Safety Instrumented Systems and the AWAKE Plasma Cell Control as a Use Case

THCPA01, Functional safety and machine protection

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Outline

1. Goals
2. AWAKE plasma cell
3. Requirements
4. Project lifecycle engineering: **design**
5. Lessons learned and conclusions

Goals

Overview the **LIFECYCLE** of the safety instrumented system engineering

- Highlight the importance of the **REQUIREMENTS**: hazard identification and risk assessment
- Focus on the **DESIGN phase** using **standards**
  (1) Machine/installation/process was not designed with a safe mission
  (2) Use of not safety certified components

Functionality

- Show the integration with a basic **process control system (BPCS)**

AWAKE

- It is a proof-of-principle experiment which explores the use of **plasma** to accelerate particles to high energies over short distances.
- Use SPS accelerator protons to create **wakefields** and then a second beam of electrons is accelerated to *TeV* energies.

ILC Cavity: 35 MV/m

Plasma cell: 35 GV/m ➔ **35 MV/mm !!**
No need of vacuum, no magnets nor RF

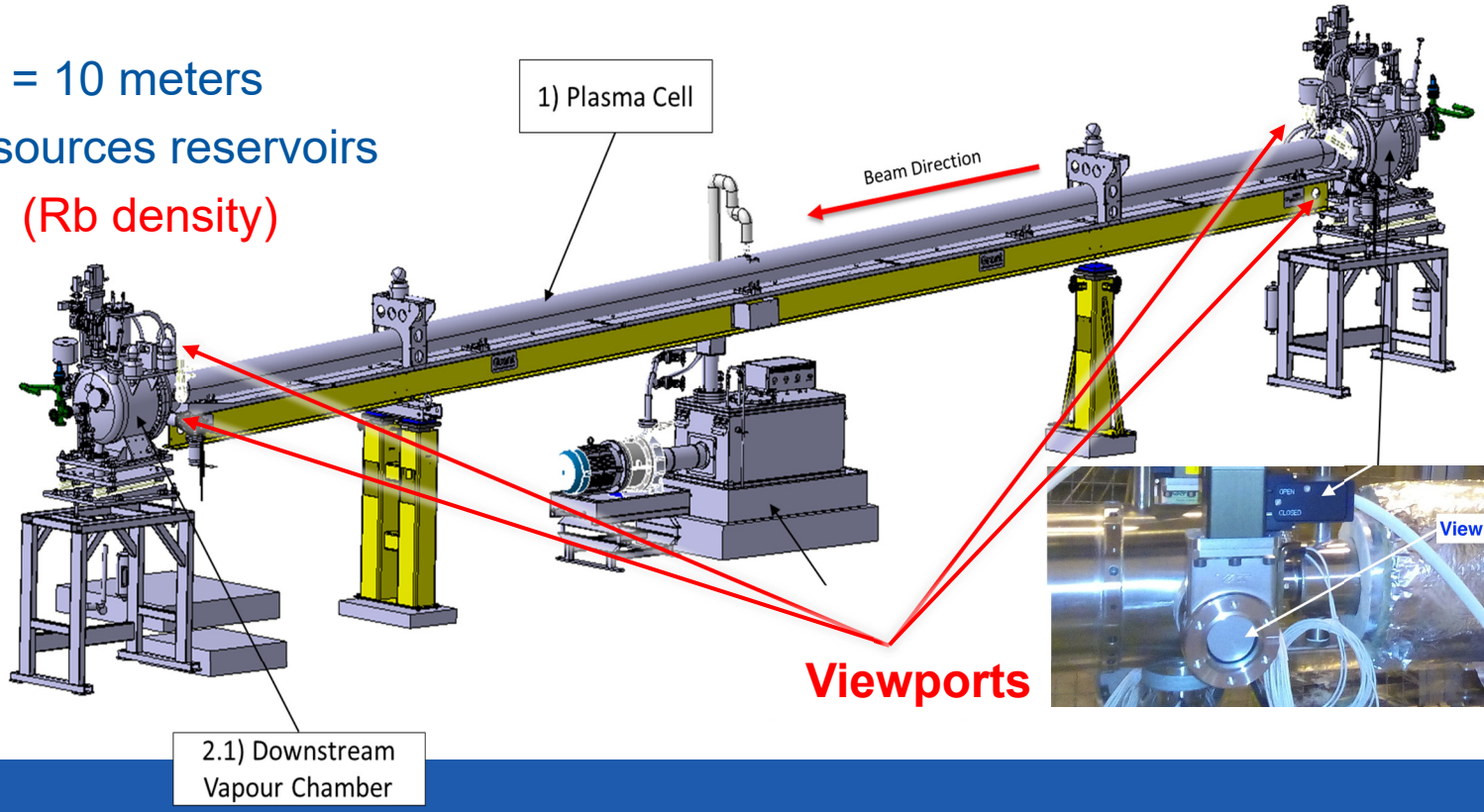
http://www.cern.ch/awake

AWAKE plasma cell

Plasma cell = 10 meters

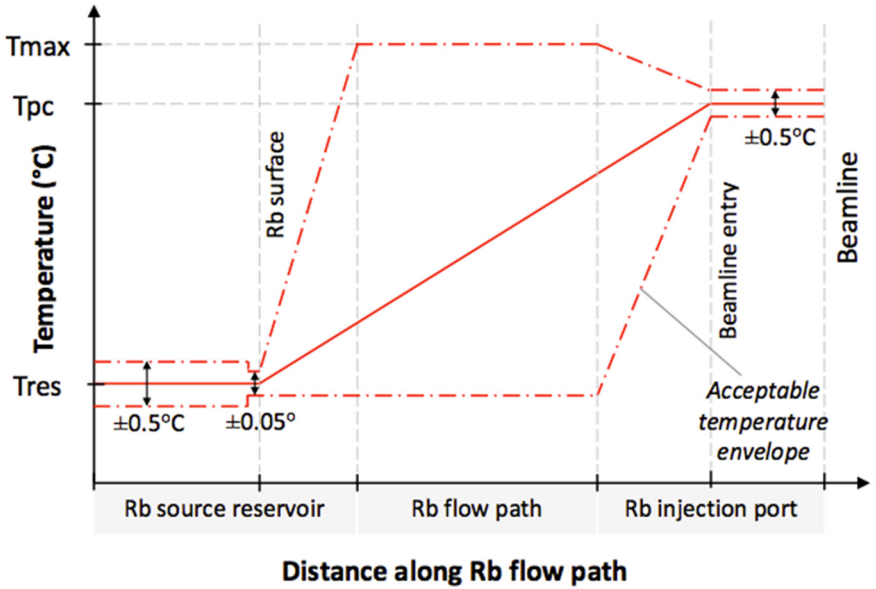
2 rubidium sources reservoirs

4 viewports (Rb density)



Operational requirements

1. Keeping the 10 meters plasma cell **isothermal** (~220 ºC) avoiding cold spots and possible intermediate rubidium condensation.
2. Avoiding temperature dispersion larger than **0.05 ºC** in some specific places
3. Providing a **safe environment** during operation with rubidium



Standards in Functional Safety Engineering

IEC 61508: Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems

IEC 61511: Functional safety for the Process Industry

ISA 84: Safety Instrumented Systems (SIS)

ISA 84.01-1996 did not require a quantitative assessment of PFDavg. Instead, it stated that the user could rely on past performance of an existing SIS design as the basis for justification of its continued use.

Functional safety standards

Simplified lifecycle

(1) Analysis

- Hazard identification
- Risk assessment
- Safety functions

(2) Realization

- **Design**
- Installation
- Commissioning

(3) Operation

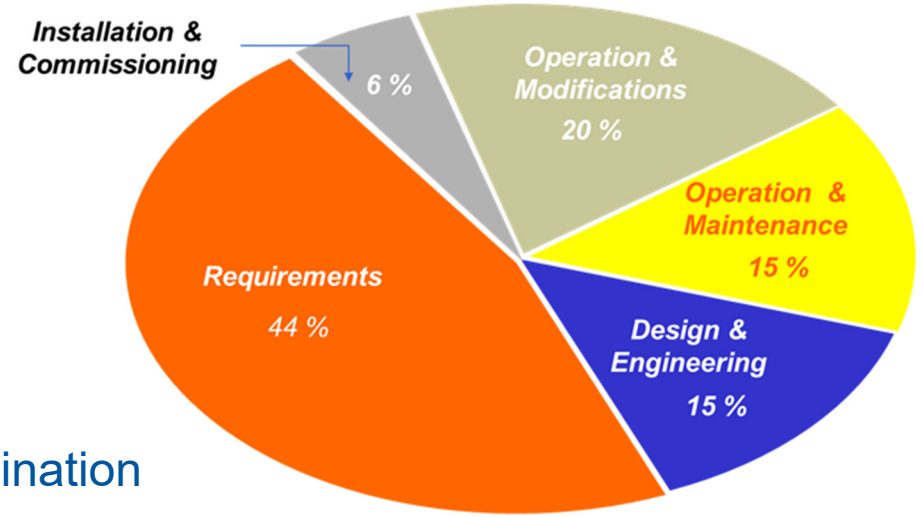
- Maintenance for SIL
- Management of change

Management of safety

(1) Analysis

- **Hazard analysis**
- **Risk assessment**
- **SIL determination**

- Safety instrumented function determination (requirement)



Failures
Source: Yokogawa 2016

Analysis @ AWAKE

- **Safety file** or the result of the hazard analysis and risk assessment
- FMEA like document:
  - **Hazards**
  - **Causes**
  - **Hazardous events**
  - **Consequences**
  - **Risk**
  - **Actions**

27 hazardous events analyzed

RISK ASSESSMENT FORM OHS-0-0-2

Description of the activity: Rb Vapour Source Operation
Type of activity: OPERATION
Date: 05 July 2016

	Hazard	Causes	Hazardous Event(s)	Consequences	Control measure(s)
TYPE	BIOLOGICAL SAFETY				
	Biological agents	N/a			
	Legionella	N/a			
TYPE	CHEMICAL SAFETY				
	Asbestos	N/a			
	Asphyxiant	Argon gas present for system protection	Uncontrolled release of argon gas into tunnel	Potential asphyxiation of personnel local to release	Use of piping and connectors suitable for high pressure gas Installation of piping done by certified personnel Labelling of argon bottle and piping to ensure personnel aware
		Portable argon gas required for rubidium loading and recycling	Uncontrolled release of argon gas into tunnel	Potential asphyxiation of personnel local to release	Use of piping and connectors suitable for high pressure gas Installation of piping done by certified personnel Labelling of argon bottle a

FMEA: Failure Modes and Effects Analysis

Analysis @ AWAKE

Table 1: Hazard analysis summary

Hazard	Cause	Effect
Rb	Oxygen contact	Burning, fire
Beam	Collisions	Radiation injury
Laser	Exposure	Eye damage
Toxic	Overheating	Respiratory

Risk evaluation [R]		Probability of the hazardous event			
		1	2	3	4
Potential severity	A	A1	A2	A3	A4
	B	B1	B2	B3	B4
	C	C1	C2	C3	C4
	D	D1	D2	D3	D4

Risk evaluation table

Weakest point on the **viewports**

SIS
Control system

SIL 2

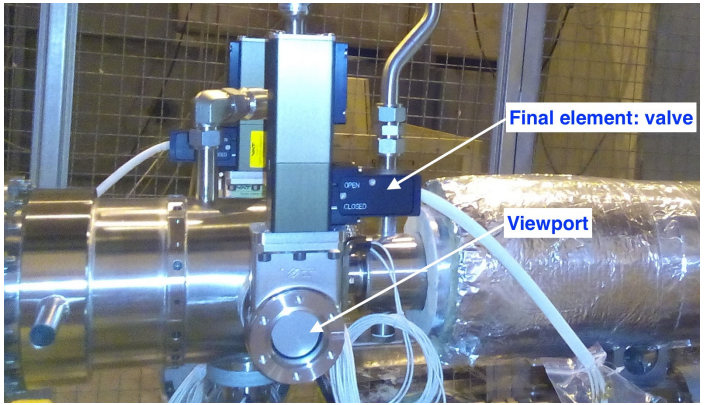
Access Control

Thermo-switch

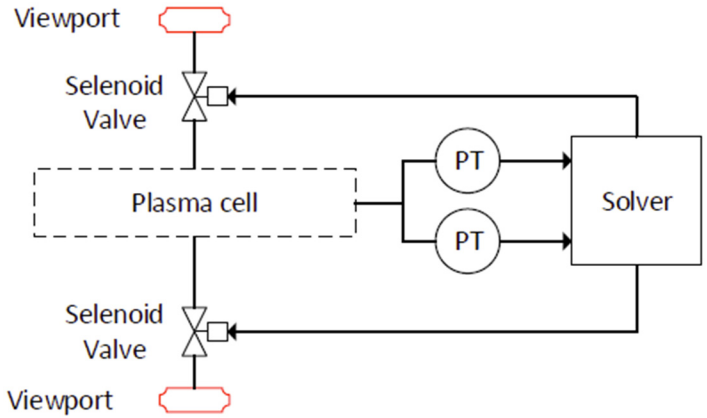
Analysis @ AWAKE

Safety Instrumented Function (SIF): **SIL 2**

Isolate the **rubidium** inside the plasma cell by closing the valves behind the viewports once a leak of the plasma cell is detected



Plasma cell (viewports)

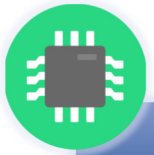


Safety Instrumented Function Loop

(2) Realization

Procedure to **achieve** specified **SIL**

IEC 61508



Hardware Safety Integrity

- Quantify **random** hardware failures

AND

- Comply with requirements for **Architectural Constraints**

Systematic Safety Integrity

- Comply with requirements for **systematic** safety integrity

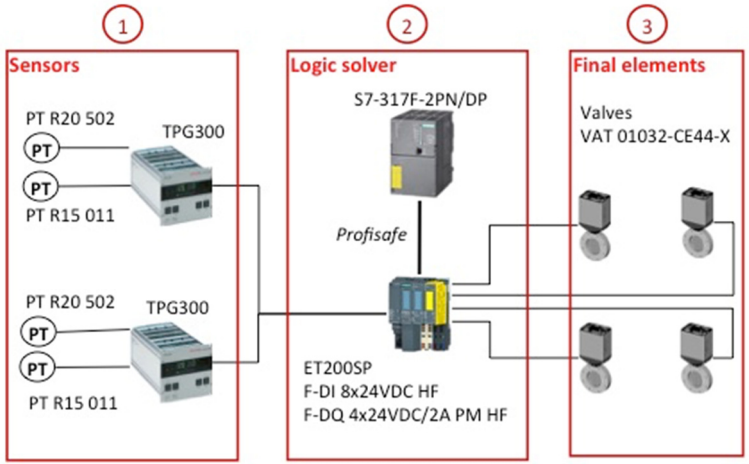
OR

- Comply with requirements for Proven in Use (PIU)

Hardware Safety Integrity

Quantify *random* hardware failures

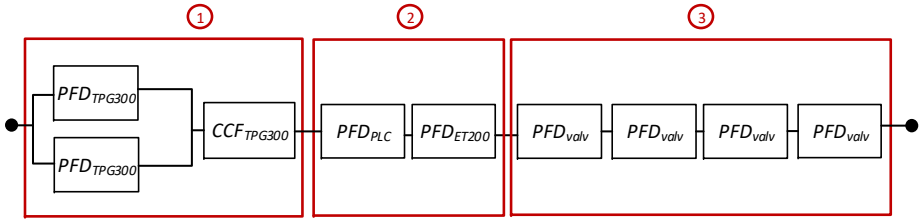
PFD (Probability of failure under demand)



Safety Instrumented Function architecture

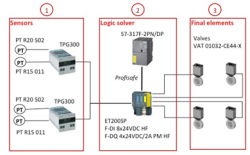
SIL	PFD_{avg}	Risk Reduction
4	$10^{-5} \leq PFD < 10^{-4}$	100,000 to 10,000
3	$10^{-4} \leq PFD < 10^{-3}$	10,000 to 1,000
2	$10^{-3} \leq PFD < 10^{-2}$	1,000 to 100
1	$10^{-2} \leq PFD < 10^{-1}$	100 to 10

*IEC 61508 **Low demand** SIL determination*



Reliability Block Diagram

Hardware Safety Integrity



SIF architecture

Quantify *random* hardware failures

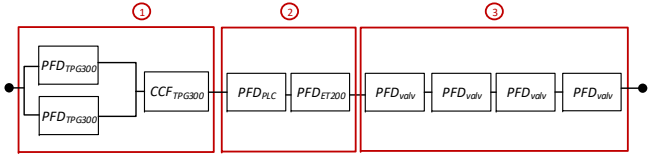
PFD (Probability of failure under demand) simplified calculation:

$$PFD = \lambda_D * \frac{T}{2} \qquad (1)$$

λ_D: *failure rate*
T: proof test frequency

PFD of the selected architecture:

$$PFD_{Total} = PFD_1 + PFD_2 + PFD_3 \qquad (2)$$



Reliability Block Diagram

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IEC 61508 Low demand SIL determination

1 Non safety certified

$$PFD_1 = \frac{\lambda_D^2 * T^2}{3} + \beta\frac{\lambda_D * T}{2}$$

β: 20% (fraction of failures that have a common cause)
T: 4 weeks $PFD_1 = 6.15*10^{-5}$
MTTF: 156years* (MTTF=1/λ_D) >> SIL 2
** Pfeiffer notification*

2

Fail safe Siemens PLC
(including ET200M)

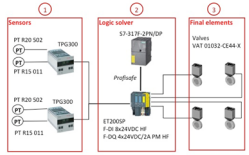
Certified **SIL 3**
$10^{-4} \le PFD_2 < 10^{-3}$

3 Non safety certified

Table 3: Valve SIL 2 PFD boundaries

PFD_3	PFD_{valve}	λ_D	MTTF
10^{-2}	$PFD_3/4=0.0025$	$6.518*10^{-2}$	15.34
10^{-3}	$PFD_3/4=0.00025$	$6.518*10^{-3}$	154

Hardware Safety Integrity



SIF architecture

Architectural Constraints (IEC 61508 places an upper limit on the SIL that can be claimed for any SIF on the basis of the HFT of its subsystems)

Route 1_H: based on:

- HFT: Hardware failure tolerance
- SFF: Safe Failure Fraction

Route 2_H: gives more importance on components reliability given by users feedback.

SFF= (Safe Failures + DD failures) / (All Failures)

1

TPG300
Type B: complex
HFT=1
Unknown SFF

Constraint:
SFF > 60%

	Type A			Type B		
HFT / SFF	0	1	2	0	1	2
<60%	SIL 1	SIL 2	SIL 3	N/A	SIL 1	SIL 2
60% ≤ 90%	SIL 2	SIL 3	SIL 4	SIL 1	SIL 2	SIL 3
90% ≤ 99%	SIL 3	SIL 4	SIL 4	SIL 2	SIL 3	SIL 4
≥ 99%	SIL 3	SIL 4	SIL 4	SIL 3	SIL 4	SIL 4

Type: degree of confidence in the behavior under fault conditions

3

Solenoid valves
Type A: simple
HFT=0
Unknown SFF

SFF > 60%
Otherwise need **redundancy**

Systematic safety integrity

** Formal verification:*
*- PLCVerif: **THPHA159***
*- ITER use case: **THPHA161***

- Systematic capability (**SC[1..4]**). Measure of the **confidence** that the systematic safety integrity meets the requirements of the specified SIL

Route 1s

Based on techniques and measures for avoidance & control of systematic failure tables

(1) Hardware & Software design
(2) Environment
(3) Operation

1

TPG300
SC1 compliant
Design (EMI, env. stress, online monitoring)
Separated and redundant TPG300
SC1 -> SC2

2

S7-315F (fail safe PLC)
SIL 3 compliant for systematic fail.

(IEC 61511) Application software must be SIL2
- **Low variability Language (ladder)**
- **Verification by formal methods***

3

Solenoid valves
Basic information from supplier

The four valves must have an **SC2 to claim the required SIL 2**

(3) Operation

Proof test

- Living system: Proof coverage is crucial for the **SIL maintenance**.
- Proof coverage includes **the full SIF** and not only a particular element.

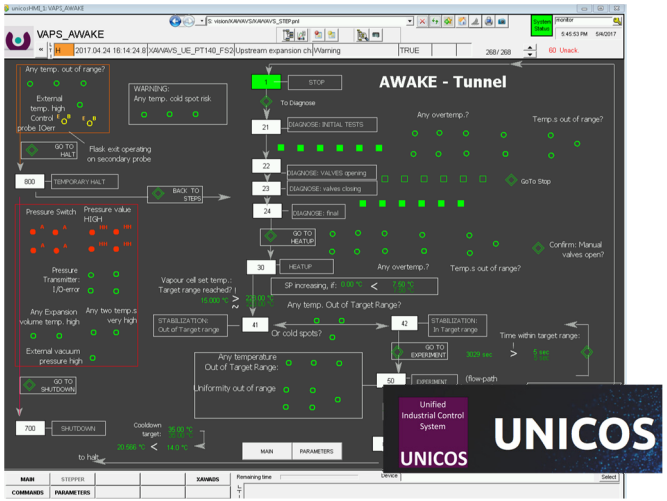
Operational procedures

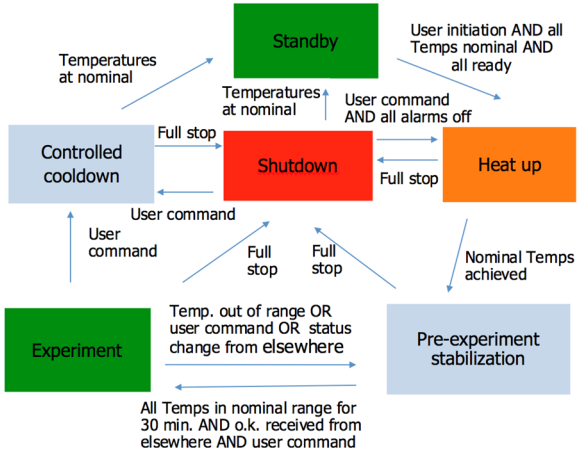
- Operators receive a full document on the safety functions
- Alarms and events are included in the supervision HMIs (alarm systems)
- Sometimes override of a SIF is possible, but this must be carefully monitored and detected

Management of change

- Procedure **ISA-84.00.01**
- All **changes** are **traced** and follow a strict procedure on validation before deployment.
- Standard gives guidelines on what to test/verify again in case of a change.

BPCS: UNICOS-CPC framework





Simplified Main Finite State Machine

Control functionalities

- PLC + SCADA based application
- Based on the UNICOS-CPC framework (ISA-88)
- 100 TT (PT100), 6 PT, 8 *OnOff* valves, 17 PWM
- Get an isothermal behavior till ~ 220 ^{O}C

Integration & safety

- BPCS: first layer of protection (no credit given)
- Second layer of protection (important alarms)
- Natural integration with the SIS
- Monitoring of the SIS events & alarms (interface)

Lessons learned & conclusions

✓ AWAKE **plasma cell**: equipment already designed without “safe” considerations:

- Meeting the specified SIL would need to replace the solenoid valves by other with safe characteristics, or proven reliability data, or a different architecture.
- Or the viewports could be reinforced, hence the SIL requirement lowered

✓ **Design** engineering based on sector specific **standards**: IEC 61508 & IEC 61511 (ISA 84)

- SIL compliance: reliability of the hardware (**random**) and the **architecture constraints** and **systematic capabilities**.
- **Non safety classified equipment** can be employed but requires additional information (maintenance database and user experience). But “Prior in use” or “**Proven in use**” claims require substantial evidence and cannot be easily be used
- **Proof test frequency** is a key factor
- Allocate safety instrumented functions to the SIS and not to the BPCS.

✓ **Formal verification** of the solver **logic** becomes significant for the systematic capabilities

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