SPS extraction, LHC transfer lines, LHC injection

PROTECTION AT INJECTION

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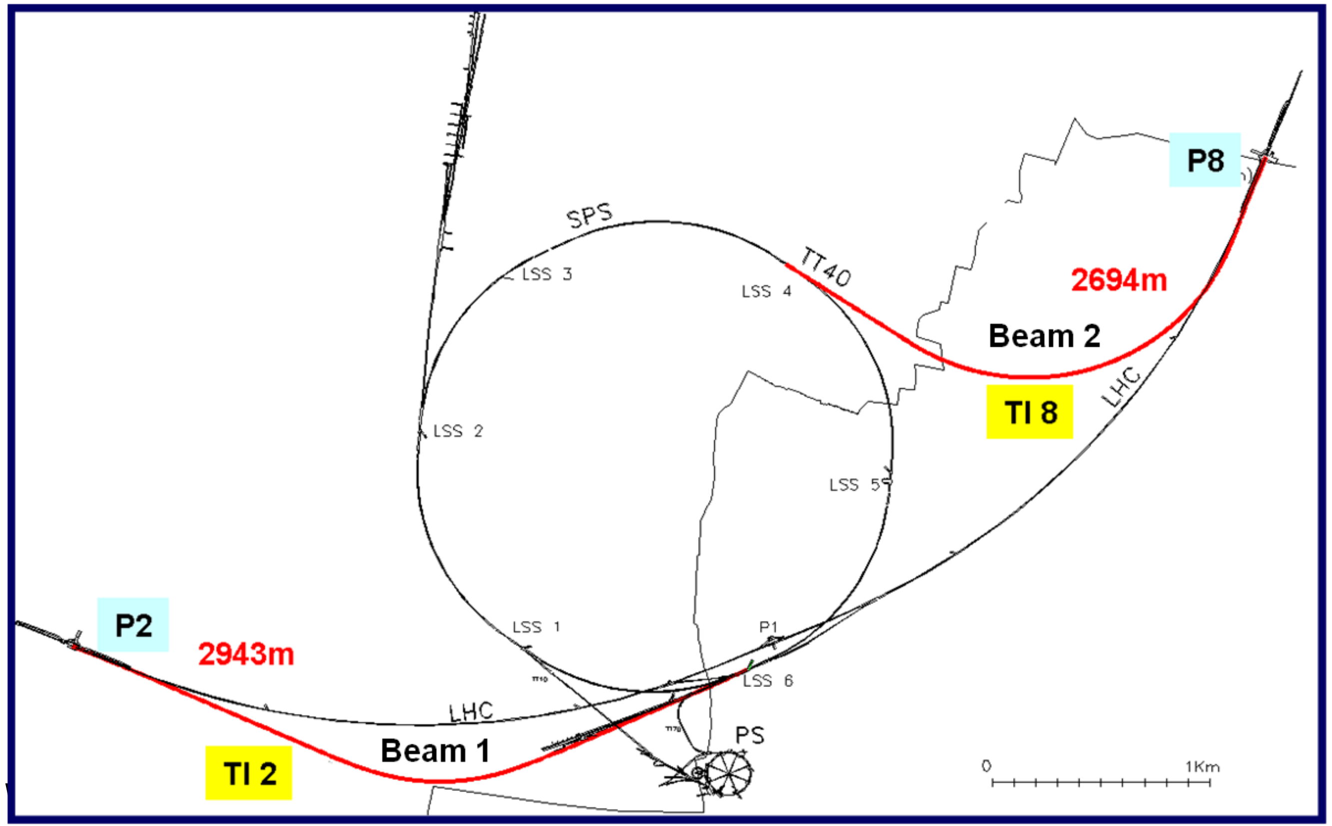
Introduction - Injection

- LHC filled from the SPS through transfer lines @ injection energy 450 GeV;
- Full nominal injected batch: 288 bunches of 1.15e+11 protons, emittance 3.5 μm. In total 12 injections needed to fill LHC.
- Failures during injection: single turn failures
- Injected intensity of full nominal batch factor ~ 20 above assumed “damage” limit at 450 GeV
- Injection protection concerns the WHOLE injection process:
  - SPS extraction + transfer lines + injection into LHC

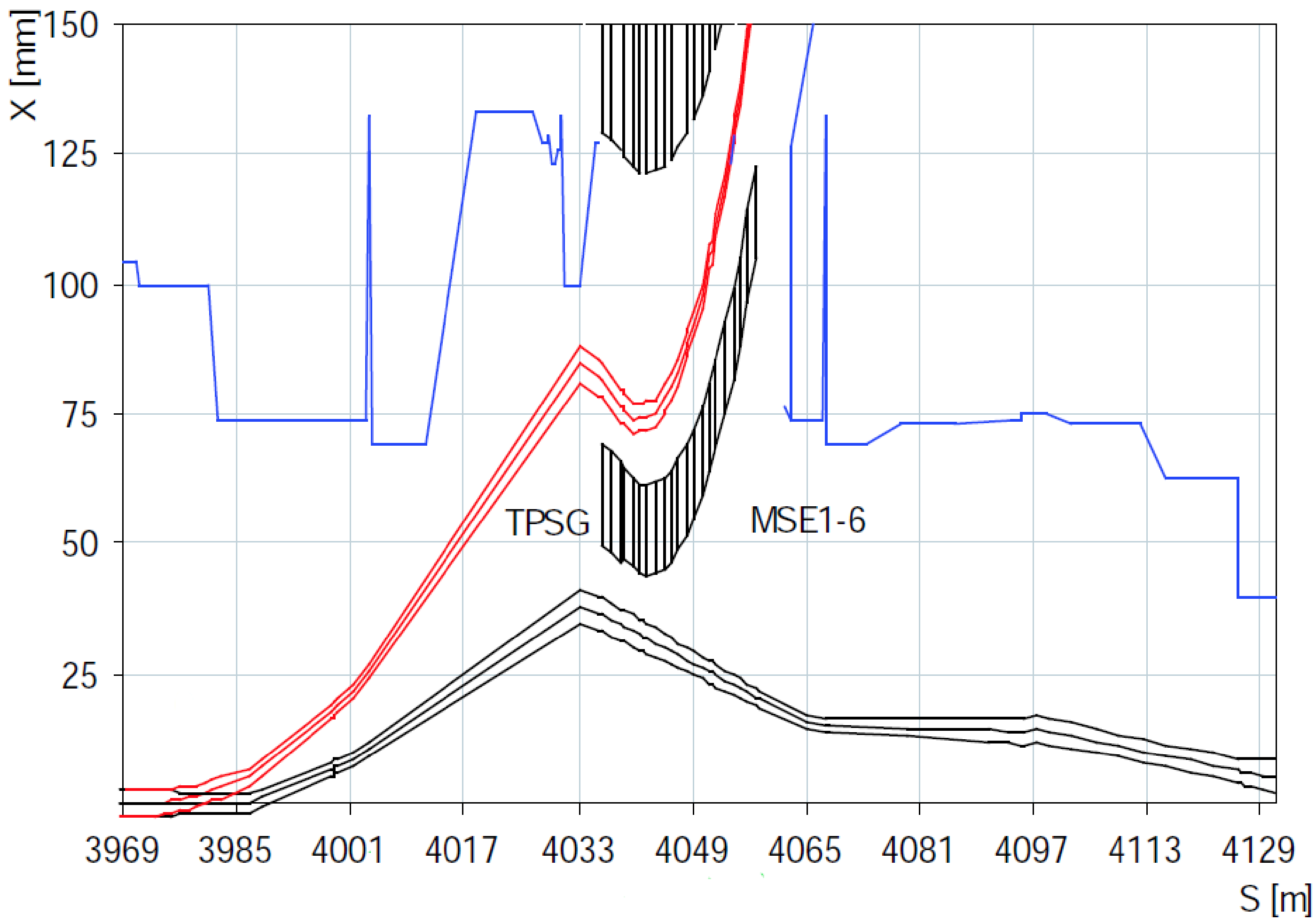


Injection points in the LHC are in experimental insertions, downstream of experiment.

Beam 1: point 2, ALICE
Beam 2: point 8, LHCb

SPS extraction

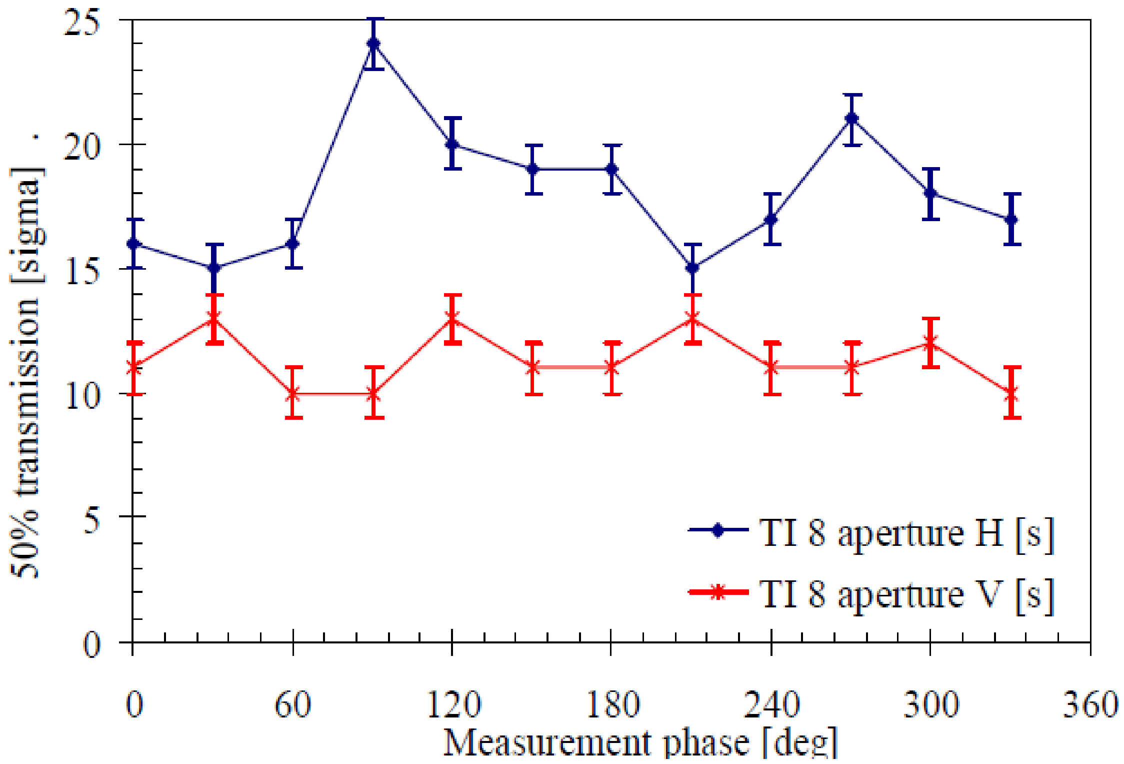
- SPS LHC extraction in point 4 (beam 2) and point 6 (beam 1)
  - Fast extraction
    - Large orbit bump (~ 30 mm)
    - MKE extraction kickers, rise time 1 μs, flattop 8 μs, 0.5 mrad kick
    - MSE(/T) extraction septa: 12 mrad kick

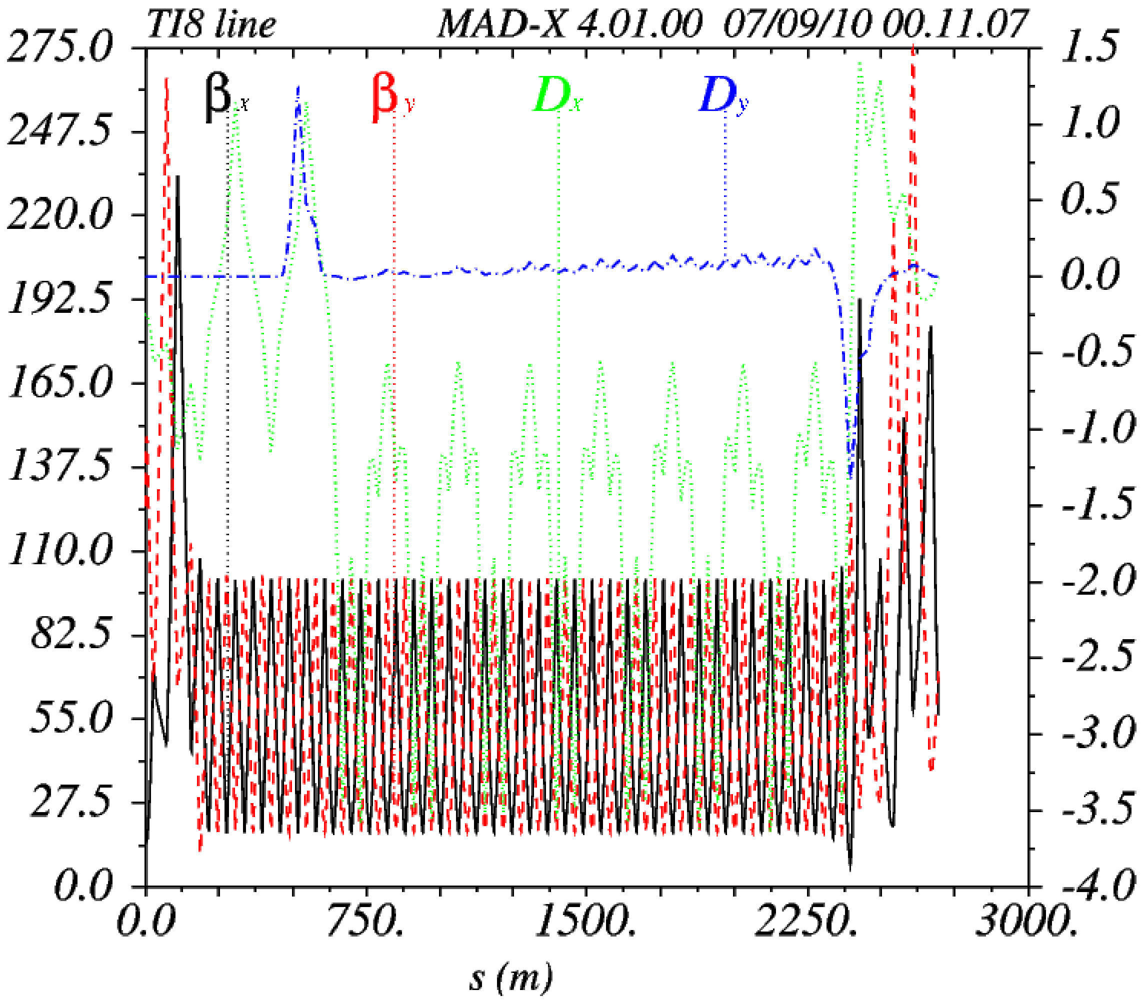


LHC Transfer Lines

3 km long transfer lines (TI 8 and TI 2):

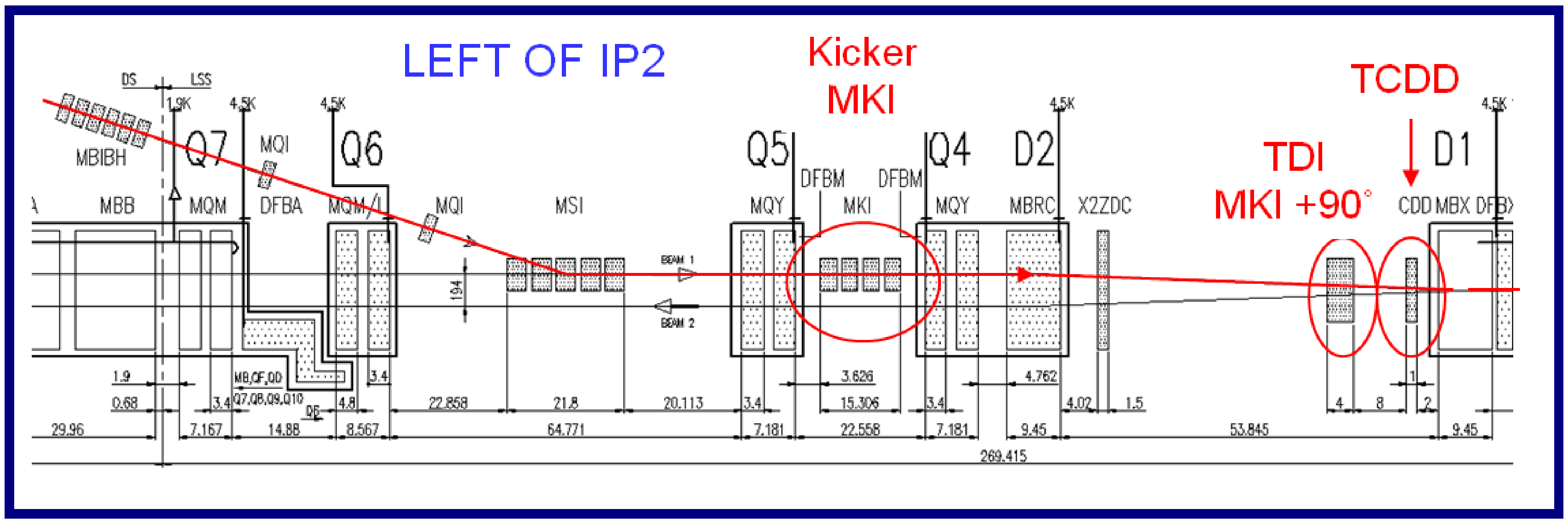
- Design aperture 6 σ. Measured: 9-10 σ.
- Large dispersion in transfer line ~ 4m in horizontal plane
- 2 moveable transfer line dumps per line (TED) to study line without injecting into the LHC. Dumps can take a full nominal LHC injection batch (288 bunches).

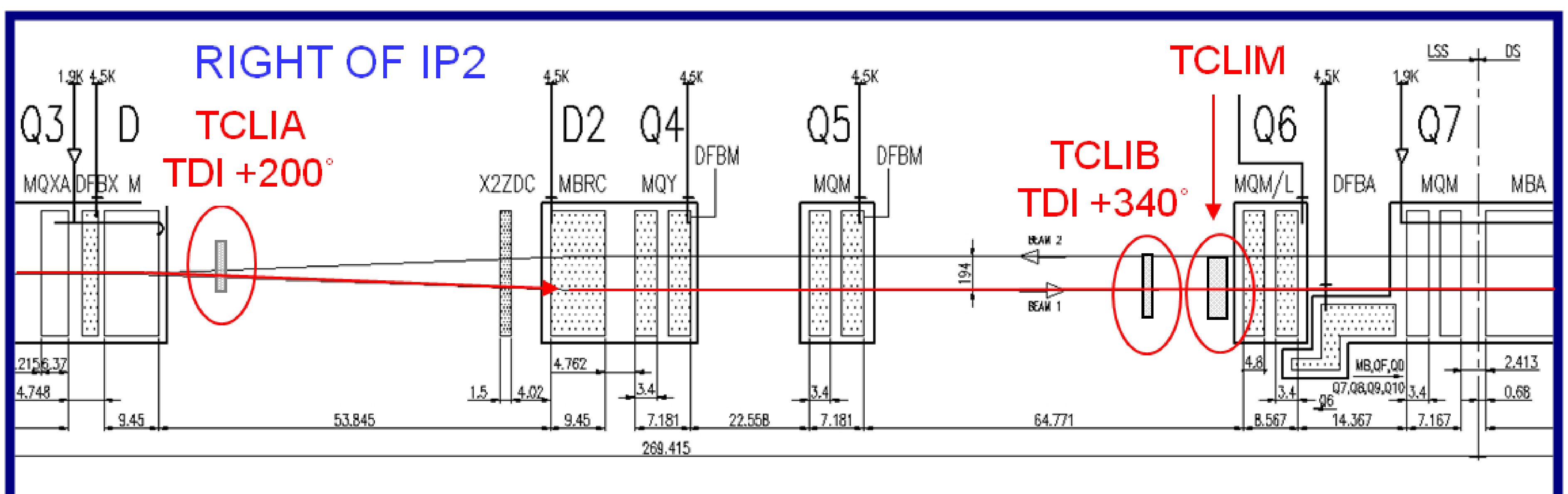




LHC Injection

- LHC injection: horizontal injection septum (12 mrad), vertical injection kicker (0.85 mrad); vertically off-centre through the LHC quadrupole (Q5)
- Protection against kicker failures: TDI + TCLIs
- Measured aperture: > 6 σ



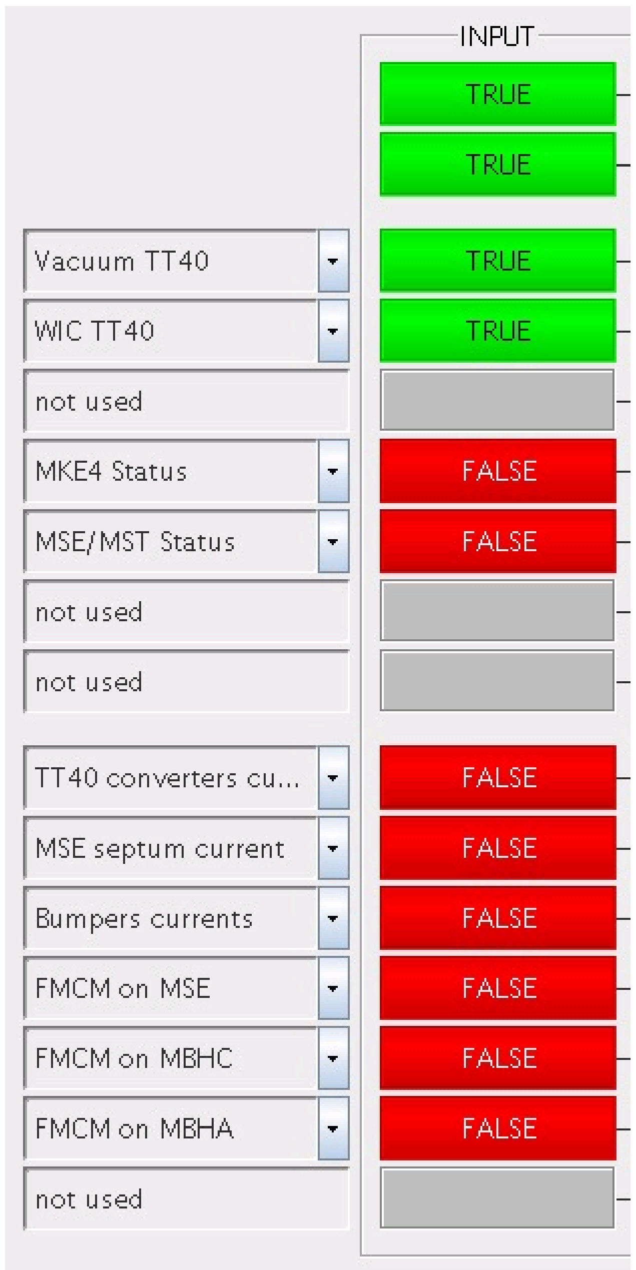


Surveillance - Interlocking

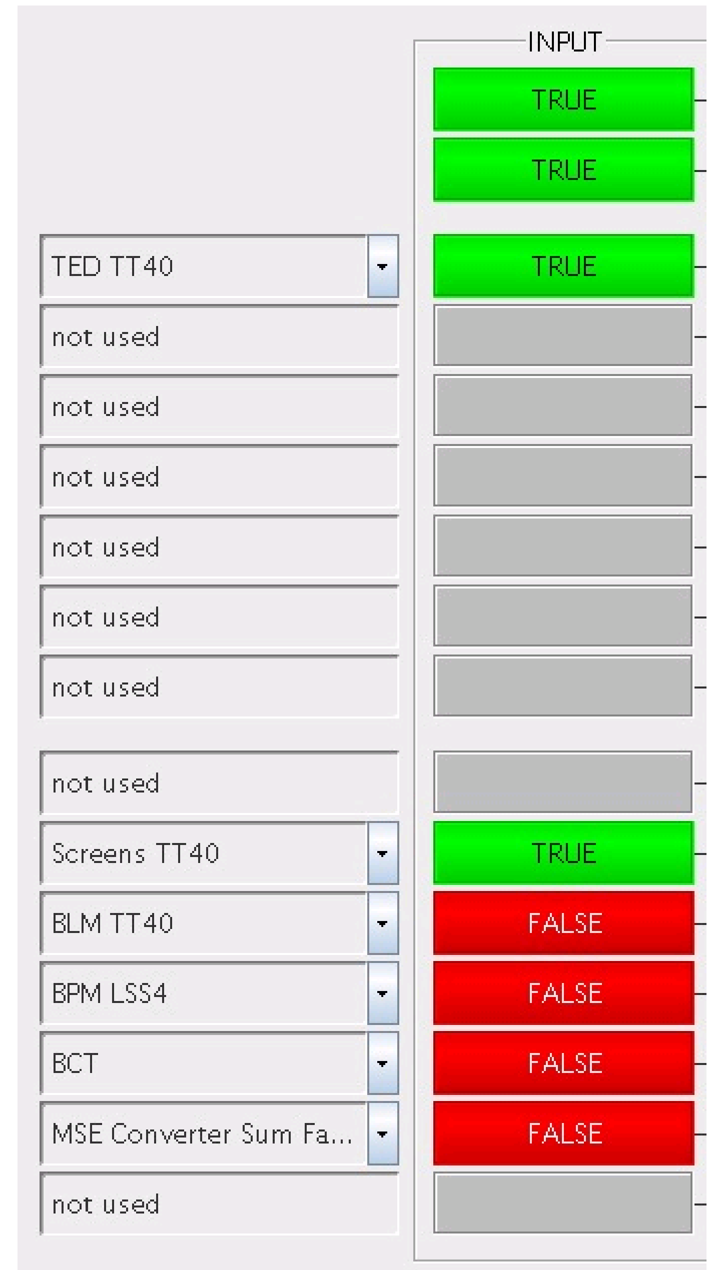
- All interlocked systems involved in extraction, transfer and injection have to give green light to have beam extracted from the SPS
- Interlocking system: a la LHC beam interlocking controllers (BIC)
  - Masking allowed for some inputs with SPS setup beam flag (10^{12} p^+)
- Extraction systems:
  - Extraction bump amplitude, bumper currents, septa currents, other magnet currents, BLMs, septa girder position, extraction kicker status, upper transfer line dump (TED) status (moving), magnet status, vacuum, software interlocks
  - Fast Magnet Current Change Monitor (FMCM): extraction septum (time constant for current decay 23 ms: 10 σ oscillation reached in 0.25 ms), and others
- Transfer lines:
  - Magnet current surveillance, magnet status, BLMs, BTV screen positions, transfer line collimator jaw positions, experiment inputs, lower TED status, FMCMs, vacuum, software interlocks
- Injection systems (using LHC setup beam flag):
  - Injection permit from experiments, collimator jaw positions, beam dump, magnet current surveillance, FMCM, vacuum, software interlocks, **LHC beam permit**

Extraction Interlocks

Example beam 2



TT40 A



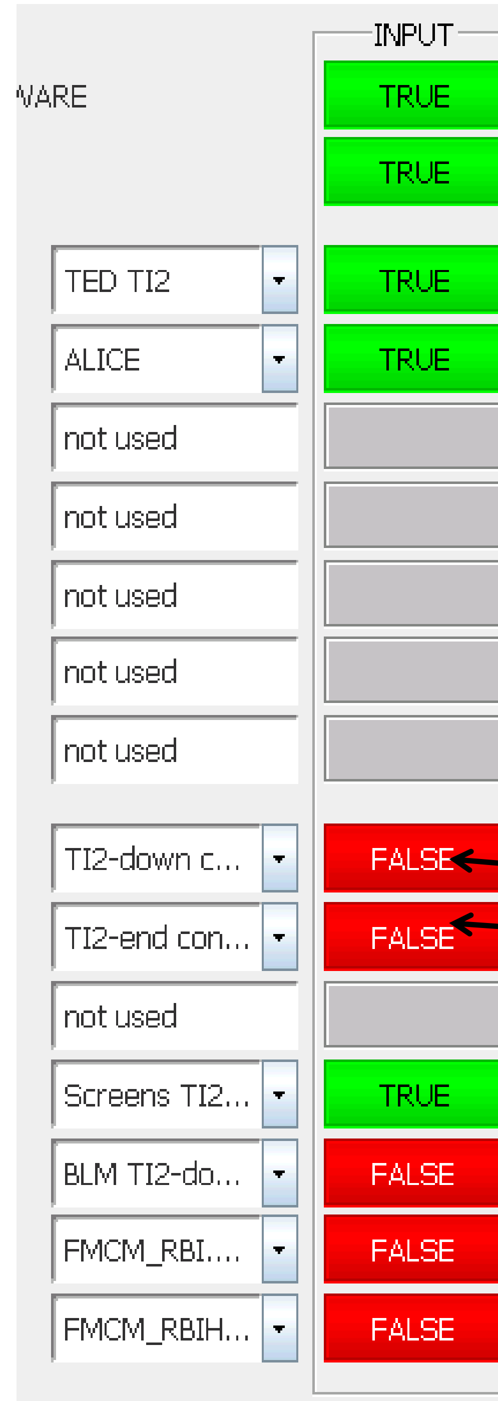
TT40 B

Transfer line Interlocks

Example beam 1

PC interlock →

TI2 U



← PC interlock

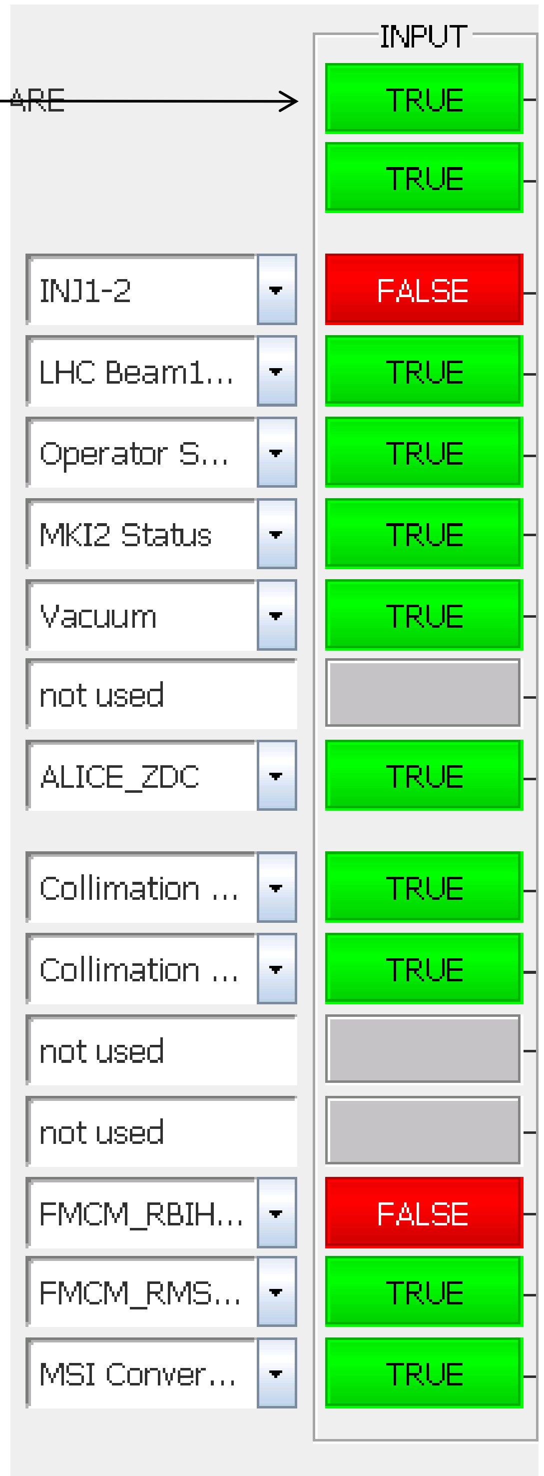
← PC interlock

TI2 D

Injection Interlocks

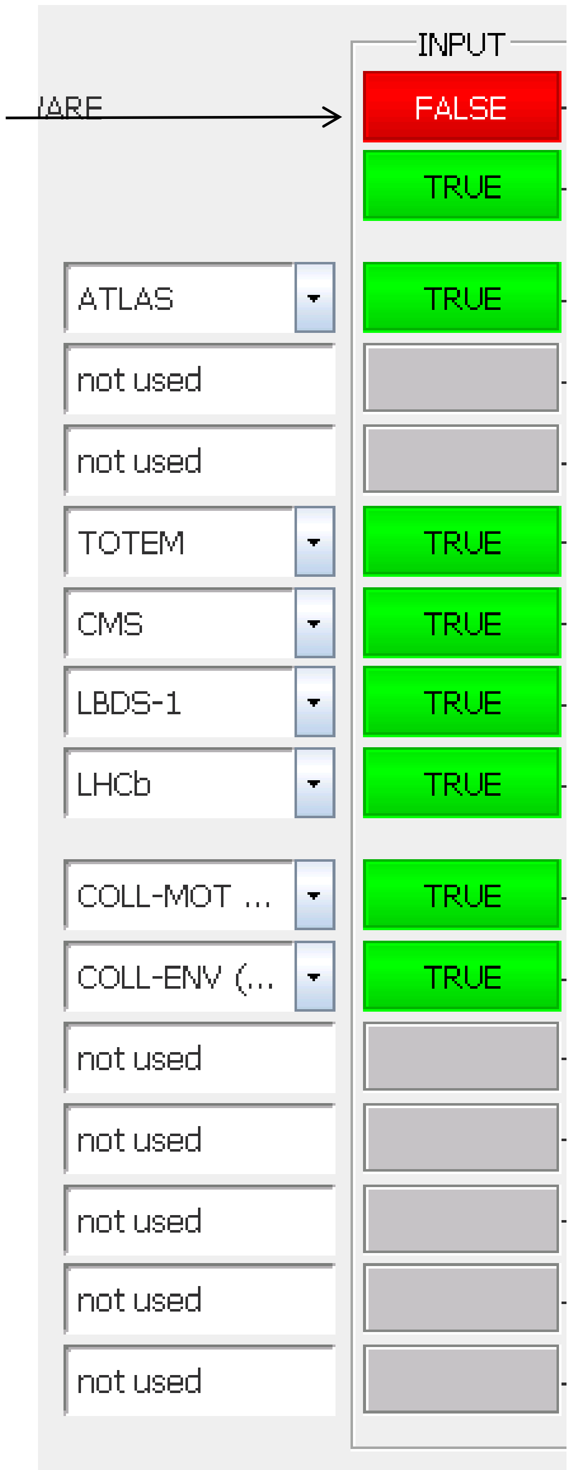
Example beam 1

Global injection software permit



INJ 1

Beam 1 specific Injection software permit



INJ 2

Additional Passive Protection Before Injection

- ALL magent current settings involved in the injection process are interlocked, except Q5: circuits on SPS timing (including the injection septum) are hardware interlocked. LHC power converters are interlocked through SIS

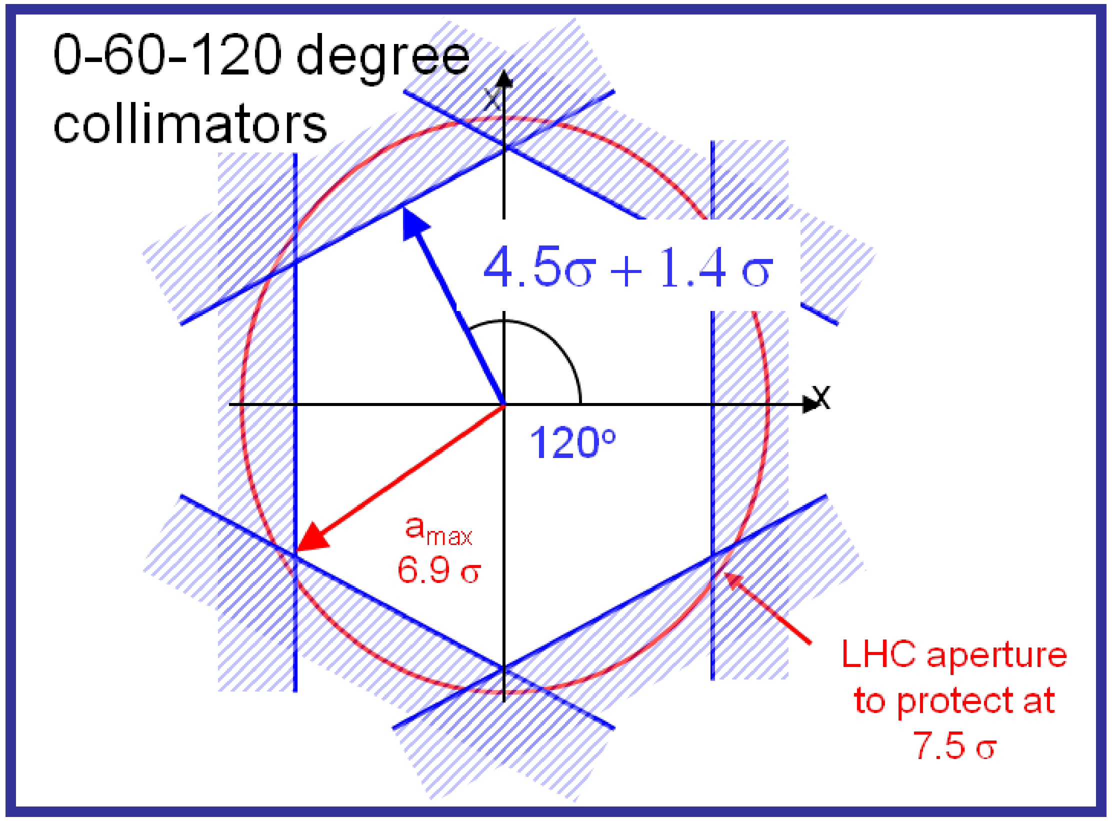
- Last check before extraction ~ 4ms for current surveillance. Very fast circuits (MSE, dipoles in TLs,...) → FMCMs.

- Final protection: **transfer line collimators (TCDI)** at the end of the line – as close as possible to the LHC.

  - Last 2 collimators right in front of the injection septum.

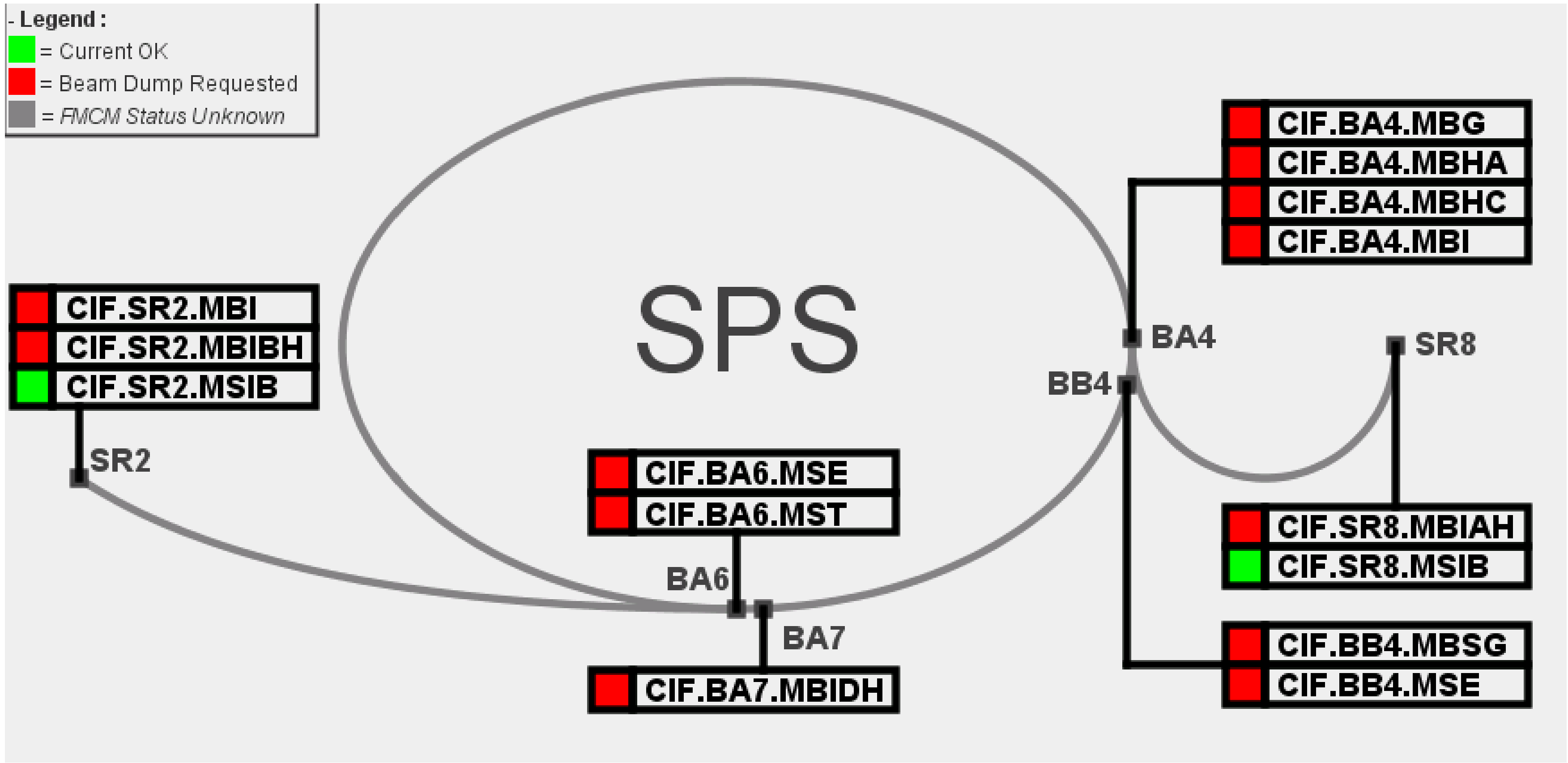
  - 3 collimators per plane in total, full phase space coverage. Protection against ANY failure upstream

  - LHC type collimators, 1.2 m long, graphite



Magnet current interlocking

- Tolerances on magnet currents for extraction and transfer:
  - 0.1-0.2 % on current of all dipoles
  - 0.5 % on current of all quadrupoles
  - 15 μrad on all trajectory corrector magnets
- All tolerances are “critical settings” (login required, digitally signed values)
- Circuits with FMCMs:



Injection only on request

- LHC beam is NOT automatically produced in the injector chain when the LHC beam cycles are loaded.

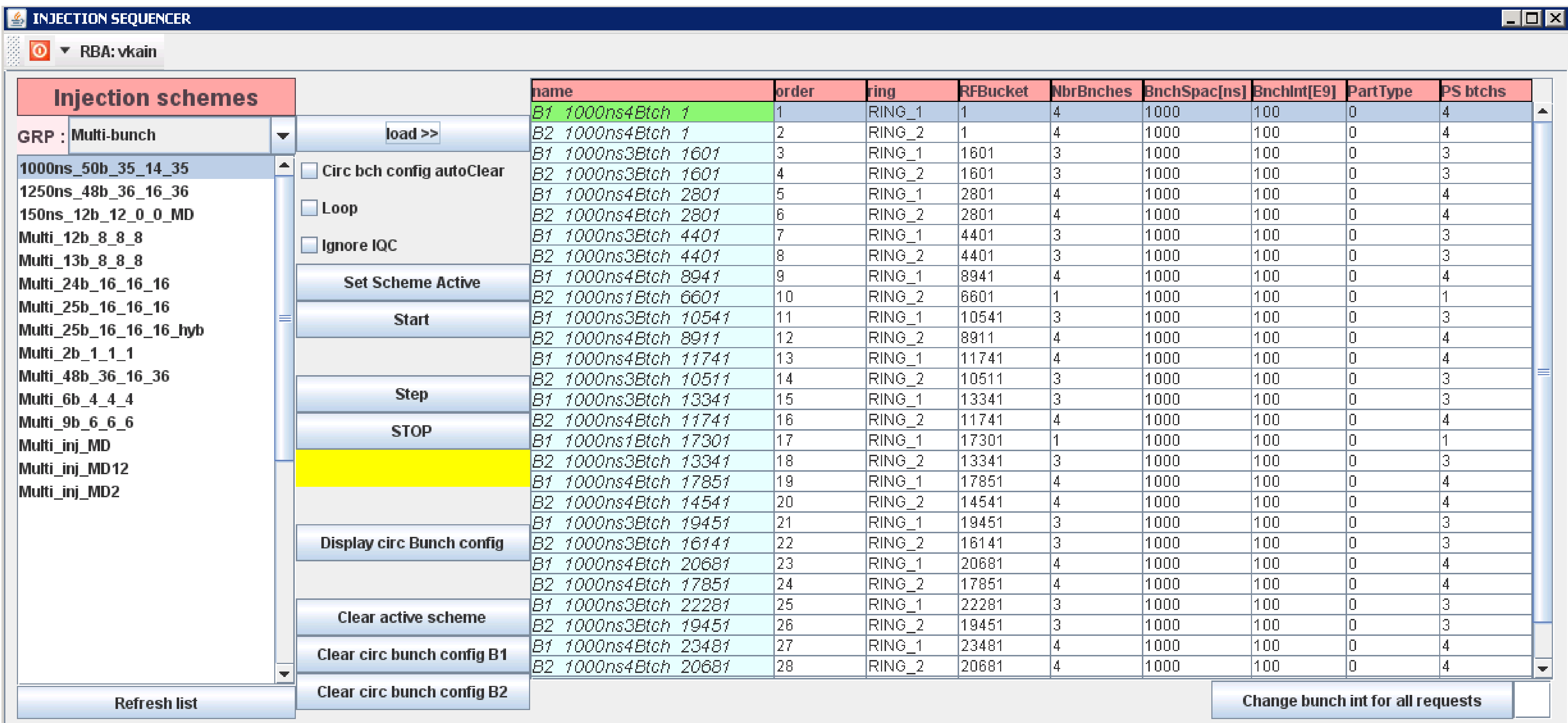
The LHC operations crew has to do a REQUEST, only then the **kicker prepulses** are generated

  - which ring to inject
  - “how many bunches” (how many PS batches)
  - which RF bucket should the first bunch of the next injected batch go into

Injection schemes are predefined.

Operations crew decides which scheme to play and when to play which request.

And we have to be careful there!!



name	order	ring	RFBucket	NbrBnches	BnchSpac[ns]	BnchInt[E9]	PartType	PS btchs
B1 1000ns4Btch 1	1	RING_1	1	4	1000	100	0	4
B2 1000ns4Btch 1	2	RING_2	1	4	1000	100	0	4
B1 1000ns3Btch 1601	3	RING_1	1601	3	1000	100	0	3
B2 1000ns3Btch 1601	4	RING_2	1601	3	1000	100	0	3
B1 1000ns4Btch 2801	5	RING_1	2801	4	1000	100	0	4
B2 1000ns4Btch 2801	6	RING_2	2801	4	1000	100	0	4
B1 1000ns3Btch 4401	7	RING_1	4401	3	1000	100	0	3
B2 1000ns3Btch 4401	8	RING_2	4401	3	1000	100	0	3
B1 1000ns4Btch 8941	9	RING_1	8941	4	1000	100	0	4
B2 1000ns1Btch 6601	10	RING_2	6601	1	1000	100	0	1
B1 1000ns3Btch 10541	11	RING_1	10541	3	1000	100	0	3
B2 1000ns4Btch 8911	12	RING_2	8911	4	1000	100	0	4
B1 1000ns4Btch 11741	13	RING_1	11741	4	1000	100	0	4
B2 1000ns3Btch 10511	14	RING_2	10511	3	1000	100	0	3
B1 1000ns3Btch 13341	15	RING_1	13341	3	1000	100	0	3
B2 1000ns4Btch 11741	16	RING_2	11741	4	1000	100	0	4
B1 1000ns1Btch 17301	17	RING_1	17301	1	1000	100	0	1
B2 1000ns3Btch 13341	18	RING_2	13341	3	1000	100	0	3
B1 1000ns4Btch 17851	19	RING_1	17851	4	1000	100	0	4
B2 1000ns4Btch 14541	20	RING_2	14541	4	1000	100	0	4
B1 1000ns3Btch 19451	21	RING_1	19451	3	1000	100	0	3
B2 1000ns3Btch 16141	22	RING_2	16141	3	1000	100	0	3
B1 1000ns4Btch 20681	23	RING_1	20681	4	1000	100	0	4
B2 1000ns4Btch 17851	24	RING_2	17851	4	1000	100	0	4
B1 1000ns3Btch 22281	25	RING_1	22281	3	1000	100	0	3
B2 1000ns3Btch 19451	26	RING_2	19451	3	1000	100	0	3
B1 1000ns4Btch 23481	27	RING_1	23481	4	1000	100	0	4
B2 1000ns4Btch 20681	28	RING_2	20681	4	1000	100	0	4

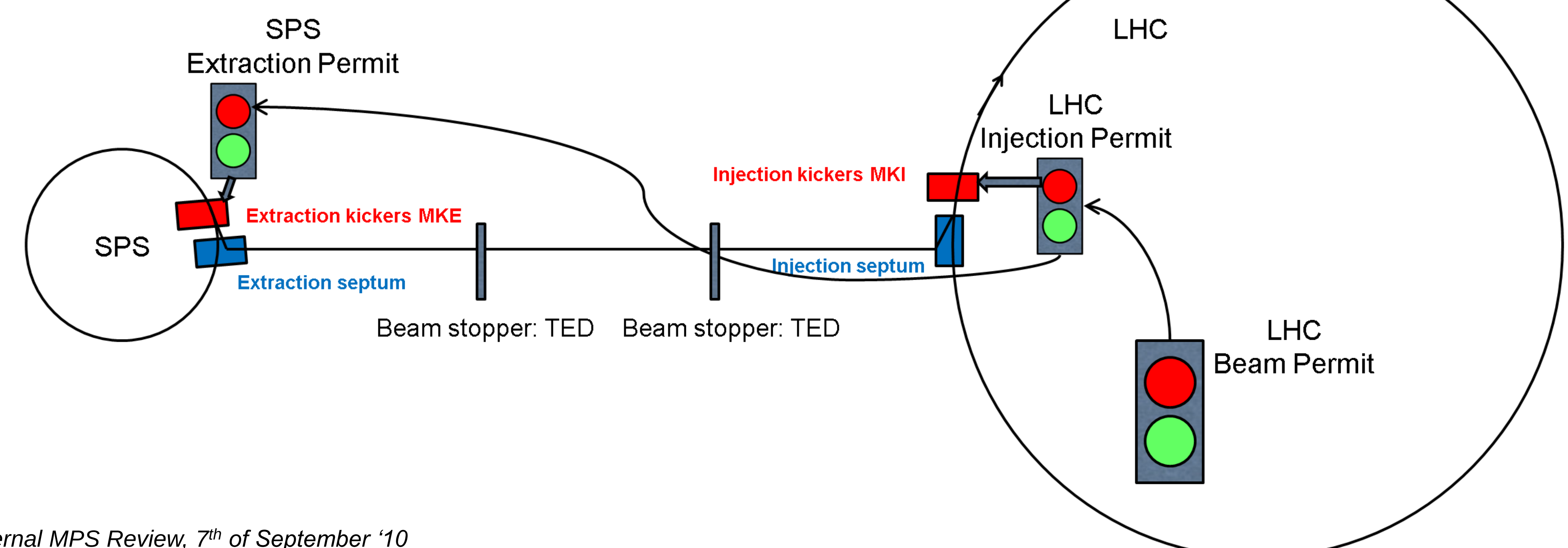
Kickers only pulse if they have the PERMIT

- ...and if energy is correct (BETS = beam energy tracking system) and for the injection kicker: if the abort gap keeper (AGK) gives green light → see Jan's talk

- LHC injection kicker needs: injection permit (produced by the injection BICs)
- SPS extraction kicker needs: extraction permit (produced by the extraction master BIC)

- Injection permit = LHC beam permit + injection BICs OK
- Extraction permit = injection permit + transfer line BICs OK + extraction BICs OK +

  \+ **combination of flags**



Master BICs for the extraction permit

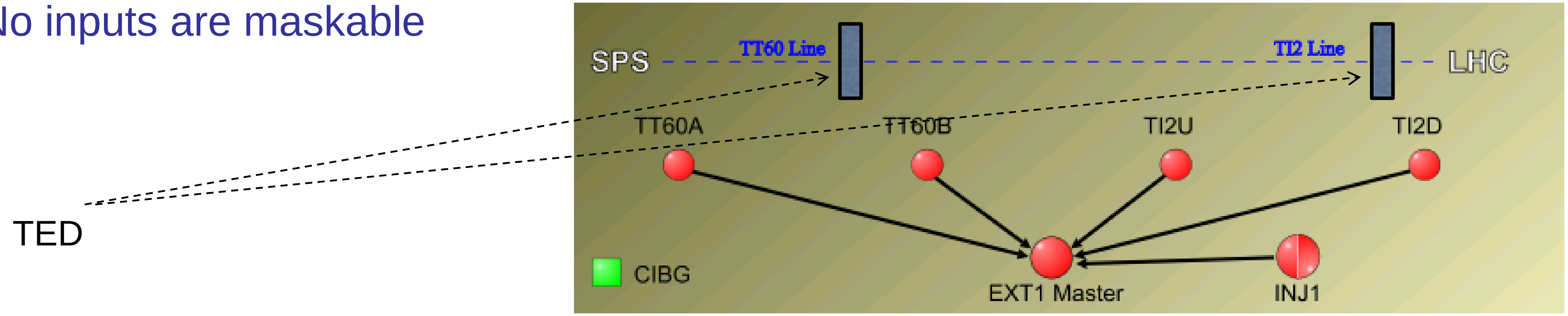
- Extraction permit for the extraction kickers is generated by a special BIC

- TED position is taken into account to ignore downstream inputs for necessary operational flexibility

- Principle:

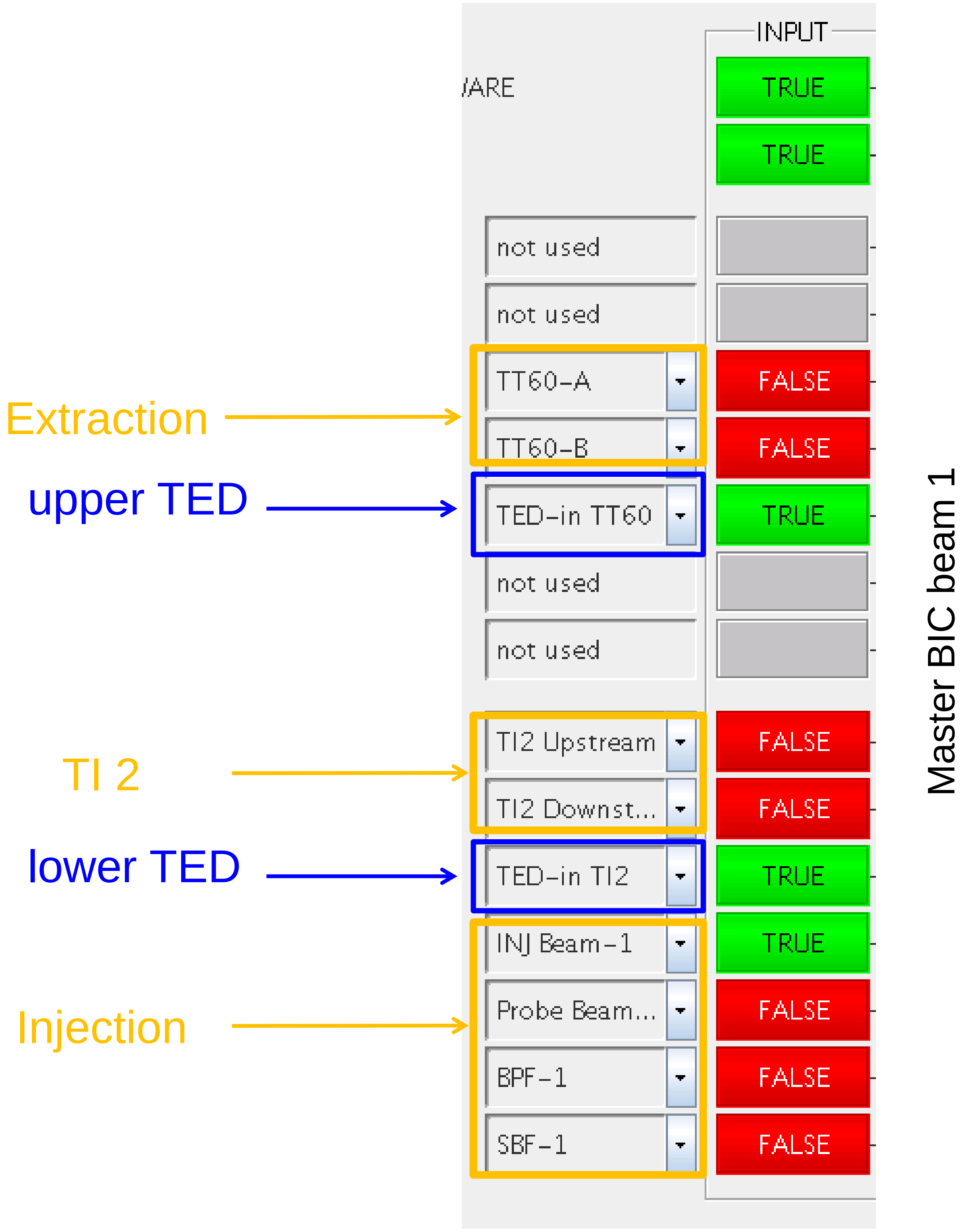
Extraction permit = extraction BICs OK AND (TED in OR BICs downstream OK)

No inputs are maskable



Beam 2 Extraction BIC another complication: CNGS uses the same extraction channel

Extraction Master BIC



Beam Presence

- Not everything is interlocked in the LHC. The final check for all conditions fine: circulating beam established.

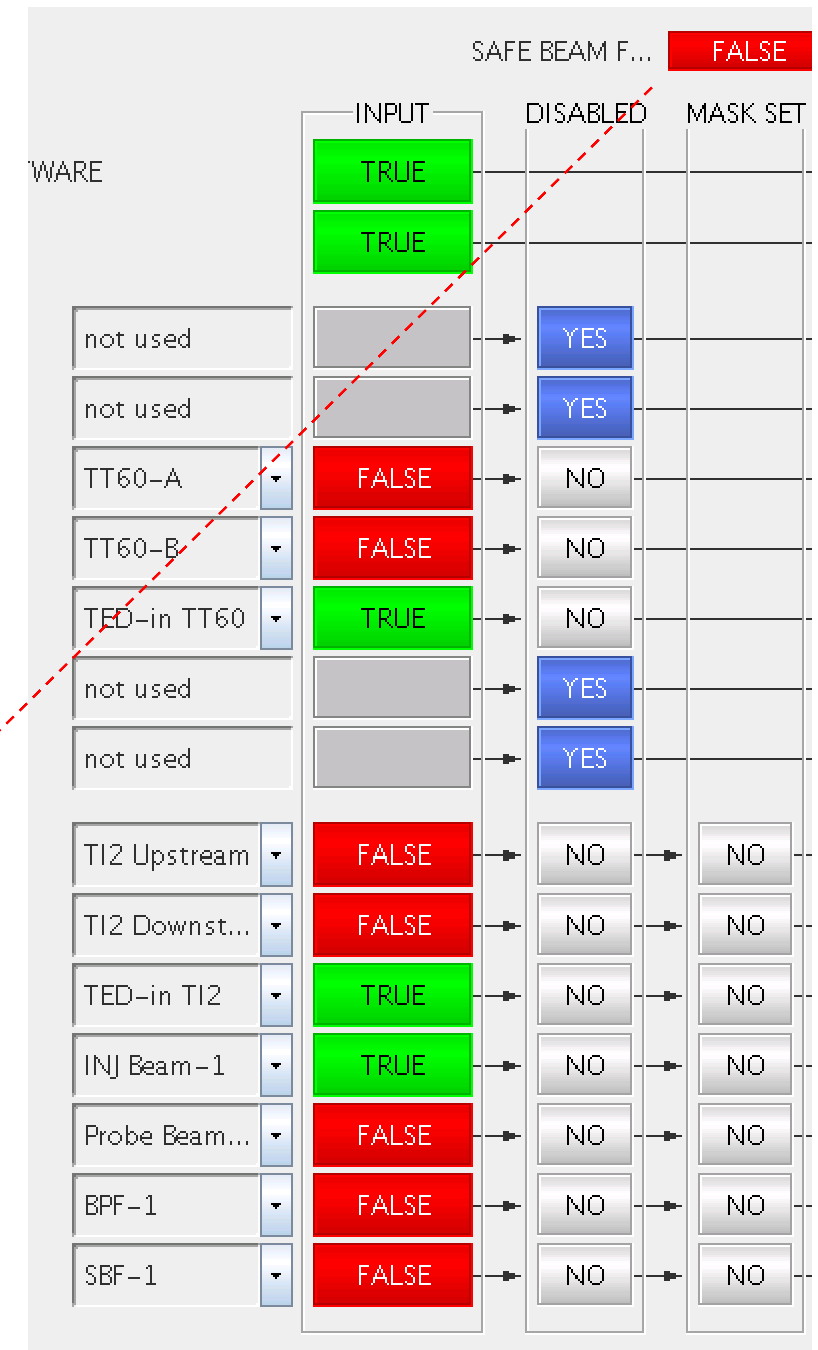
- → High intensity beam can only be injected into the LHC if beam is already circulating

  → Beam presence flag: derived from LHC FBCT

- If "Beam presence flag" is false, only beam below the "probe beam threshold" can be injected.

- Beam intensity > SPS Set-up beam intensity can only be injected, if beam is circulating and the LHC set-up beam flag is false. → FORCING LHC set-up beam flag.

- The Extraction Master BICs look after this logic:

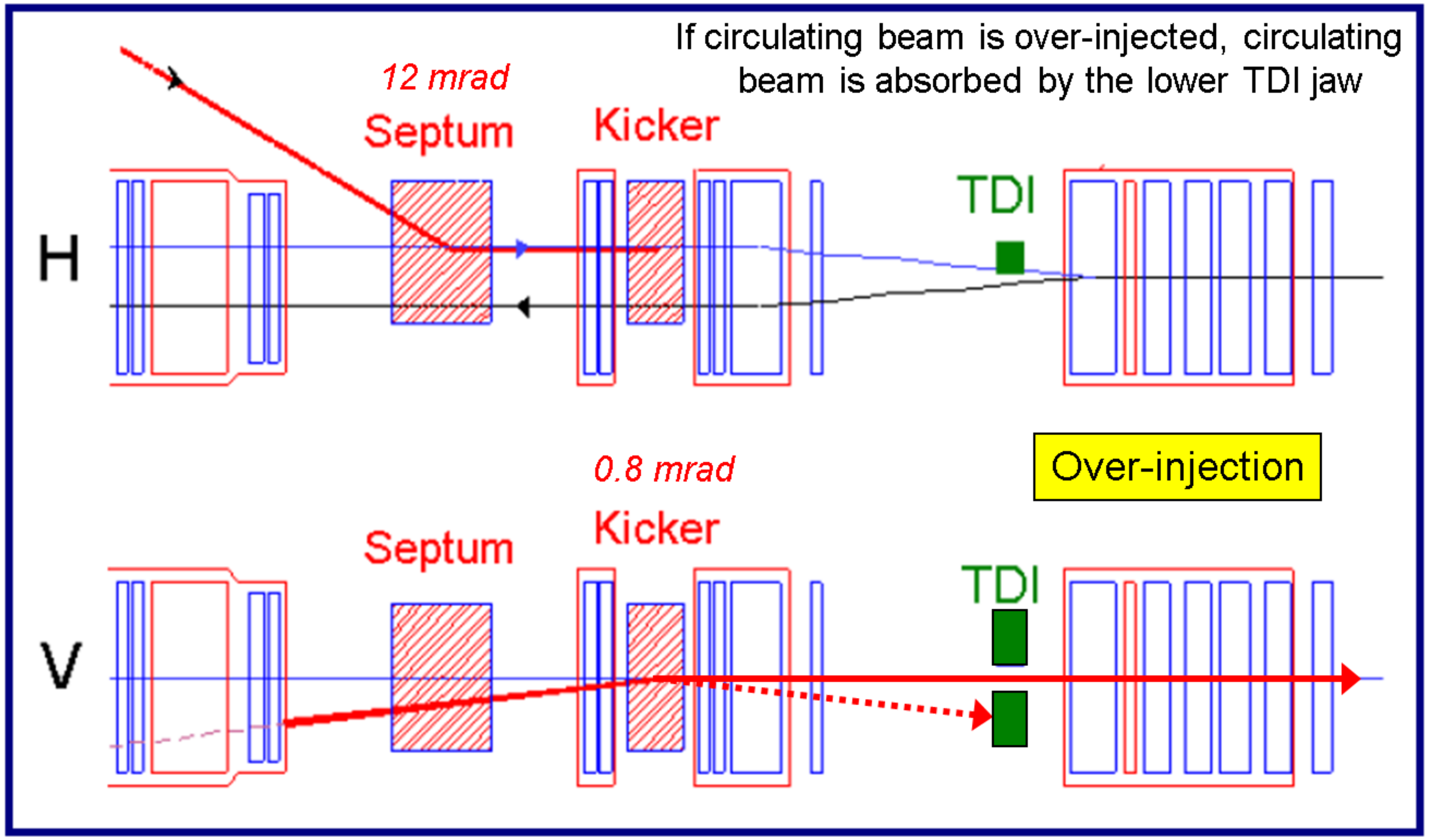


Injection is only possible if :

Probe Beam Flag ||
[Beam Presence && (NOT.(LHC Set-up Beam Flag) ||
SPS Set-up Beam Flag)]

Overinjection

- Because of the beam presence concept, we have to overinject our physics beam onto the probe beam
- Our control system has to allow us to overinject

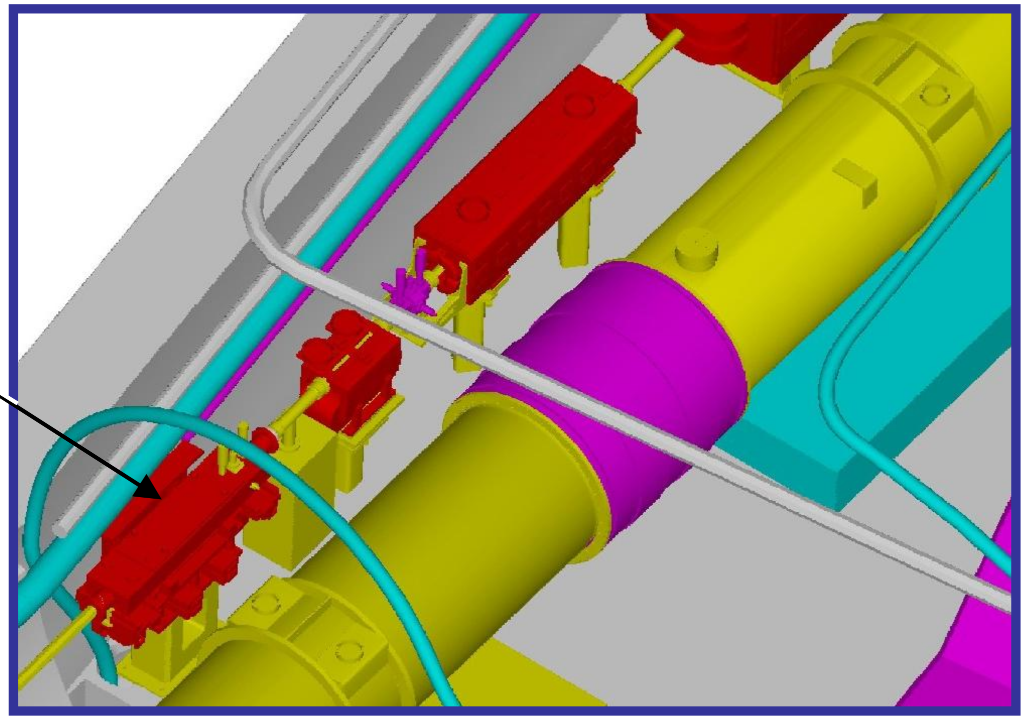


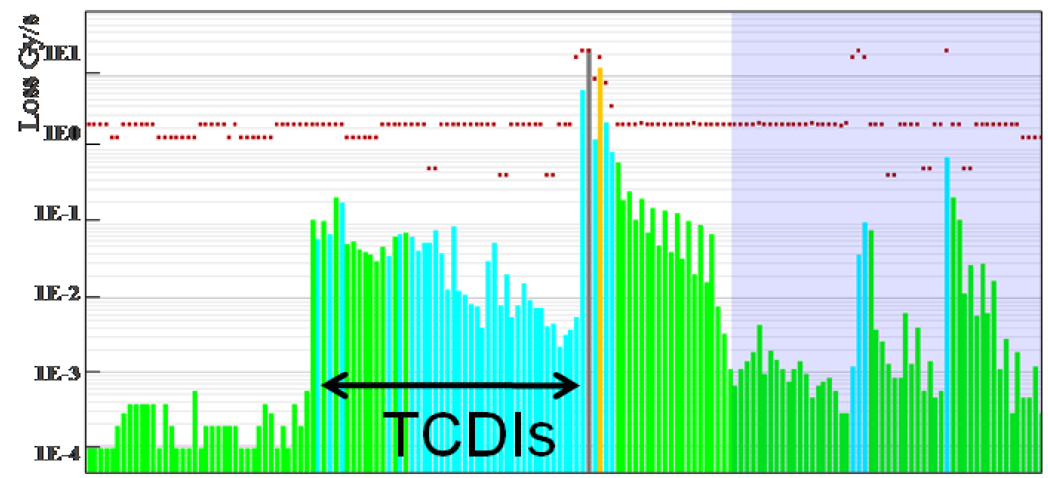
- ...the TDI has two jaws.
- The injection SIS checks each injection request: protects against overinjection onto more than bunch circulating.

Issues – Transfer line collimators

- Collimator setting tight (4.5 s) and partly large dispersion at collimators, and they are close to LHC superconducting magnets.

TI8
TCDIH060





Injection 4 nominal bunches: factor 10 margin to BLM thresholds

Longitudinal and transverse in the SPS parameters in the SPS have to be very well under control. Otherwise tails,…

- Settings management:
  - Transfer line collimator settings management and interlocking behaviour like LHC ring collimator (movement blocked when going across threshold,...)
  - Should eventually find a solution which allows to change thresholds only rarely. Or have very strict state machine implementation for LHC operations.

Transfer line collimators: still to come

- So far injections below set-up beam limit.
- Validation of protection level of the transfer line collimators (phase space coverage) will come in the coming days.
  - Maximum amplitudes escaping the systems should be below 6.9 s.
- Comment on circuits which are within or after the transfer line collimation section:

TI8	
MBIAH	FMCM
3 x MCIAV	-
MCIAH, MCIAV	-
MSI	FMCM

"slow": in case of trip 185 ms to reach 10 σ (refers to 3 x MCIAV)

TI2	
MBIBH	FMCM
MCIAV	-
MSI	FMCM

Will verify whether these correctors need to be disallowed for trajectory correction.

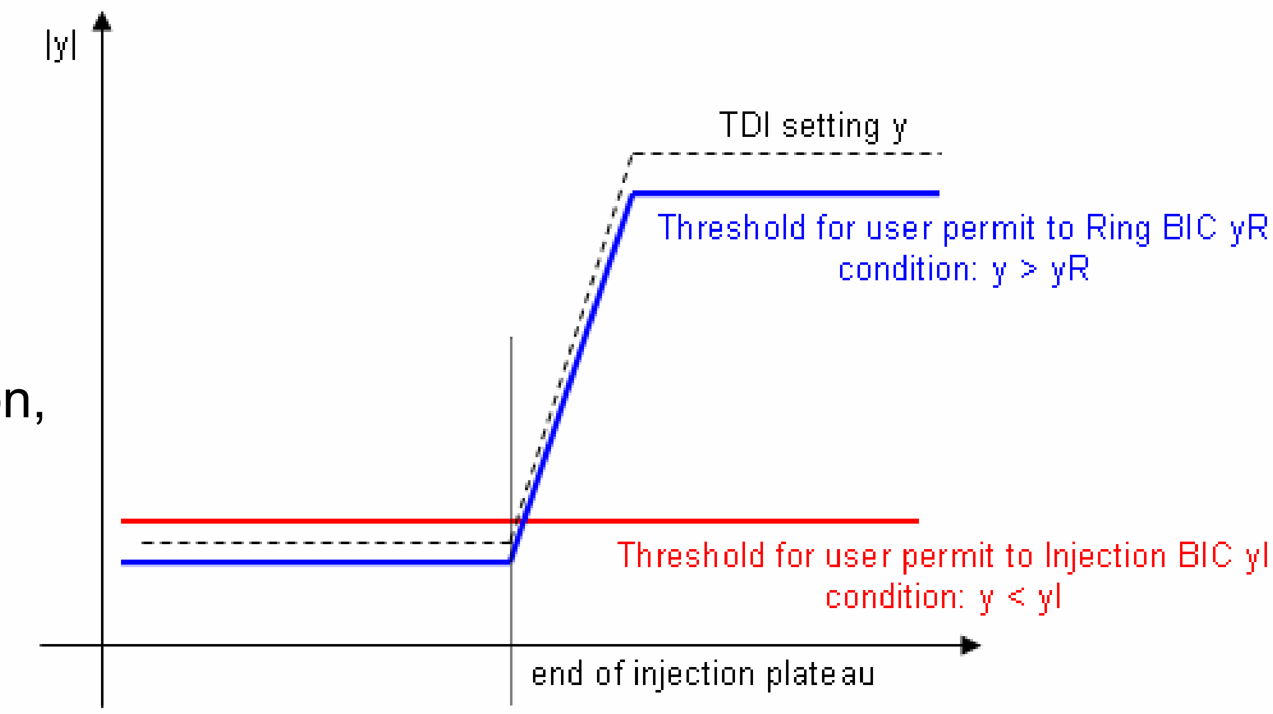
→ Issue of copying settings from low intensity cycle to high intensity cycle: state machine.

Issues – TDIs and TCLIs

- TDI + TCLIs: Same settings management and interlocking behaviour as for ring collimators, except: interlocking entry to injection BIC AND ring BIC

TDI movement blocked,
when moving across threshold

→ to move out TDI after injection, thresholds have to be changed.



- State machine or modification of the blocking behaviour for outer threshold
- No energy gaps yet, they will come
- Verification of setting and required protection level with scanning injection kicker strength
  - Verification of TDI setting is very important: 4 m long object, angular misalignment can be very important: had 900 urad tilt error on one jaw of TDI beam 1

The LHC needs to be in correct state

- Many things are interlocked – but not everything
- We have the beam presence flag
- Some things might not be immediately visible only during failure... e.g. wrong protection element settings + thresholds etc
- → MCS checks, sanity checks in sequencer..., state machine which does not allow to inject if e.g. thresholds are not injection thresholds.
- More about this in Laurette's talk

Experience so far - Examples

In red: **critical**

- Injection kicker faults: Jan's presentation
  - Everything with beam was caught so far by the TDI
- Injection into empty LHC with main quadrupoles not at injection settings
- Injection into empty LHC with RF off
- Accidental overinjections: caught by TDI
- Injection into wrong ring
- **Running for weeks with transfer line collimators out by accident**
- **Beam presence flag went false with 4 nominal bunches in (150 ns trains)**
- Injection into LHC with bump left in from MD
- Beams dumped during overinjection due to low BLM threshold on close by collimator
- Beams dumped during injection of high intensity (4 bunches) due to losses on transfer line collimators: scraping not working in the SPS

Conclusion

- Failures at injection are single turn failures. The intensity of a full nominal injected batch is ~ factor 20 above the assumed damage limit at injection energy.

- A sophisticated protection system has been implemented across the SPS extraction, transfer lines and LHC injection systems, which has been partly working already for many years with excellent reliability.

- One of the key concepts of injection protection: no injection into an empty LHC.

- Before going to the injection of 12 bunches (above set-up beam flag) the outstanding verifications of the injection protection system have to be carried out.

Remaining Issues

- The current implementation of the interlocking behaviour of the passive injection protection requires the implementation of a state machine to be sure that the correct settings are loaded. Energy gaps as soon as possible for the TDI and TCLIs

- Check the impact of the circuits within the transfer line collimation section in case of failure and decide trajectory correction strategy

- More protection against accidental overinjection

- We rely on the correct working of the safe machine parameters

- More sanity checks before injection (copy of steering from low intensity cycle to high intensity cycle,...injection settings of the LHC,...)

- Reference orbit

EXTRA SLIDES

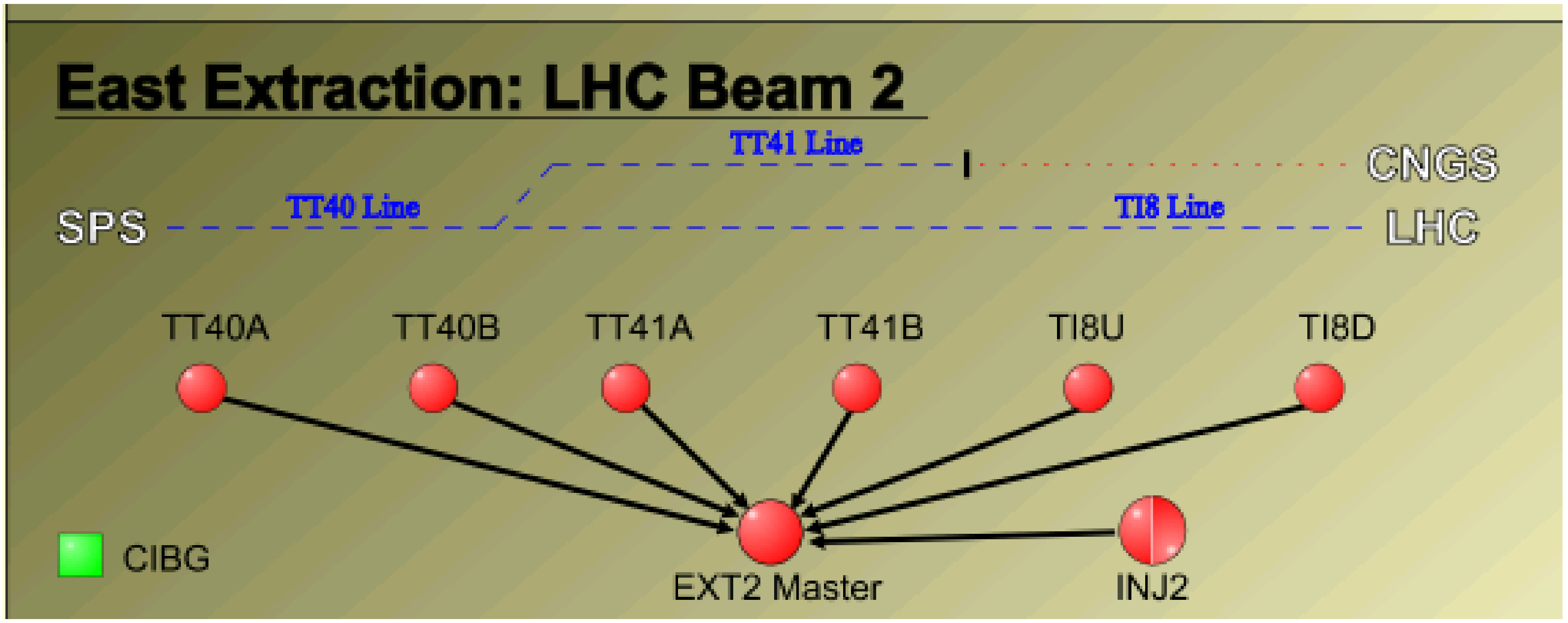
A couple of things to clean up

- Set tight tolerances on the injection delays

- Make extraction kicker tolerances on strength, length and delay “critical”.

- Disallow “disable” during normal operation

Beam 2 Extraction – LHC/CNGS



TT40 = BIC TT40 A && BIC TT40 B
TT41 = BIC TT41 A && BIC TT41 B
TI8 = BIC TI8 up && BIC TI8 down
TED-TT40 = TED TT40 in
TED-TI8 = TED TI8 in

CNGS = E400 && {TED-TT40 || (NOT.(TED-TT40) && TT41)}

F = Probe Beam Flag ||
[Beam 2 Presence && (NOT.(LHC Safe Beam 2 Flag) ||
SPS Safe Beam Flag)]

LHC = E450 && { TED -TT40 ||
(NOT.(TED-TT40) && TI8 && [TED-TI8 ||
(NOT.(TED- TI8) && Injection Permit && F)]) }

Extraction Permit = TT40 && [(LHC && NOT.CNGS) || (NOT.LHC && CNGS)]