Safety Analysis of the TCDQ

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Selected slides by J.Uythoven
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Objective of the meeting and Topics

Topics

- Tasks overview
- TCDQ system description
- The modelling framework
- Quantification and results
- Conclusions and Outlook

Scoping the problem

Scope

- Probability of failure of the TCDQ systems (two TCDQ) to be configured to protect the LHC elements at the occurrence of an asynchronous beam dump over 1 year of LHC operation, 400 fills

Within the scope

- TCDQ configuration at LHC injection, ramping and colliding (top energy)
- Servo and remote (manual adjustment) controls
- PLC for control and interlocking functions, input-outputs boards, motors and motor drive power converters, position measurements, communications

Outside the scope

- MCS, the timing system, the local BIC, the operator in the control room
- Calculation of frequency and consequences of an asynchronous beam dump (estimate from LBDS reliability studies, R. Filippini 2006)

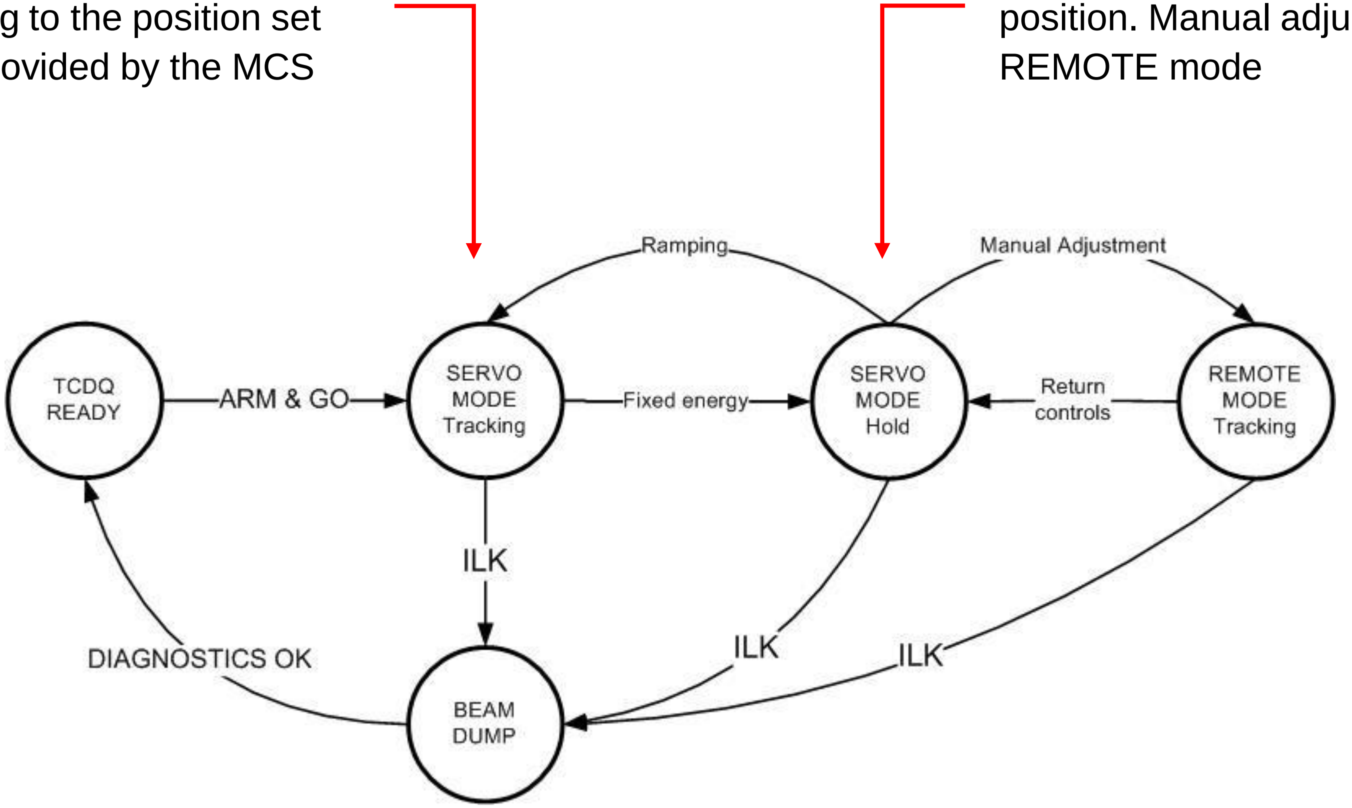
TCDQ operation modes

Injection-Ramping

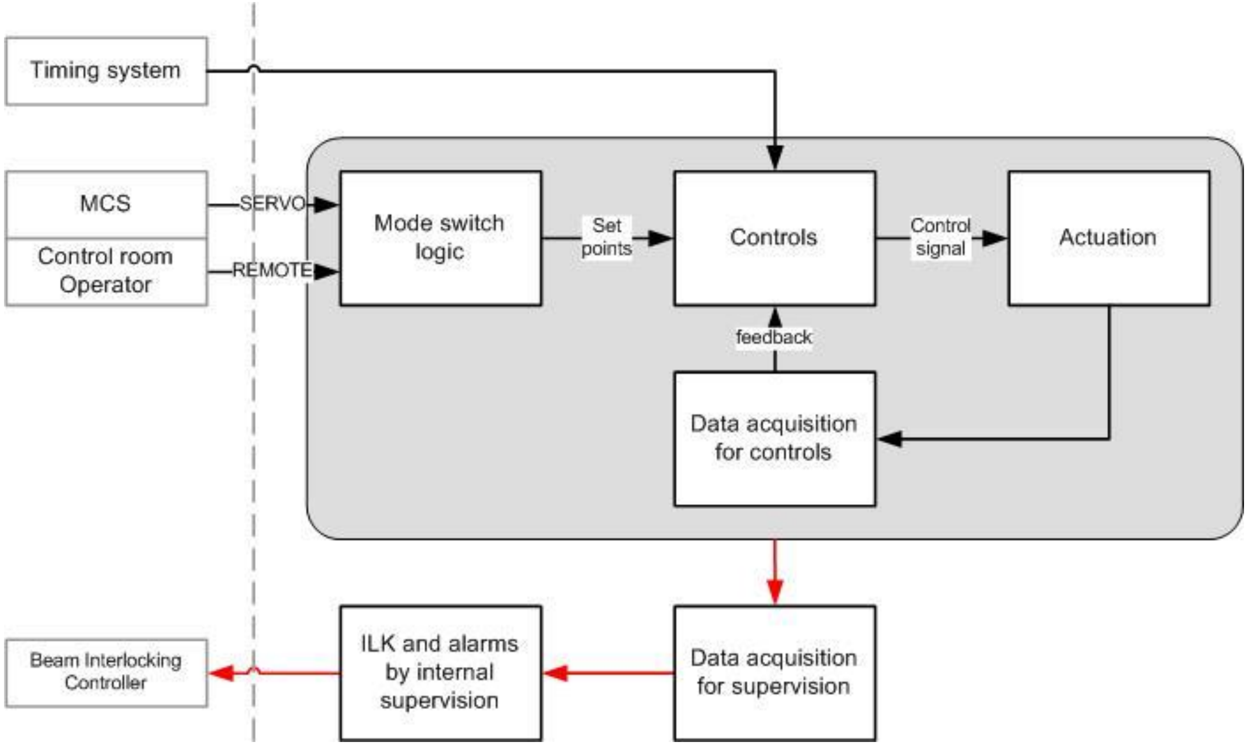
TCDQ tracks beam position according to the position set points provided by the MCS

Colliding

TCDQ keeps the required position. Manual adjustments in REMOTE mode



TCDQ functional description



TCDQ control loop

Mode switch logic

Controls in servo/remote

Data acquisition for controls (position, settings)

TCDQ actuation

TCDQ supervision

Data acquisition

ILK functions to BIC

Blocks are functions

TCDQ safety analysis: modeling steps

Initiating event

- The asynchronous beam dump

System failure model

- Fault tree of the TCDQ to position itself in the correct place

Data collection

- Failure events (independent and CCF),
- Failure rates, probabilities on demand
- Supervision, tests and periodical checks

Analysis and quantification

- Operation scenario of 400 fills (10 hours each), 4000 hours/ year
- 1 fill = about 2 hours tracking position and 8 hours hold position
- 1 remote mode every 10 fills

Data collection

Failure events

- 80 independent failure events, several dependencies and common causes of failure (CCF)

Failure data

- Failure rates and probability of failure on demand are at assembly level.
- Some deduced from previous reliability analysis (LBDS studies)

Periodical checks

- Rearming of between two LHC fills demand almost all components of TCDQ
- Yearly calibration and test

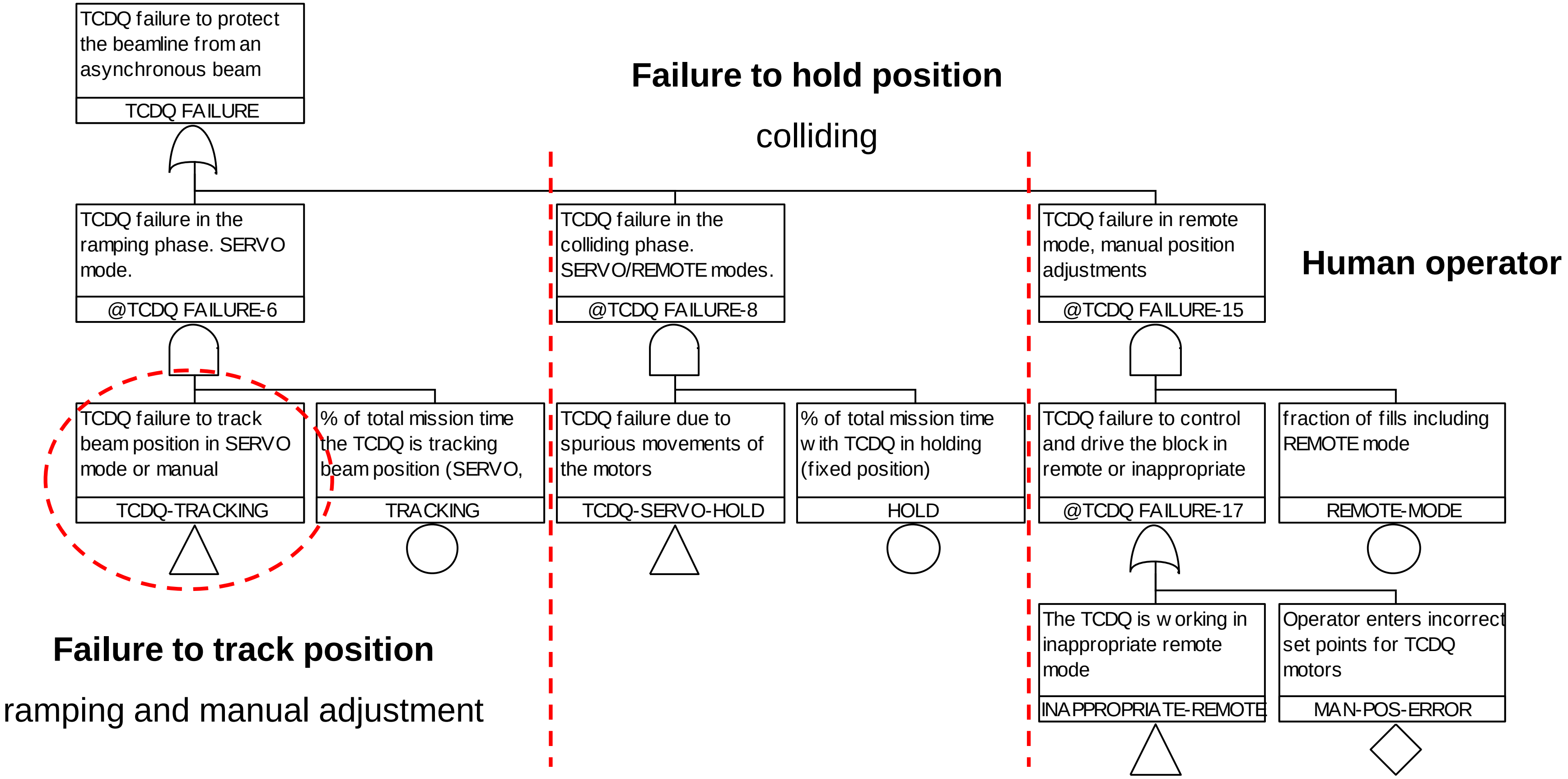
REMARK: spurious ILK, power supply (fail safe), and break-short false contacts results in false beam dumps are not included.

The Failure Model

- **Fault tree:** It represents about 80 failure events, dependencies and CCF in a logic structure. Leaves account for basic failure events of TCDQ components (Risk Spectrum®)

- **The fault tree is split into two branches**
- <u>Tracking beam position</u>: TCDQ failures to track beam position in servo control mode or by manual adjustment (whenever position has to be changed).
- <u>Hold position</u>: TCDQ failure to hold the required position at fixed energy

The Fault Tree



Failure to hold position

colliding

Human operator

Failure to track position

ramping and manual adjustment

TCDQ failure to protect the beamline from an asynchronous beam
TCDQ FAILURE

TCDQ failure in the ramping phase. SERVO mode.
@TCDQ FAILURE-6

TCDQ failure in the colliding phase. SERVO/REMOTE modes.
@TCDQ FAILURE-8

TCDQ failure in remote mode, manual position adjustments
@TCDQ FAILURE-15

TCDQ failure to track beam position in SERVO mode or manual
TCDQ-TRACKING

% of total mission time the TCDQ is tracking beam position (SERVO,
TRACKING

TCDQ failure due to spurious movements of the motors
TCDQ-SERVO-HOLD

% of total mission time with TCDQ in holding (fixed position)
HOLD

TCDQ failure to control and drive the block in remote or inappropriate
@TCDQ FAILURE-17

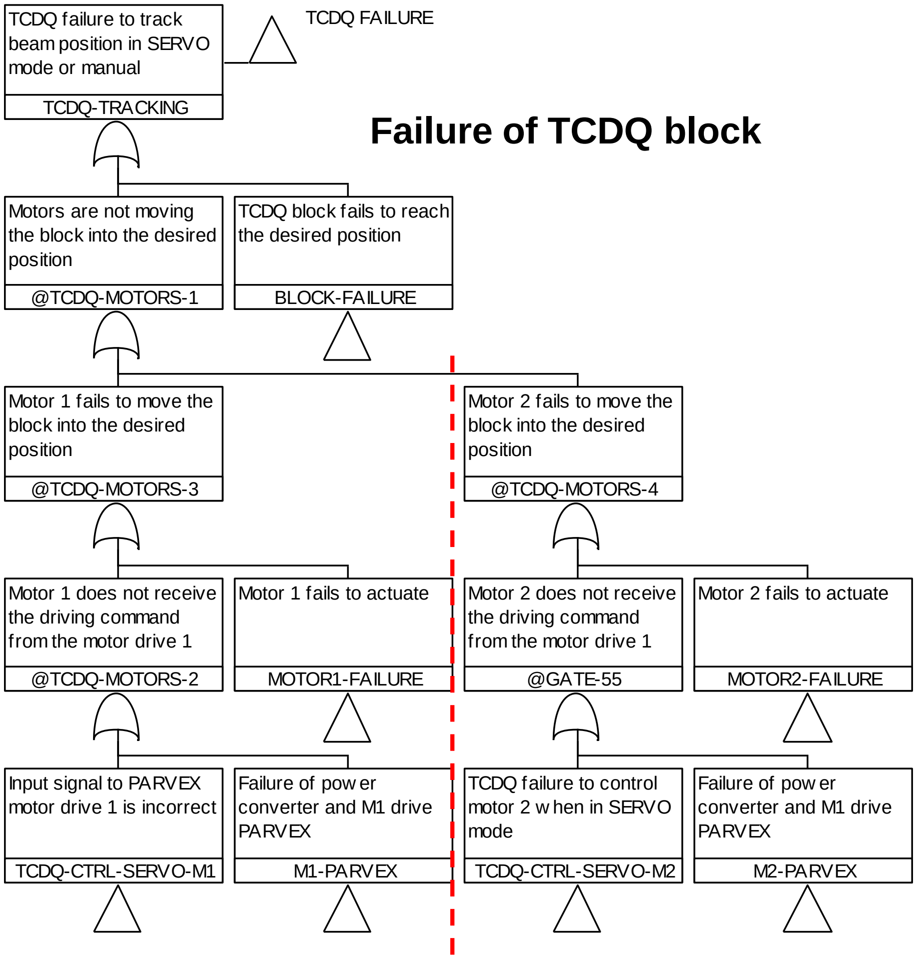
fraction of fills including REMOTE mode
REMOTE-MODE

The TCDQ is working in inappropriate remote mode
INAPPROPRIATE-REMOTE

Operator enters incorrect set points for TCDQ motors
MAN-POS-ERROR

The Fault tree

Position tracking



Failure of TCDQ block

TCDQ failure to track beam position in SERVO mode or manual
TCDQ-TRACKING
TCDQ FAILURE

Motors are not moving the block into the desired position
@TCDQ-MOTORS-1

TCDQ block fails to reach the desired position
BLOCK-FAILURE

Motor 1 fails to move the block into the desired position
@TCDQ-MOTORS-3

Motor 2 fails to move the block into the desired position
@TCDQ-MOTORS-4

Motor 1 does not receive the driving command from the motor drive 1
@TCDQ-MOTORS-2

Motor 1 fails to actuate
MOTOR1-FAILURE

Motor 2 does not receive the driving command from the motor drive 1
@GATE-55

Motor 2 fails to actuate
MOTOR2-FAILURE

Input signal to PARVEX motor drive 1 is incorrect
TCDQ-CTRL-SERVO-M1

Failure of power converter and M1 drive PARVEX
M1-PARVEX

TCDQ failure to control motor 2 when in SERVO mode
TCDQ-CTRL-SERVO-M2

Failure of power converter and M1 drive PARVEX
M2-PARVEX

Failure Motor 1

Tracking errors

Spurious controls

Incorrect set points

Incorrect timing

Failure Motor 2

Tracking errors

Spurious controls

Incorrect set points

Incorrect timing

The Fault tree

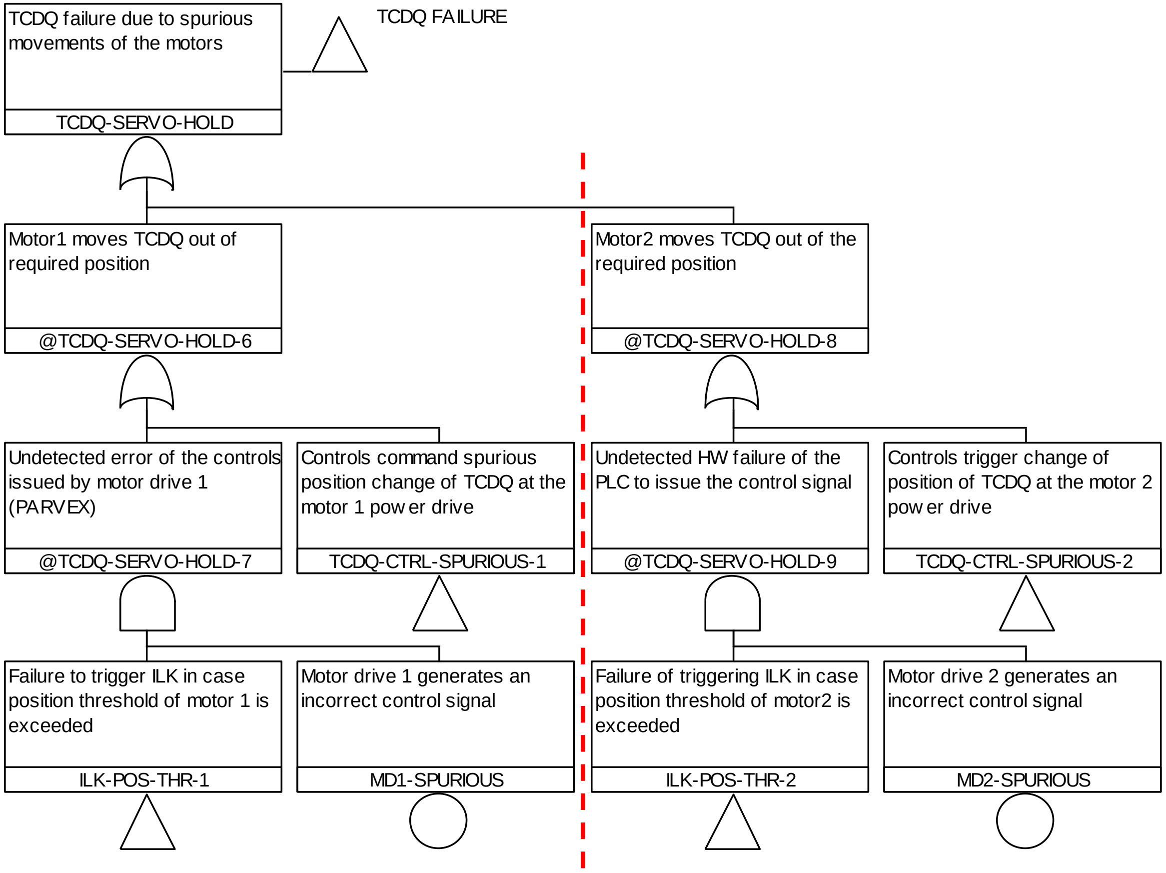
Servo mode, hold position

Failure motor 1

Spurious controls

Failure motor 2

Spurious controls



TCDQ FAILURE

TCDQ failure due to spurious movements of the motors
TCDQ-SERVO-HOLD

Motor1 moves TCDQ out of required position
@TCDQ-SERVO-HOLD-6

Motor2 moves TCDQ out of the required position
@TCDQ-SERVO-HOLD-8

Undetected error of the controls issued by motor drive 1 (PARVEX)
@TCDQ-SERVO-HOLD-7

Controls command spurious position change of TCDQ at the motor 1 power drive
TCDQ-CTRL-SPURIOUS-1

Undetected HW failure of the PLC to issue the control signal
@TCDQ-SERVO-HOLD-9

Controls trigger change of position of TCDQ at the motor 2 power drive
TCDQ-CTRL-SPURIOUS-2

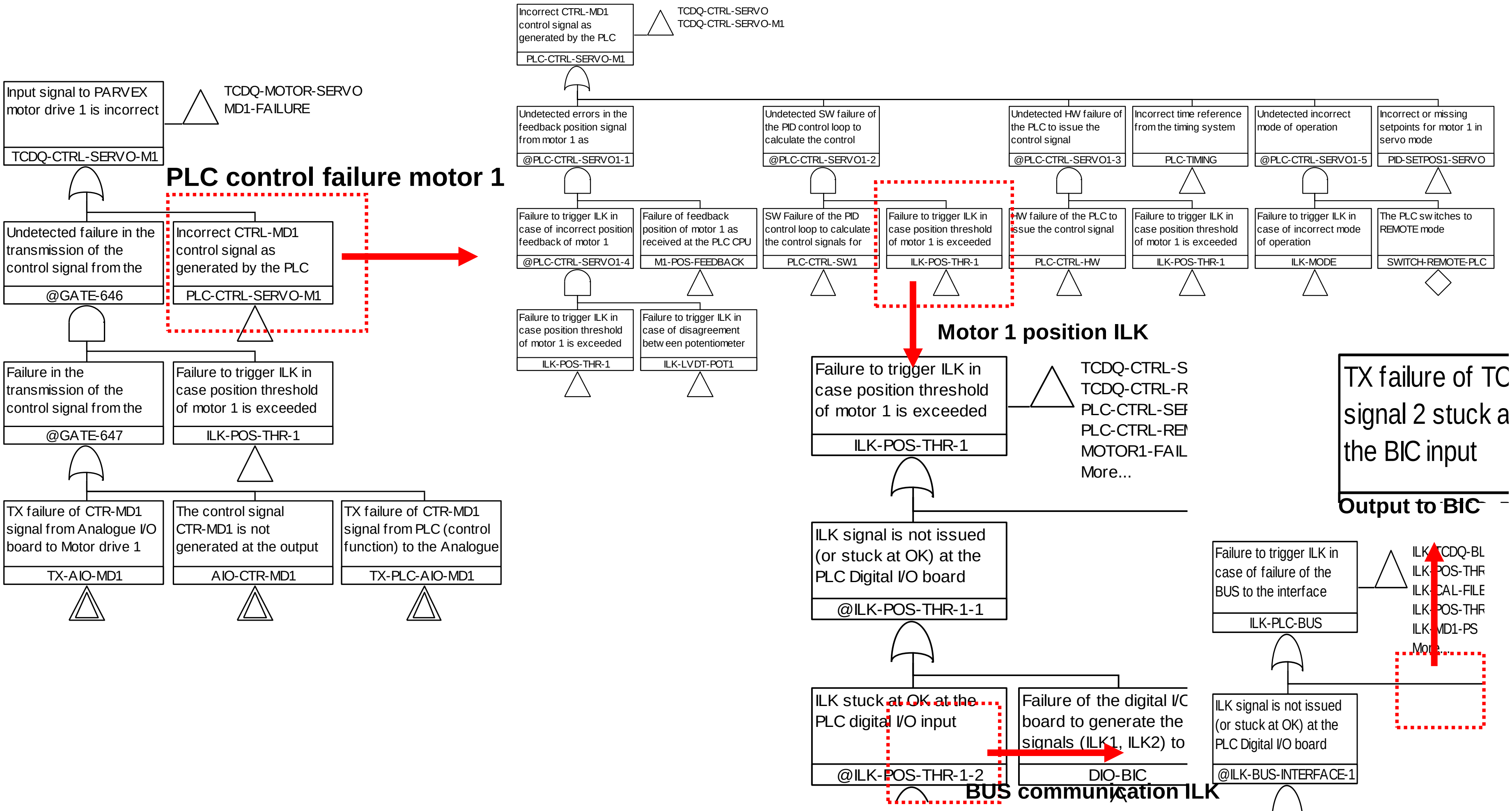
Failure to trigger ILK in case position threshold of motor 1 is exceeded
ILK-POS-THR-1

Motor drive 1 generates an incorrect control signal
MD1-SPURIOUS

Failure of triggering ILK in case position threshold of motor2 is exceeded
ILK-POS-THR-2

Motor drive 2 generates an incorrect control signal
MD2-SPURIOUS

…navigation in the fault tree structure



Input signal to PARVEX motor drive 1 is incorrect
TCDQ-CTRL-SERVO-M1
TCDQ-MOTOR-SERVO
MD1-FAILURE

PLC control failure motor 1

Undetected failure in the transmission of the control signal from the
@GATE-646

Incorrect CTRL-MD1 control signal as generated by the PLC
PLC-CTRL-SERVO-M1

Failure in the transmission of the control signal from the
@GATE-647

Failure to trigger ILK in case position threshold of motor 1 is exceeded
ILK-POS-THR-1

TX failure of CTR-MD1 signal from Analogue I/O board to Motor drive 1
TX-AIO-MD1

The control signal CTR-MD1 is not generated at the output
AIO-CTR-MD1

TX failure of CTR-MD1 signal from PLC (control function) to the Analogue
TX-PLC-AIO-MD1

Incorrect CTRL-MD1 control signal as generated by the PLC
PLC-CTRL-SERVO-M1
TCDQ-CTRL-SERVO
TCDQ-CTRL-SERVO-M1

Undetected errors in the feedback position signal from motor 1 as
@PLC-CTRL-SERVO1-1

Undetected SW failure of the PID control loop to calculate the control
@PLC-CTRL-SERVO1-2

Undetected HW failure of the PLC to issue the control signal
@PLC-CTRL-SERVO1-3

Incorrect time reference from the timing system
PLC-TIMING

Undetected incorrect mode of operation
@PLC-CTRL-SERVO1-5

Incorrect or missing setpoints for motor 1 in servo mode
PID-SETPOS1-SERVO

Failure to trigger ILK in case of incorrect position feedback of motor 1
@PLC-CTRL-SERVO1-4

Failure of feedback position of motor 1 as received at the PLC CPU
M1-POS-FEEDBACK

SW Failure of the PID control loop to calculate the control signals for
PLC-CTRL-SW1

Failure to trigger ILK in case position threshold of motor 1 is exceeded
ILK-POS-THR-1

HW failure of the PLC to issue the control signal
PLC-CTRL-HW

Failure to trigger ILK in case position threshold of motor 1 is exceeded
ILK-POS-THR-1

Failure to trigger ILK in case of incorrect mode of operation
ILK-MODE

The PLC switches to REMOTE mode
SWITCH-REMOTE-PLC

Failure to trigger ILK in case position threshold of motor 1 is exceeded
ILK-POS-THR-1

Failure to trigger ILK in case of disagreement between potentiometer
ILK-LVDT-POT1

Motor 1 position ILK

Failure to trigger ILK in case position threshold of motor 1 is exceeded
ILK-POS-THR-1
TCDQ-CTRL-S
TCDQ-CTRL-R
PLC-CTRL-SE
PLC-CTRL-RE
MOTOR1-FAIL
More...

ILK signal is not issued (or stuck at OK) at the PLC Digital I/O board
@ILK-POS-THR-1-1

ILK stuck at OK at the PLC digital I/O input
@ILK-POS-THR-1-2

Failure of the digital I/C board to generate the signals (ILK1, ILK2) to
DIO-BIC

BUS communication ILK

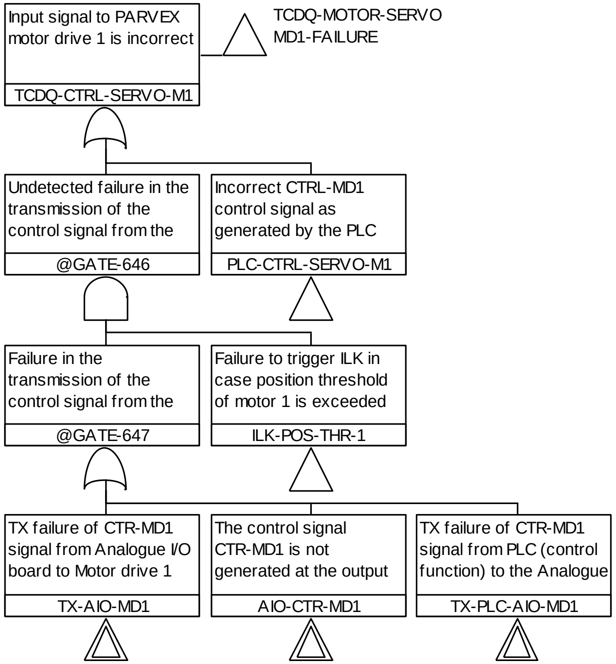
TX failure of TC signal 2 stuck a the BIC input

Output to BIC

Failure to trigger ILK in case of failure of the BUS to the interface
ILK-PLC-BUS
ILK-TCDQ-BL
ILK-POS-THR
ILK-CAL-FILE
ILK-POS-THR
ILK-MD1-PS
More...

ILK signal is not issued (or stuck at OK) at the PLC Digital I/O board
@ILK-BUS-INTERFACE-1

Fault tree: documentation



PLC-CTRL-SERVO-M1	Models the failure of PLC control function to generate the correct command to DC motor 1	PLC CPU Bus communications ETHERNET MCS Set points table Timing card	Calculation of control signal to motor 1
		PLC CPU Bus communications Analogue I/ O Digital I/ O ETHERNET Threshold table Potentiometer 1 LVDT	ILK function for position threshold and feedback comparison for motor 1
ILK-POS-THR-1	Models the failure of the PLC interlock function to trigger the ILK to BIC in case the position threshold of motor 1 is exceeded	PLC CPU Bus communications Digital I/ O board Threshold table	Position threshold ILK of motor 1
TX-AIO-MD1	Models the failure of the transmission from the Analogue IO board to the motor drive (PARVEX) power converter of motor 1	TX from Analogue I/ O output to MD1 input	Control signal motor 1
AIO-CTR-MD1	Models the failure of the analogue IO board to present the control signal of motor 1 at its output	Analogue I/ O board output and analogue I/ O board	Control signal motor 1
TX-PLC-AIO-MD1	Models the TX failure of control signal of motor 1 from the PLC to the analogue I/ O board	PLC Profibus internal communications	Control signal motor 1

Analysis and Quantification

Results overview

Assumptions

- One year of LHC operation consists of 400 fills
- 1 Fill is 10 hours, of which 2 hours injection-ramping, 8 hours colliding
- 1 remote manual adjustment every 10 fills, of 2 hours length
- All failures are discovered at the rearming before next fill
- Demand rate = 0.4 asynchronous beam dump per beam line, per year (LBDS reliability study, R. Filippini)

Safety figures-of-merit (average Probability of Failure on Demand**)**

- TCDQ is 1.82 E-5 per demand (5th% = 2.7 E-06, 95th % = 5.4 E-05)
- Two TCDQ are 3.64 E-05 ⇒ **SIL4**

Quantification and Results: Main contributors

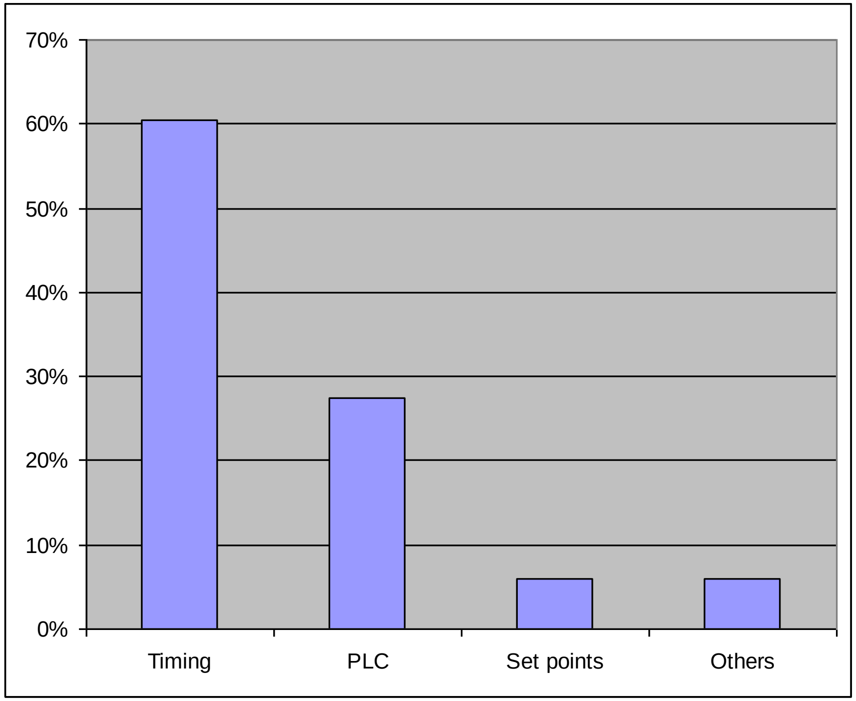
- **Start signal (60.5%)**

  Failure of the PLC time card to transmit start signal to PLC
- **Control and supervision (27.5%)**

  PLC CPU fails with both control and supervision functions
- **Position settings (6.0%)**

  ETHERNET board fails to transmit position settings to PLC
- **Several others (6.0%)**

  Failure event and missed fault detection (< 0.6% each)



Discussion of results: default case study

Results insights

Conservative assumptions

- Misconfigurations of TCDQ, either small or big, lead always to failure

Optimistic assumptions

- Source of asynchronous beam dump is the LBDS, while other sources exist
- Rearming cover diagnostics of the system components, which is recovered to an as good as new state.

Sensitivity analysis

1. **Sensitivity to operation scenario**

   The TCDQ is always demanded in “tracking configuration”
   - 10 hours of fill, instead of 2 hours

2. **Sensitivity to failure data**

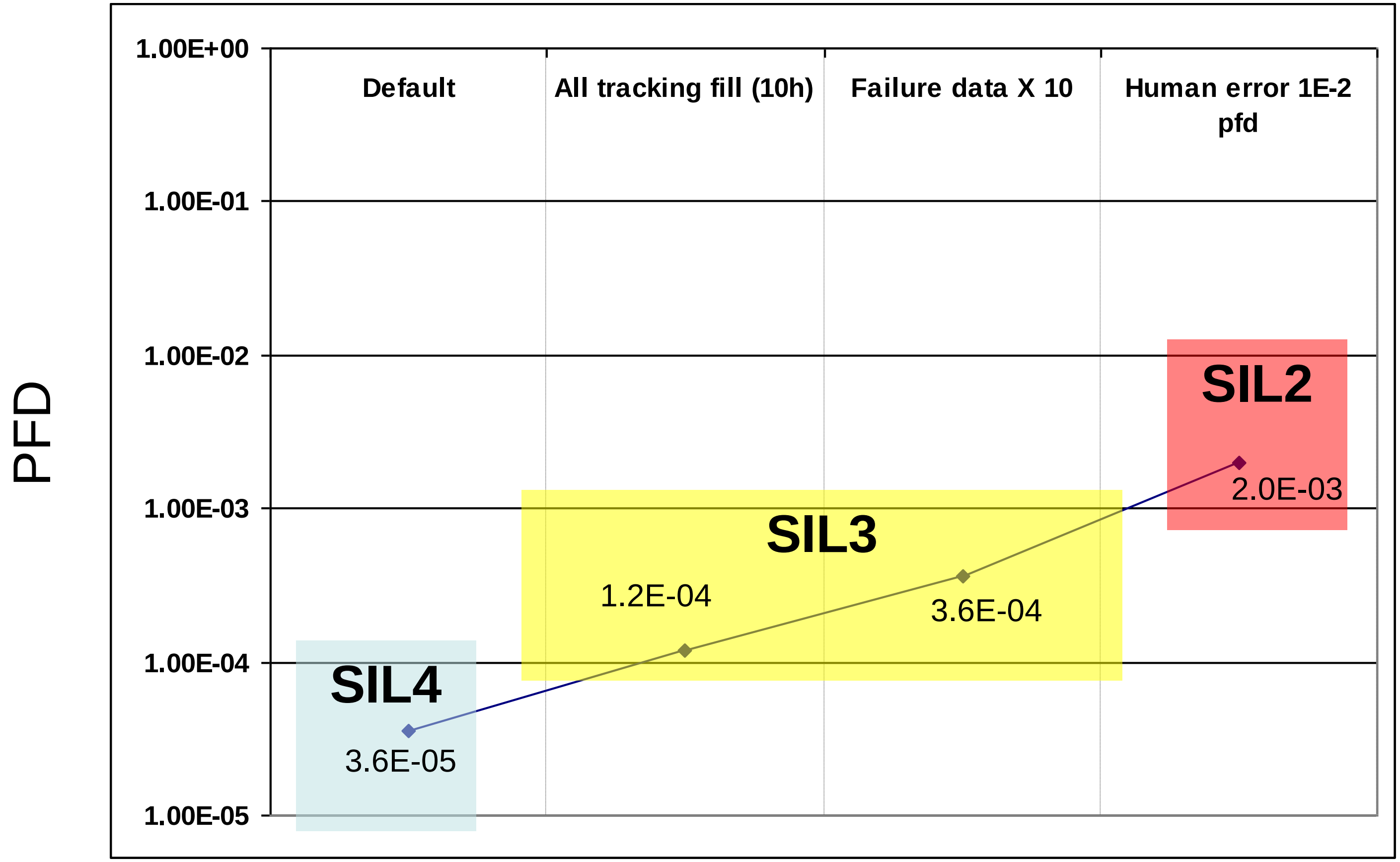
   Failure data increased of a factor 10

3. **Sensitivity to external factors: human error**

   Human errors when TCDQ is in remote mode.
   - Probabilities on demand 1E-3 to 1E-2

REMARK: the model is updated to include the external failure events

Sensitivity analysis: Results



Operator manual adjustments of TCDQ

- A study of the task and performance conditions has not been performed.

<u>Assumptions</u> for manual adjustment of TCDQ position:

- Manual adjustments are performed in 1 of 10 fills, or 40 times a year based on the assumed 400 fills per year.
- A manual misconfiguration of the TCDQ always leaves the TCDQ unavailable to protect the LHC in the event of an asynchronous beam dump.
- Multiple adjustments may be performed in a fill that includes a manual adjustment and adjustments are made to both TCDQ motors. In this sensitivity analysis, all adjustments are viewed as a single operation.

Basis for Human Error Probability = 0.01

Source	**Description**	**Value**
THERP	**Initial-screening** model Table 20-2 Failure to perform rule-based action correctly when written procedures are available and used (1) **Errors per critical step without recovery factors**	0.05
	Initial-screening model Table 20-2 (2) **Errors per critical step with recovery factors**	0.025
NARA	Generic Task Type A2 **Start or reconfigure a system from the Main Control Room following procedures, with feedback.**	1E-3
Kirwan (p. 204)	Human Performance Limiting Values **Single operator carrying out task(s), less than optimum ergonomics**	1E-3
ATHEANA	Suggested calibration points for experts, e.g. **The operator(s) is “Unlikely” to fail.** The level of difficulty is quite low and we should not see any failures if all the crews/operators were to experience this scenario.	0.01

“Best” value for HEP ~ 0.01 Without crediting features to be documented in a detailed analysis of task, ergonomics, and performance conditions (V. Dang, PSI)

Some factors that could reduce the human error probability

To be examined in a detailed analysis of the task, interface, and other performance conditions:

- **how desired manual settings are determined**
- the **information (input) used** to determine these settings
- **how the desired settings are entered** (e.g. absolute settings, absolute change, percent change, etc.)
- **system feedback**: how the operator may perceive the overall system response to the new settings and whether the new settings have the desired effect
- the **"aids"** (tables, etc.) that would support the operators in determining whether the desired settings are reasonable
- **technical interface / TCDQ features**
  - a) compare manually entered settings to previous values set by the MCS for the given LHC state or energy (i.e. current values before the adjustment),
  - b) automatic "sanity checks" for the entered settings, or
  - c) limit values, one-sided limit values?
- Administrative provisions for **independent checking and/or confirmation** of the settings

Conclusions

1. **“Risk assessment”** (IEC 61508) for ABD and consequences leads to the requirement that TCDQ must meet SIL 4.
2. **This safety analysis** assesses the expected unavailability of TCDQ (prob. of failure on demand). It does not review the SIL-related requirements on design, maintenance, and operation of the system.
3. **The probability of failure** is estimated to be 3.6E-5 for the two TCDQs (one per beam line). Two major assumptions underlying this value are:
   - MCS and timing system inputs to TCDQ are correct
   - The system is operated only in servo (automatic) mode with no manual adjust. of TCDQs.

   With these assumptions, the TCDQs satisfy **SIL 4**.
4. **The dominant contributions** to TCDQ unavailability are:

   1) **failure of PLC timing card**, 2) failure of PLC CPU control and supervision functions 3) failure of Ethernet to transit set points to PLC

   Note: all 3 dominant contributors appear to be single points of failure, based on the provided documentation.

2009: check TCDQ position relative to beam energy

Conclusions (cont.)

5. **Potential means** to address dominant contributors (tentative)

   a - acknowledge start signal and feedback status of TCDQ before injection

   b - PLC internal checks to prevent complete failure of controls and supervision

   c - ILK software to be checked at regular intervals

   Note: it may be that some of these means are already implemented.

6. **Manual adjustments** of TCDQ

   An analysis of the manual adjustment task, associated ergonomics, and performance conditions has not been performed. At this time, a “best” value for the probability of misconfiguration of the TCDQ is 0.01 per manual adjustment. This corresponds to 1E-3 per “demand” when the fractions of fills that include a manual adjustment phase is 1/10.

   Based on the conservative treatment of manual adjustment failures (all errors result in an unsafe configuration of TCDQ), the TCDQ would only satisfy SIL2.

   An analysis of the manual adjustment task, procedures, and performance conditions would be useful in order to identify the defenses currently in place and possible improvements.

Acknowledgement

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I am also grateful to **V. Dang** for the fruitful discussions during the preparation of this work

The END