Performance of Injection Protection Systems

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- Injection Protection System Principle
- Passive Protection
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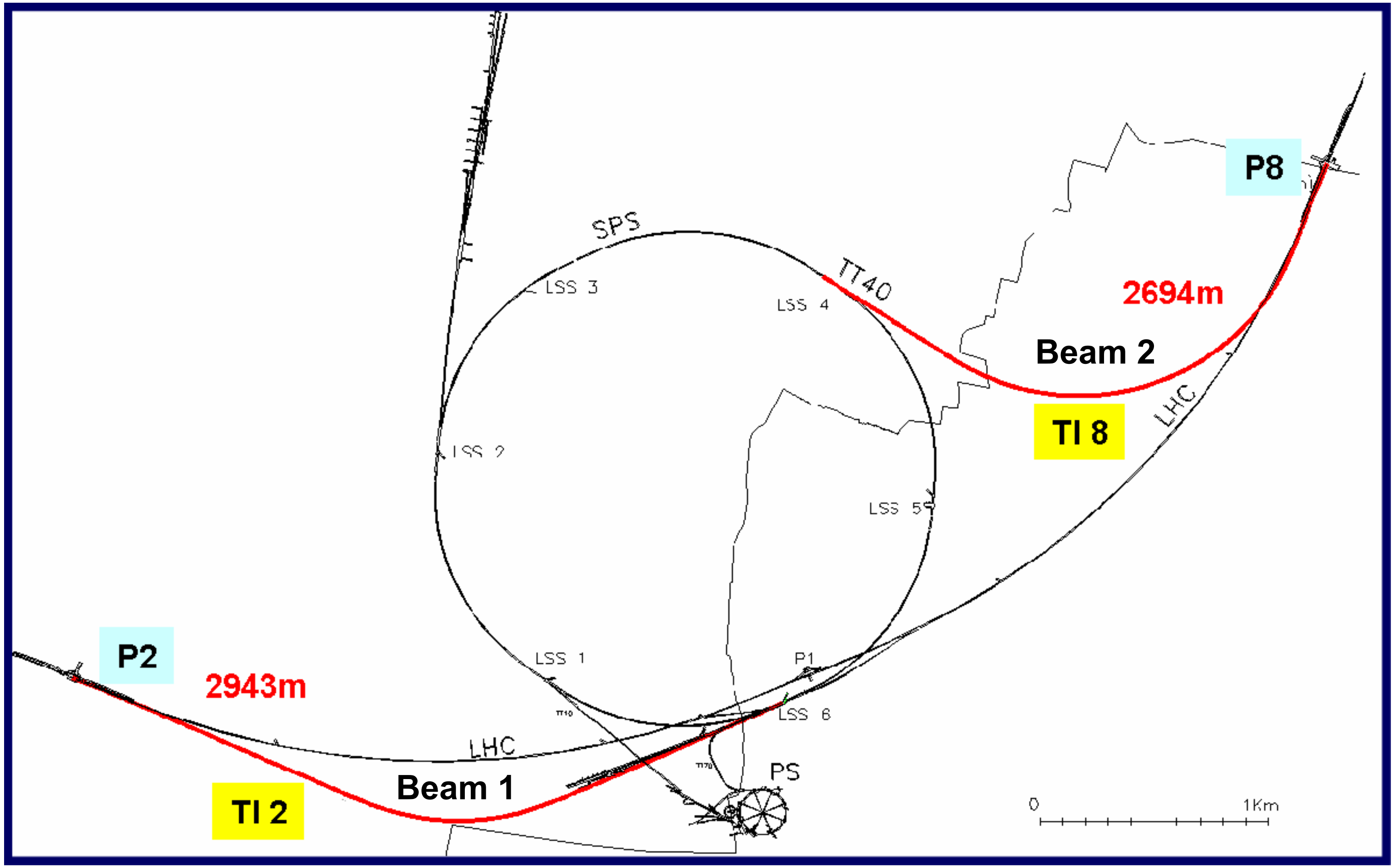
Input from B. Goddard, R. Genand, R. Schmidt,J. Wenninger, M. Werner

SPS Extraction - Transfer - LHC Injection

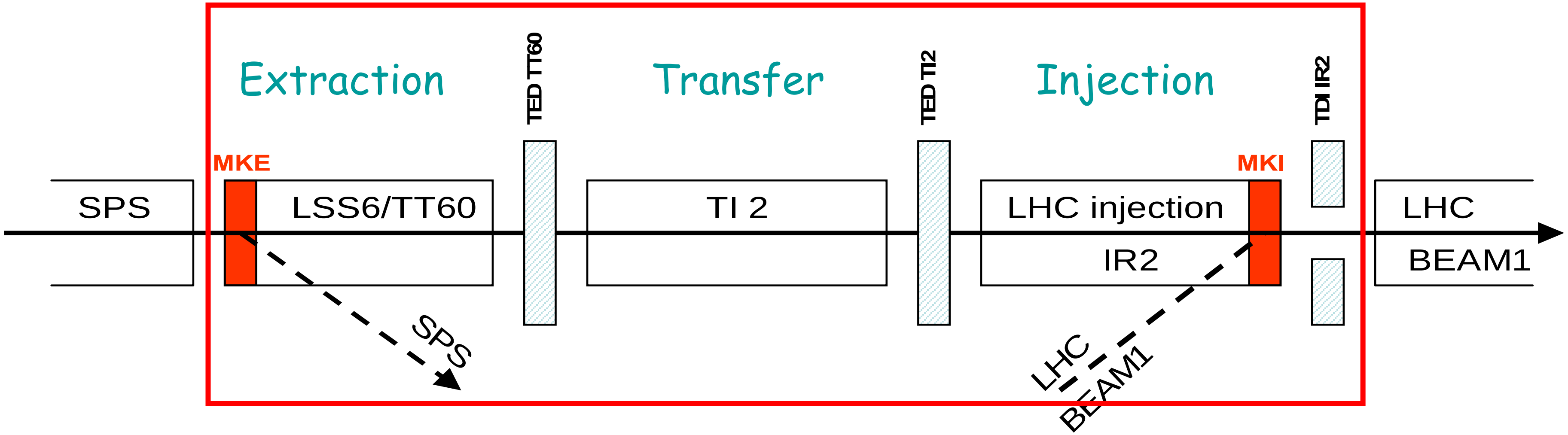


Injection Process

To define the **Injection Protection System, SPS Extraction, Transfer and LHC Injection** must be treated together.

SPS:
MSE…extraction septum
MKE…extraction kicker

LHC:
MSI…injection septum
MKI…injection kicker

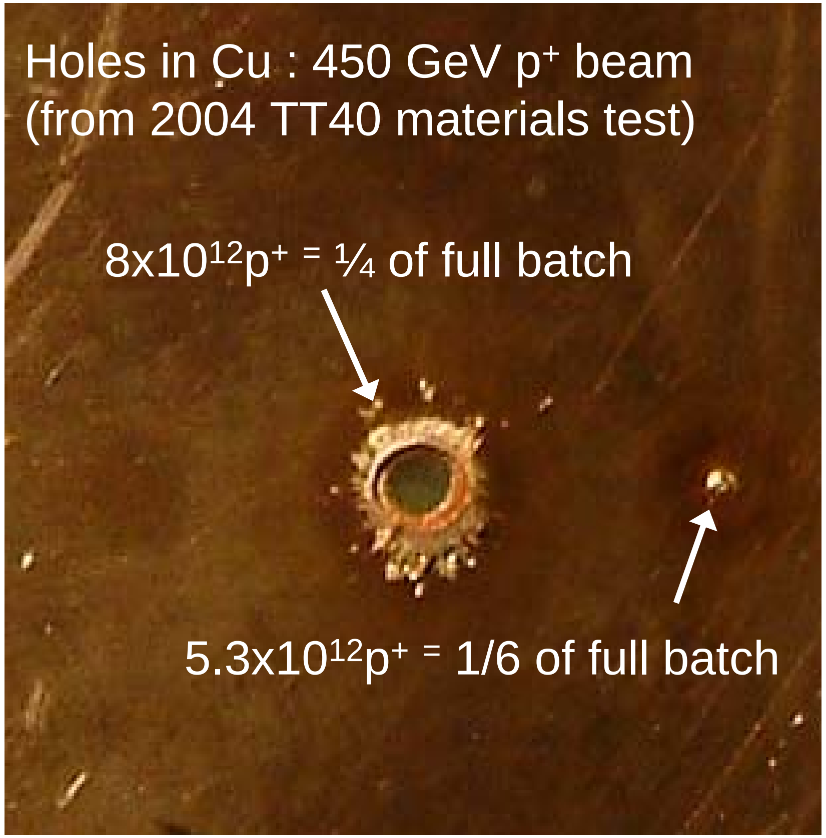


TED…beam stopper in transfer line
TDI…injection stopper in injection region

BEAM2: LSS4/TT40 – TI 8 – IR 8

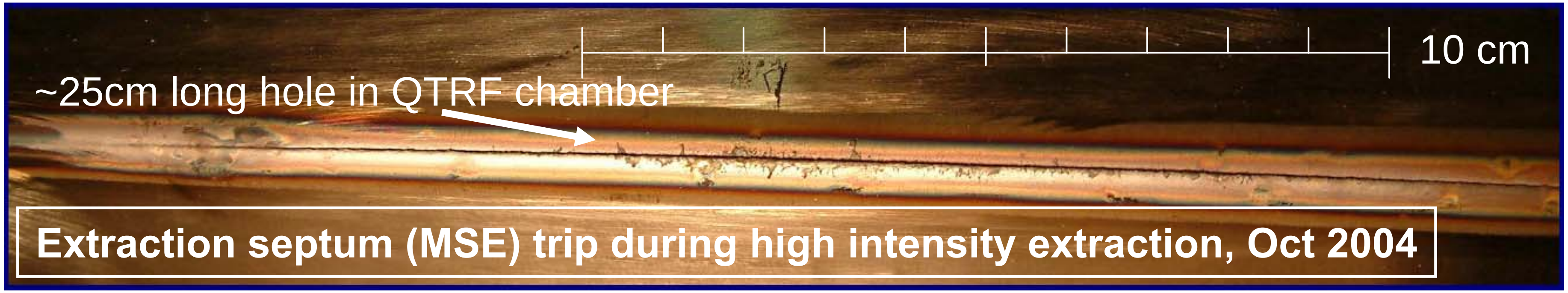
Injection/Extraction Constraints

Full nominal injected LHC batch: $3.3 \times 10^{13} p^+$, 450 GeV



- **Damage limit:**
  $\sim 2 \times 10^{12} p^+$, **~5 % of injected batch**
- **Small Aperture:**
  - 7.5σ LHC aperture at 450GeV
  - Tight aperture in transfer line (MSI injection septum $\sim 7\sigma$)

What can go wrong: magnet trips, kicker failures, wrong settings…



- Magnet trips can move trajectory by many σ in short time (MSE extraction septum: 40σ in 1ms)
- Kicker erratics, missings, timing etc.
- Operator error
- Corrupted settings

Injection Process

Slow failures:

10σ in > 2-3ms: relying on **interlocking**

Fast failures:

10σ in < 2-3ms: **interlocking + collimators**

Ultra-fast failures:

10σ in few μs: **collimators**

Principle of Machine Protection for Injection Process

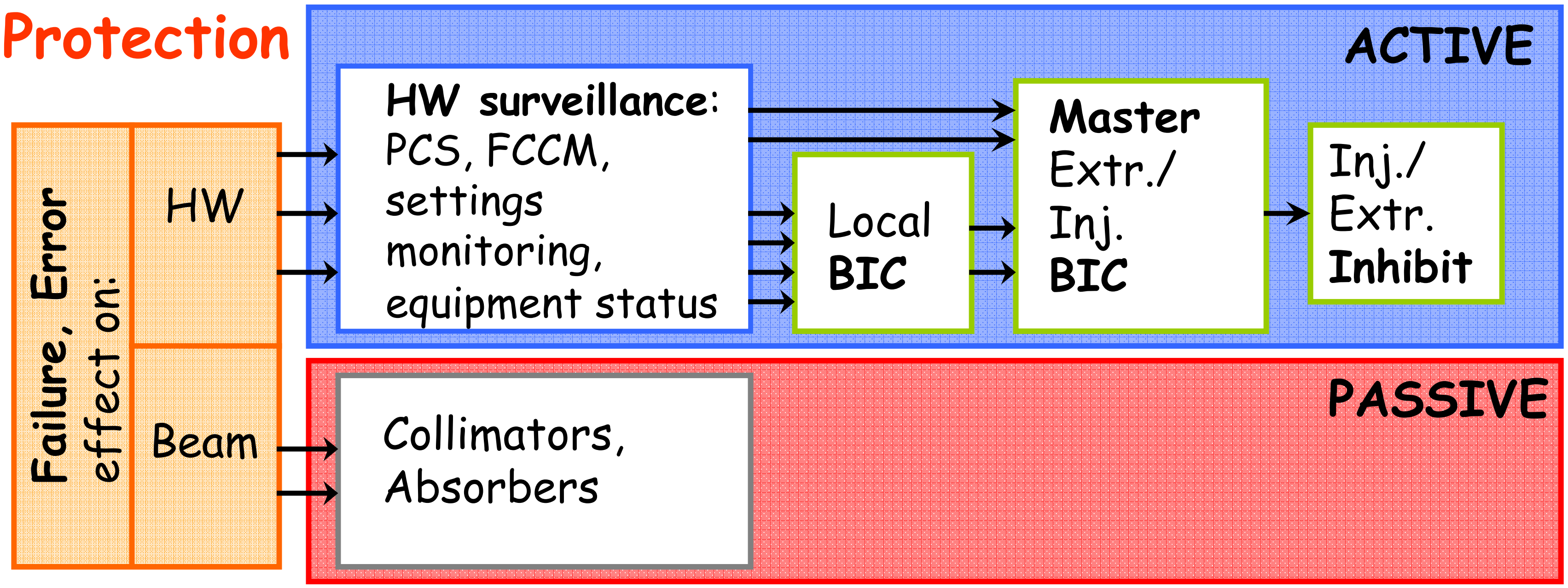
Avoidance

Procedures to avoid dangerous situations

e.g. never inject high intensity beam in empty LHC

Beam Presence Flag → protects against many failures

Protection



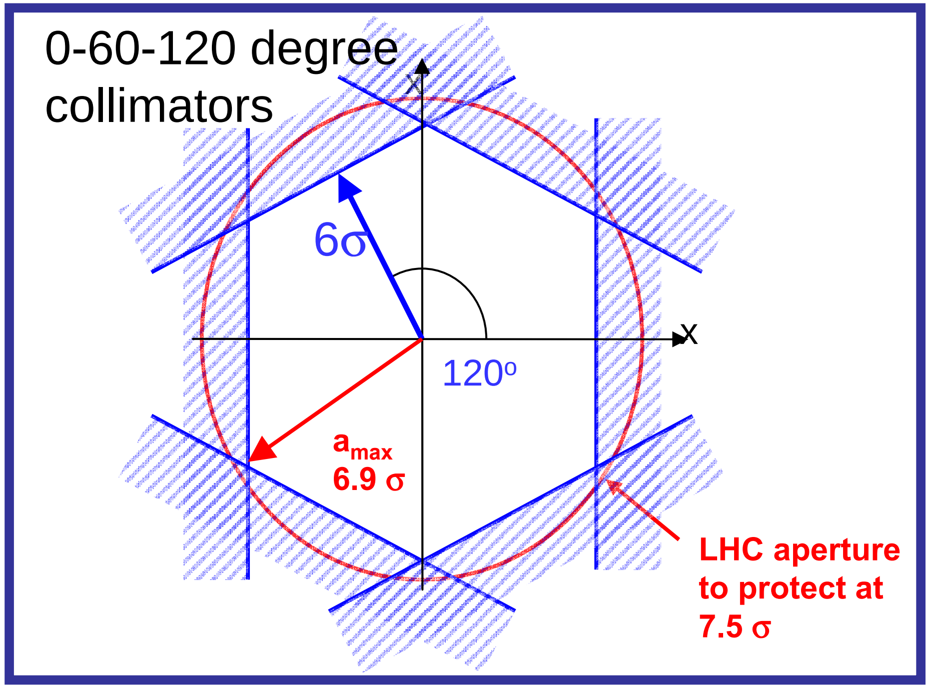
Passive Protection for fast and ultra-fast failures

- Protection of LHC aperture and MSI injection septum aperture:
  - **TCDI collimators** for failures upstream of injection regions
  - **"generic"** protection system with full phase coverage
- Dedicated collimators for kicker failures:
  - MKI (LHC) failure: **TDI beam stopper + TCLI collimators** are 90° downstream
  - MKE (SPS) failure: **TPSG diluter** is 90° downstream
- No dedicated collimators for septum failures
  - Protection from MSE and MSI failures ⇒ **interlocking**

TCDI Transfer Line Collimators

- Close to LHC and injection septum (last 300m matching section of TLs)
- Robust, based on LHC collimator design (1.2m C jaw)
- FLUKA model of 300m of TI 8 ⇒ **local shield for each TCDI**

- 3 collimators / plane (0-60-120°)
- Setting: 4.5σ, tolerances: ≤1.4 σ
- 2 motors/ jaw (angular control)
- **Protection level 6.9 σ**: result from comprehensive **Monte-Carlo simulation** including all imperfections: β beat, mismatch from SPS, tolerances,…

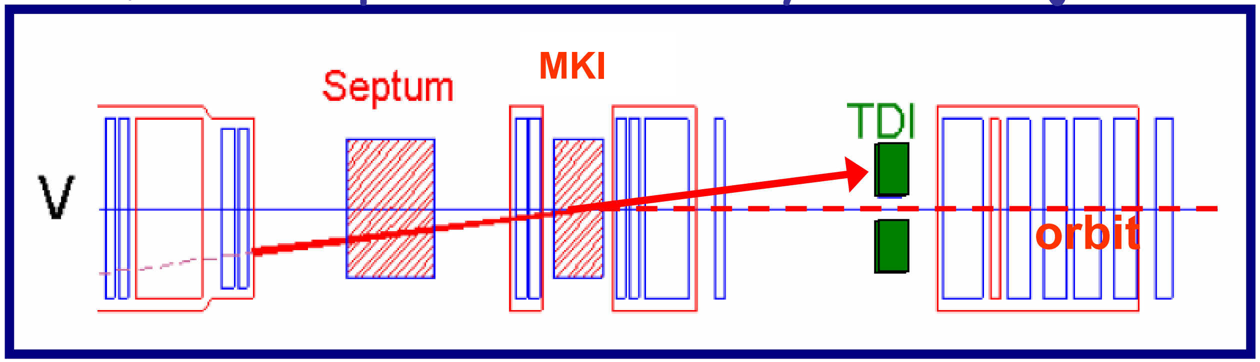


TDI injection stopper, TCLI collimators

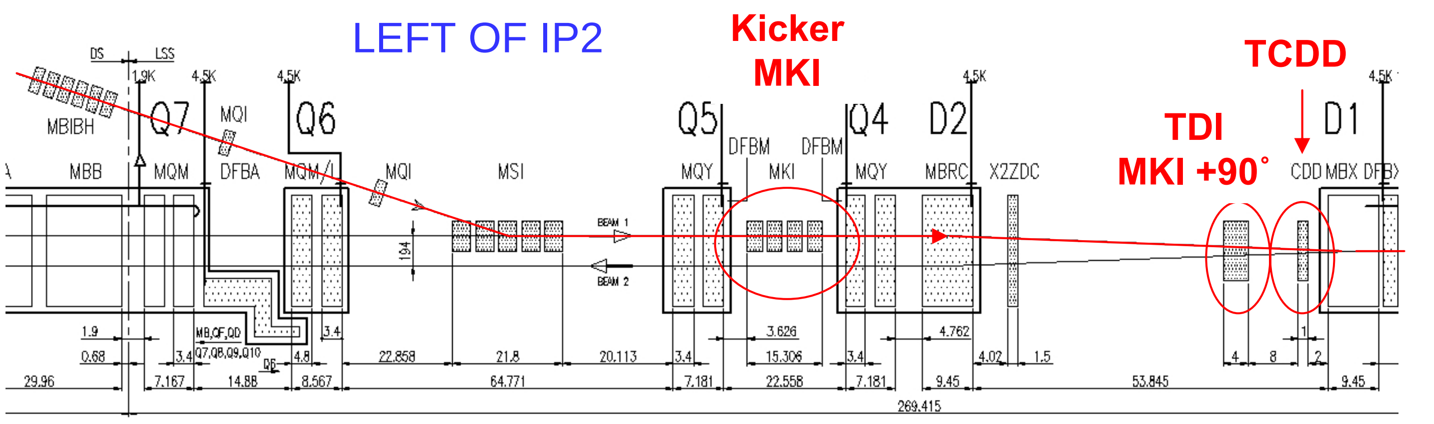
- **TDI injection stopper:**
  - Protect LHC (especially D1) against MKI kicker failures
  - 90° downstream of the MKI ~4m long hBN+Al+Cu jaws
  - local protection of SC LHC magnet D1 with mask -> TCDD (1m, Cu)

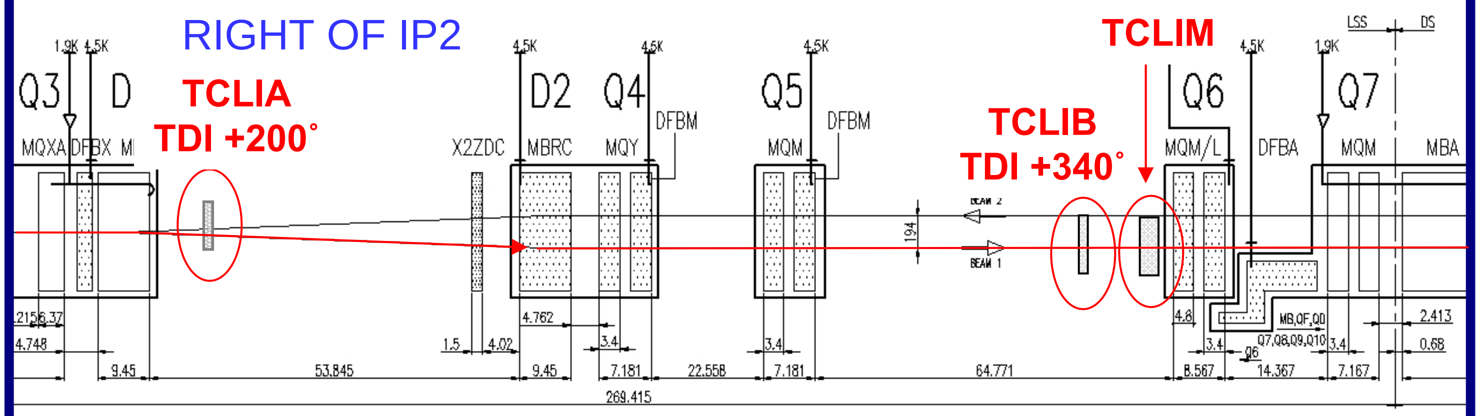
- Auxiliary collimators **TCLIs**
  - For MKI-TDI phase advance ≠90°, and for flexibility (halo load…)
  - At nx180°±20° from TDI (1.2m long C jaws)

Overview, vertical plane: functionality of TDI injection stopper



TDI - TCDD - TCLI





Topview

Interlocking for Extraction – Transfer -Injection

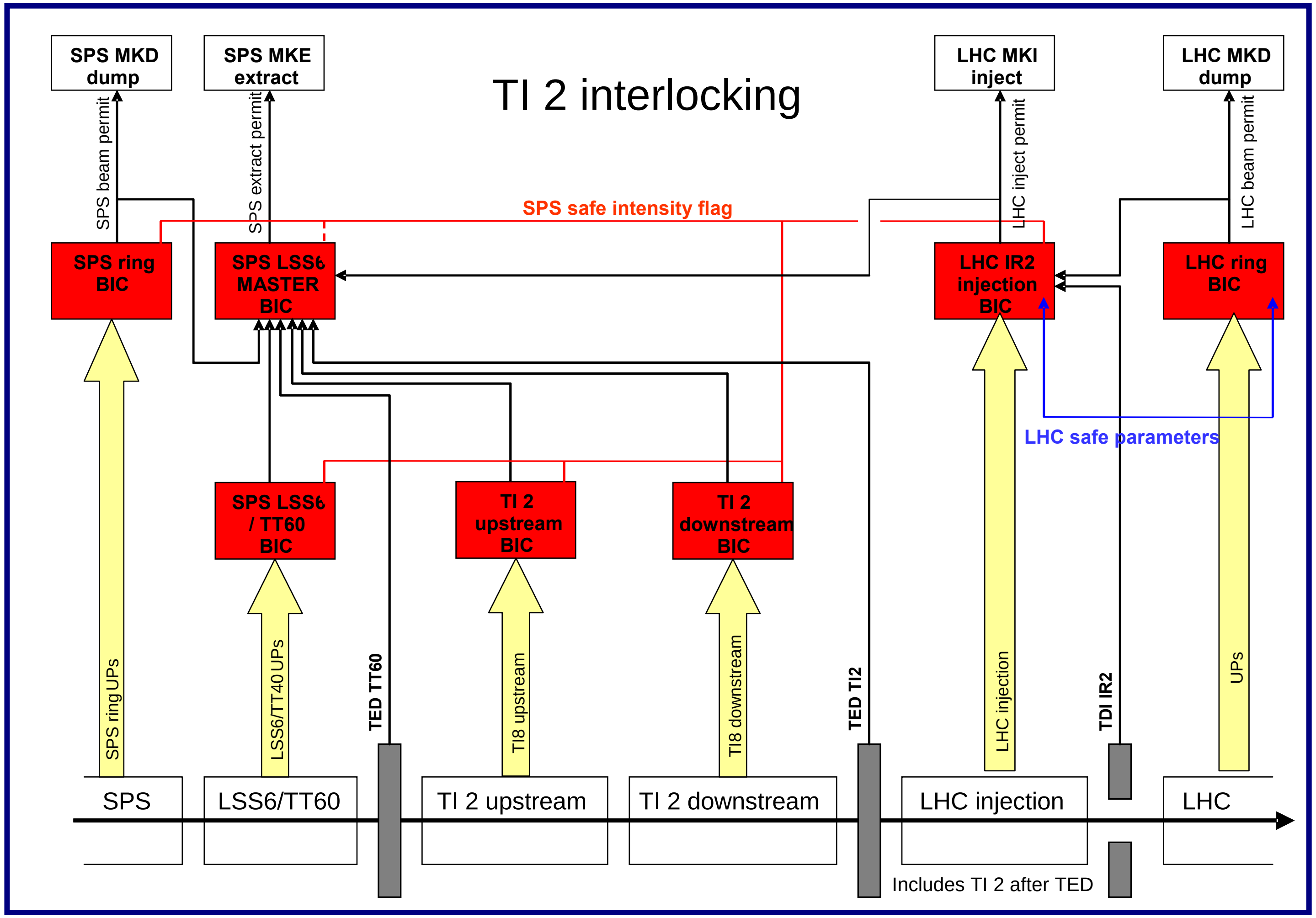
- Segmented Interlocking System, different possible operational modes in a safe way
  - e.g. Extraction without injection, IF TED (transfer line beam stopper) in the beam

- Without "LHC injection permit" NO "SPS extraction permit"

- Beam Presence condition for high intensity injection

- Safe Beam Flag: "maskable" interlock signals are ignored

Interlocking System: linking injection with extraction



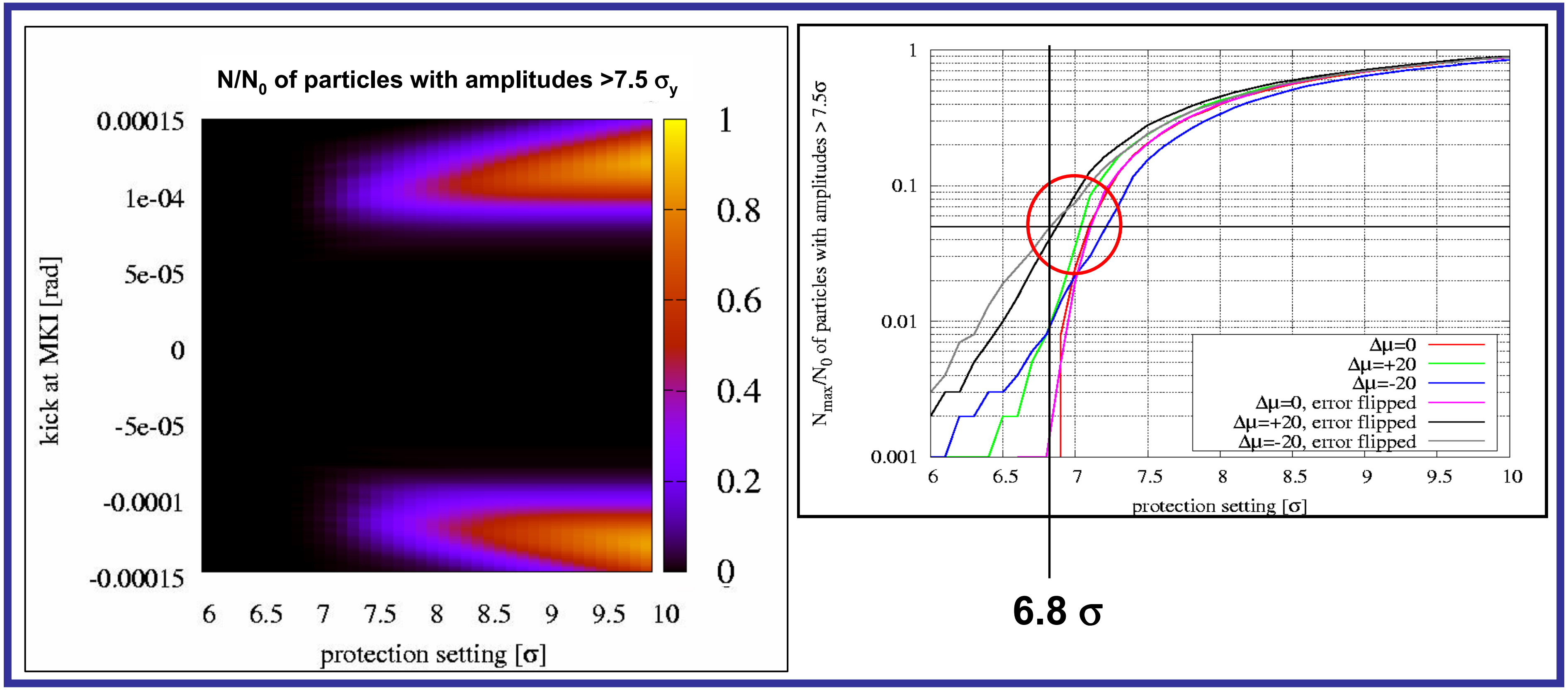
Protection level simulations to quantify system performance

Safe LHC injection ⇒ losses on aperture below 5% damage limit during injection

- Extensive tracking simulations to check performance
- MKI kicker failure scanned with injection absorber setting
- Full Monte Carlo of **single and grouped** failures at injection
  - 14 magnet and kicker families (SPS extraction, Transfer Line, LHC injection) for LSS4 - TI 8 – IR8
  - Full TL + LHC injection region aperture model (~3 km)
  - All imperfections and errors included

Injection kicker failure simulation results

- TDI, TCLI collimator setting of 6.8σ, to guarantee max. 5% above 7.5σ
- Increasing collimator opening increases risk of damage

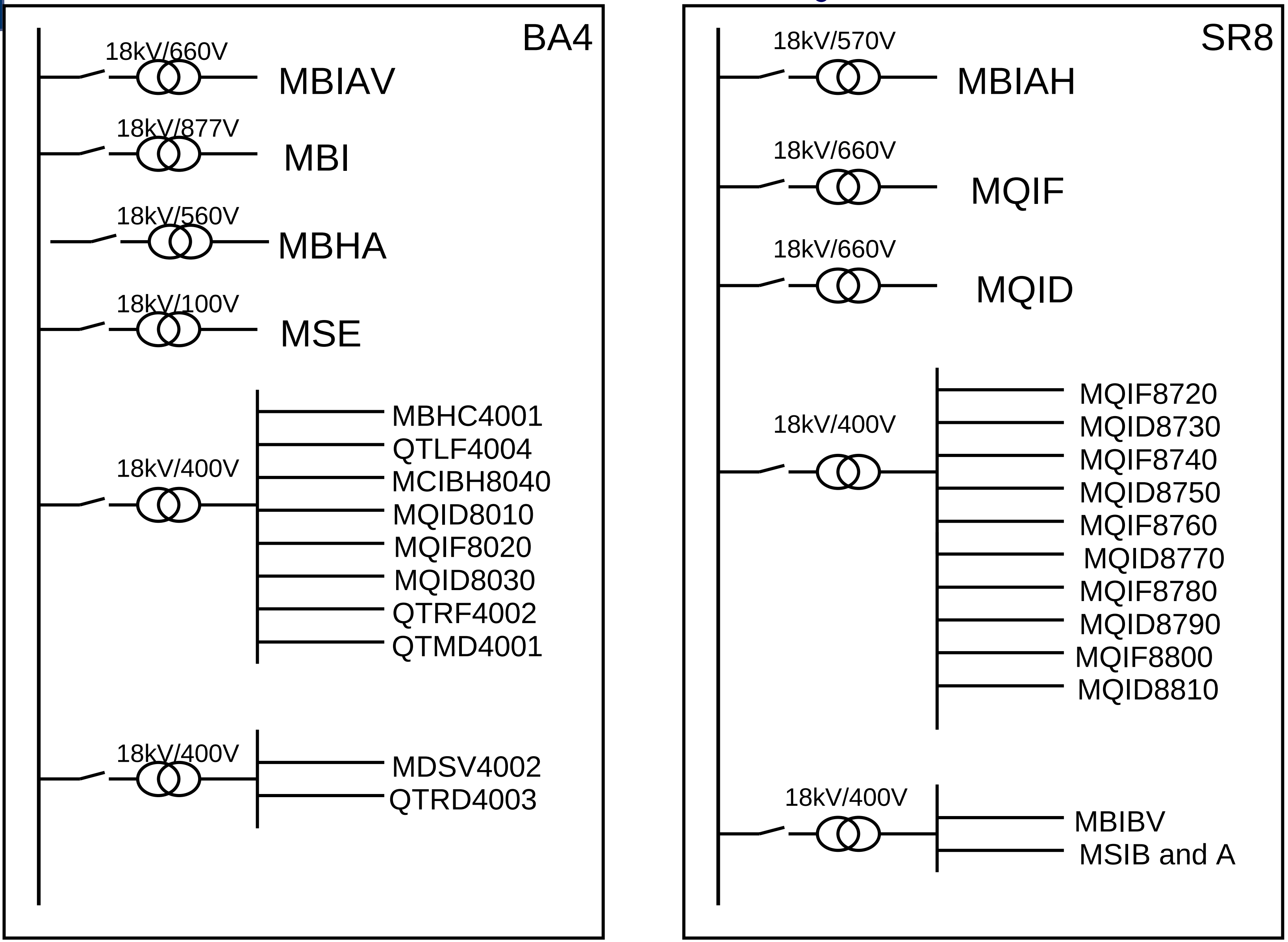


Single failure tracking Monte Carlo results (1000 seeds per failure)

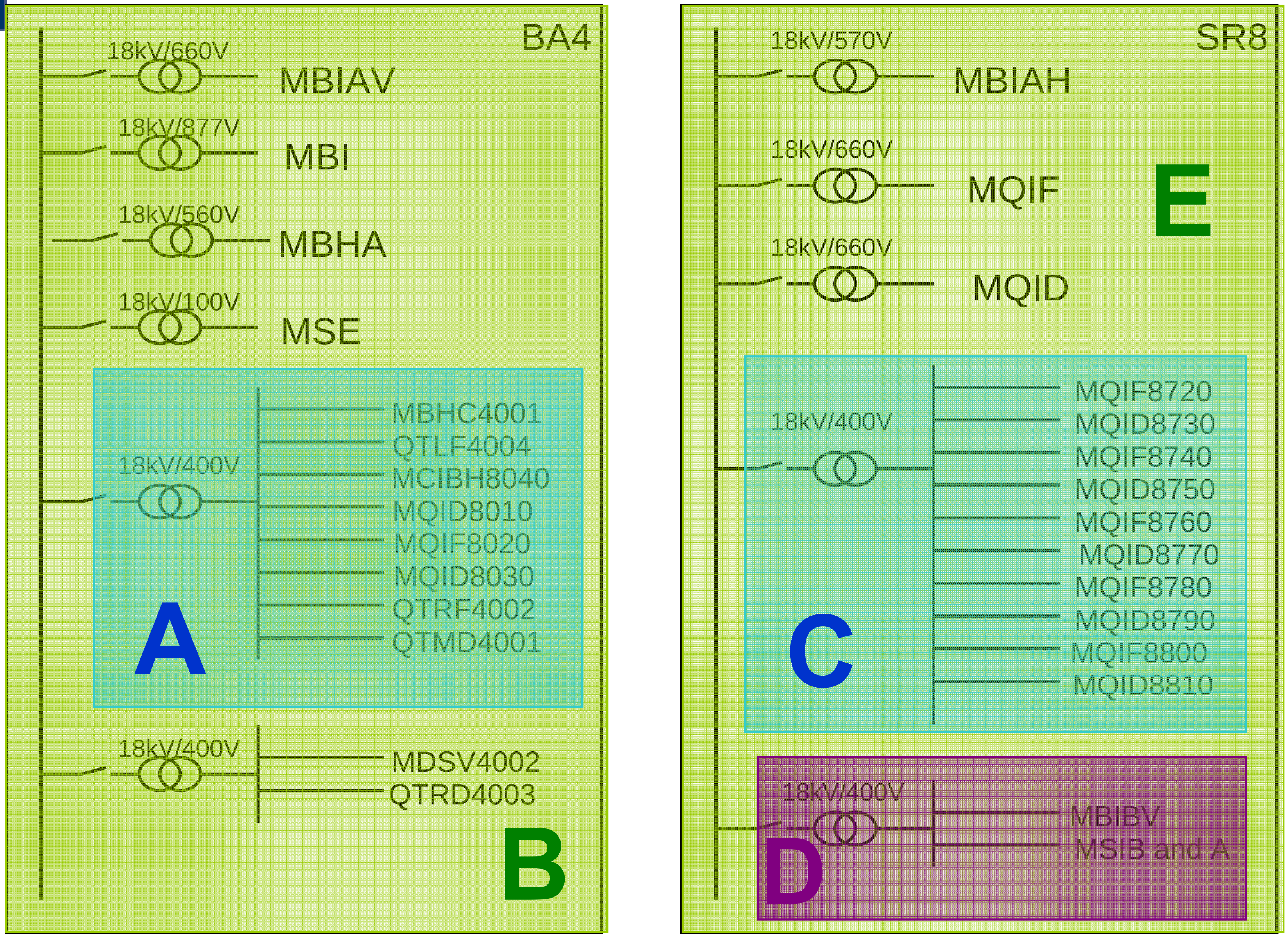
Family	Tolerable error [$\Delta k/k_0$]	required reaction time [ms]	Covered by	
			LHC	TL
MPLH (LSS4 bumper)	0.185	201.0	TCDI	PCS
MKE (LSS4 kicker)	0.125	-	TCDI	-
MSE (LSS4 septum, τ=23ms)	0.005	0.1	TCDI	FCCM
MBHC (TT40 H bend)	0.005	5.1	TCDI	FCCM
MBHA (TT40 H bend)	0.012	31.47	TCDI	PCS
MBI (main TI 8 bends)	0.003	2.7	TCDI	FCCM
MCIBH (start TI 8 H bend)	0.630	389.0	TCDI	PCS
MBIAH (end TI 8 H bend)	0.003	7.9	FCCM	FCCM
MBIBV (end TI 8 V bend)	0.003	43.4	PCS	PCS
3MCIAV (end TI 8 V bend)	0.183	98.43	PCS	TCDI
MSI (LHC injection septum)	0.0035	3.5	FCCM	n/a

- PCS = standard Power Convertor Surveillance (≥3ms)
- FCCM = Fast Current Change Monitor, **dedicated new system**

Grouped Failures: Powering Scheme for Extraction - Transfer - Injection (beam2)



Grouped Failures



Grouped failure tracking Monte Carlo results (1000 seeds per failure)

Group	Tolerable time after switch-off [ms]	Covered by	
		LHC	TL
A	1.3	TCDI	FCCM on MBHC (0.1% tolerable error)
B	0.1	TCDI	FCCM on MSE
C	15.8	TCDI	PCS
D	3.5-5.8, > 20	FCCM on MSI	TCDI/PCS
E	4.0-5.4, > 20	FCCM on MBIAH, MSI	FCCM on MBIAH (0.15% tolerable error)

- In some cases grouped failures can be ~ 5 times worse than single failures
  - e. g. MBHC
- Grouped failures covered with protection for single failures BUT: requires increased performance

Discussion of results

- **Fast magnet Current Change Monitor (FCCM)** is required
  - Specification: $\Delta I/I=0.1\%$, reaction time ~50μs
- With FCCM at the MSI injection septum **LHC protection looks OK**
- Transfer Line (TL): FCCMs are proposed for MSE, MBI, MBIAH, MBHC
  - MKE extraction kicker faults can still cause damage to the TL… possible solutions being studied.
- **All other single failures are covered for Transfer Line & LHC**
  - **Transfer Line collimation system (TCDI) gives full protection from upstream failures**
  - **Failures at end of line: slow enough for normal power converter surveillance or FCCM**
- **Grouped Failures: can be ~ 5times faster than single failures**
  - Covering single failures also covers grouped failures
  - But needs increased surveillance system performance

Fast Current Change Monitor for MSE extraction septum

FCCM tested for MSE
by M. Werner from DESY this month

FCCM measures changes of magnet voltage: no comparison with reference value

- Managed to detect $\Delta I/I<0.3\%$, reaction time < 50 μs
  - larger ripple on test-bench MSE power supply than real circuit (0.17% instead of 0.04%)
- Looks promising, needs to be finalized

Conclusions

- Tracking simulations extensively used to define protection systems and to determine protection levels
  - Quantitative results ⇒ requirements identified, specification of surveillance performance
  - LHC "fully protected" with foreseen active and passive protection
    - Require Fast Current Change Monitor to measure 0.1% ΔI, ~50μs reaction time
    - FCCM Development (M. Werner) looks promising even for fast extraction septum
    - Appropriate interlocking system has been specified
  - At present the protection systems cannot fully exclude TL damage
    - alternative solutions are being studied
- Simulations for total power cut and combined failures (protection device failure + other failure) will be carried out