# Safe injection into the LHC

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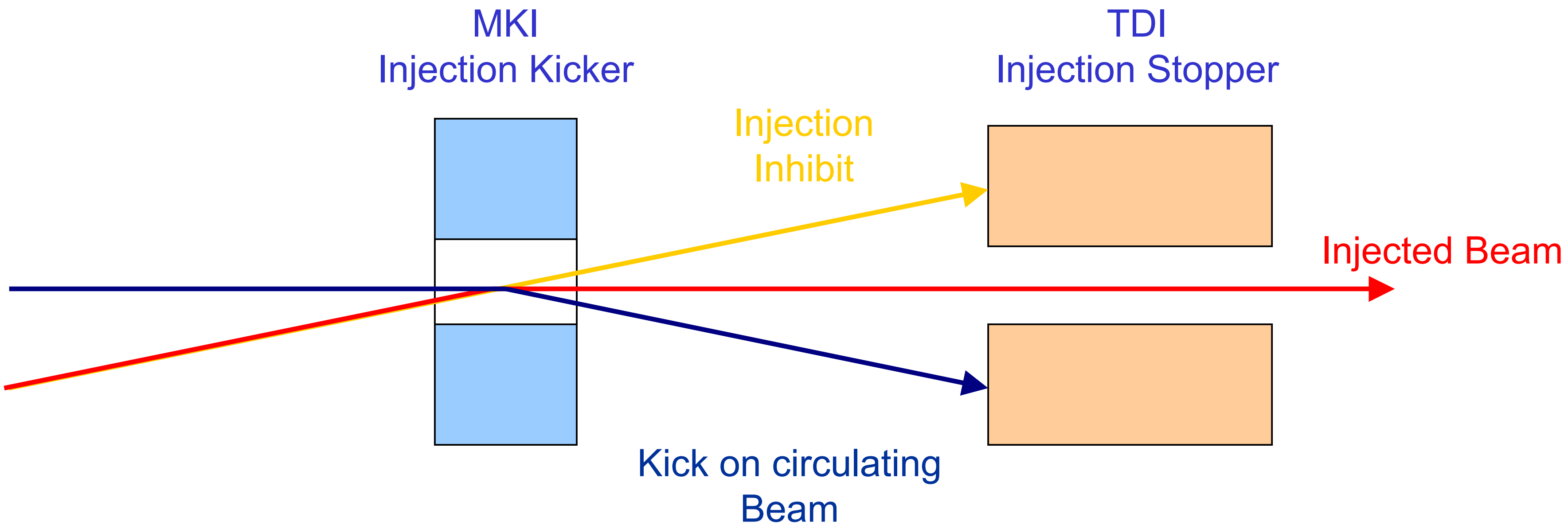
A summary of ideas discussed in different LHC working groups
Thanks to all contributors

# Outline

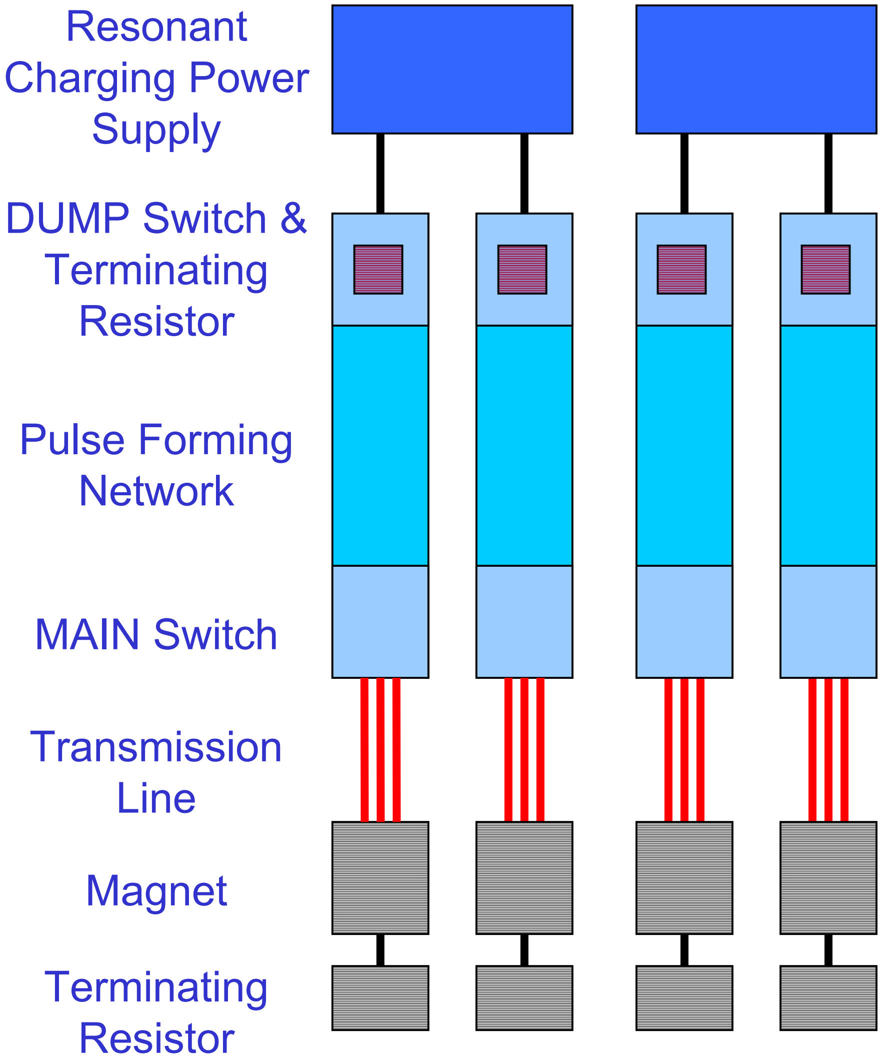
- Injection process
- Injection kicker system
  - Architecture, process, failures
  - Protection against internal failures
- Operational scenarios
  - Injection inhibit (1 turn deadlock)
  - Inject and dump (first turn, n turns)
  - Inject and probe
  - Inject and fill (beam abort gap conservation)
- Conclusions & open issues

# Injection Process - General

## Vertical plane



# Kicker System – Architecture

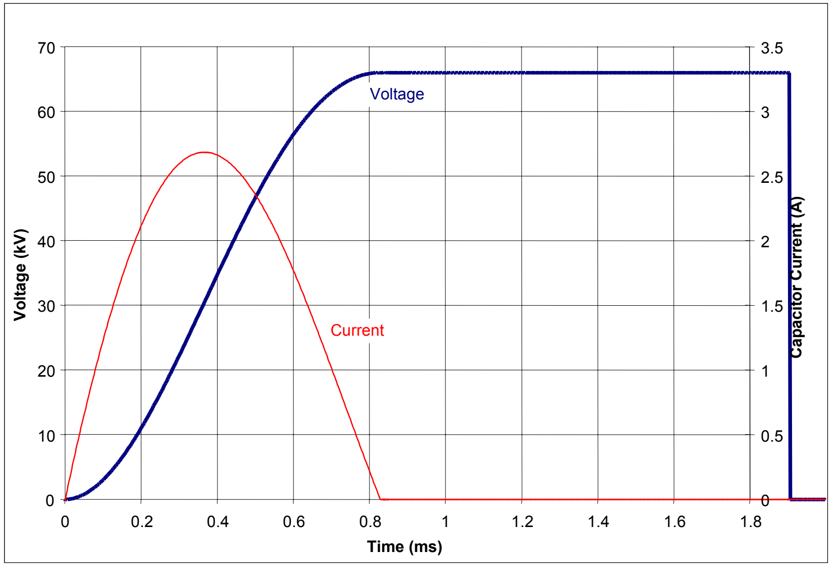


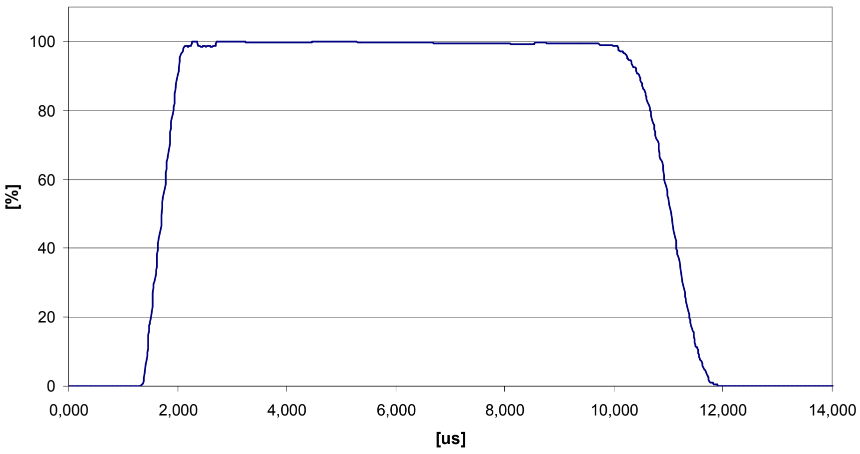

**Injection Kicker Parameters**

| | | |
|---|---|---|
| Number of magnets per system | 4 | |
| Kick strength per magnet | 0.325 | T.m |
| Characteristic impedance | 5 | Ω |
| Nominal charging voltage | 54 | kV |
| Nominal pulse current | 5.4 | kA |
| Kick flat top ripple | <±0.5 | % |
| Kick flat top duration (adjustable) | ≤7.8 | μs |
| Kick rise time 0.5 - 99.5% | 0.9 | μs |
| Kick fall time 99.5 – 0.5% | <3 | μs |
| Repetition time | 15 | s |

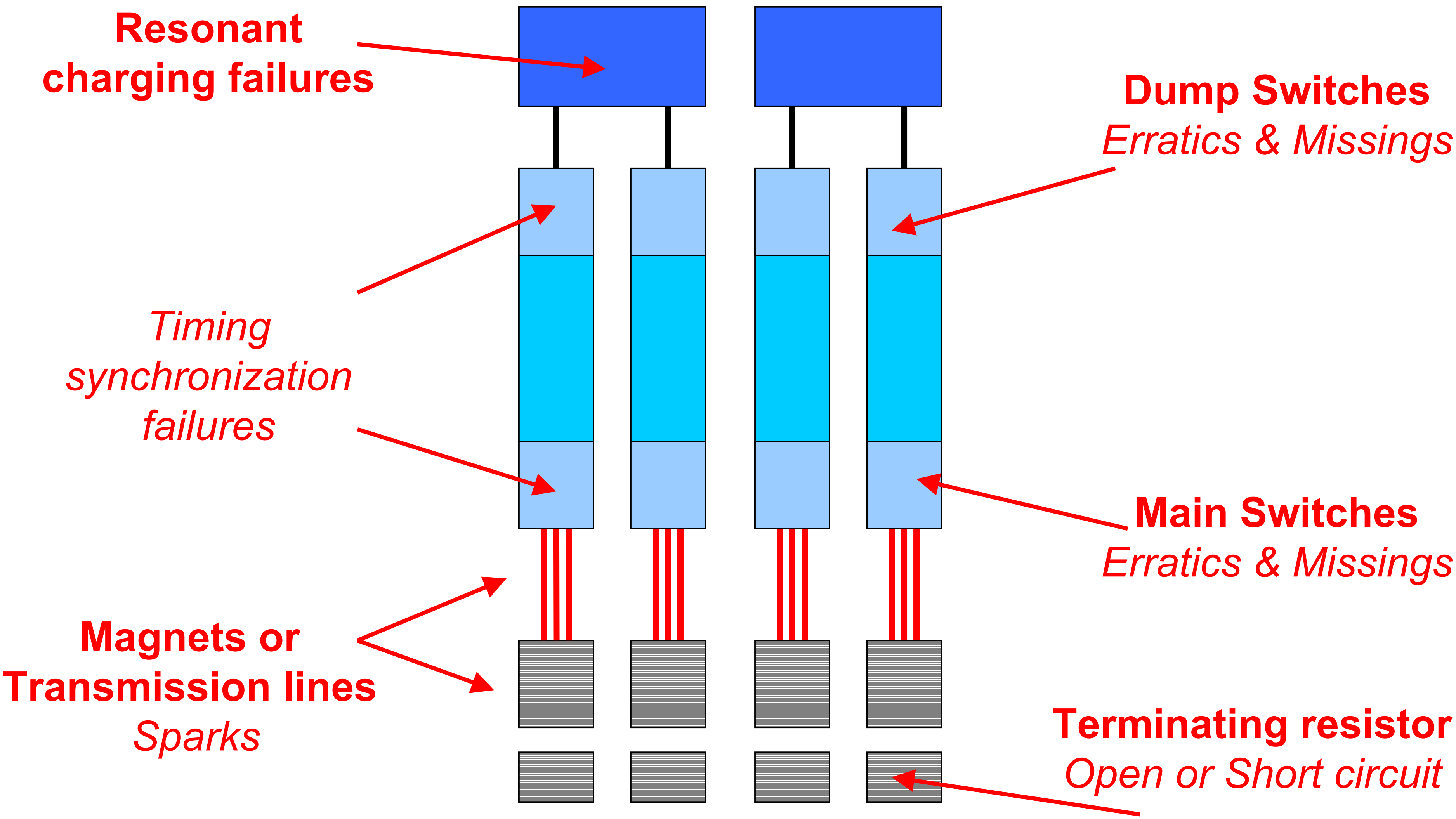
# Kicker System – Process

| | | |
|---|---|---|
| Slow | -1000 ms | Start injection process |
| | -750 ms | Start charging of primary capacitor bank |
| | -2 ms | Trigger resonant charging |
| | -1 ms | Start control secondary voltages |
| Fast | -10 μs | Receive injection pre-pulse, Start internal delay for fine timing adjustment |
| | 0 | Inject beam |



# Kicker System – Internal Failures



# Resonant Charging Failures

## Faults

- **Bad secondary voltage** (Vs) at the end of the resonance on one or on n PFNs
- **Bad reference settings** w.r.t the injection energy

## Actions

- **Tracking of the Vs with the machine energy** through the Beam Energy Meter (BEM) between T = - 1 ms and T = 0 and **inhibit injection if an absolute discrepancy higher than 0.5 % is detected** between the Vs and the beam energy.
  - Automatic injection inhibit once acceleration has started
  - Redundant path to control at injection the correct operation of the beam dumping system beam energy tracking system

## Reaction delay

- Injection inhibit possible up to **250 ns** before T=0

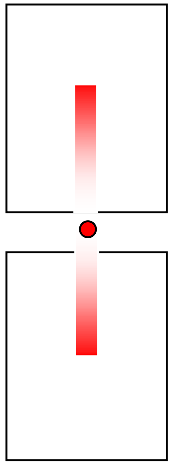
# Erratic MAIN Switch

**Faults** Magnetic field in one of the four kicker magnets asynchronous with circulating and injected beam

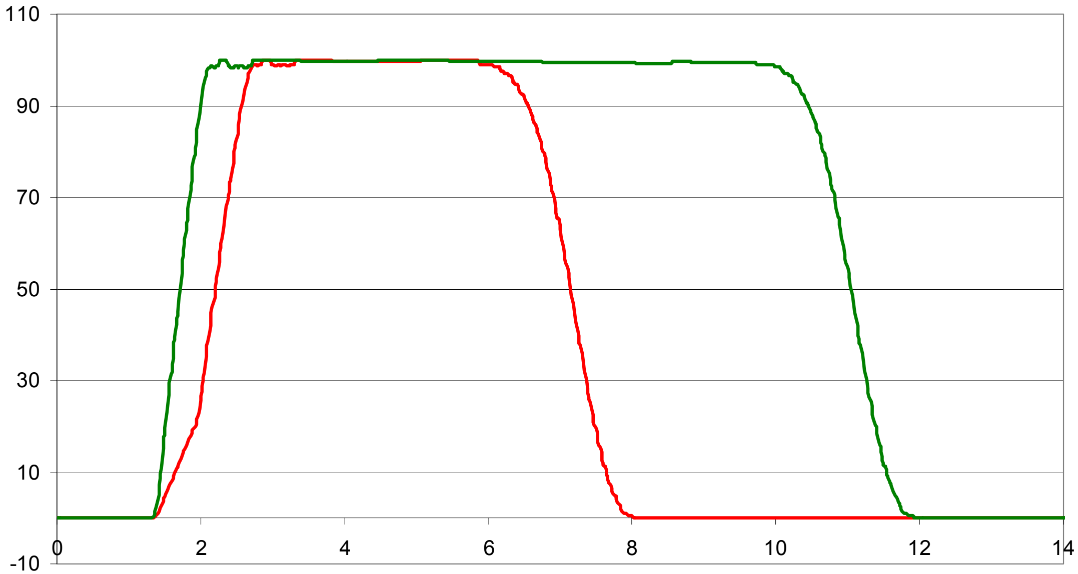
**Actions** Trigger other MAIN & DUMP switches → circulating and injected beams swept into TDI & beam partially along the LHC

**Reaction delay** → **600 ns**

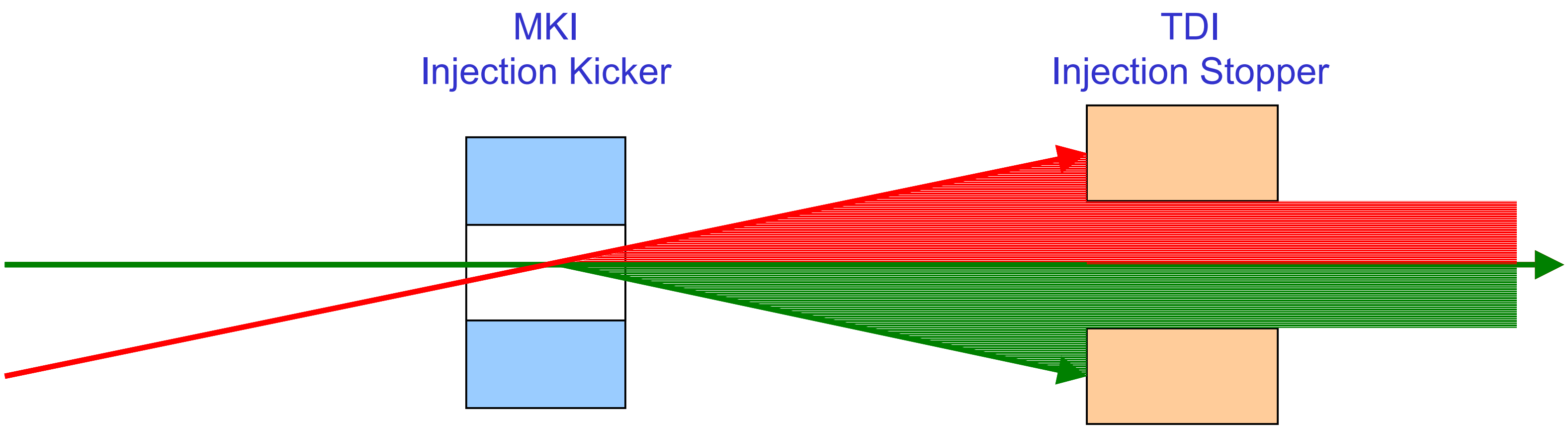
**Beam position on TDI**



TDI position at ±8.5σ



# Erratic MAIN Switch (cont'd)



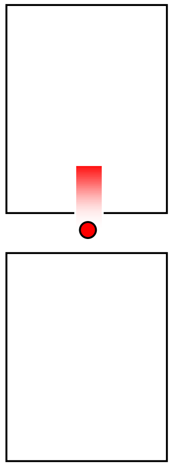

| Impact of Erratic on | | | |
|---|---|---|---|
| Circulating Beam | Injected Beam | Bunches on TDI | Bunches escaping TDI |
| No | No | Full batch | **0** |
| Yes | No | Swept = 125<br>Centred = 130 | **13**<br>tr = 4, tf = 9 |
| Yes | Yes | Swept = 116<br>Centred = 130 | **22**<br>tr = 4, tf = 18 |

# Missing MAIN Switch

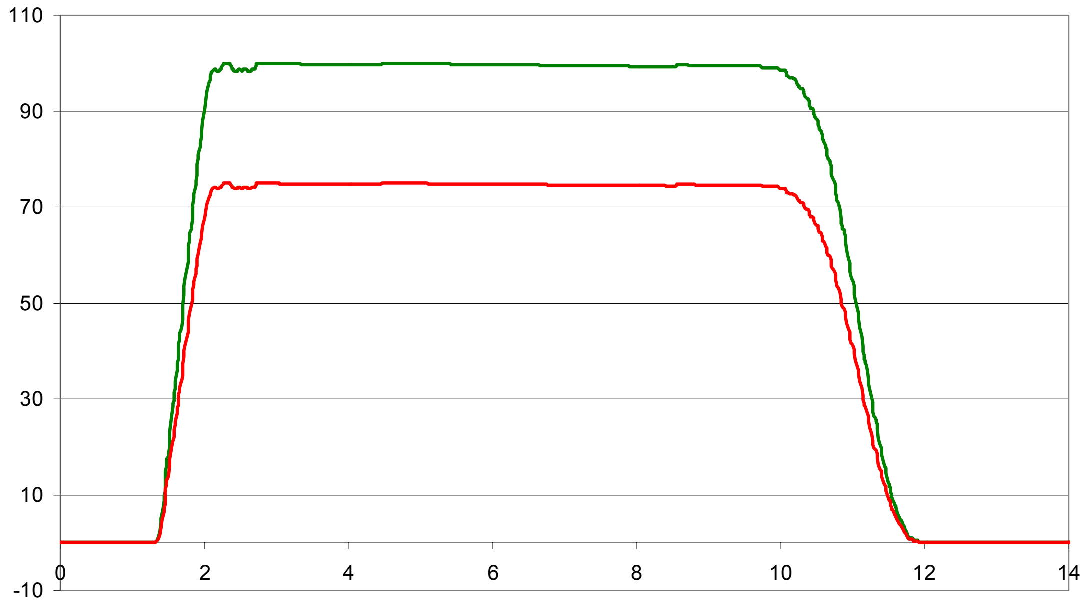
**Faults** Magnetic field in one of the four kicker magnets is missing

**Actions** No action possible. Injected beam will be sent to the lower part of the upper TDI

**Beam position on TDI**



TDI position at ±8.5σ

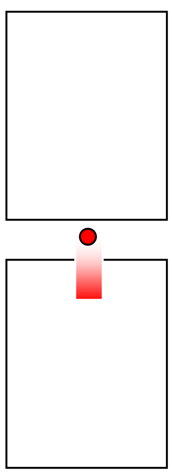


# Magnet Spark

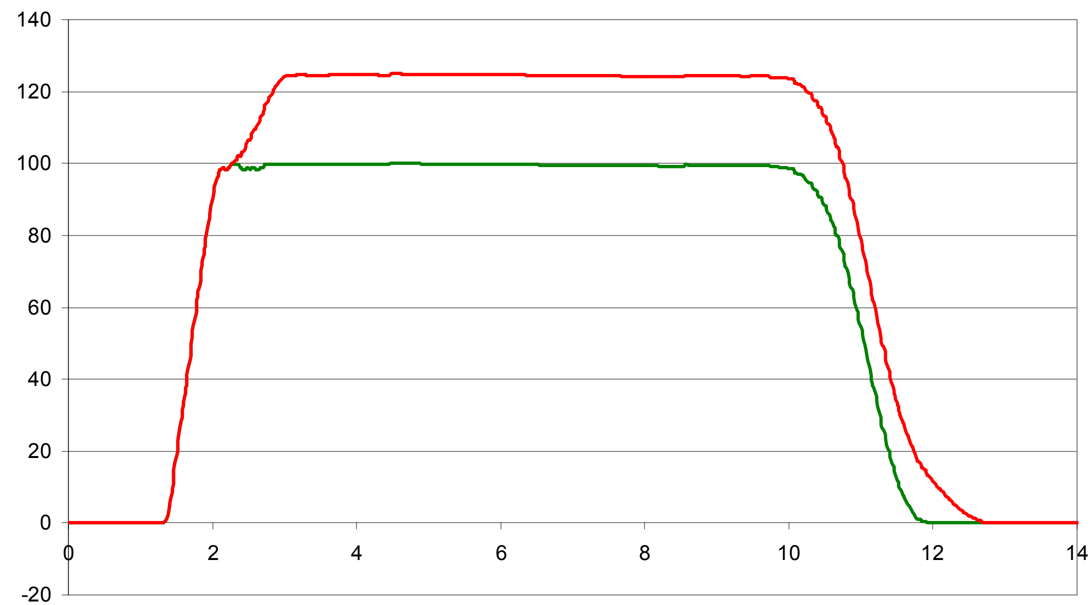
**Faults** Spark at the magnet exit at the end of current kick rise time (worst case)

**Actions** No action possible. Injected beam will be sent to the upper part of the lower TDI or, in the worst case, will be sent to the edge of the TDI or just miss the TDI and go to the injection collimators.

**Beam position on TDI**



TDI position at ±8.5σ



# Internal failures - Others

- DUMP switch erratic
  → Trigger other DUMP switches & Inhibit injection
  → Reaction delay lower than 250 ns
- Wrong timing synchronisation between circulating and injected beam
  → Same as an **erratic MAIN switch** (less beam escaping the TDI due to a faster kick rise time)
- Spark at the beginning of the magnet and at the beginning of the current kick
  → Same as a **missing MAIN switch**
- Terminating resistor short circuit
  → Same as a **magnet spark** at the exit
- Terminating resistor open circuit (will induce a spark at the magnet exit)
  → Same as a **magnet spark** at the exit

# Injection Inhibit

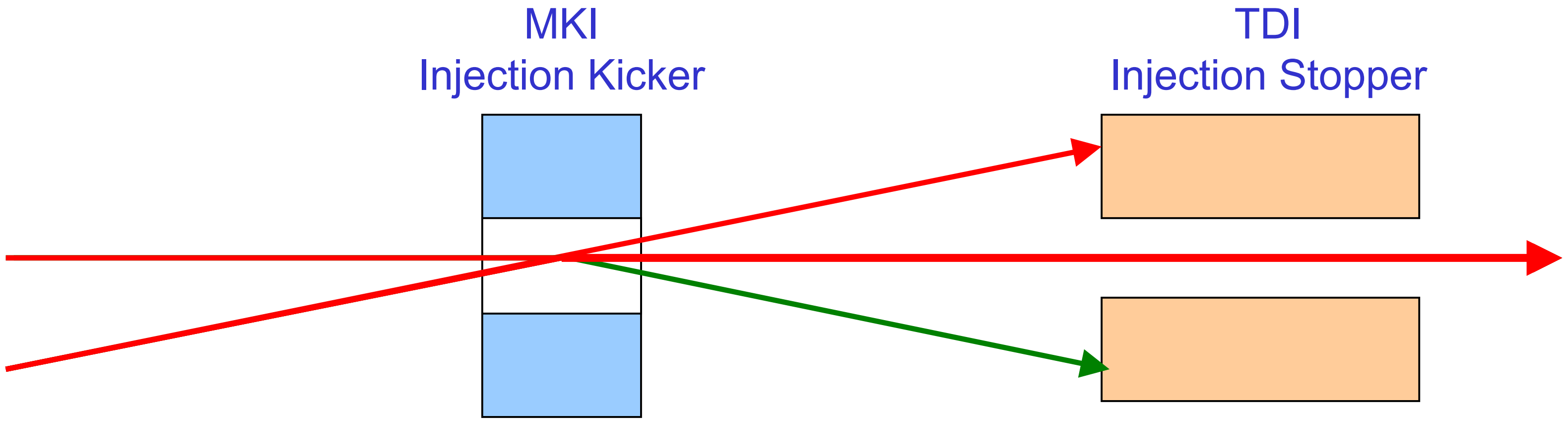
- **Injection kicker** systems **will be connected** to the LHC **beam permit loop** and **injection** into LHC **permitted** only **when the loop is closed**.
- **Opening** of the **beam permit loop** will automatically **inhibit** the **injection** with a reaction delay of 250 ns.
- **Propagation delays** between **beam dumping system** and **injection kicker** must be taken into account **in order to avoid** the **1 turn deadlock**.
  - →At injection, opening the beam permit loop in point 6 will immediately trigger the beam dump and will require ~100 μs to reach the injection kicker in point 2.
  - →If a dump request occurs in the 100 μs window before an injection, circulating beam will be correctly dumped but beam injection will be allowed with a beam dump system not ready (capacitor re-charging)…

# Inject & Dump

An operation mode of the dump and injection systems where the dump is set up to fire N turns after injection and before any new injection.

- **When**
  - First commissioning
  - Injection studies
  - Setting up
- **How**
  - Prepare injection in “Inject & Dump” mode
  - Injection of a pilot beam at T = 0
  - Dump beam at T = 0 + dt
  - Any time can be programmed, minimum value of dt = 0 (dump during the first turn)
- **Injection kicker timing system** must be the **master** during the “Inject & Dump” mode in order to **avoid** to fall into the **1 turn deadlock**.

# Inject & Probe




1. Inhibit of high intensity beam injection if no beam is circulating
   → Beam intensity interlock (BII)
2. Injection of a pilot bunch first
3. Probe
   → Continuous measurement of circulating beam inside LHC in order to be sure that next injected beam would circulate
4. Injection of a beam with higher intensity only if circulating beam is still OK
   a. If there is no circulating beam (BII) → go to **Step 1**
   b. If there is a pilot bunch present (BII) at the longitudinal position of the fresh beam to come in, it will be deflected to the TDI → go to **Step 3**
   c. If there is circulating beam (BII), inject a new beam → go to **Step 3**

# Inject & Dump with an Intense Beam

1. Inhibit of high intensity beam injection if no beam is circulating
2. Injection of a pilot bunch
3. Probe
4. Injection of a beam with higher intensity only if the pilot beam is still OK
5. Dump circulating beam at higher intensity beam injection time T + dt

# Inject & Fill

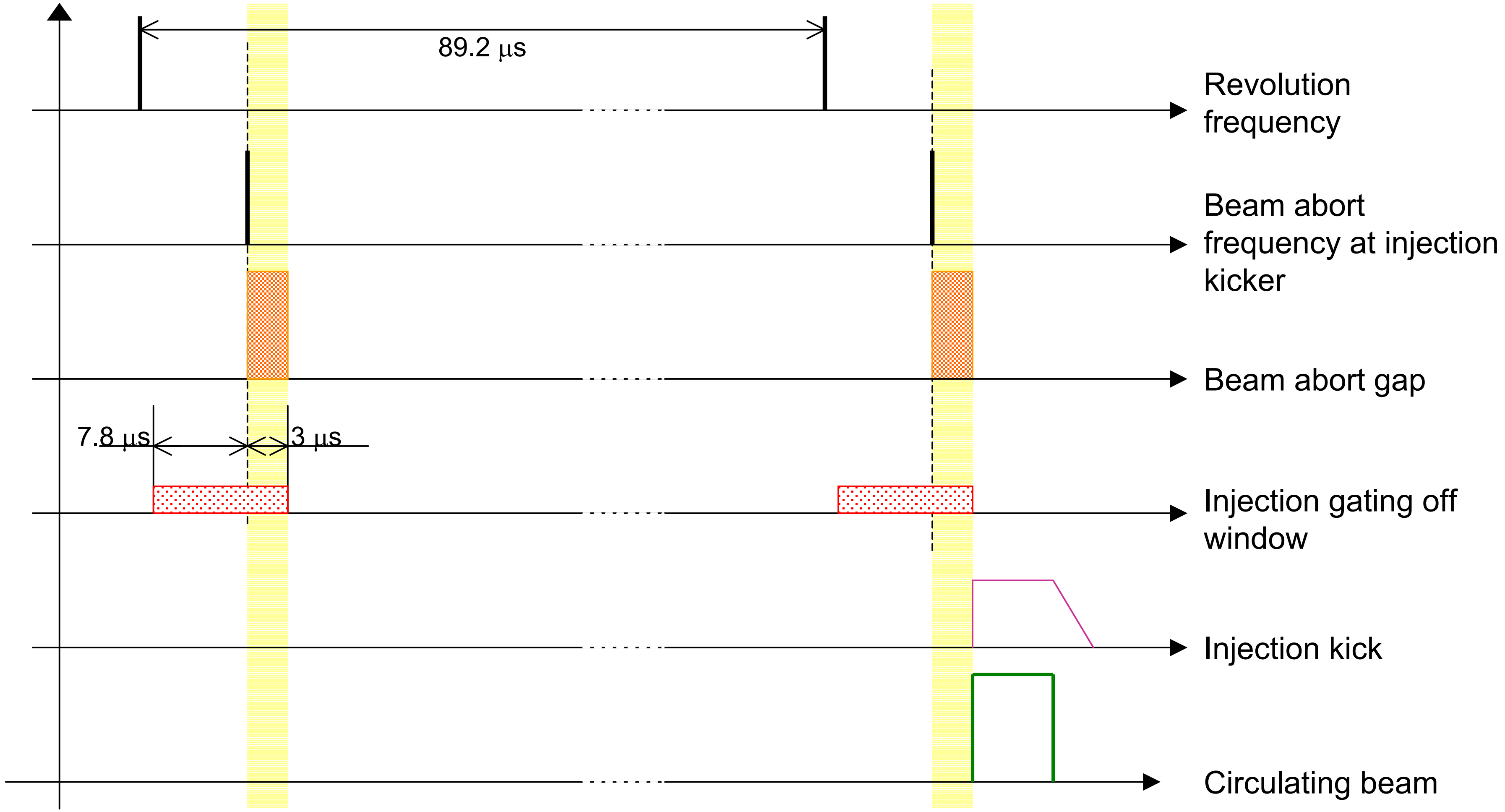
## Errors during filling

- Bad phase between abort gap and revolution frequency
- Abort gap filled by a wrong injection

## Actions

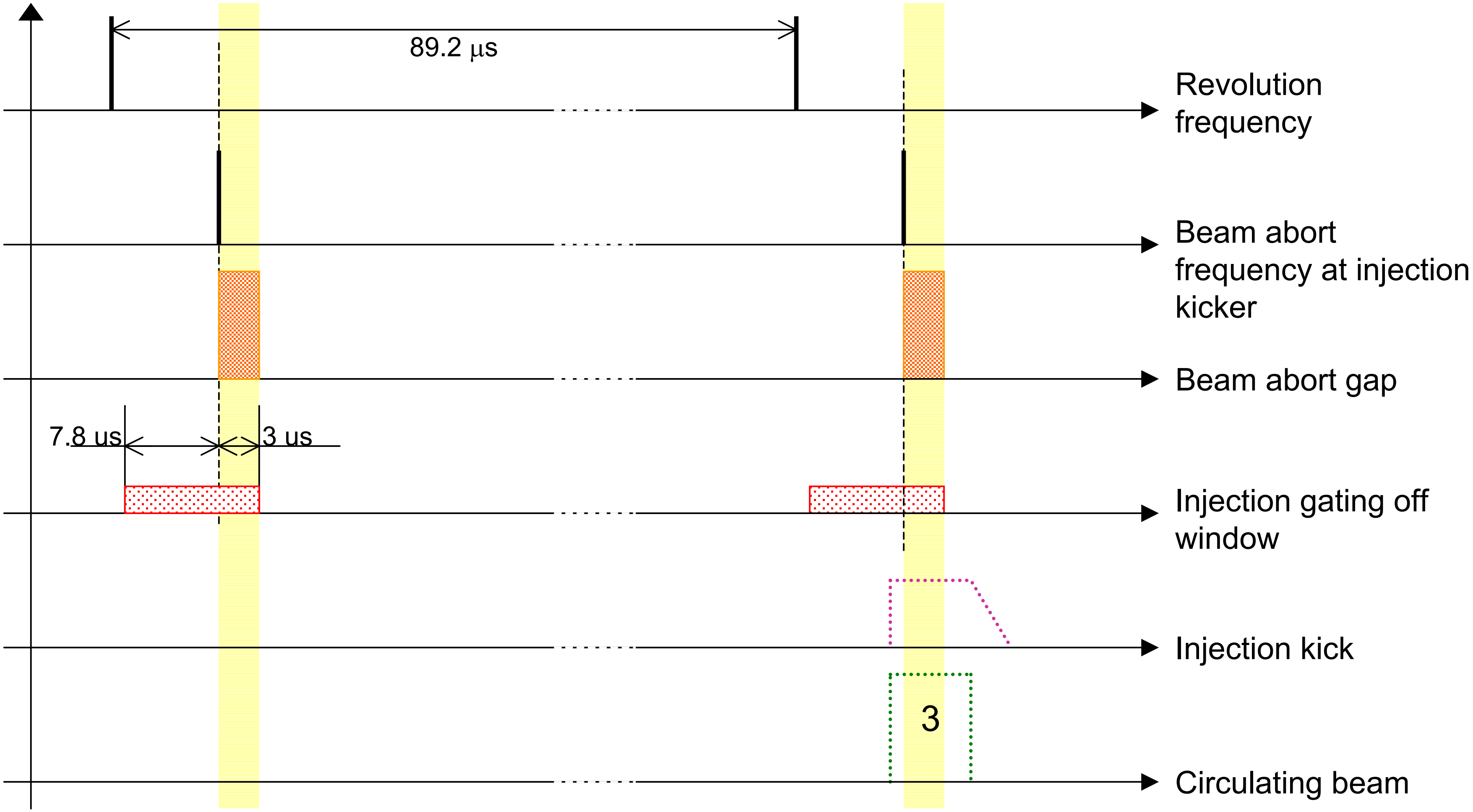
- As a **fixed phase difference** w.r.t the revolution frequency **between** the **abort gap at the injection kicker and at the dump extraction kicker** exists, the **injection kicker timing system can be bound to the extraction kicker synchronization system** in order to avoid to fill the abort gap by a wrong injection.
- **Authorization to inject** can be **gated off** around the abort gap
  - Injection pre-pulse inhibit → no kick from injection kicker
  - Badly injected beam is sent to the TDI
- 3.3.4…injection pattern → **different gate & kicker lengths for the injection of the last SPS-batch**
- For the present filling scheme, the inhibit gate can be set to 10.8 μs (4 PS-batch injection) up to the last injection where it has to be reduced to 8.8 μs

# Inject & Fill - Injection Gating Off – Case 1



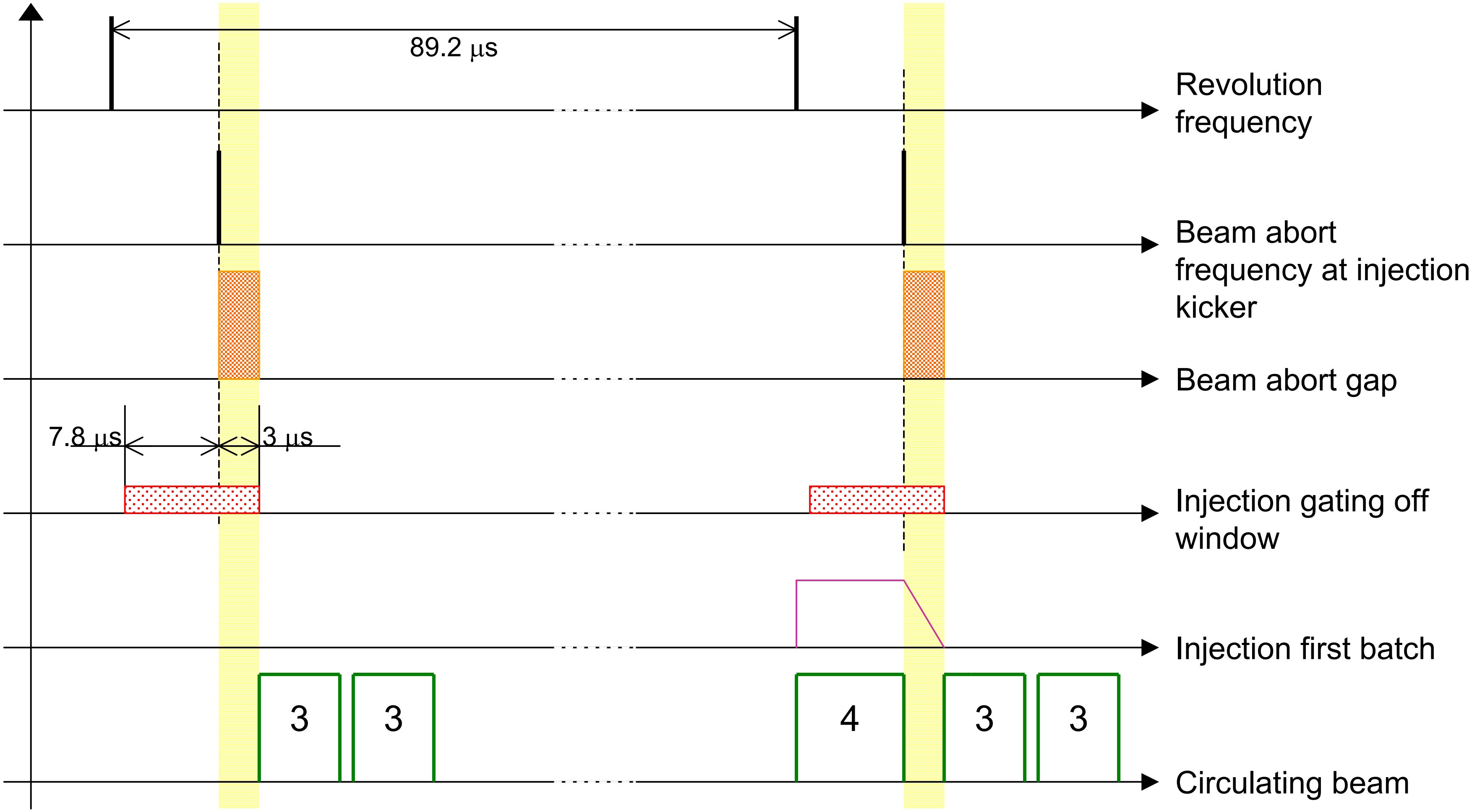

First injection correctly synchronized → beam correctly injected

# Inject & Fill - Injection Gating Off – Case 2



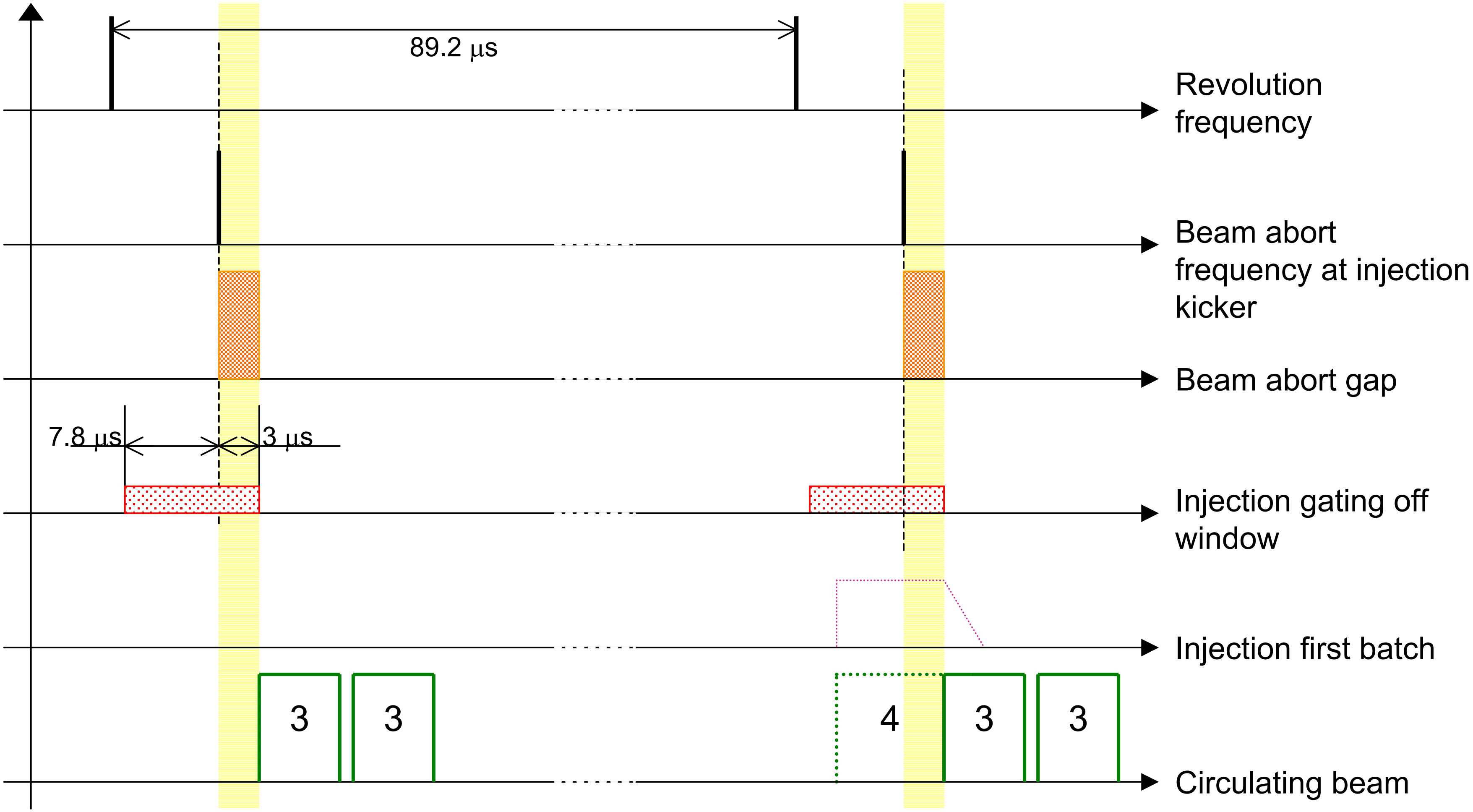

First injection not correctly synchronized → injection kicker inhibit, beam to TDI

# Inject & Fill - Injection Gating Off – Case 3



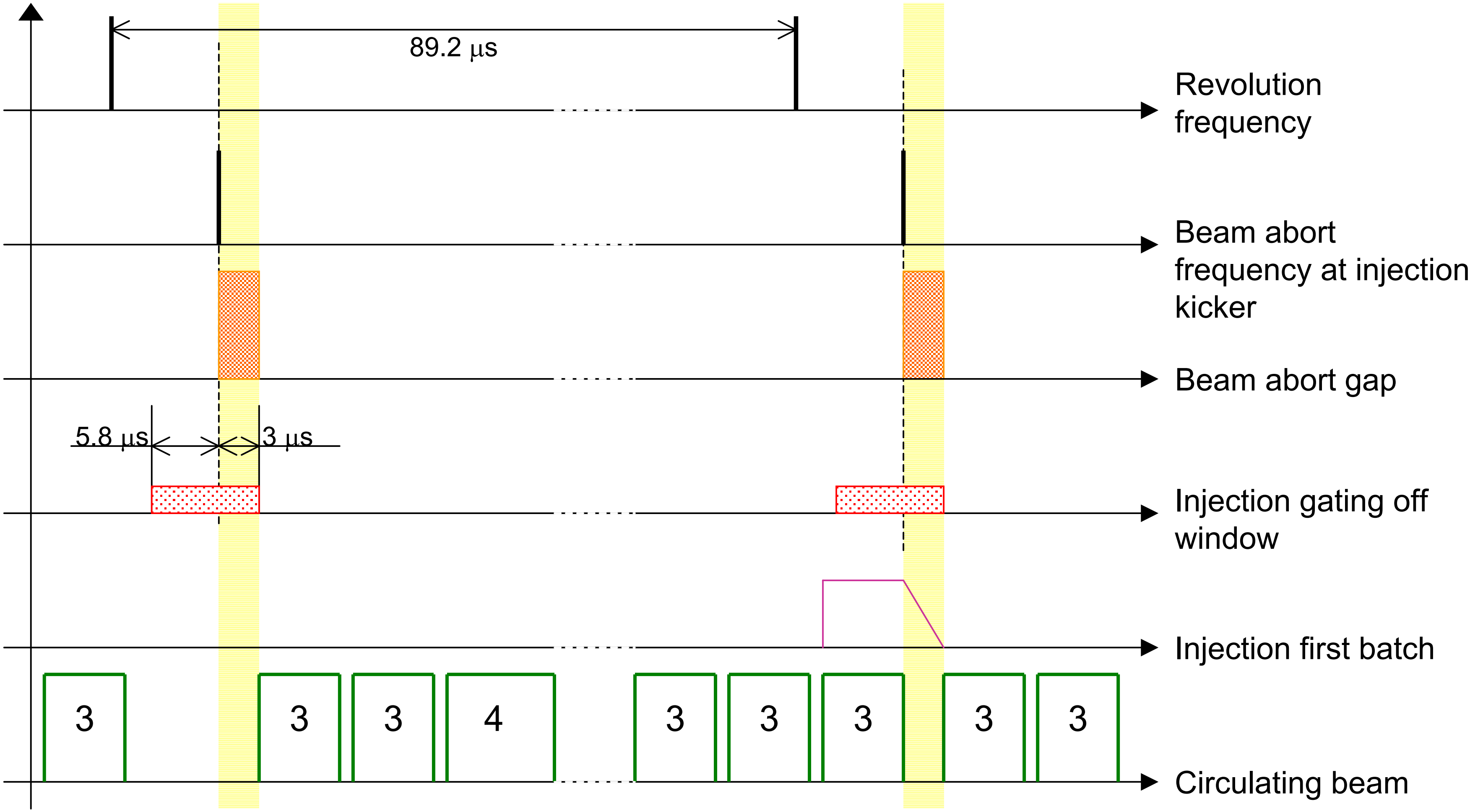

Injection not correctly synchronized w.r.t filling pattern but outside the inhibit window → beam injected in a wrong position, abort gap is OK (must dump this beam !!!)

# Inject & Fill - Injection Gating Off – Case 4



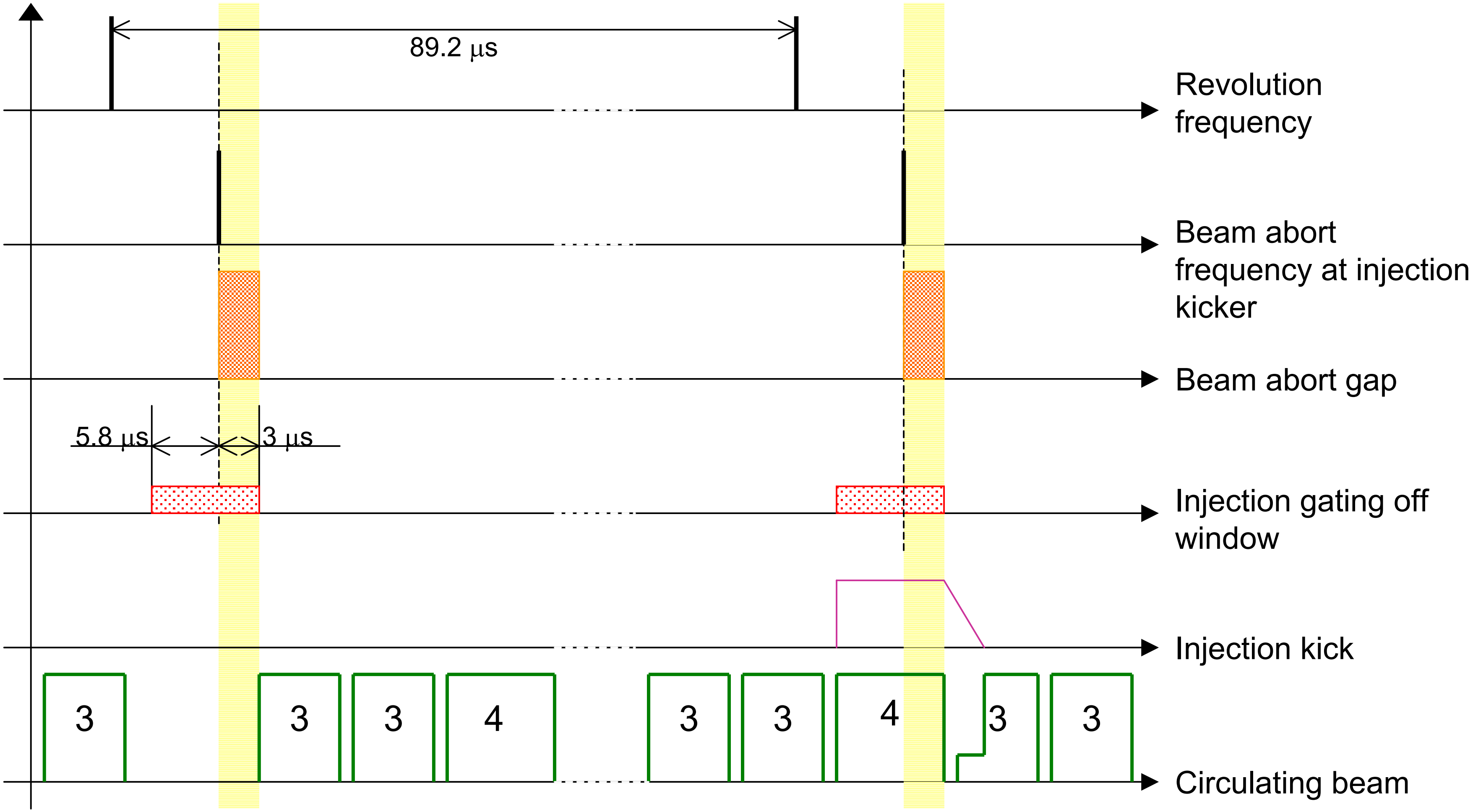

Injection not correctly synchronized w.r.t filling pattern and inside the inhibit window → injection kicker inhibit, beam to TDI

# Inject & Fill - Injection Gating Off – Case 5




**Last injection** correctly synchronized, injection inhibit window reduced to 8.6 μs and injection kick length reduced to 6 μs → beam injected, abort gap is OK

# Inject & Fill - Injection Gating Off – Case 6




**Last injection**, correctly synchronized, inhibit gate reduced to 8.6 μs, but injection kick length maintained at 7.8 μs and 4-PS-batch → beam injected, abort gap filled and beam losses on batch 1

# Inject & Fill – Filling Pattern

- **Injection gating** could be **simplified with a fixed gate length** of 10.6 μs if we **change the filling pattern** from

  Abort_gap ⊕ 334 ⊕ 334 ⊕ 334 ⊕ 333

  to

  Abort_gap ⊕ 333 ⊕ 334 ⊕ 334 ⊕ 334

  or

  Any filling pattern with the longest batch as last injection

- In this case, a **fixed injection gating** combined with a **fixed injection kick length** set to its maximum value will permit to
  - **Don’t touch Batch1** when injecting last batch
  - **Prevent the beam abort gap**

# Conclusions

A **safe injection** into LHC will be **guaranteed** by:

1. The **fast interlock logic within the injection kickers** in order to react to internal failures and reduce their impacts on the beams.
2. The **different protection devices** (injection stoppers and injection collimators) foreseen **in the injection region**. Their correct positions w.r.t the machine mode have still to be guaranteed.
3. The **rigorous application of a succession of different injection modes** in order to increase progressively beam intensity from a pilot beam up to a nominal beam. A coherent integration of the different scenarios within the controls system has to be foreseen and an automatic sequencing implemented.

# Open issues

- The **“1 turn” deadlock** between beam dumping systems and injection kicker systems has to be studied into more details.
- In order to implement the “Inject & Probe” mode, a **Beam Intensity Interlock** (BII) has to be developed.
- The **Beam Energy Meter** (BEM) foreseen for the beam dumping system will also be used in the injection kickers in order to track the injection kick strength with machine energy. A **functional specification** for the BEM is **in progress**.
- A **modification of the filling pattern** with the longest batch as last injection will permit to protect the beam abort gap during filling.