goal #1 – no serious overdose



Example:
Safety Goal #1 – no serious overdose



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.**

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

Risk Categorization

		Severity				
		1 Negligible	1 Minor	3 Marginal	4 Critical	5 Catastrophic
Occurrence	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

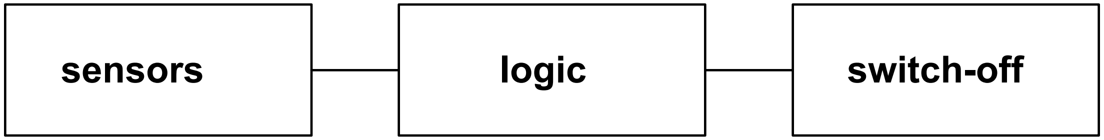
E 7a.1 Error in Dose Monitoring System 1

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

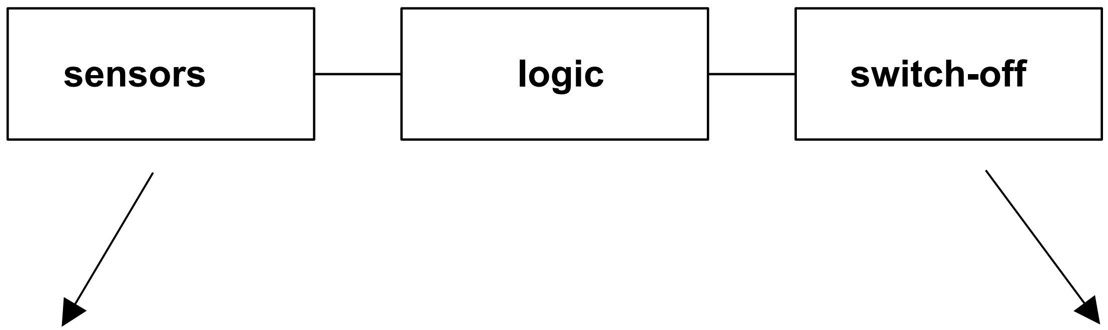
Patient Safety System PaSS

- Elements of (any) safety system:



Elements of a safety system

Elements of a safety system

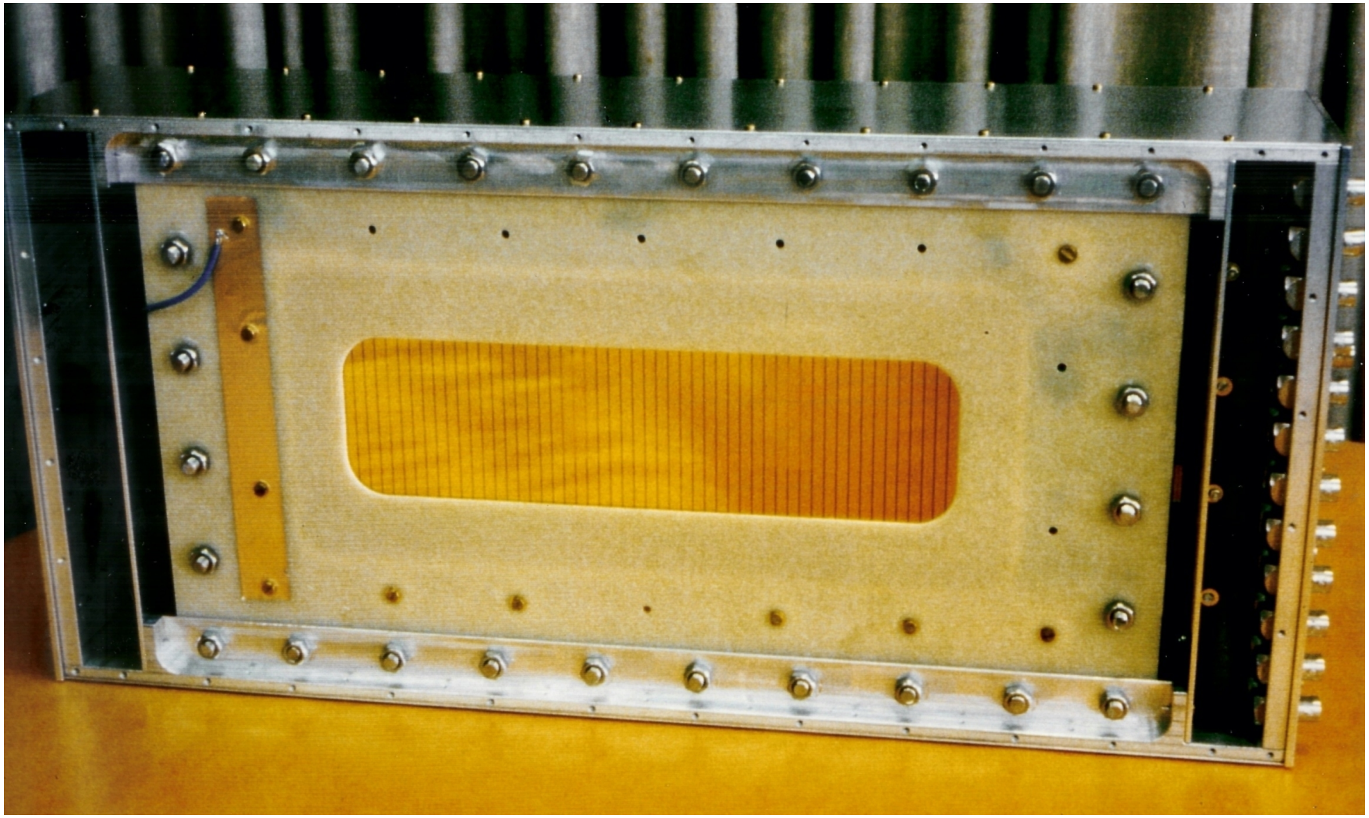


beam detectors
Hall-probes (magnetic field)
end switches (beam blocker)
…

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

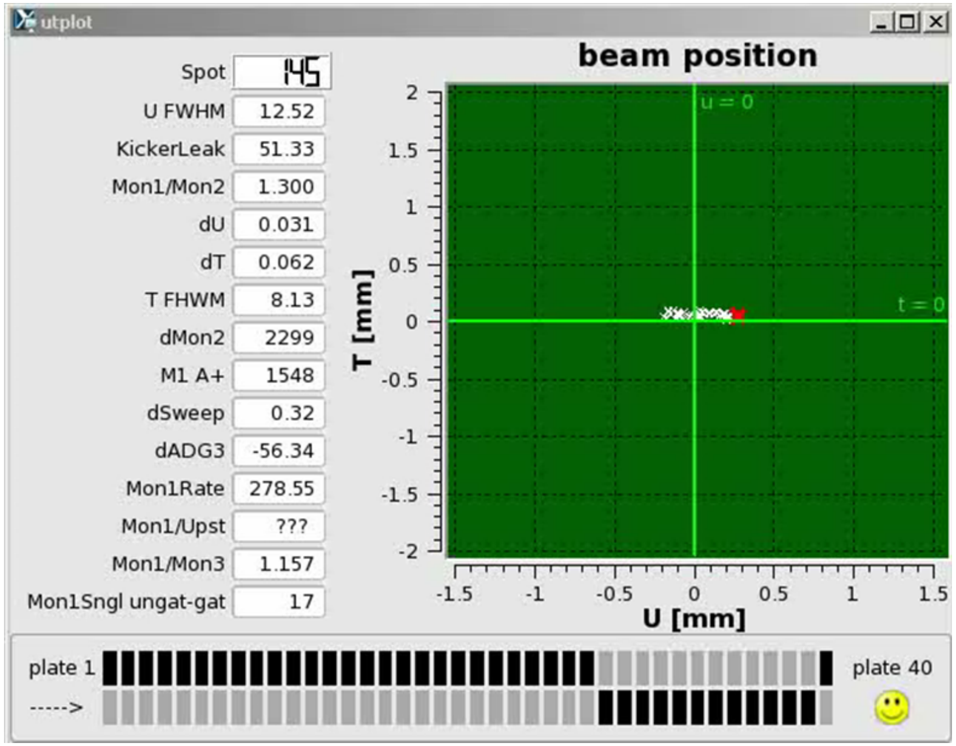
kicker magnet
beam blocker
radio frequency
ion source

Example:
measuring beam position with strip detectors

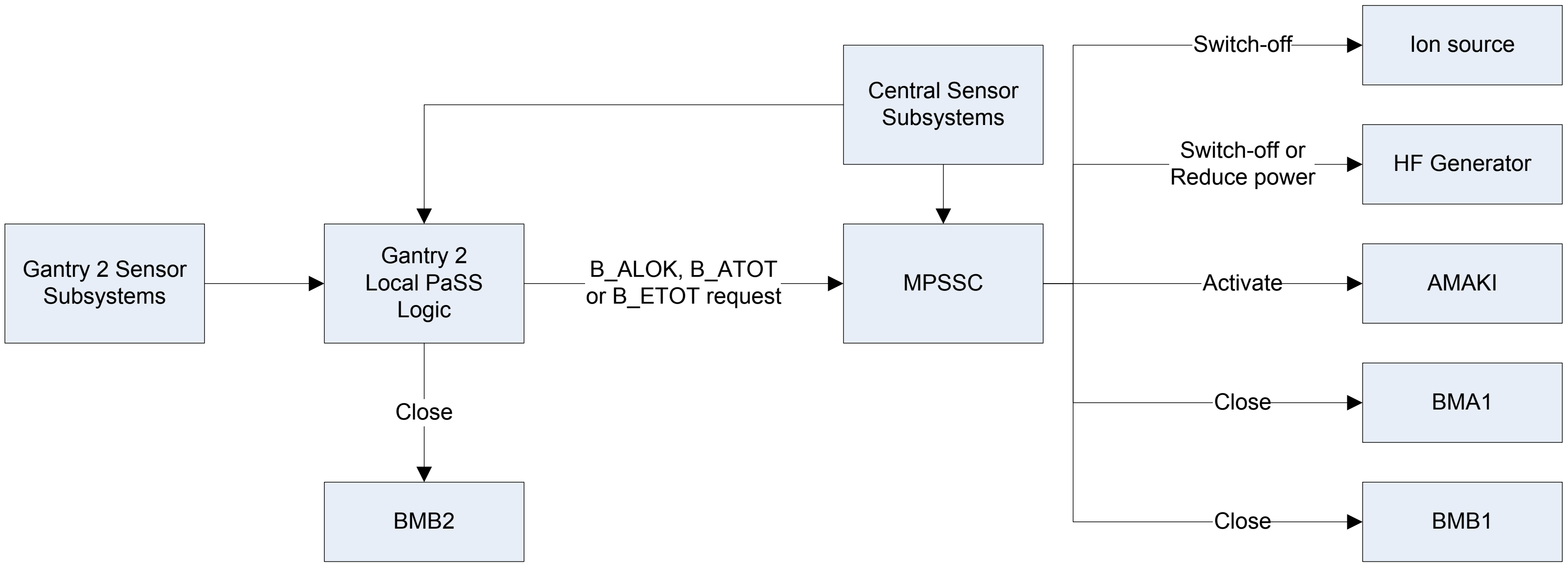


Measuring beam position

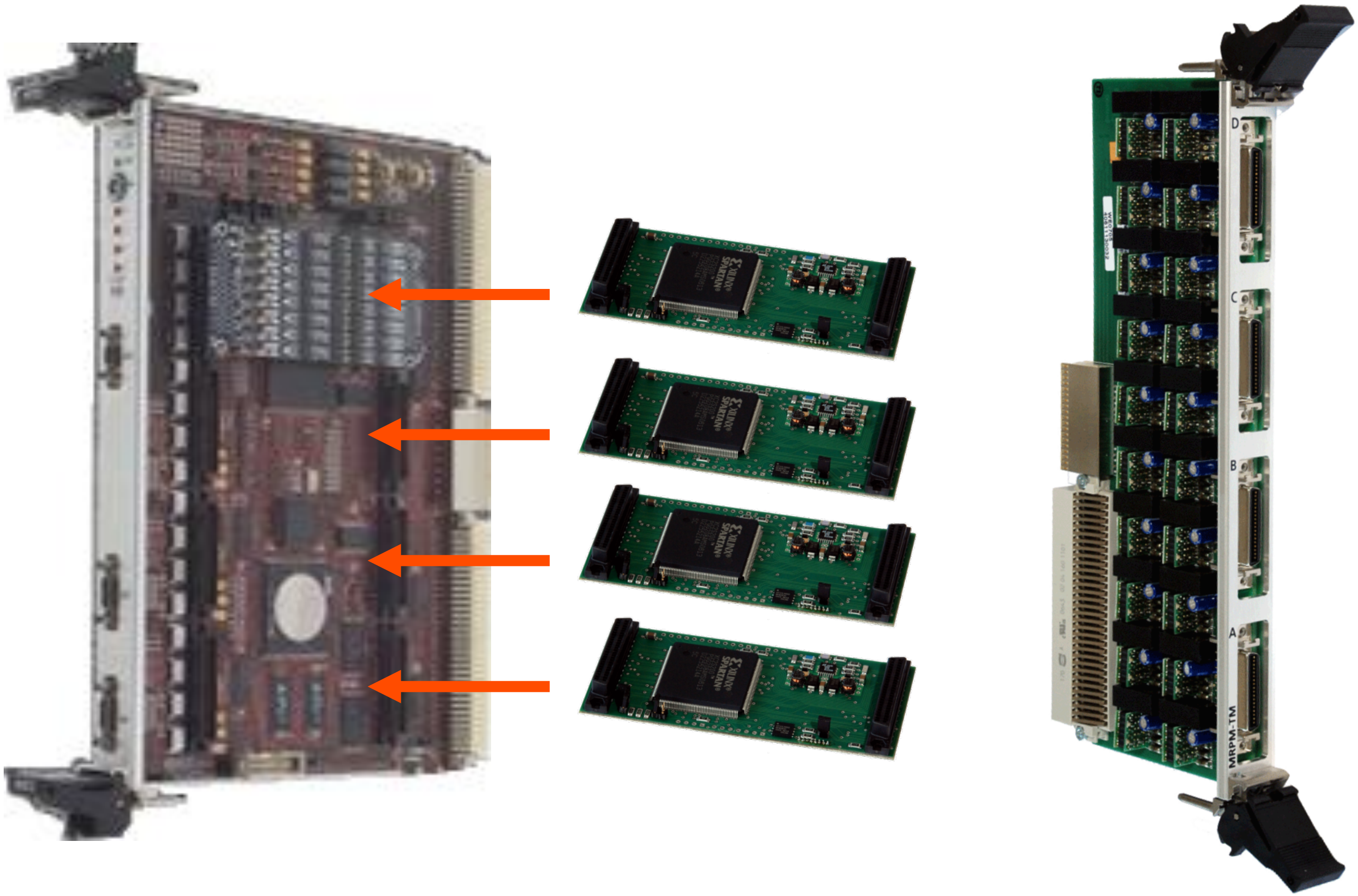
- read out strips after each spot
- determine position and compare with nominal value
- if deviation > tolerance:
  →beam switch-off by PaSS! („interlock“)



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



PSI Safety System Hardware



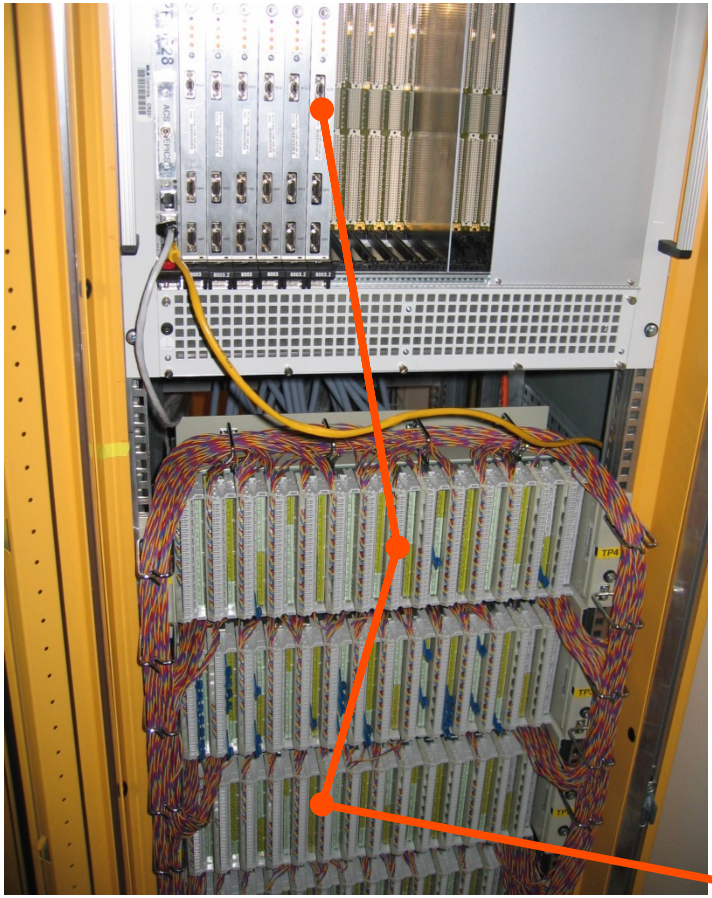
HYTEC Carrier Board
(Type VICB8003.2)

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



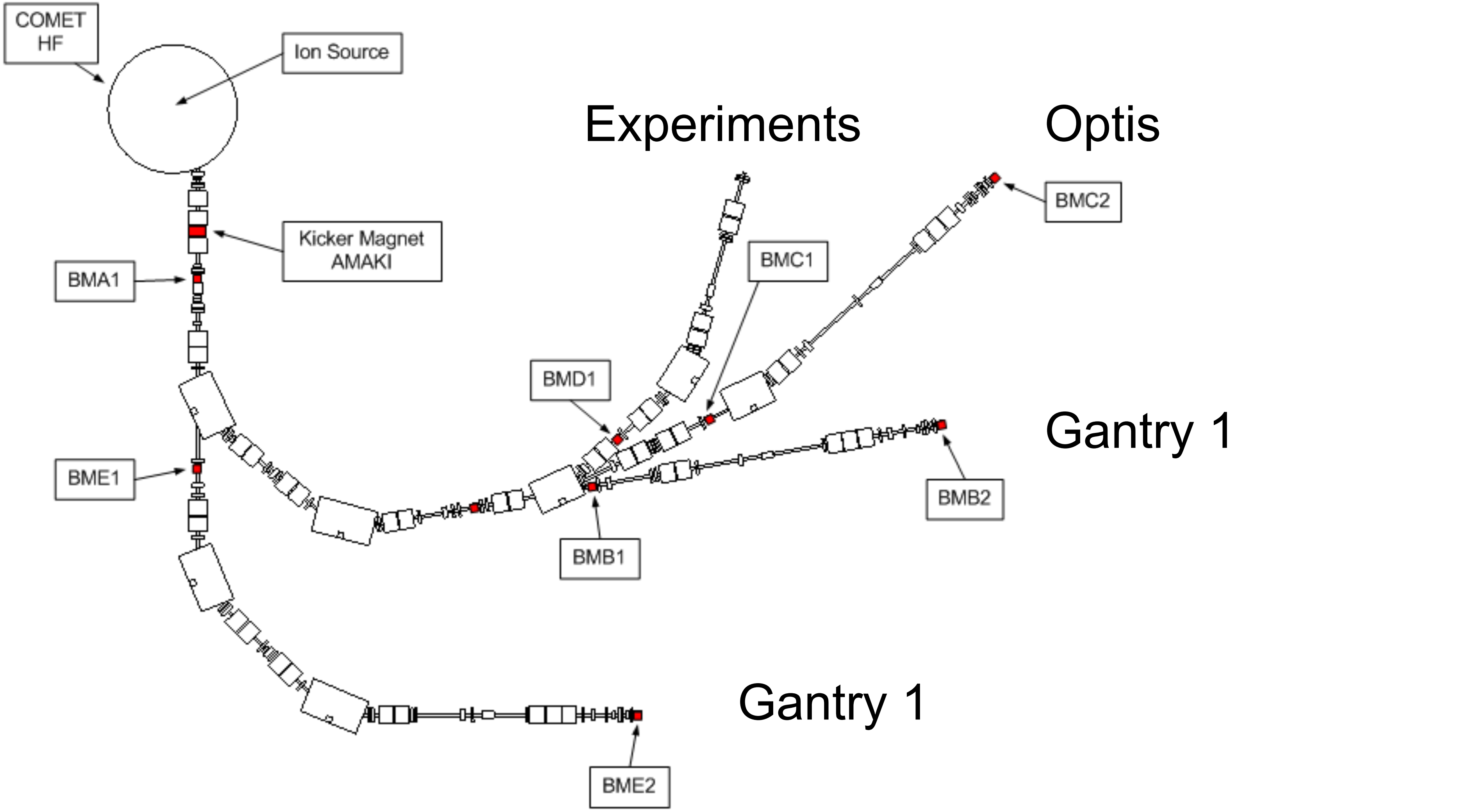
3-wire current loop interface

To/From Sensor Subsystem / Final Element

How do we switch off the beam?

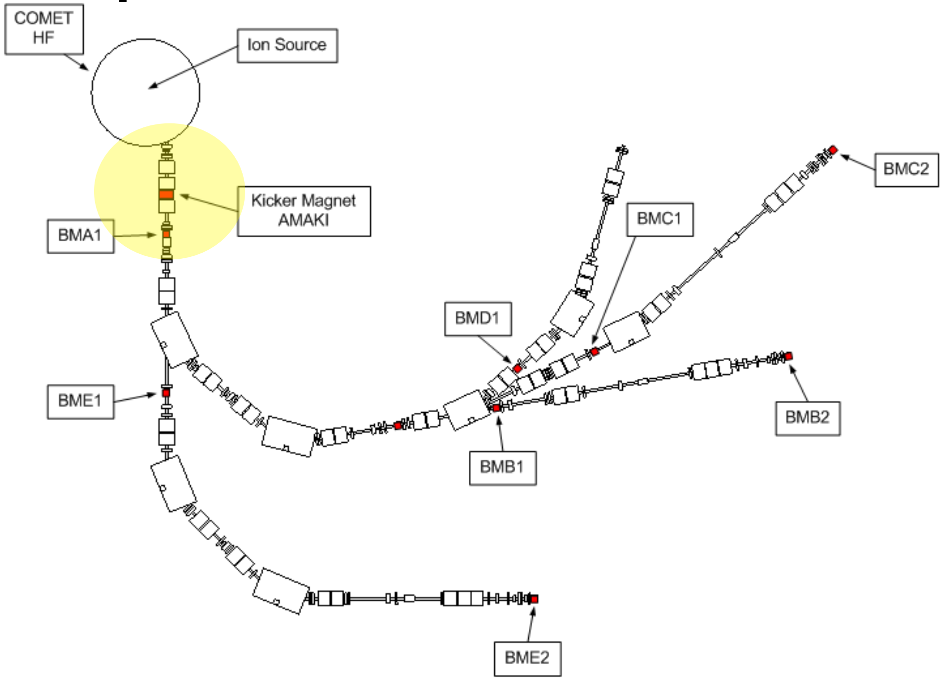
(«Final Elements»)

Proscan Final Elements



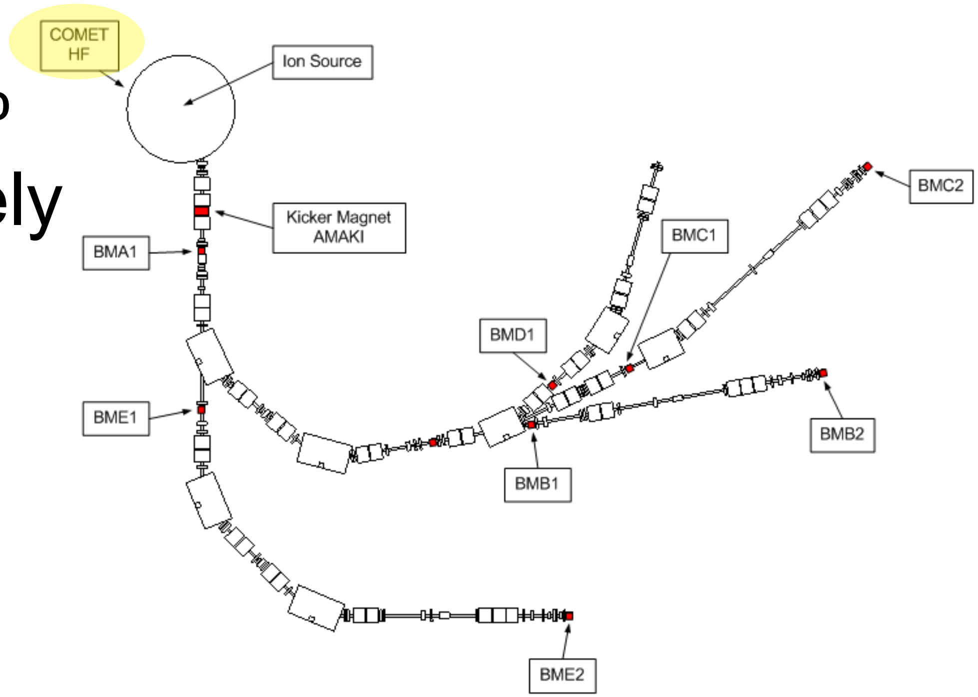
Kicker magnet

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



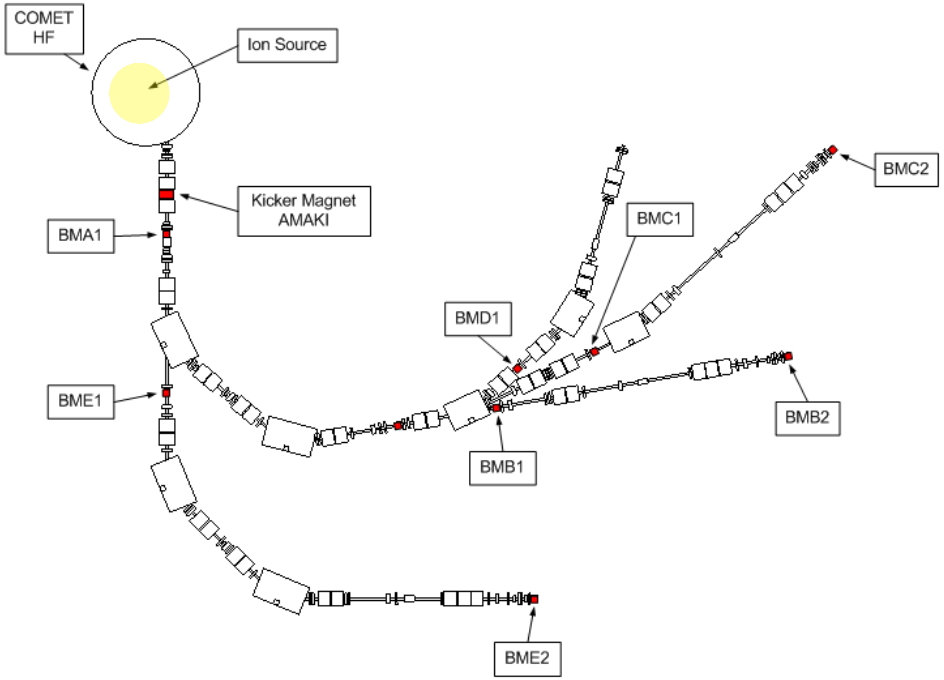
High Frequency Generator

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



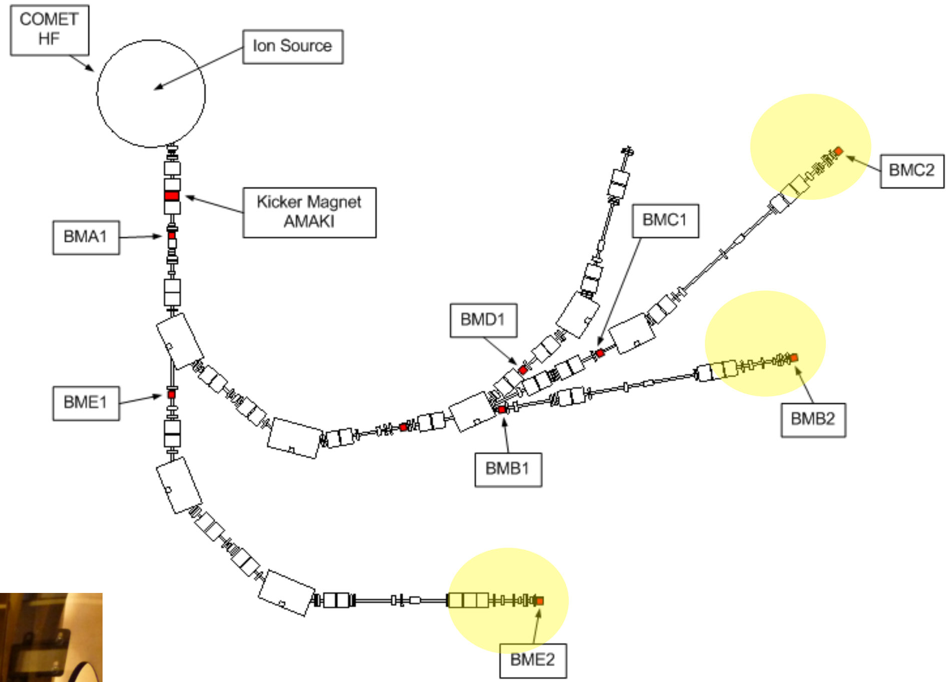
Ion source

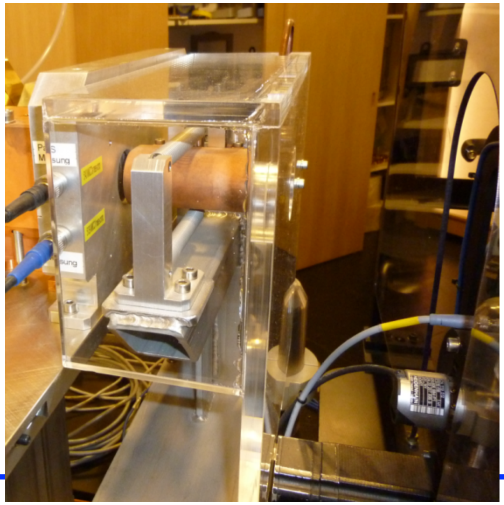
– De-energize ion source
– Switch-off in < 20 ms



Fast Mechanical Stoppers

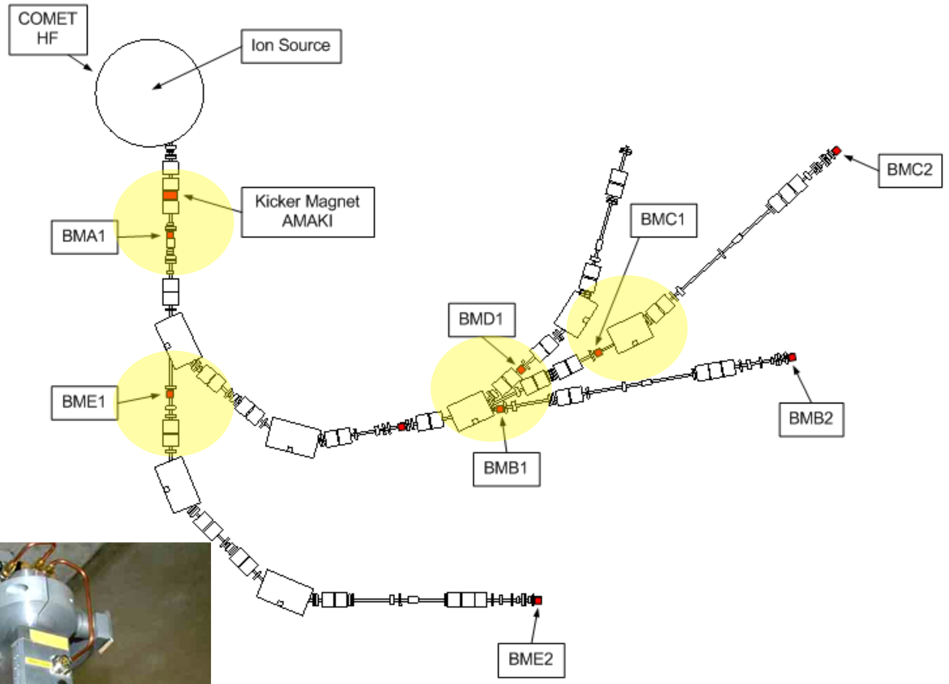
- copper block 5 cm length
- moved by pressured air & mechanical spring
  - Switch-off in < 100 ms





Slow Mechanical Stoppers

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



3 Interlock-Levels

<table>
<tr><th>Final Element</th><th>Control Function</th><th colspan="3">Safety Function</th><th>PaSS Components</th></tr>
<tr><td>BMB2</td><td></td><td rowspan="2">ALOK</td><td rowspan="2" colspan="2">escalates</td><td rowspan="2">local PaSS</td></tr>
<tr><td>AMAKI</td><td>beam off</td></tr>
<tr><td>BMB1</td><td rowspan="5"></td><td rowspan="5"></td><td rowspan="3">ATOT</td><td rowspan="3">escalates</td><td rowspan="3">MPSSC</td></tr>
<tr><td>BMA1</td></tr>
<tr><td>HF reduced</td></tr>
<tr><td>HF off</td><td rowspan="2"></td><td rowspan="2">ETOT</td><td rowspan="2">E_OR</td></tr>
<tr><td>IQ off</td></tr>
</table>

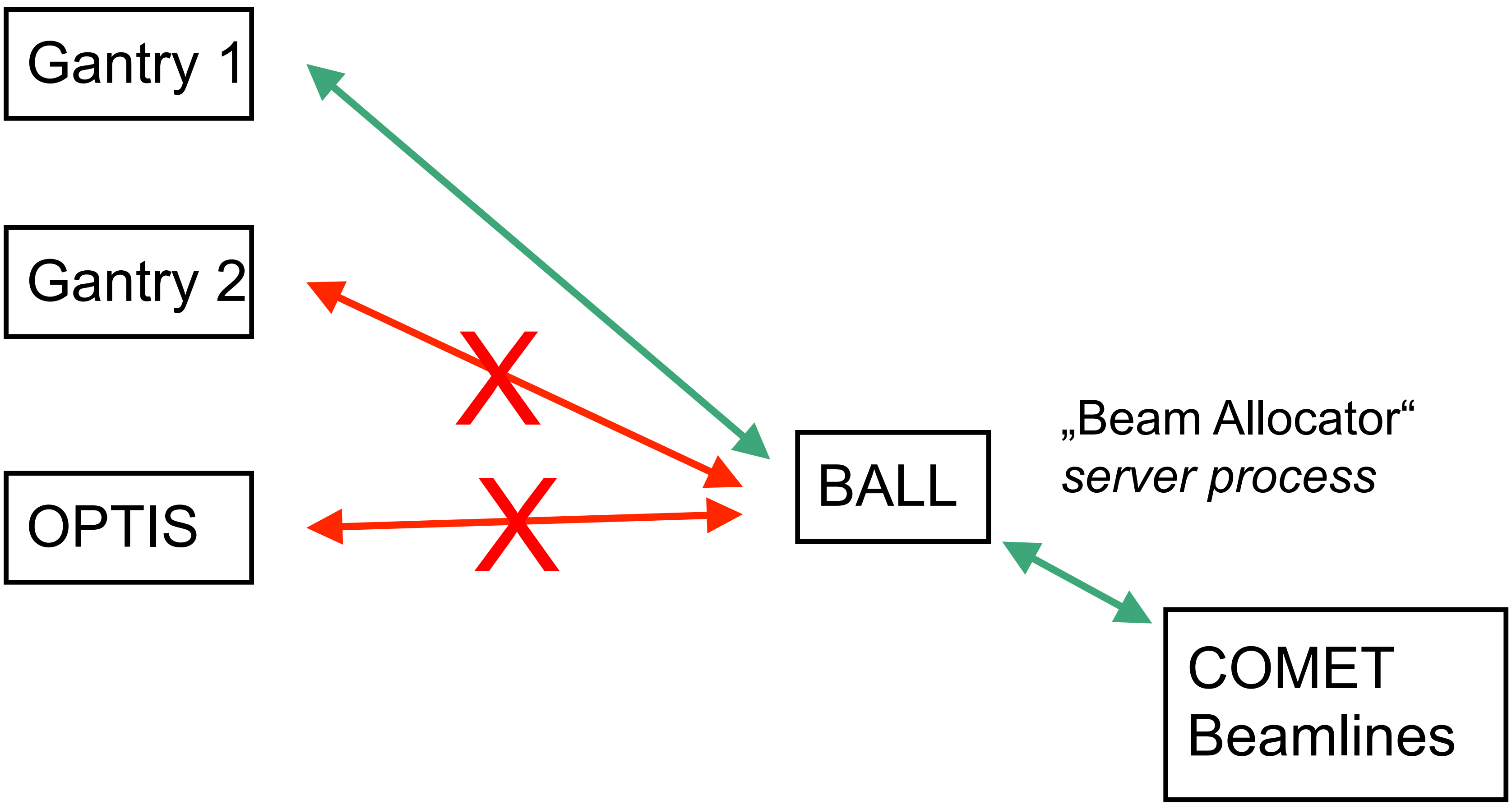
Recovery of failing beam switch off

<table>
<tr><th rowspan="2">Paragraph in this report</th><th rowspan="2" colspan="4">Failure of final element</th><th rowspan="2">Recovered by</th><th>Reaction time till next fastest final element reacts</th><th colspan="2">Extra dose delivered using regular settings (60 Gy total dose; 6 Gy/s dose rate)</th><th>Extra dose delivered using hypofractionation (10 Gy total dose; 6 Gy/s dose rate)</th><th>Extra dose delivered if beam current excursion by factor 10 (100 → 1’000 nA)</th></tr>
<tr><th>ms</th><th>Gy</th><th>% of total dose (60 Gy)</th><th>% of total dose (10 Gy)</th><th>% of total dose (60 Gy)</th></tr>
<tr><td>10.4.1.1</td><td rowspan="4">AMAKI</td><td colspan="3"></td><td>HF reduced</td><td>0.70</td><td>0.0042</td><td>0.007</td><td>0.042</td><td>0.07</td></tr>
<tr><td>10.4.1.2</td><td rowspan="3">+ HF reduced</td><td colspan="2"></td><td>HF off</td><td>0.98</td><td>0.006</td><td>0.01</td><td>0.06</td><td>0.1</td></tr>
<tr><td>10.4.1.3</td><td rowspan="2">+ HF off + IQ off</td><td></td><td>BMB2</td><td>60</td><td>0.36</td><td>0.6</td><td>3.6</td><td>6.0</td></tr>
<tr><td>10.4.1.4</td><td>+ BMB2</td><td>BMB1, BMA1</td><td>1’000</td><td>6.0</td><td>10</td><td>60</td><td>100</td></tr>
</table>

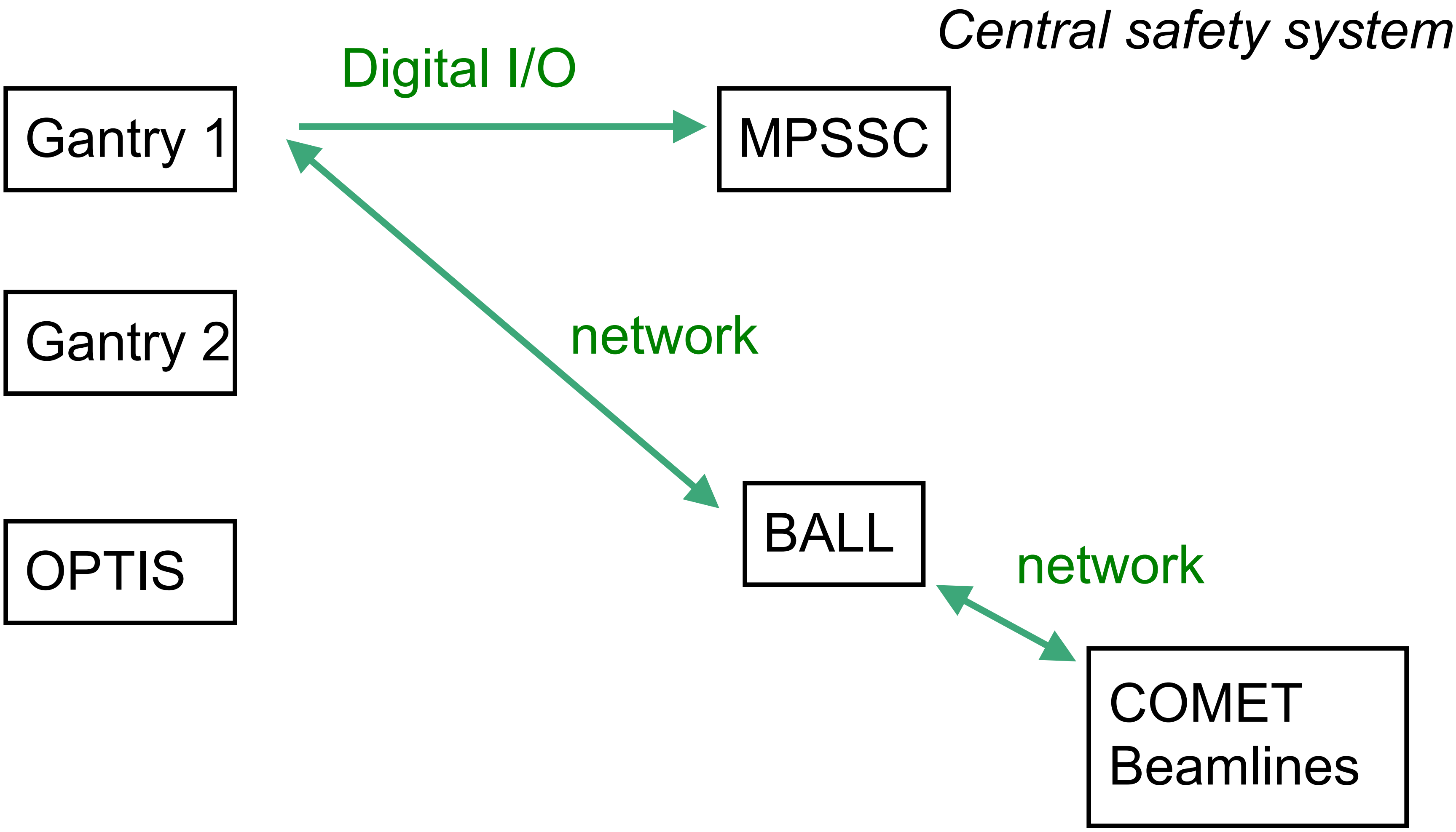
The concept of Mastership

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

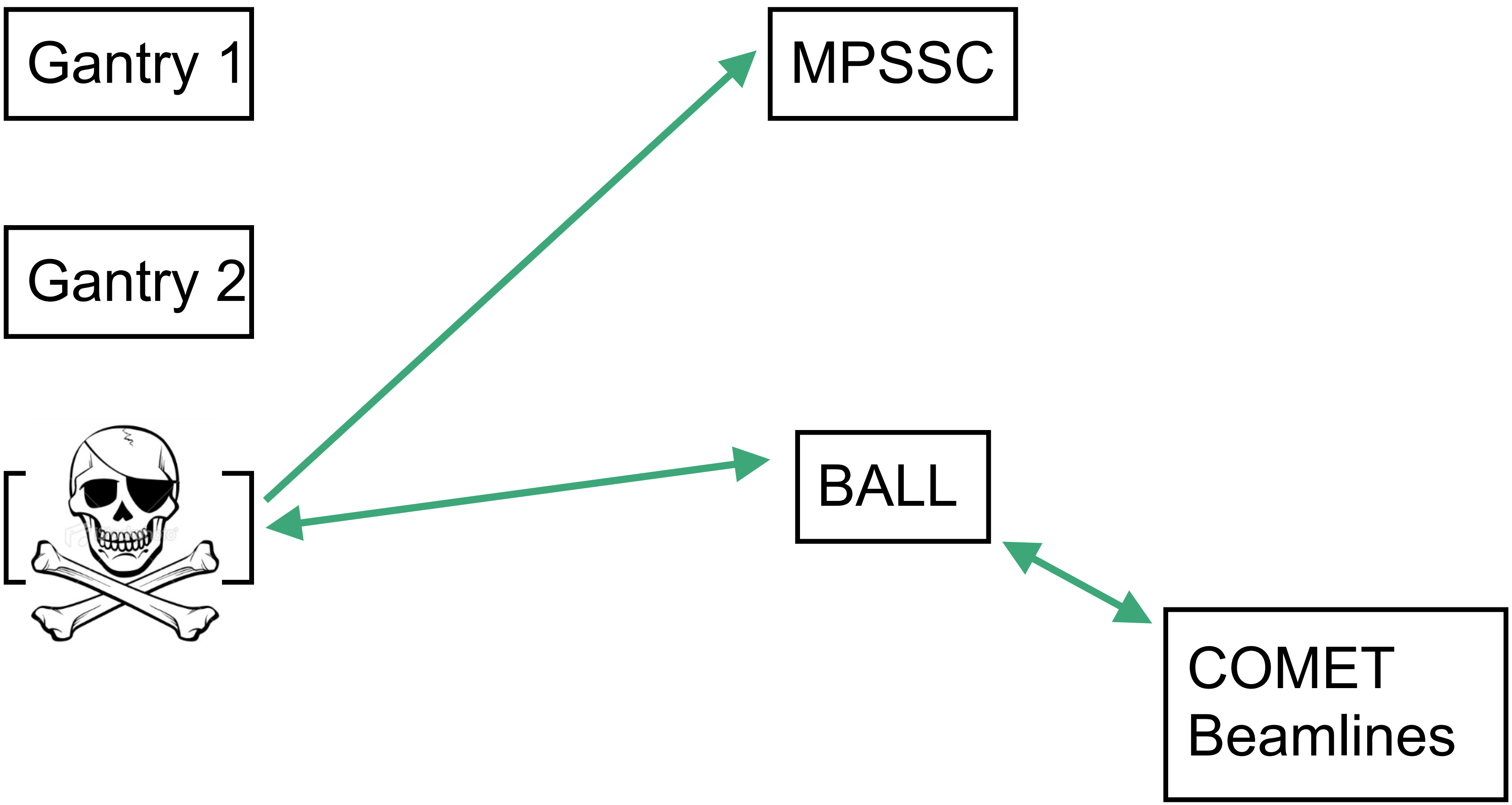
The concept of Mastership



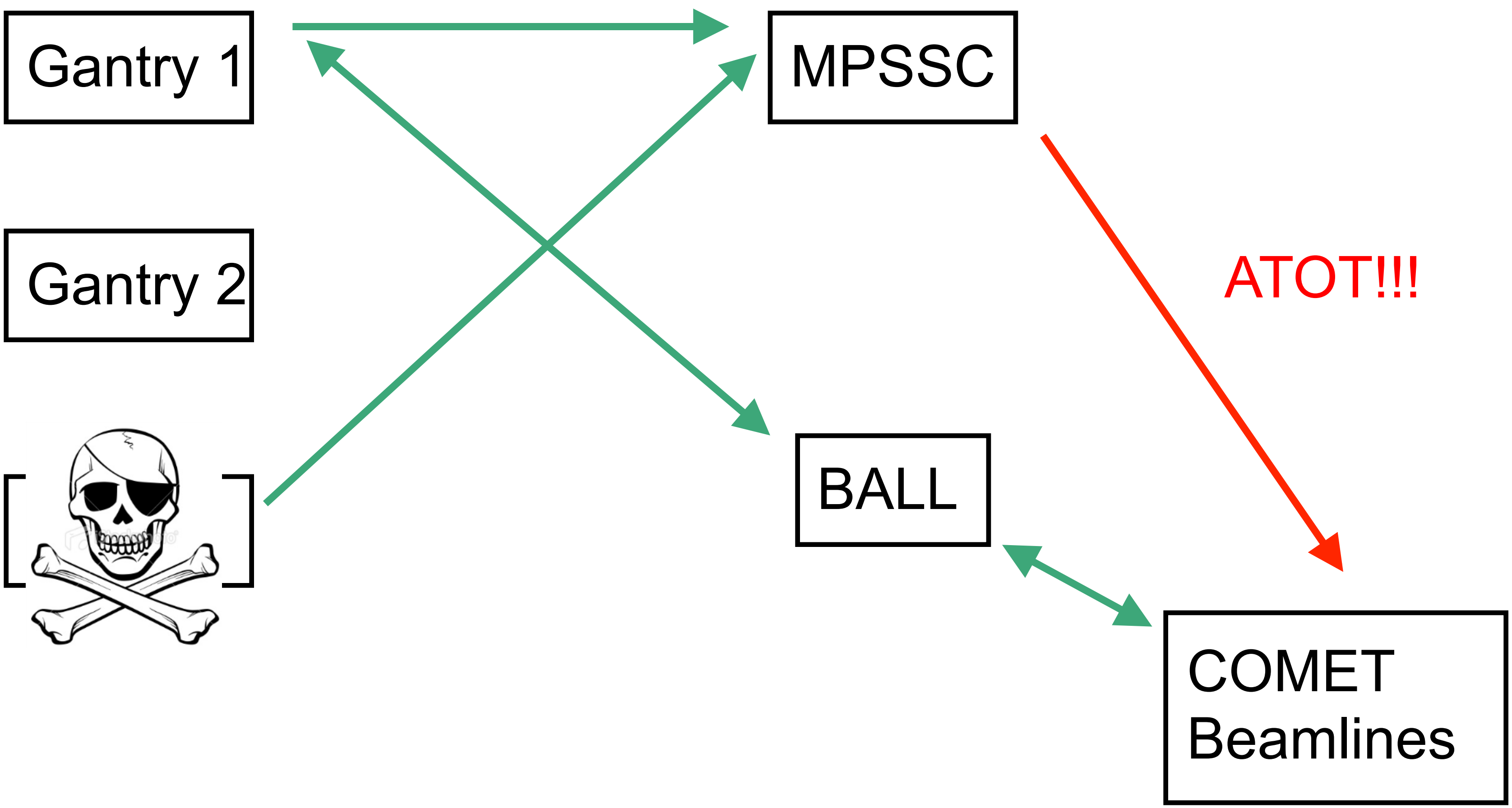
Mastership verification



Mastership verification

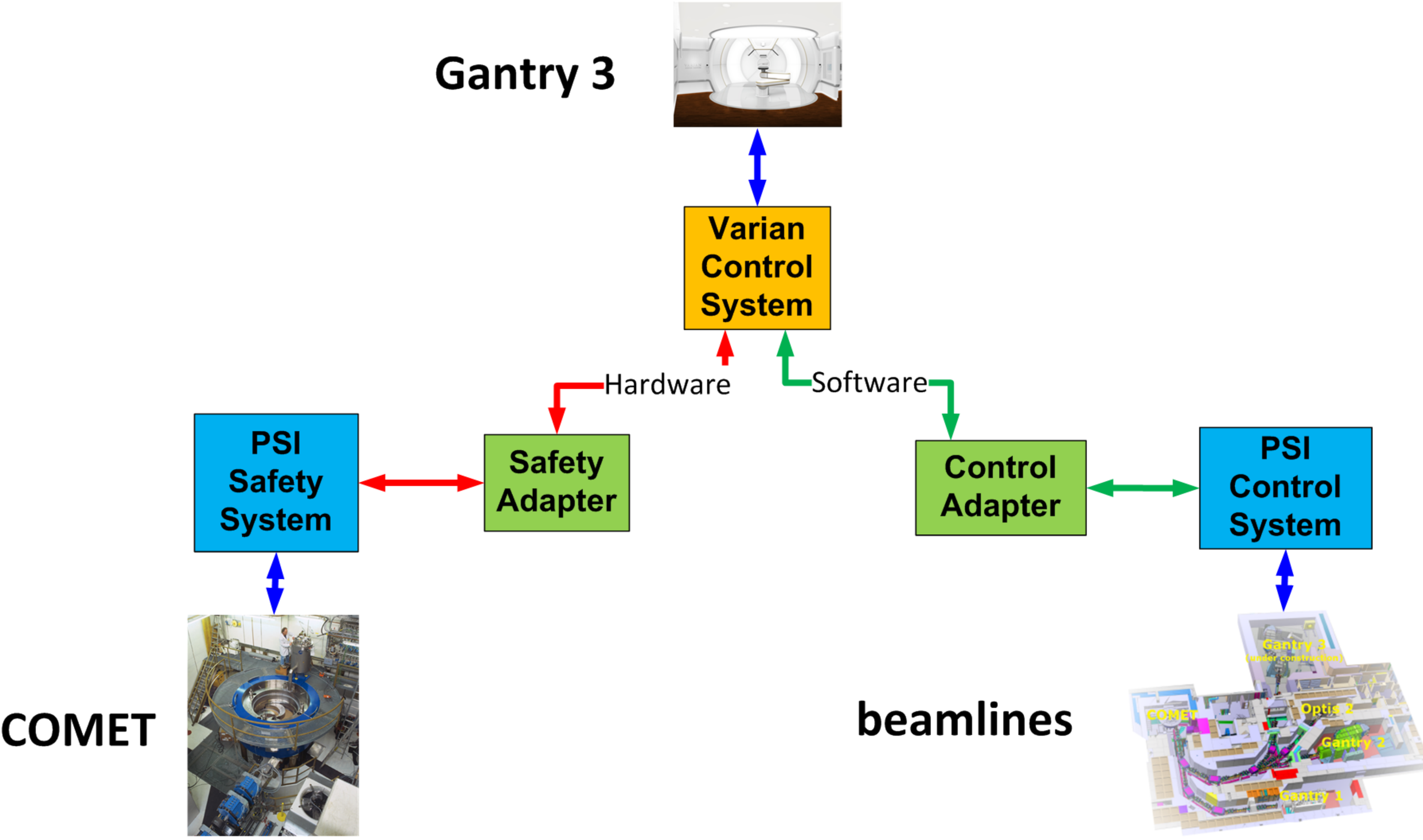


Mastership verification

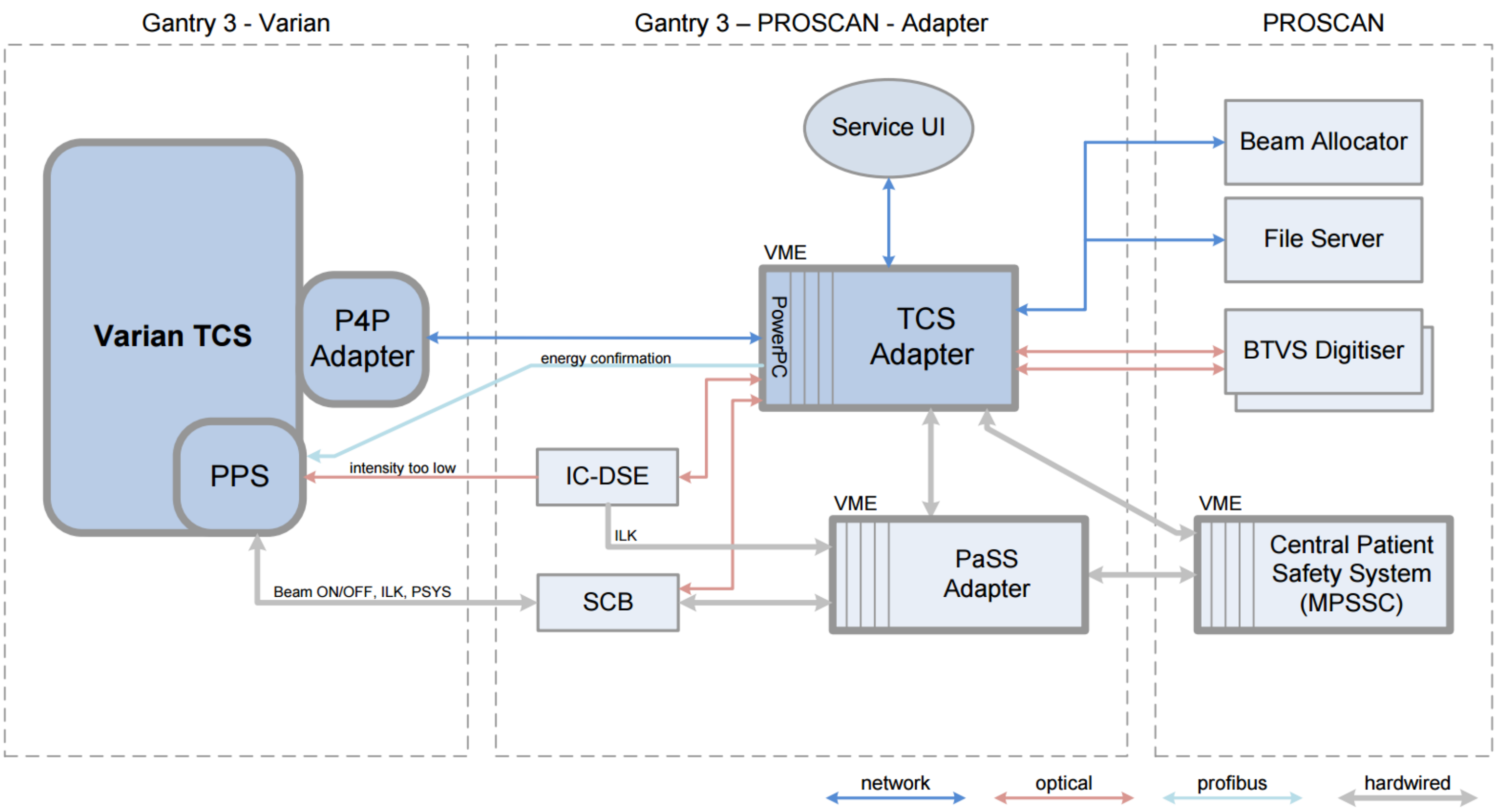


Integration of Gantry 3

- 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

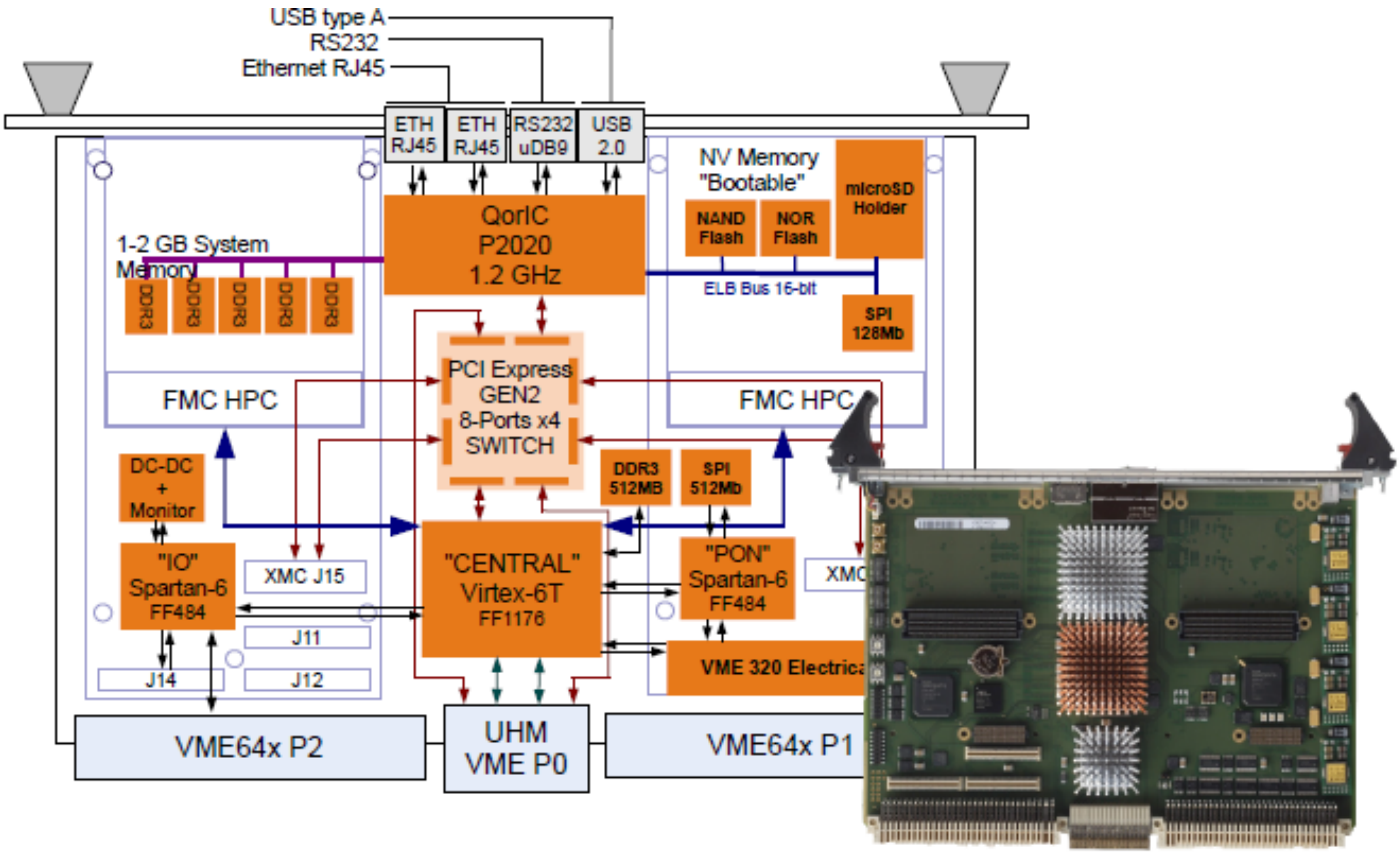

Gantry 3
Varian Control System
Hardware
Software
PSI Safety System
Safety Adapter
Control Adapter
PSI Control System
COMET
beamlines
Gantry 3
(under construction)
COMET
Optis 2
Gantry 2
Gantry 1

Control Adapter

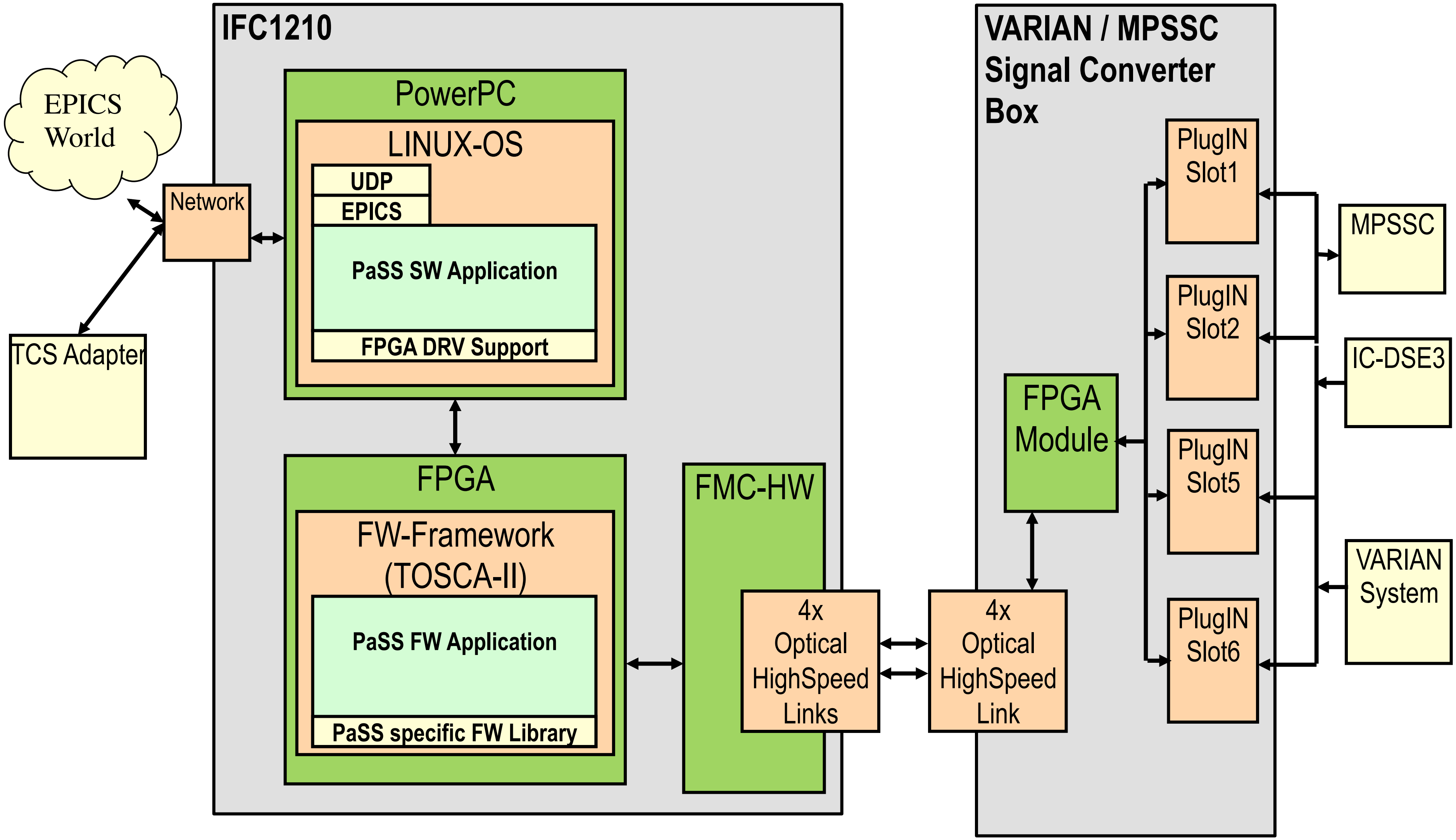


Safety Adapter

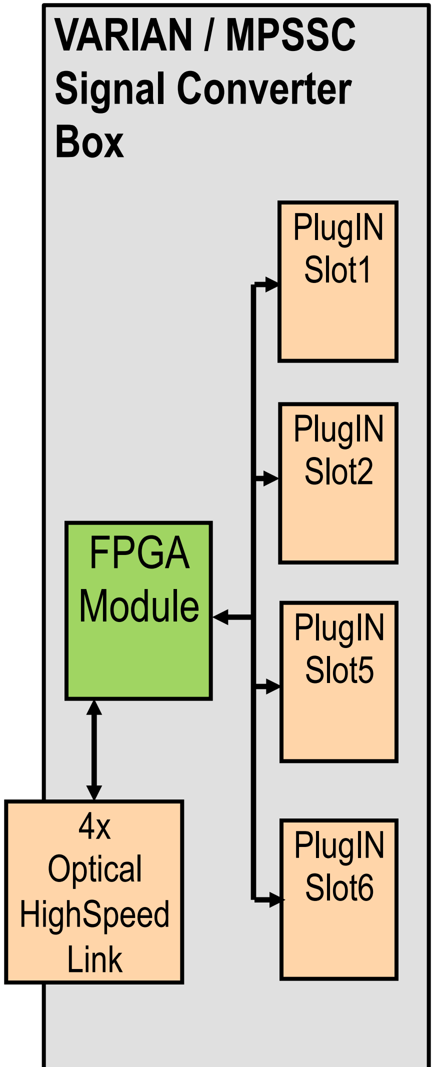
- HW based on IFC1210 (www.ioxos.ch)



Safety Adapter

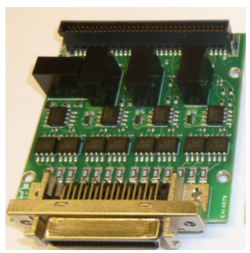


Signal Converter Box

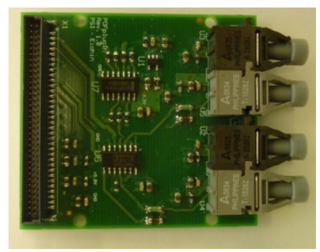


Simple HW box, which fits into 19 inch crate
Interfaces:

- 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.

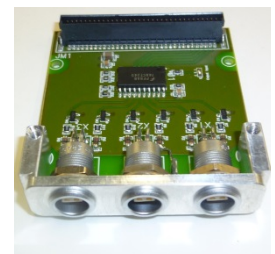


PSI 3-wire



optical

Analog +/-10V

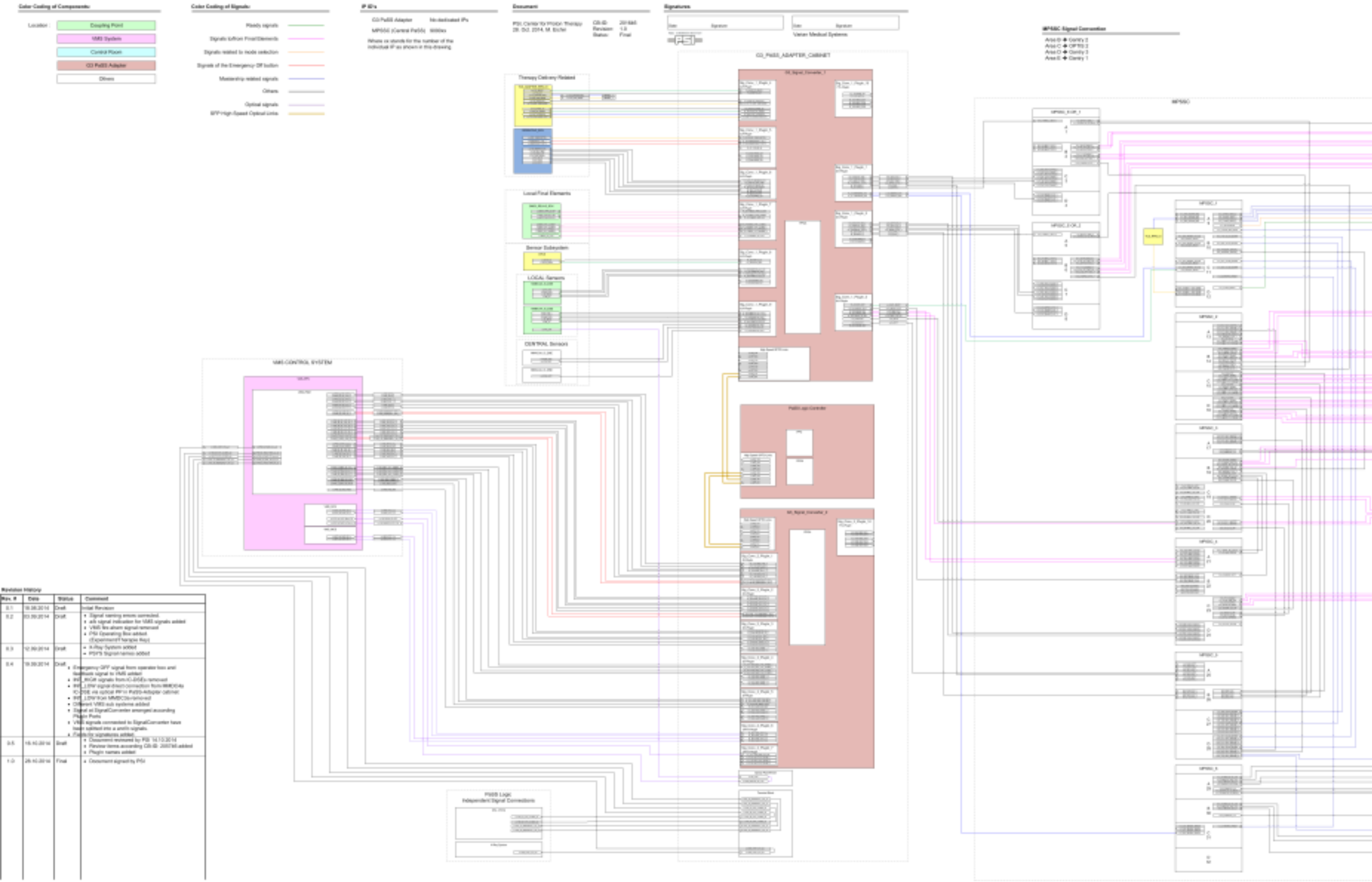


5V TTL

LVDS

- 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

Gantry 3 Patient Safety System Architecture



If you think proton therapy controls is complicated…

Union Pacific «Big Boy» 1941


1. Lubricator Steam Valve
2. Smoke Lifting Blower Valve
3. Lubricator Drain Valve
4. Lubricator Atomizer Valve
5. Lubricator Feed Valve
6. Lubricator Main Steam Valve
7. Blower Valve
8. Stoker Jet Valve
9. Injector Operating Lever
10. Stoker Booster Valve
11. Stoker Operating Valve
12. Respirator Valve
13. Respirator Valve
14. Defroster Valve
15. Injector Heater Valve
16. Injector Water Regulator Valve
17. Squirt Hose Valve
18. Stoker Jet, Left Bottom Valve
19. Stoker Jet, Left Top Valve
20. Stoker Jet, Right Top Valve
21. Stoker Jet, Right Bottom Valve
22. Stoker Jet, Left Side Valve
23. Stoker Jet, Center Valve
24. Stoker Jet, Right Side Valve
25. Ash Pan Sprinkler, Left Bottom Valve
26. Ash Pan Sprinkler, Left Top Valve
27. Ash Pan Sprinkler, Right Top Valve
28. Ash Pan Sprinkler, Right Bottom Valve
29. Main Valve, Ash Pan Sprinkler
30. Top Valve, Left Top Water Glass
31. Top Valve, Left Bottom Water Glass
32. Steam Heat Valve
33. Bottom Valve, Left Top Water Glass
34. Drain Valve, Left Top Water Glass
35. Drain Valve, Left Water Column
36. Drain Valve, Left Bottom Water Glass
37. Bottom Valve, Left Bottom Water Glass
38. Dynamo Steam Valve
39. Fire Door Air Valve
40. Bottom Valve, Right Bottom Water Glass
41. Drain Valve, Right Bottom Water Glass
42. Drain Valve, Right Water Column
43. Drain Valve, Right Top Water Glass
44. Bottom Valve, Right Top Water Glass
45. Top Valve, Right Bottom Water Glass
46. Top Valve, Right Top Water Glass
47. Sludge Remover Shutoff Valve
48. Air Pump Steam Valve
49. Bottom Gage Cock
50. Middle Gage Cock
51. Top Gage Cock
52. Defroster Valve
53. Reverse Gear Steam Valve
54. Rail Washer Valve
55. Cylinder Cock Operating Valve
56. Cylinder Cock Main Valve
57. Fire Door Shutoff Valve
58. Cab Duster Valve
59. Right Injector Operating Valve
60. Bell Ringer Valve
61. Sander Valve
62. Automatic Brake Valve
63. Independent Brake Valve
64. Main Throttle
65. Reverse Gear
66. Sludge Remover Valve
67. Train Control Acknowledgement Handle
68. Front Engine Brake Cylinder Cutout
69. Back Engine Brake Cylinder Cutout
70. Tender Brake Cylinder Cutout
71. Headlight
72. Whistle
73. Cab Roof Ventilator
74. Reducing Valve
75. Feed Valve
76. Right Injector Overflow Valve
77. Steam Heat Regulator Valve - Under Deck
78. Smoke Deflector Operating Valve
79. Fire Door Operating Pedal