Beam Transfer and Machine Protection

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Contents of this lecture

- Principles of beam transfer and equipment involved

- Machine protection concepts for beam transfer
  CERN – SPS/LHC

Machine Protection and Beam Transfer

Beam losses at RHIC ➔ Beam Transfer very prominent

Beam losses at RHIC

- Injection mis-match
- Poor beam lifetime
  - Bad orbit, working point, chromaticity
  - emittance growth due to weak resonances, beam-beam, intra-beam, beam-gas interactions
- Beam instability
  - Transition crossing, strong orbital resonance, etc
  - Can be fast
- system failure
  - Injection kicker mis-timing, Injection damper mis-phasing
  - oscillation of a magnet power supply
  - abort kicker dis-functioning
  - RF cavity failure
    - Cause de-bunched beam

PRINCIPLES AND EQUIPMENT OF BEAM TRANSFER

Injection systems

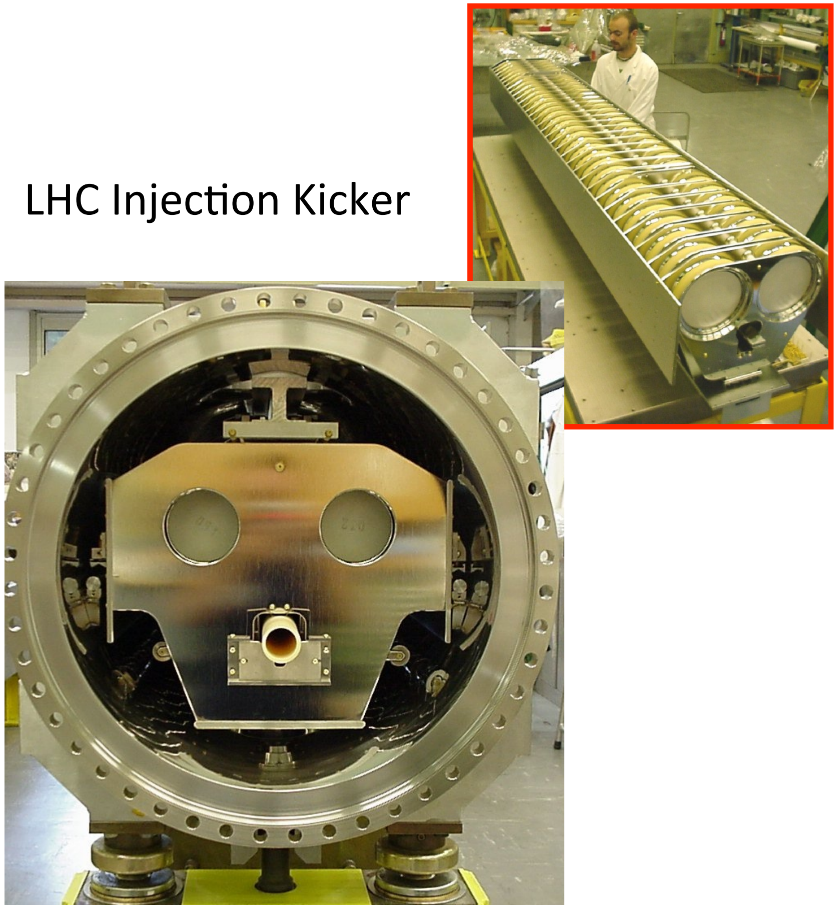
Several different techniques

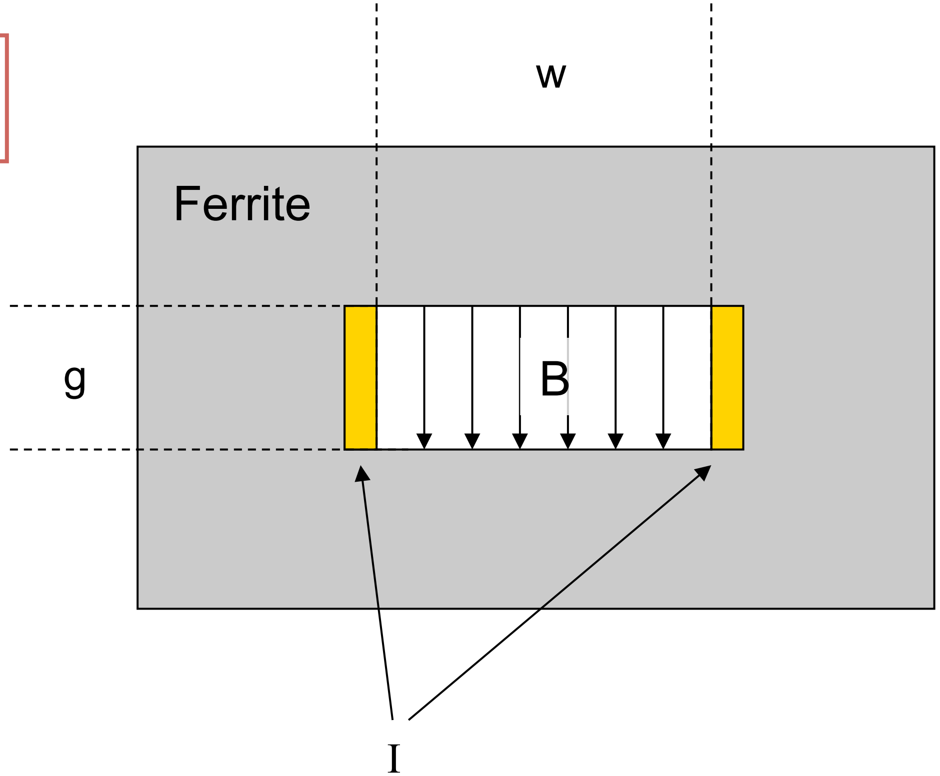
- Single-turn injection for hadrons
  - Boxcar stacking: transfer between machines in accelerator chain
  - Angle / position errors $\Rightarrow$ injection oscillations
  - Optics errors $\Rightarrow$ betatron mismatch oscillations
- Multi-turn injection for hadrons
  - Phase space painting to increase intensity
  - H- injection allows injection into same phase space area
- Lepton injection: take advantage of damping
  - Less concerned about injection precision and matching

Kicker magnet

Pulsed magnet with very fast rise time (100ns – few μs)

LHC Injection Kicker





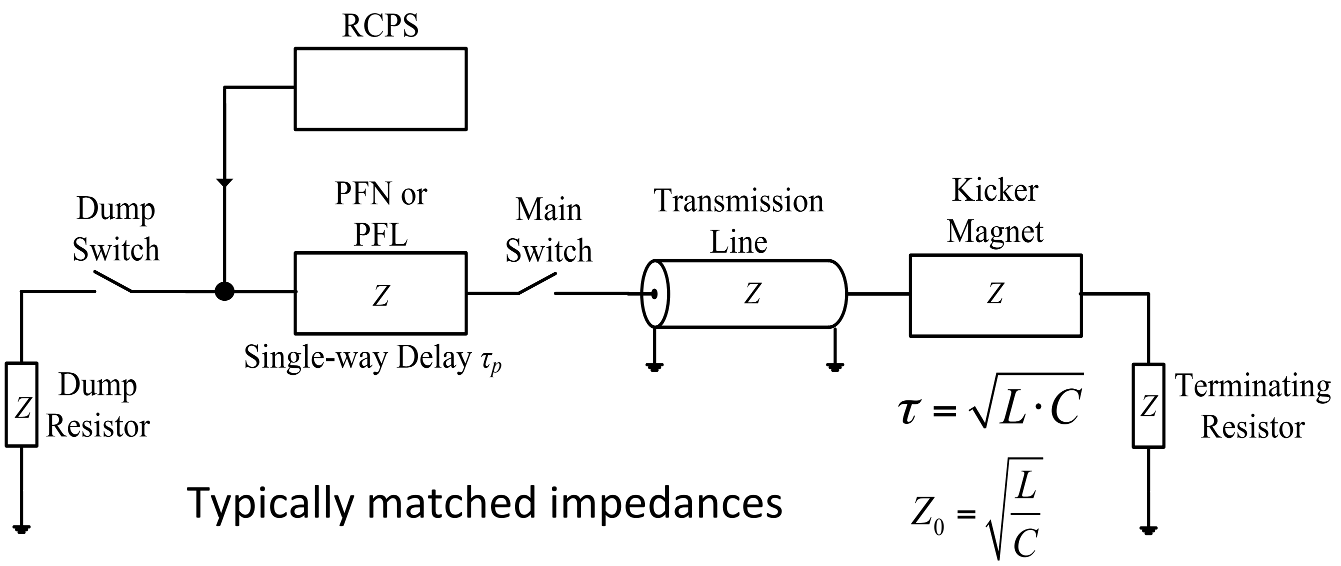
$B = \mu_0 I / g$

$L = \mu_0 w l / g$ (magnet length l)

$dI/dt = V/L$

Typically 3 kA in 1 μs rise time

Simplified Schematic of Kicker System



PFL = Pulse Forming Line (coaxial cable);

PFN = Pulse Forming Network (lumped elements);

RCPS = Resonant Charging Power Supply;

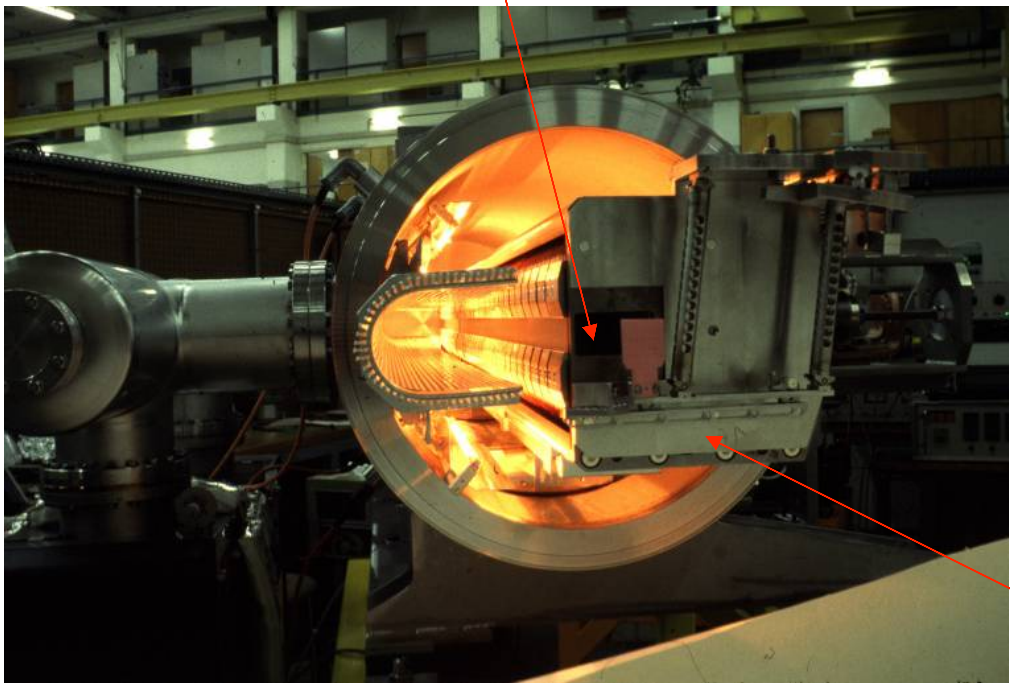
Typical circuit operation:

- PFN/PFL is charged to a voltage V_p by the RCPS;
- Main Switch closes and a pulse of magnitude ($V_p/2$) is launched, through the transmission line, towards the magnet.
- Once the current pulse reaches the (matched) terminating resistor full-field has been established in the kicker magnet;
- The length of the pulse in the magnet can be controlled in length, between 0 and $2\tau_p$, by adjusting the timing of the Dump Switch relative to the Main Switch.

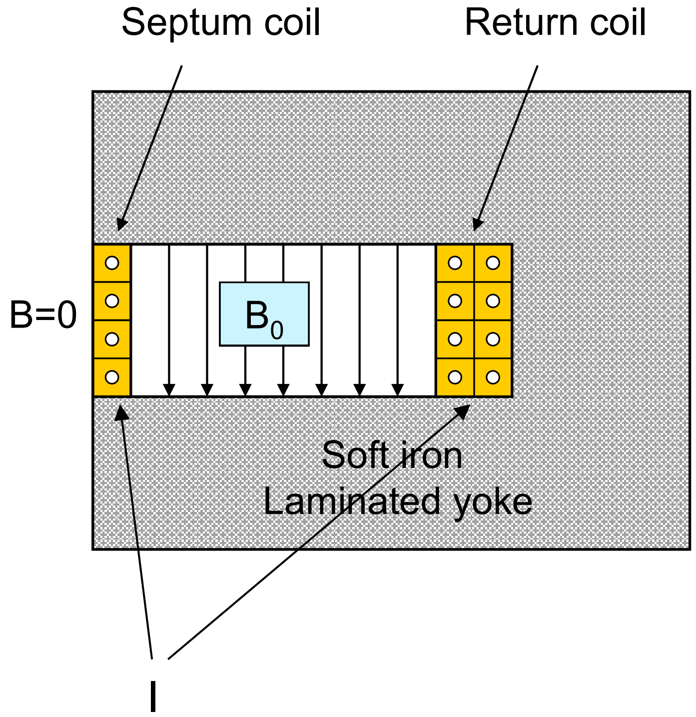
Magnetic septum

Pulsed or DC magnet with thin (2-20mm) septum between zero field and high field region

Septum coil



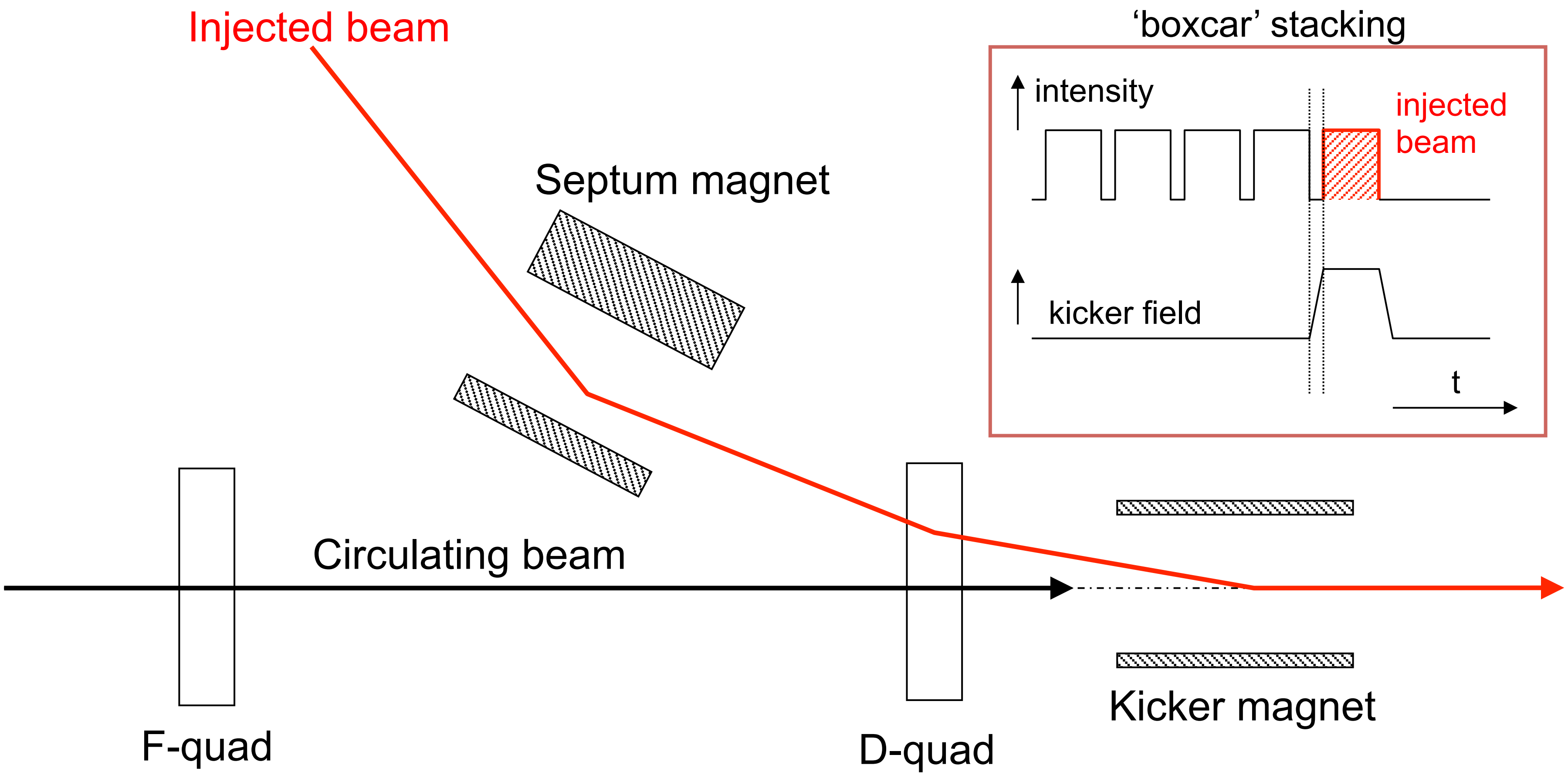
Yoke



$B_o = \mu_0 I / g$

Typically I 5-25 kA

Single-turn injection – same plane

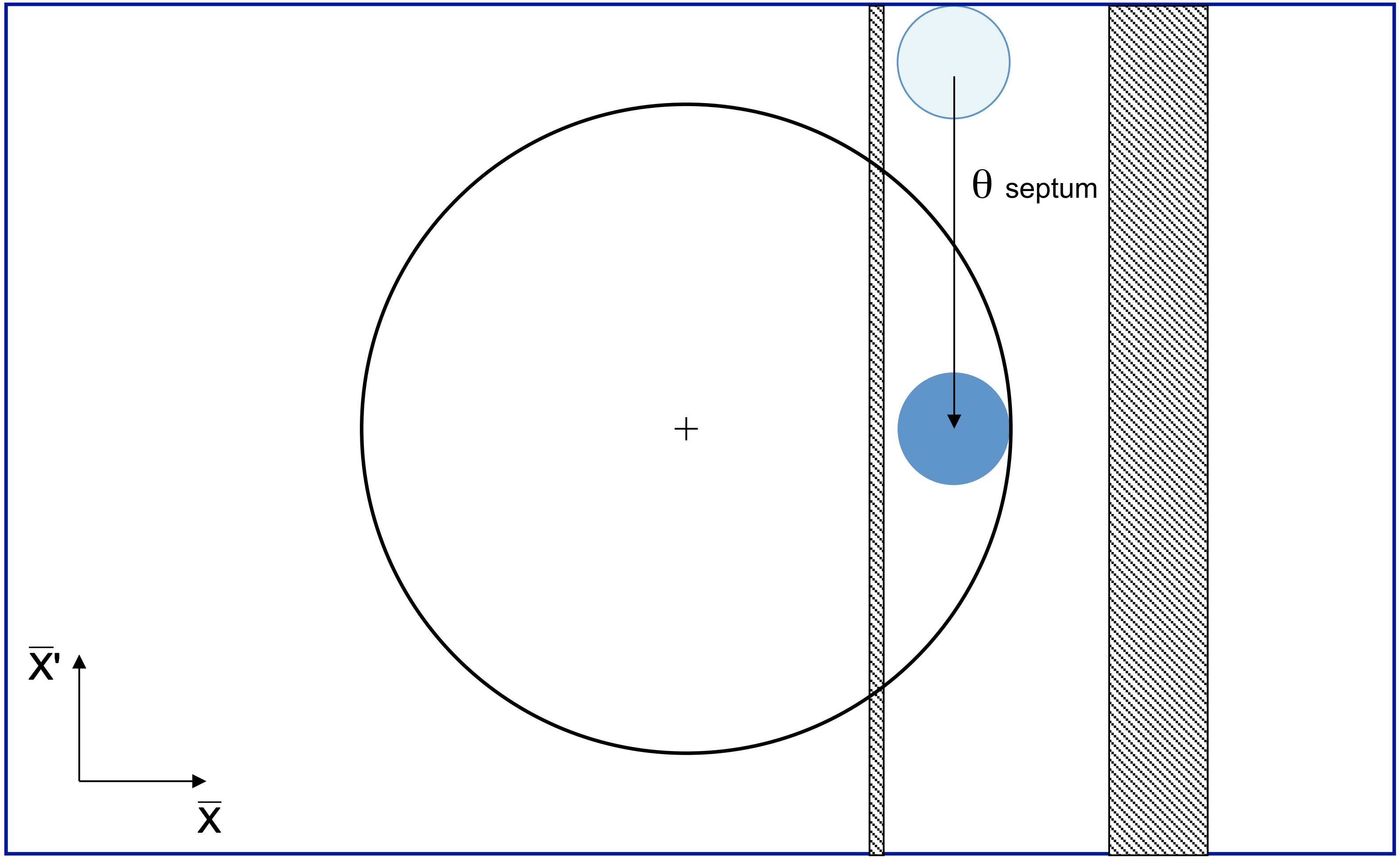


- Septum deflects the beam onto the closed orbit at the centre of the kicker
- Kicker compensates for the remaining angle
- Septum and kicker either side of D quad to minimise kicker strength

Single-turn injection

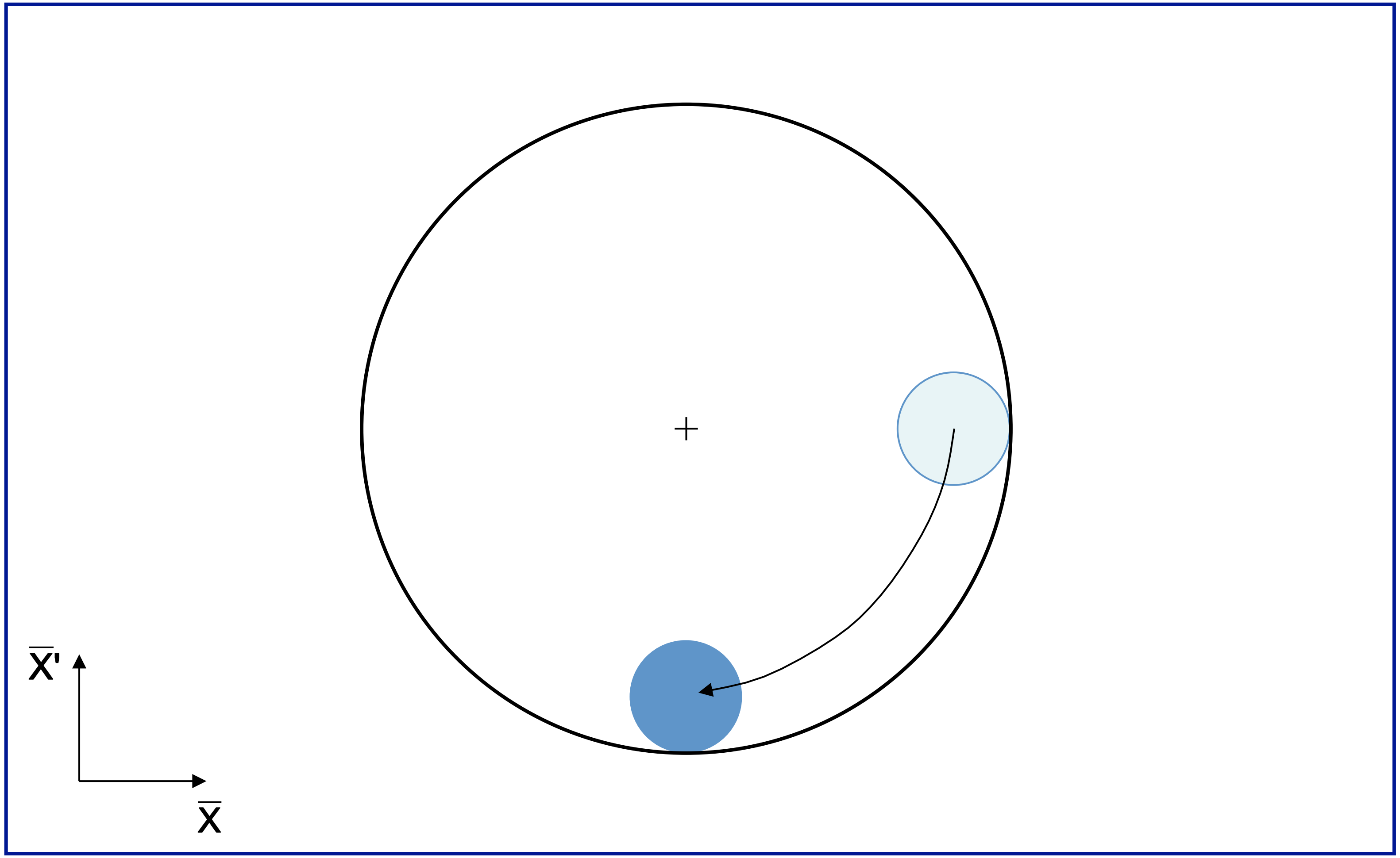
Normalised phase space at centre of idealised septum

Large deflection by septum



Single-turn injection

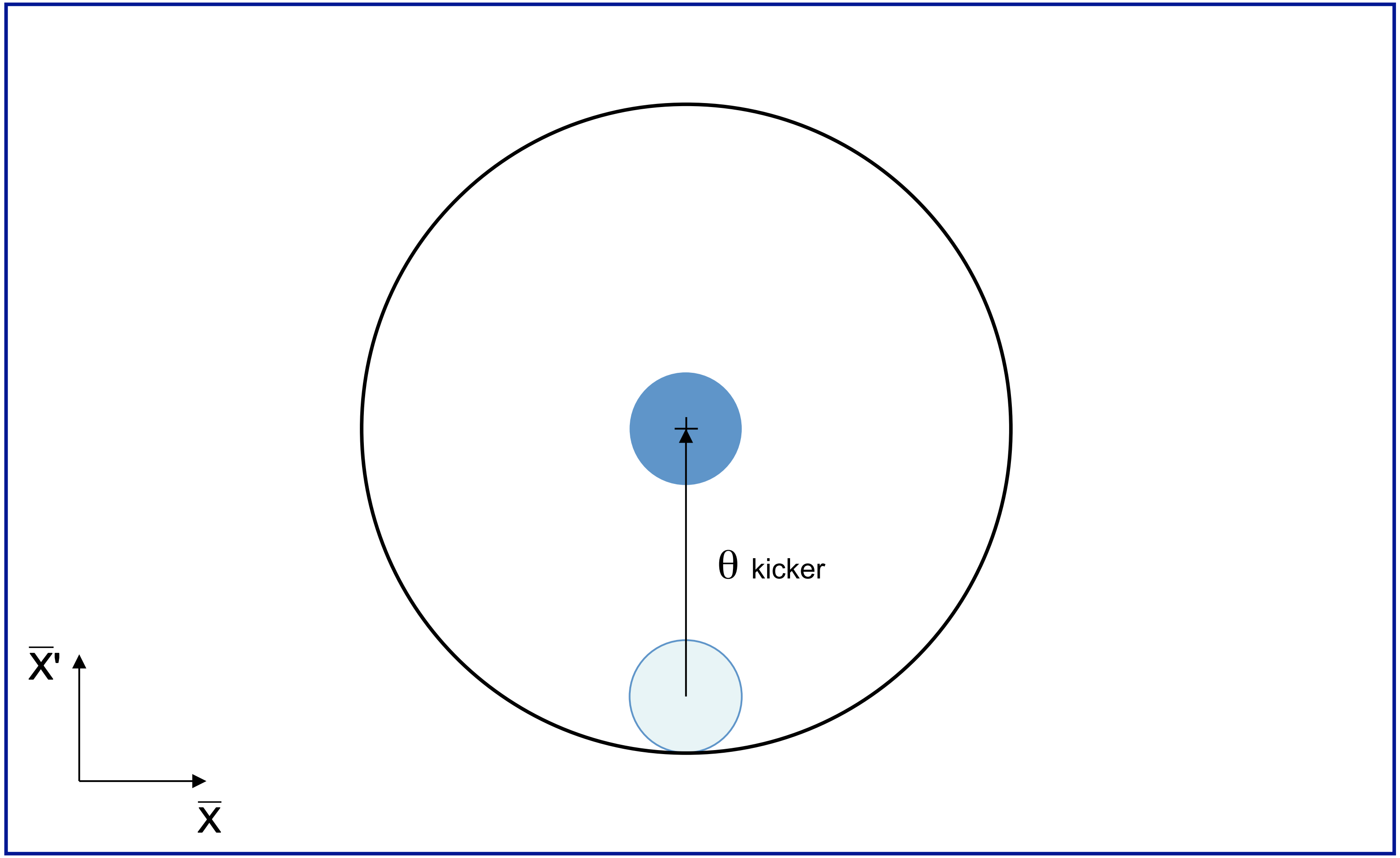
$\pi/2$ phase advance to kicker location



Single-turn injection

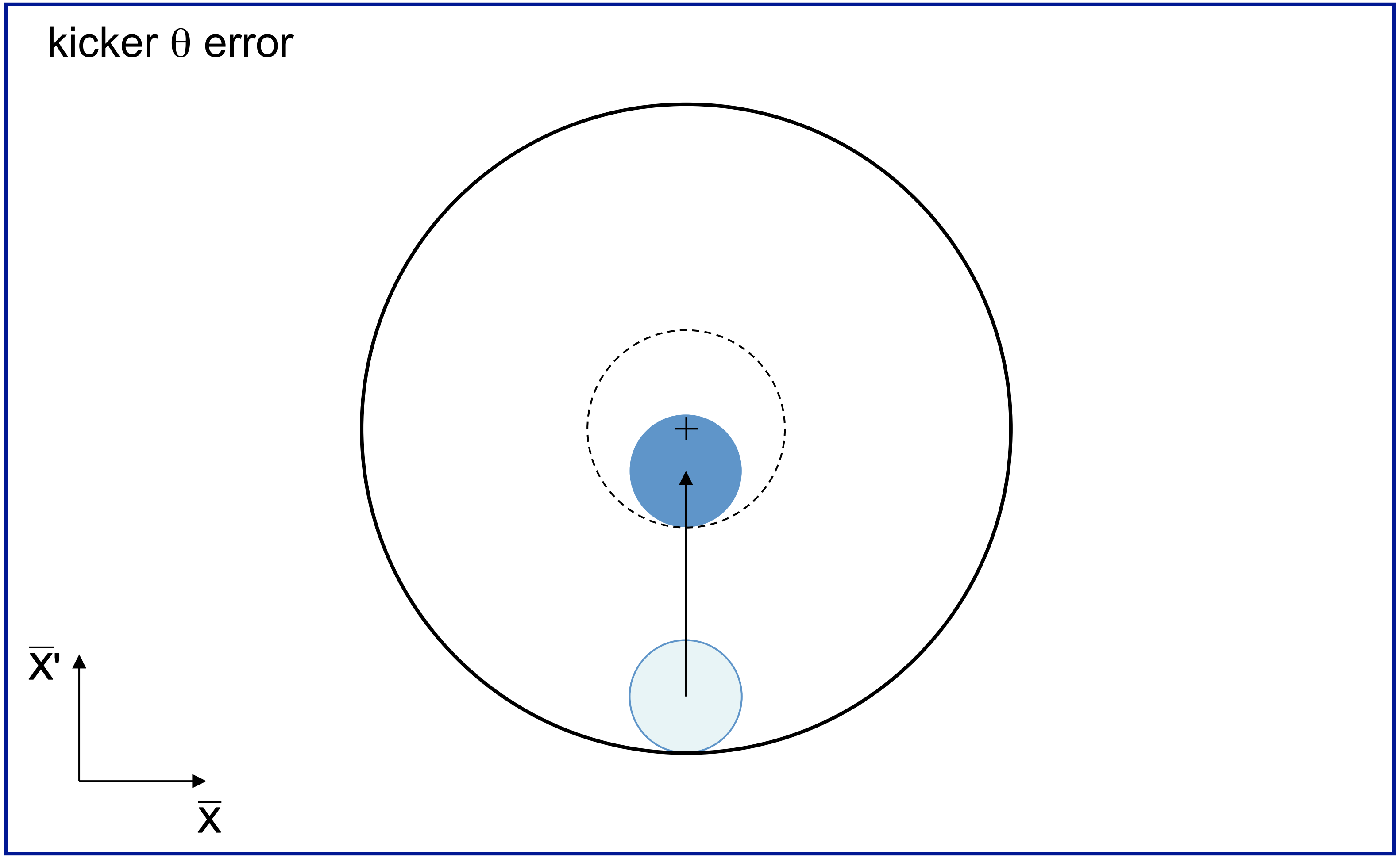
Normalised phase space at centre of idealised kicker

Kicker deflection places beam on central orbit



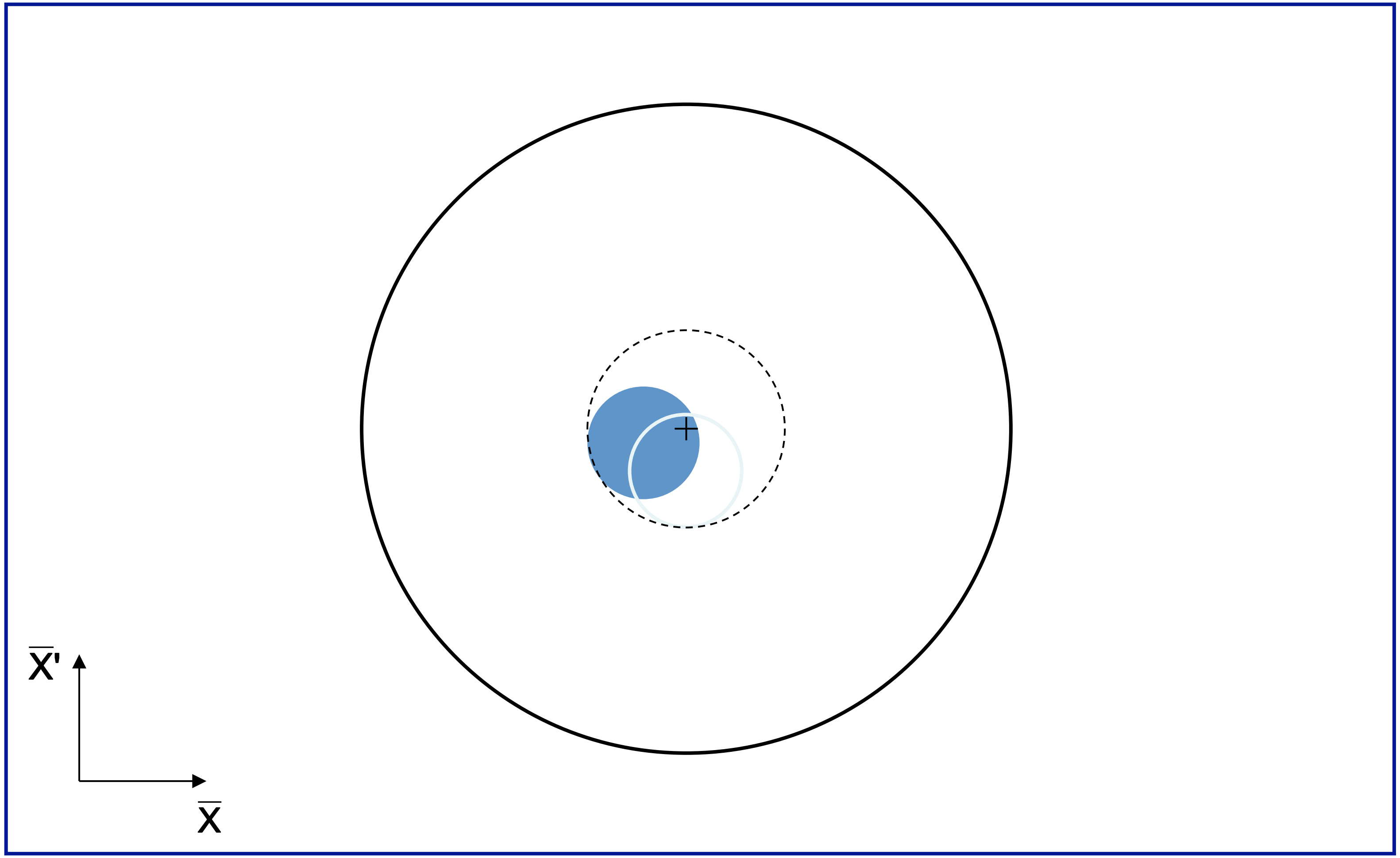
Injection Mismatch - Injection oscillations

For imperfect injection the beam oscillates around the central orbit.



Injection oscillations

For imperfect injection the beam oscillates around the central orbit.



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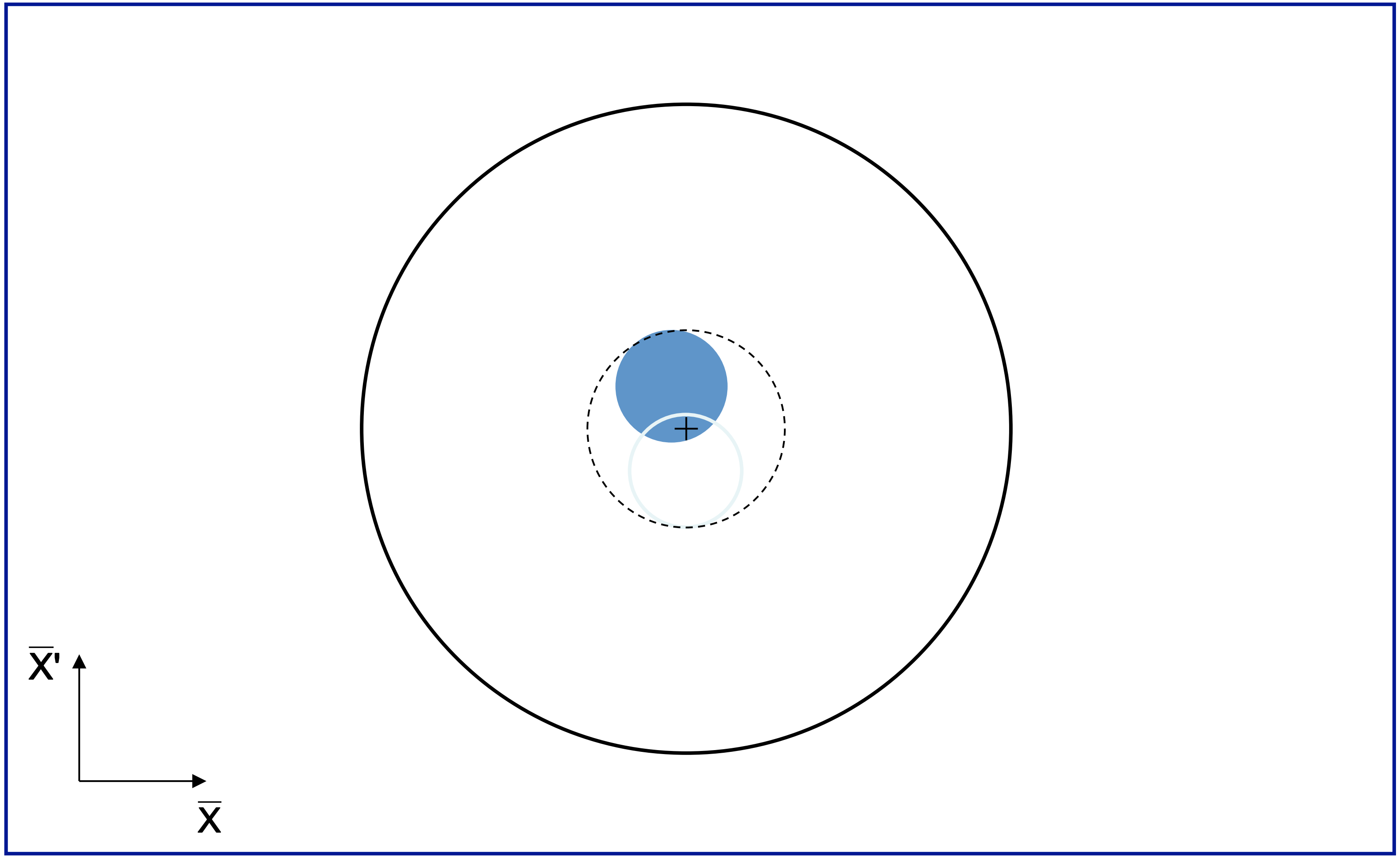

Injection oscillations

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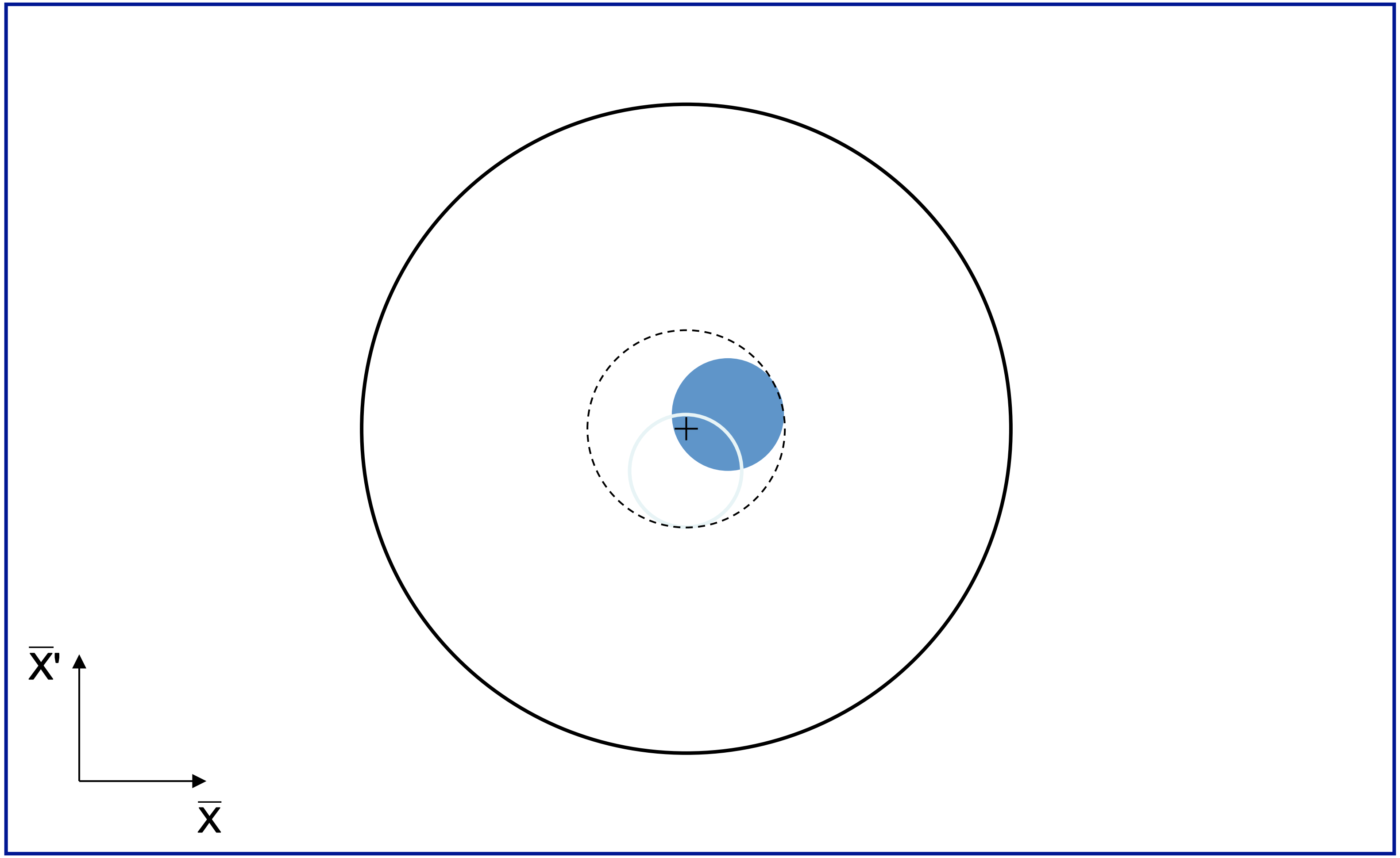
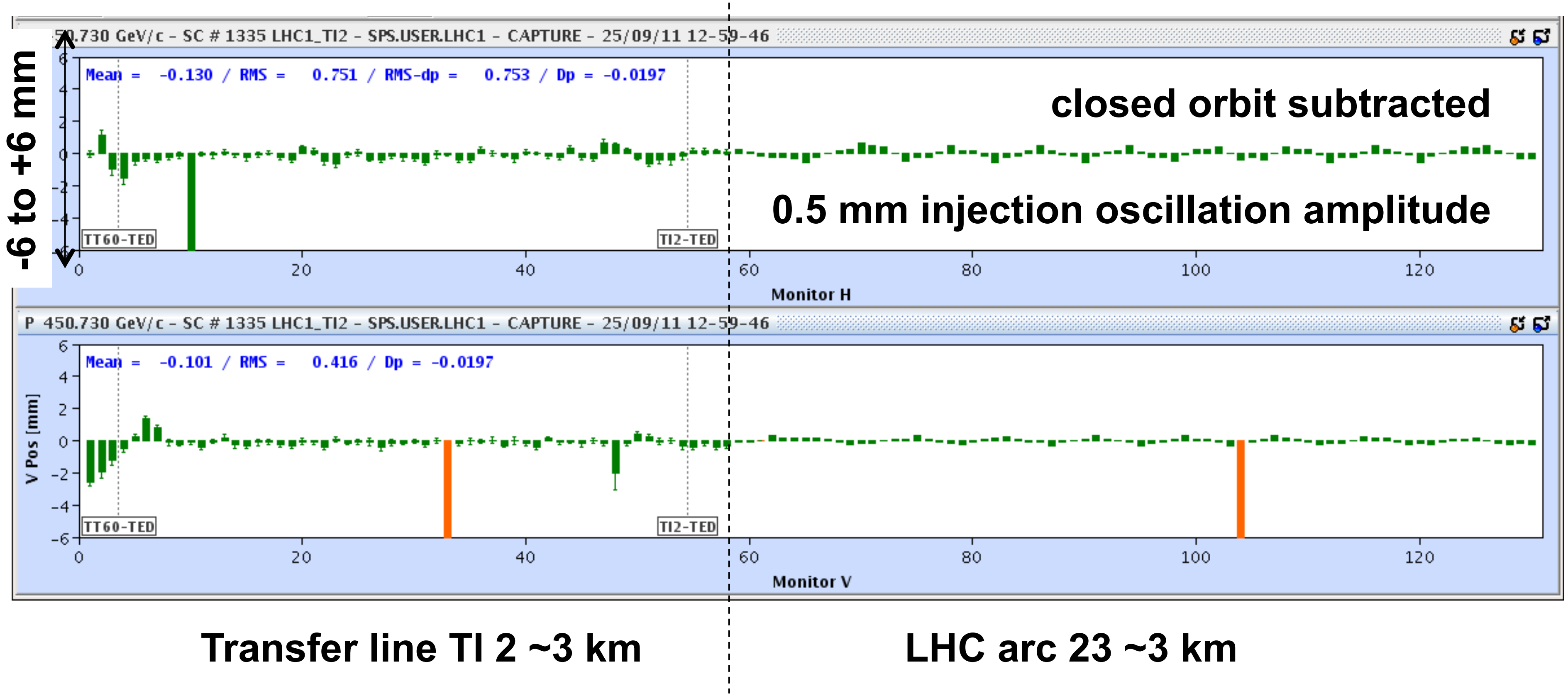


Example: LHC injection

Display of injection oscillations in LHC control room



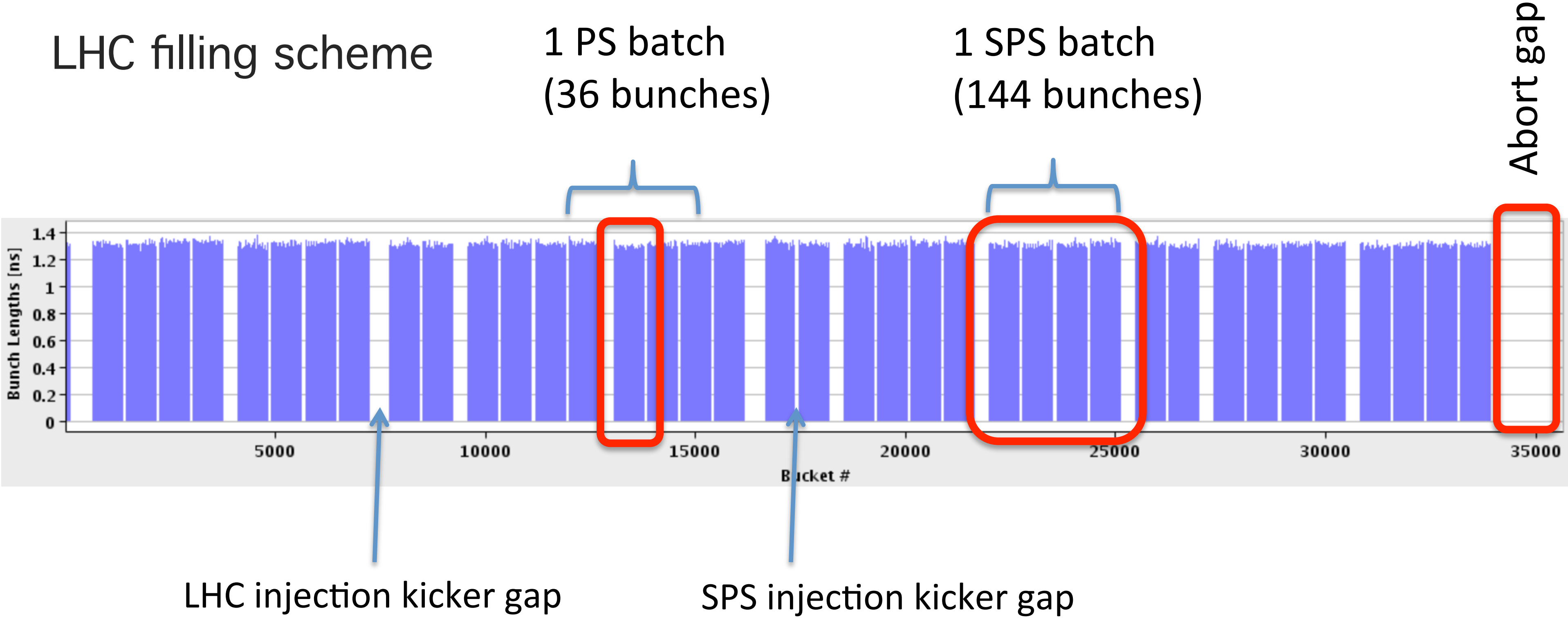
Transfer line TI 2 ~3 km **LHC arc 23 ~3 km**

Injection point in LHC point 2

Kicker magnets and synchronization

Kickers magnets have to rise their field in the gaps between the circulating beam.

LHC filling scheme



The trigger or reference frequency are generated by the RF system.

Failure Mechanisms of Kicker Systems

Kicker switches:

- need to hold off high voltage (several 10s of kV)
- need to switch high currents with short rise times (several 10 kA in < 1 μs)

Often use: thyratron switches (gas tubes)

Issues:

- erratic turn-on ➔ charge PFN/L only very last moment (~ ms before the trigger)
- “missing”: if the switch does not fire

Another reason of “missing” could be absence of RF trigger.

Other possible failure:

- flash-over: discharge between kicker electrodes while kicker has high field. Results in a reduced or increased kick strength.

Consequences of Kicker Failures

For the injected beam:

- “big” injection oscillations; too large to establish circulating beam

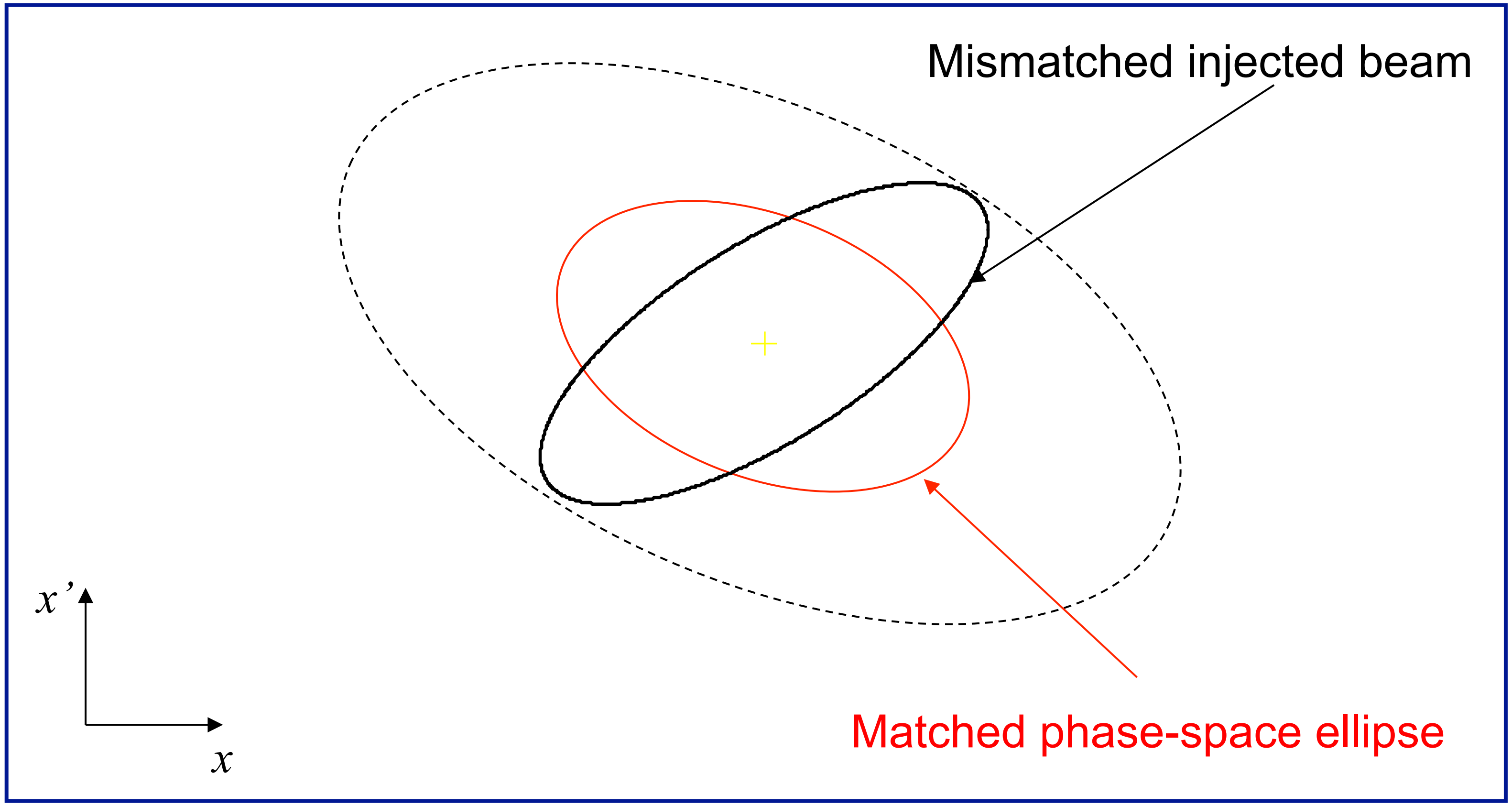
For the circulating beam:

- Like aperture kicker: big oscillations around the ring; too large to stay within aperture

Optical Mismatch at Injection

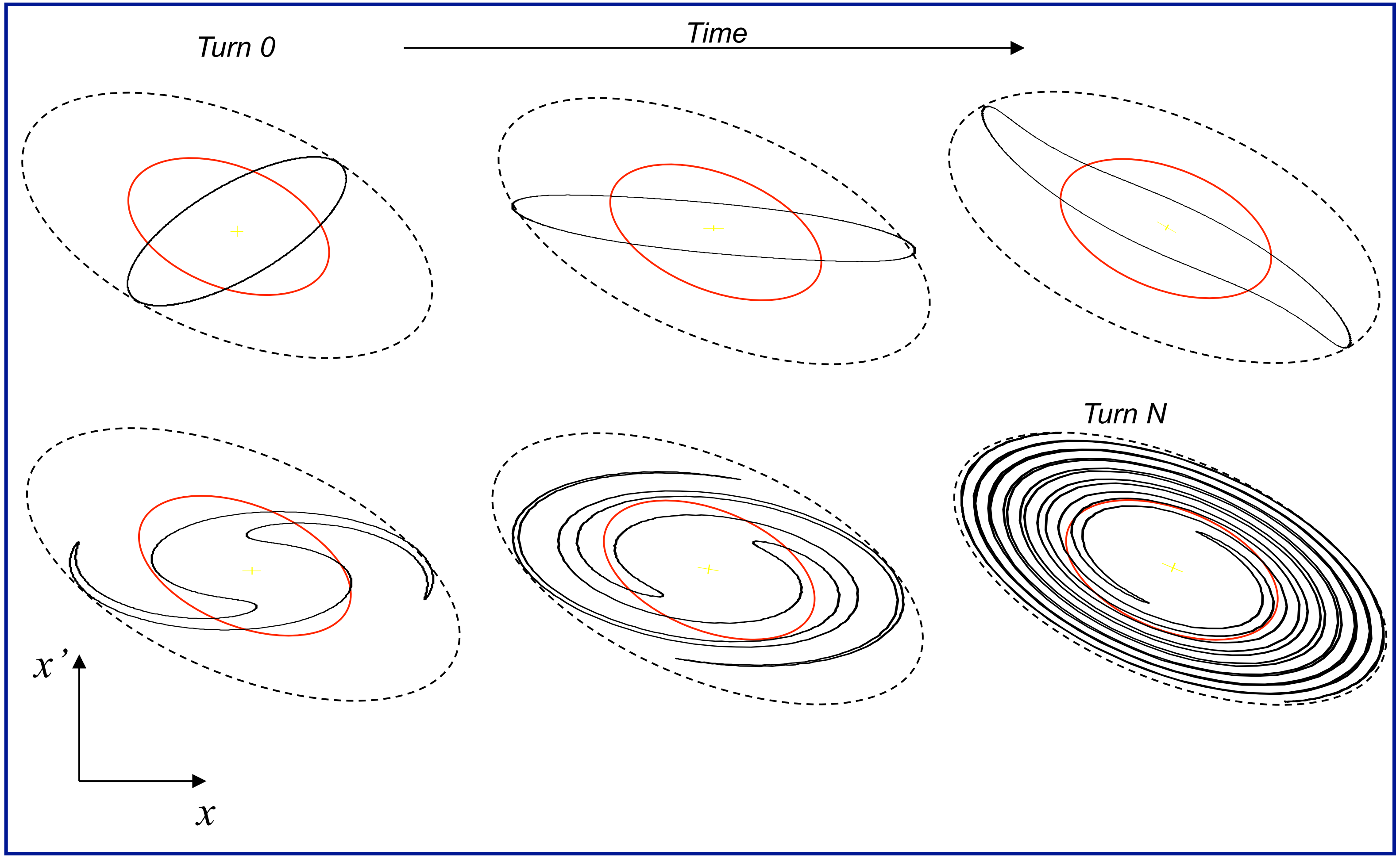
- Beam size beating around ring.
- Individual particles oscillate with conserved CS invariant:

$$a_x = \gamma x^2 + 2\alpha xx' + \beta x'^2$$



Optical Mismatch at Injection

- Filamentation fills larger ellipse <u>with same shape as matched ellipse</u>



Injection mismatch

Injection mismatch can cause very fast losses:

- single turn
- depending on the possible strength error of the involved element

Mechanism:

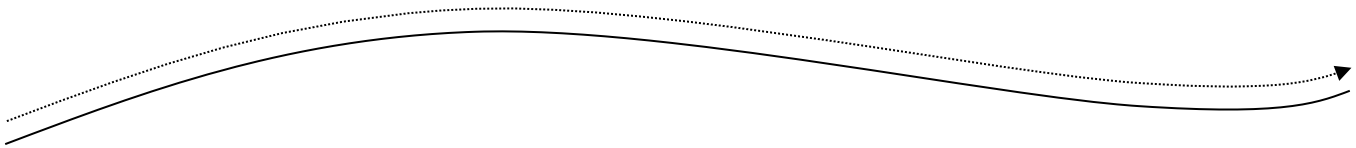
- Injection oscillations
- Mismatched beam size and beating

TRANSFER LINES

Transfer line

One pass: $\begin{bmatrix} x_2 \\ x_2' \end{bmatrix} = \boldsymbol{M}_{1\to 2} \cdot \begin{bmatrix} x_1 \\ x_1' \end{bmatrix}$

$$\begin{bmatrix} x_1 \\ x_1' \end{bmatrix}$$



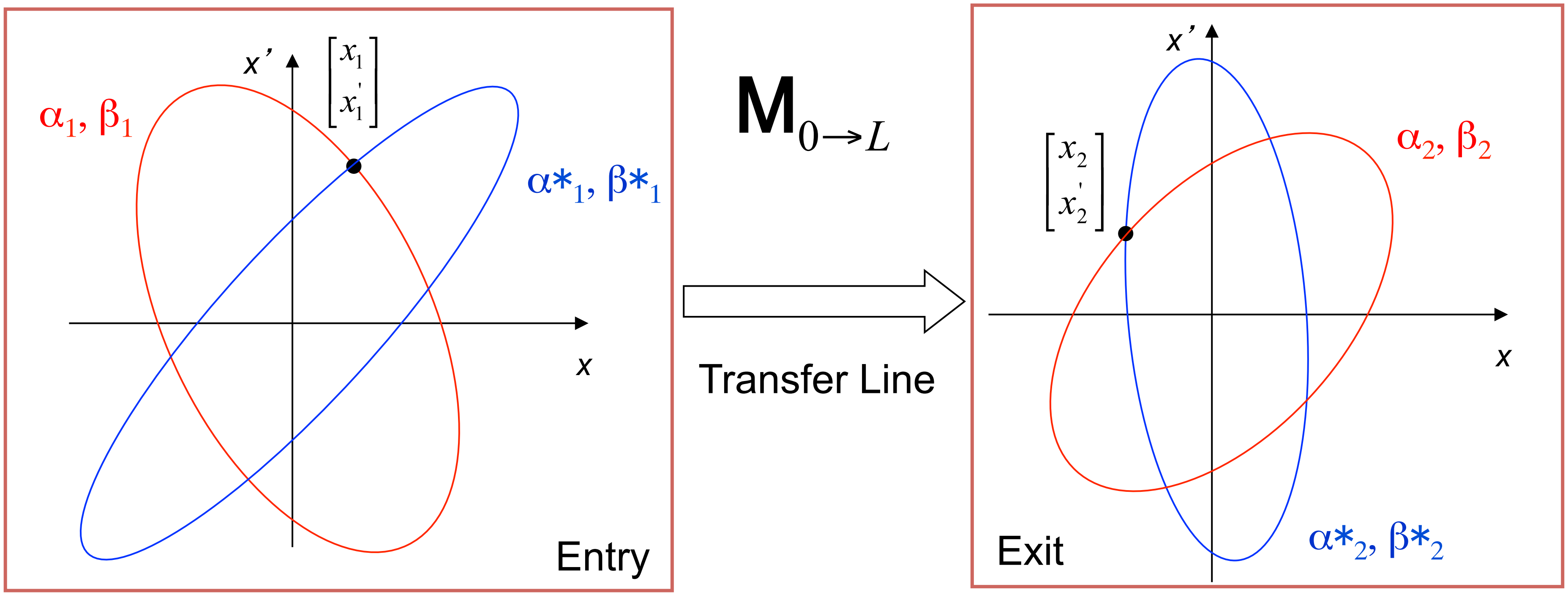
$$\begin{bmatrix} x_2 \\ x_2' \end{bmatrix}$$

$$\mathbf{M}_{1\to 2} = \begin{bmatrix} \sqrt{\beta_2/\beta_1}\left(\cos\Delta\mu + \alpha_1 \sin\Delta\mu\right) & \sqrt{\beta_1\beta_2}\sin\Delta\mu \\ \sqrt{1/\beta_1\beta_2}\left[(\alpha_1 - \alpha_2)\cos\Delta\mu - (1+\alpha_1\alpha_2)\sin\Delta\mu\right] & \sqrt{\beta_1/\beta_2}\left(\cos\Delta\mu - \alpha_2 \sin\Delta\mu\right) \end{bmatrix}$$

- No periodic condition exists
- The Twiss parameters are simply propagated from beginning to end of line
- At any point in line, $\alpha(s)$ $\beta(s)$ are functions of α_1 β_1

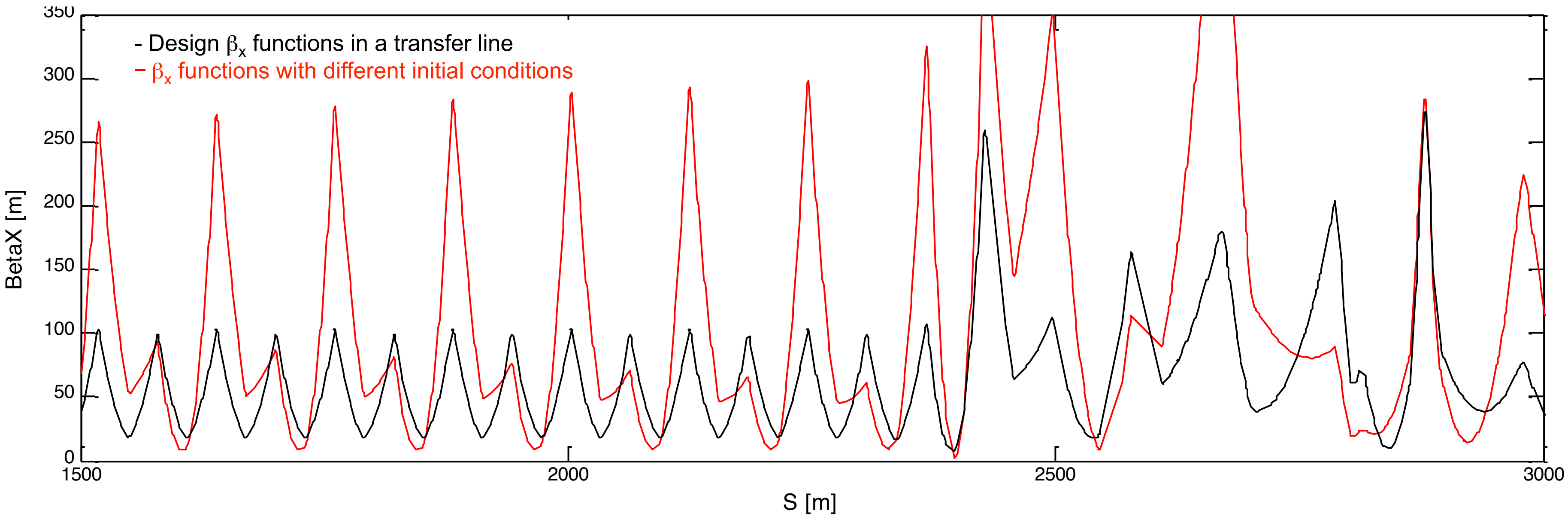
Transfer line

- On a single pass…
  - Map single particle coordinates at entrance and exit.
  - Infinite number of equally valid possible starting ellipses for single particle …… transported to infinite number of final ellipses…



Transfer Line

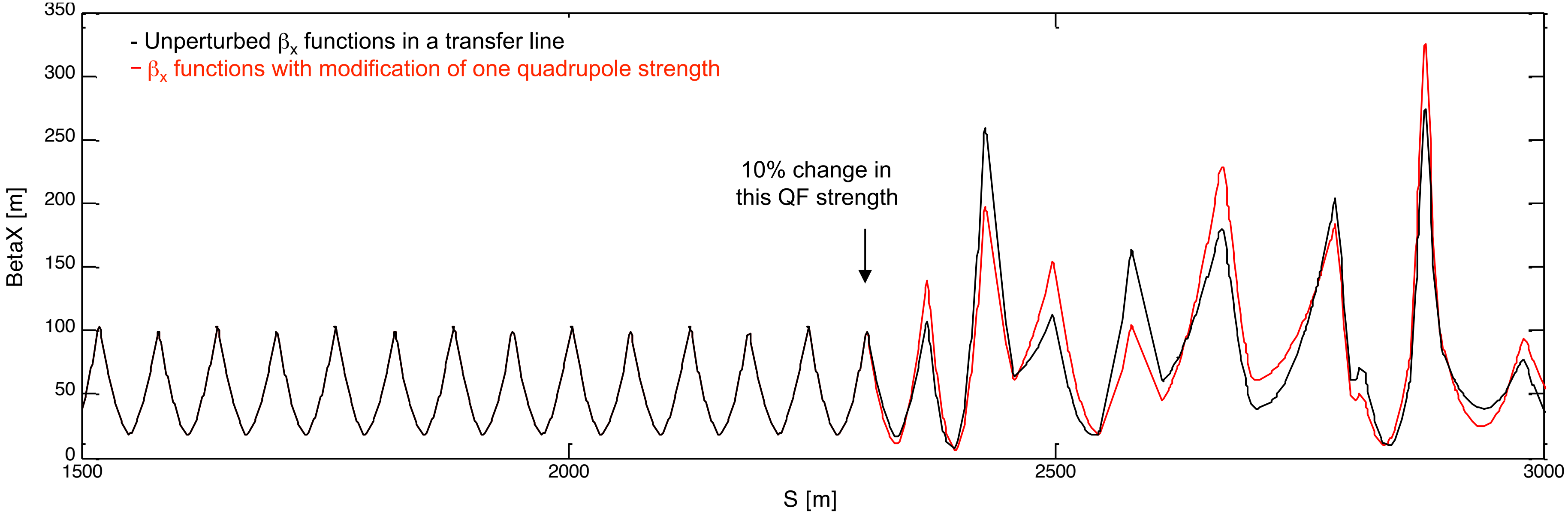
- The optics functions in the line depend on the initial values



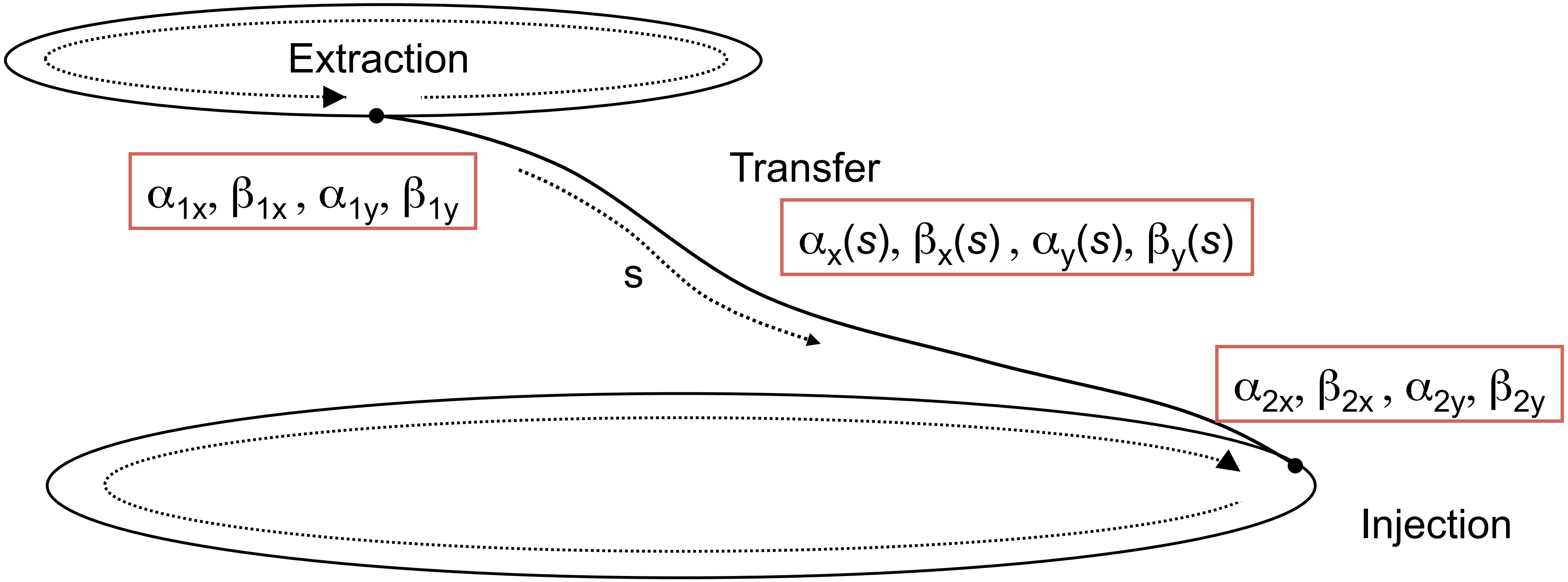
- Same considerations are true for Dispersion function:
  - Dispersion in ring defined by periodic solution → ring elements
  - Dispersion in line defined by initial D and D' and line elements

Transfer Line

- Another difference....unlike a circular ring, a change of an element in a line affects *only* the downstream Twiss values (including dispersion)



Linking Machines



The Twiss parameters can be propagated when the transfer matrix **M** is known

$$\begin{bmatrix} x_2 \\ x_2' \end{bmatrix} = \mathbf{M}_{1\rightarrow 2} \cdot \begin{bmatrix} x_1 \\ x_1' \end{bmatrix} = \begin{bmatrix} C & S \\ C' & S' \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_1' \end{bmatrix}$$

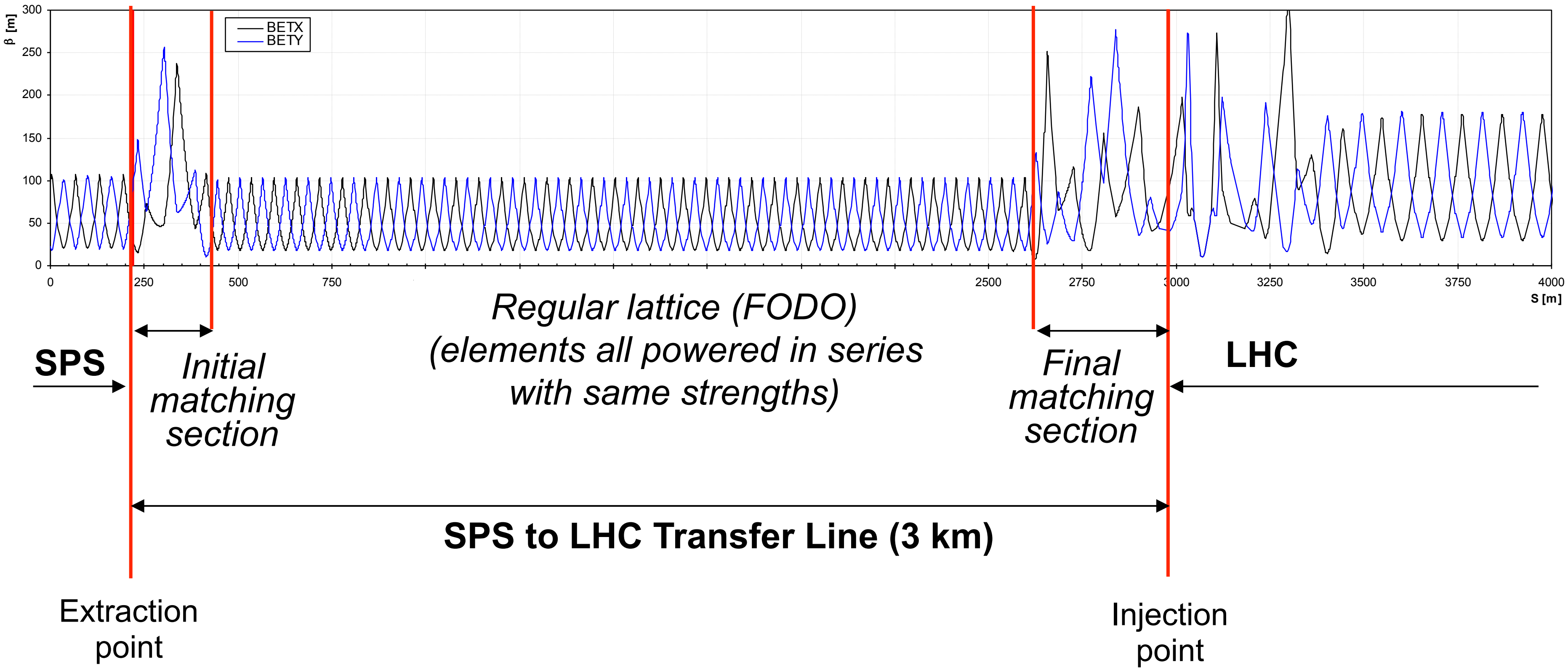
$$\begin{bmatrix} \beta_2 \\ \alpha_2 \\ \gamma_2 \end{bmatrix} = \begin{bmatrix} C^2 & -2CS & S^2 \\ -CC' & CS'+SC' & -SS' \\ C'^2 & -2C'S' & S'^2 \end{bmatrix} \cdot \begin{bmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{bmatrix}$$

Linking Machines

- Linking the optics is a complicated process
  - Parameters at start of line have to be propagated to matched parameters at the end of the line
  - Need to "match" 8 variables (α_x β_x D_x D'_x and α_y β_y D_y D'_y)
  - Maximum β and D values are imposed by magnet apertures
  - Other constraints can exist
    - phase conditions for collimators,
    - insertions for special equipment like stripping foils
  - Need to use a number of independently powered ("matching") quadrupoles
  - Matching with computer codes and relying on mixture of theory, experience, intuition, trial and error, …

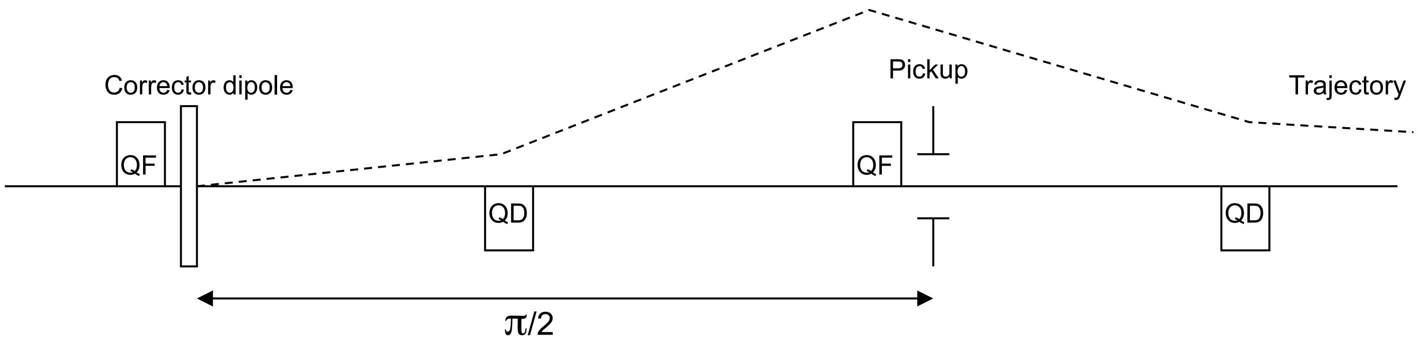
Linking Machines

- For long transfer lines we can simplify the problem by designing the line in separate sections
  - Regular central section – e.g. FODO or doublet, with quads at regular spacing, (+ bending dipoles), with magnets powered in series
  - Initial and final matching sections – independently powered quadrupoles, with sometimes irregular spacing.



Trajectory correction

- Magnet misalignments, field and powering errors cause the trajectory to deviate from the design
- Use small independently powered dipole magnets (correctors) to steer the beam
- Measure the response using monitors (pick-ups) downstream of the corrector ($\pi/2$, $3\pi/2$, …)



- Horizontal and vertical elements are separated
- H-correctors and pick-ups located at F-quadrupoles (large β_x)
- V-correctors and pick-ups located at D-quadrupoles (large β_y)

EXTRACTION

Extraction

Equipment involved: like for injection….

Several different techniques:

- Single-turn fast extraction:
  - for Boxcar stacking (transfer between machines in accelerator chain), beam abort
- Non-resonant multi-turn extraction
  - slice beam into equal parts for transfer between machine over a few turns.
- Resonant multi-turn extraction
  - create stable area in phase space ⇒ slowly drive particles into resonance ⇒ long spill over many thousand turns.
- Resonant low-loss multi-turn extraction
  - create stable islands in phase space: slice off over a few turns.

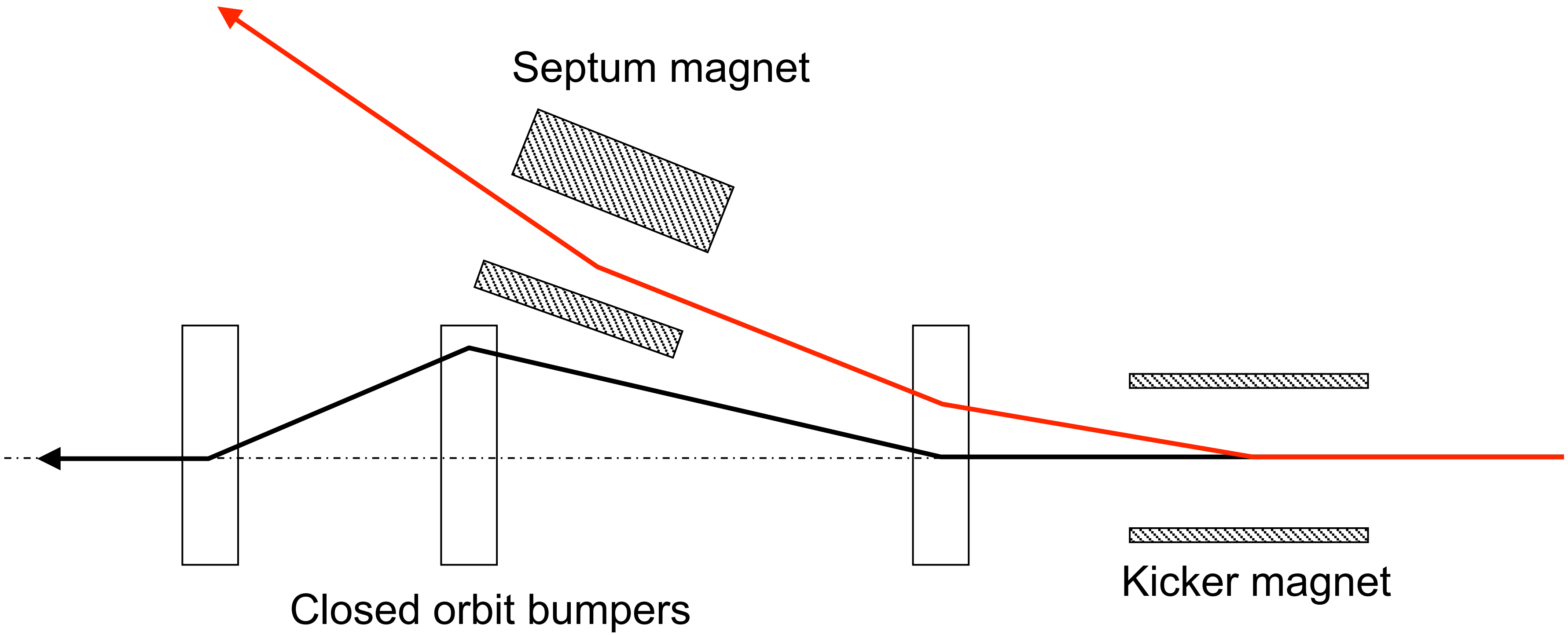
Extraction

Usually higher energy than injection ⇒ stronger elements ($\int B.dl$)

- At high energies many kicker and septum modules may be required
- To reduce kicker and septum strength, beam can be moved near to septum by closed orbit bump

Fast single turn extraction

Whole beam kicked into septum gap and extracted.



- Kicker deflects the entire beam into the septum in a single turn
- Septum deflects the entire beam into the transfer line
- Most efficient (lowest deflection angles required) for $\pi/2$ phase advance between kicker and septum

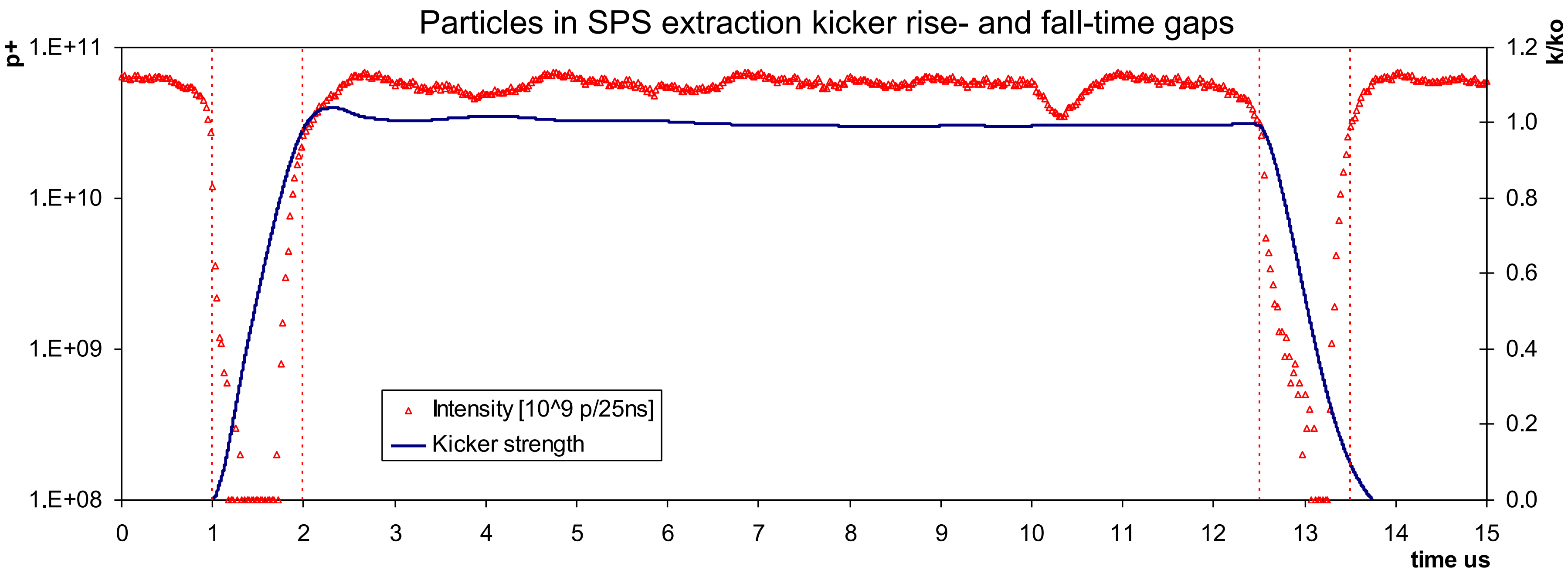
Fast single turn extraction

For transfer of beams between accelerators in an injector chain.

For secondary particle production (e.g. neutrinos)

Septum deflection may be in the other plane to the kicker deflection.

Losses from transverse scraping or from particles in extraction gap

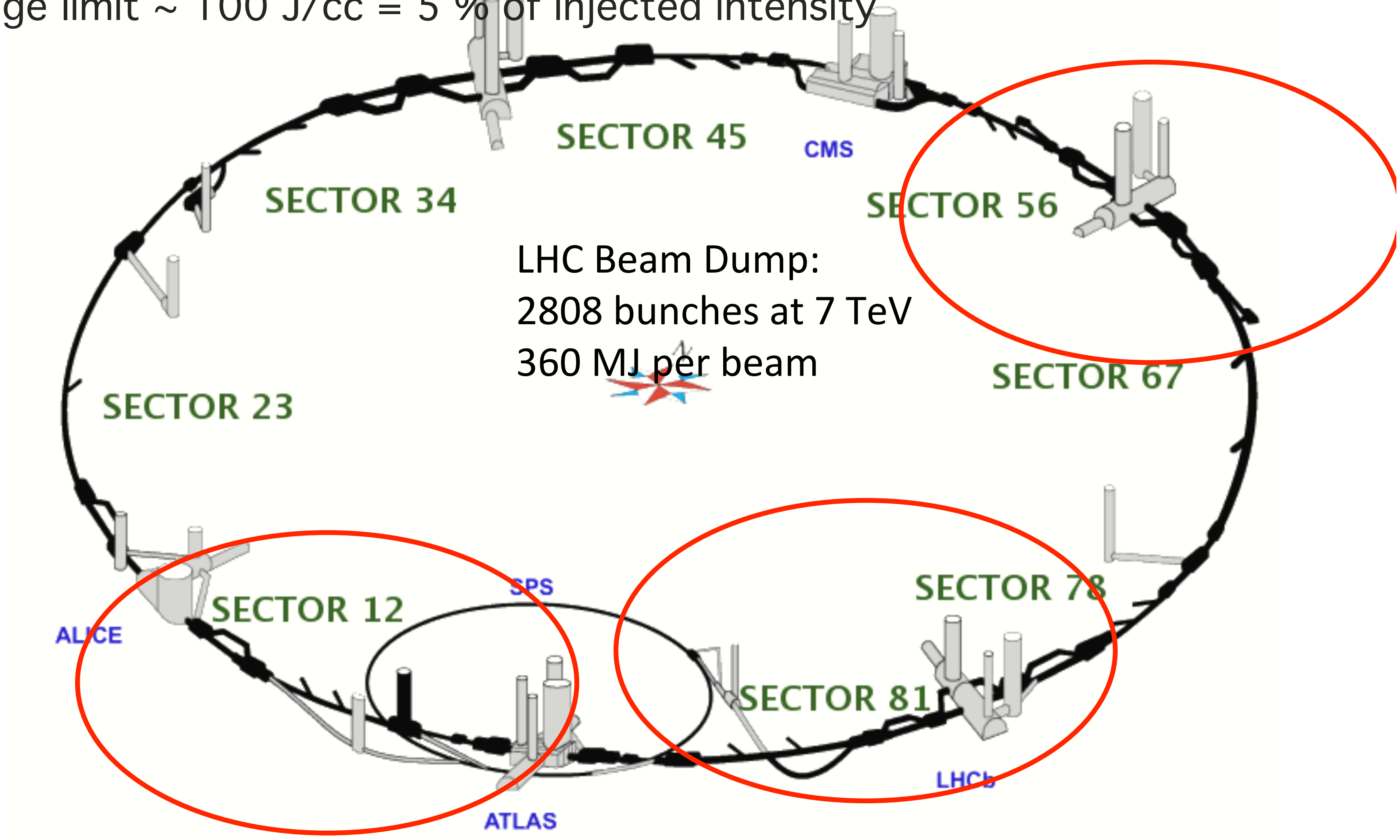


MACHINE PROTECTION FOR BEAM TRANSFER

Focus on SPS to LHC Transfer and LHC beam dump

SPS/LHC Transfer

SPS TO LHC: two 3 km long transfer lines.
Injection energy 450 GeV
Intensity: 288 bunches of 1.7×10^{11} p+ → 2.4 MJ
Damage limit ~ 100 J/cc = 5 % of injected intensity



To ensure safe injection/extraction: The Basics

- Ensure correct settings ("slow" sub-systems)
    - Energy tracking, power supply surveillance,…
- Ensure synchronization
    - Particle free kicker rise gaps
    - Gap cleaning
    - Locking to RF revolution frequency
    - System to disallow injection in already filled bucket.
    - …
- Protect against possible unavoidable kicker failures with passive protection

Monitoring, permit and kickers

Permit = Result of combination of evaluation of monitored signals

Injection permit, extraction permit, SPS beam permit,...

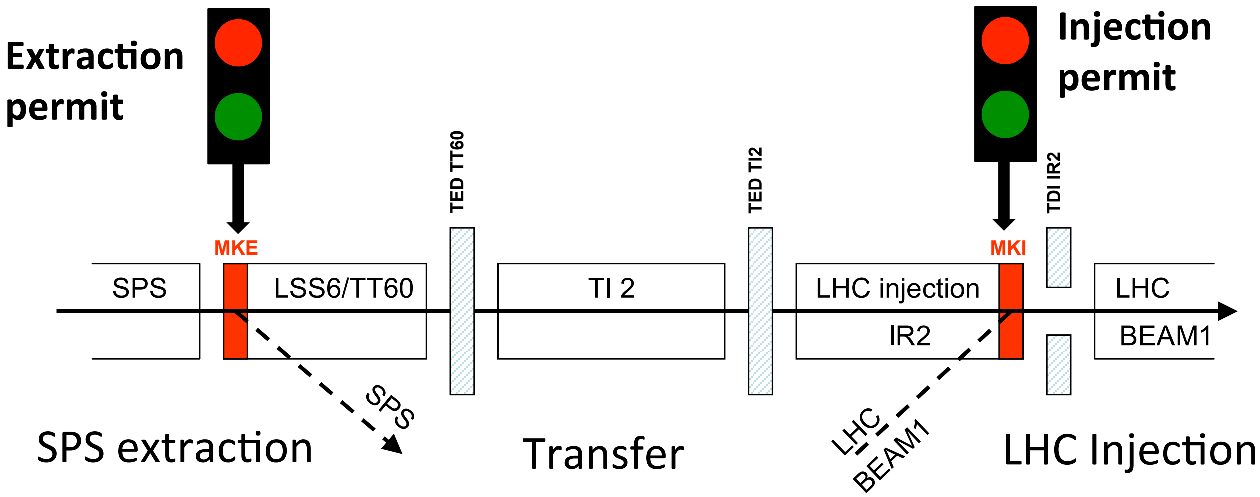
Permit connected to kicker system

Beam permit directly connected to dump kicker

SPS Extraction permit to SPS extraction kickers

➔ beam will only be extracted if permit is True

Injection permit to injection kickers



Monitoring, permit and kickers

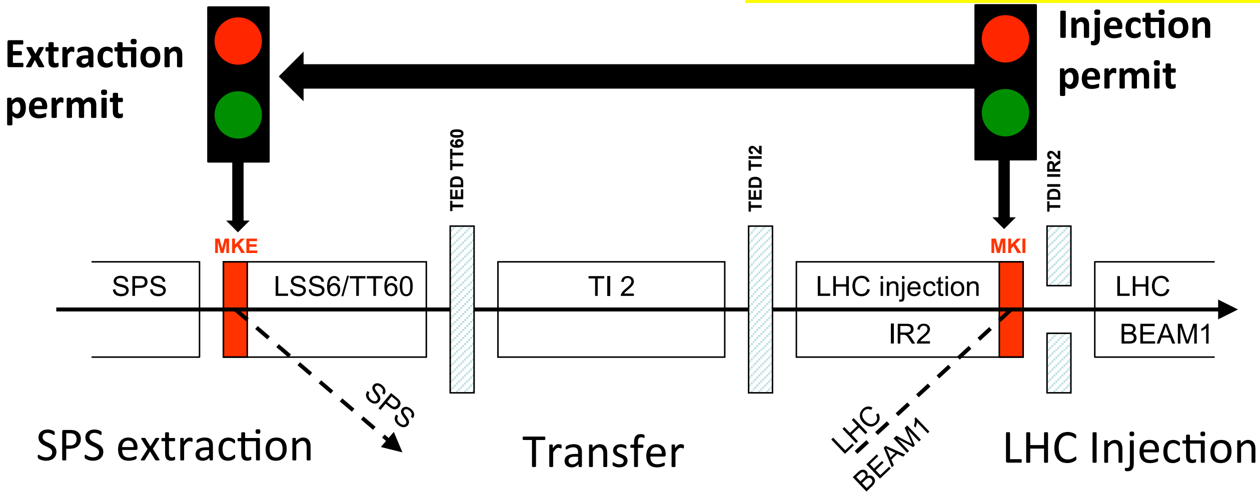
Permit = Result of combination of evaluation of monitored signals
Injection permit, extraction permit, SPS beam permit,...

Permit connected to kicker system
Beam permit directly connected to dump kicker

SPS Extraction permit to SPS extraction kickers
➔ beam will only be extracted if permit is True

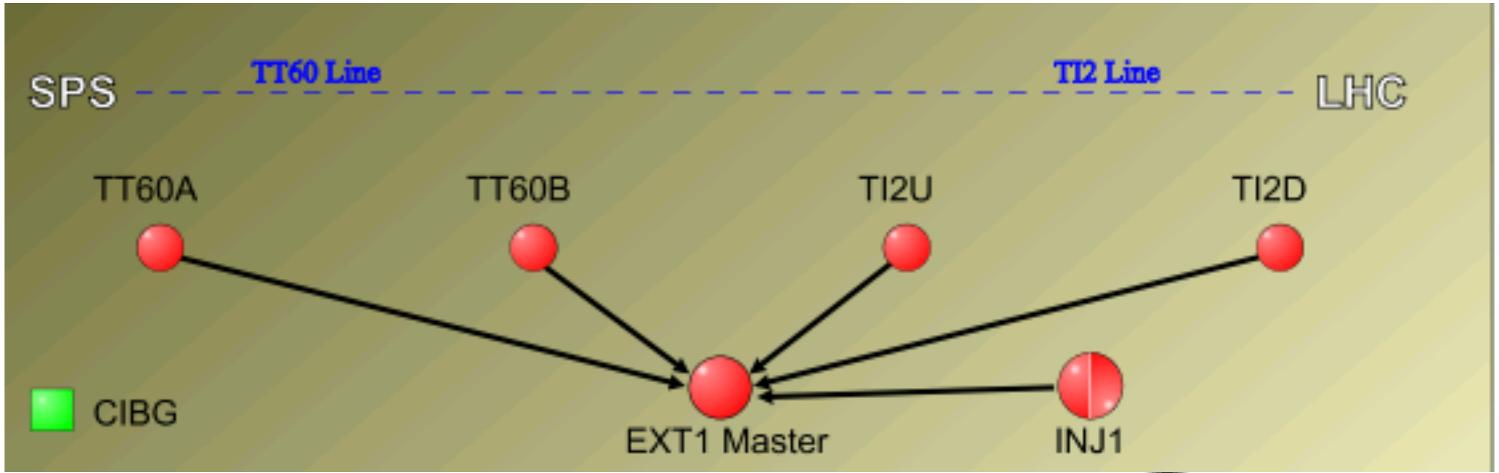
Injection permit to injection kickers

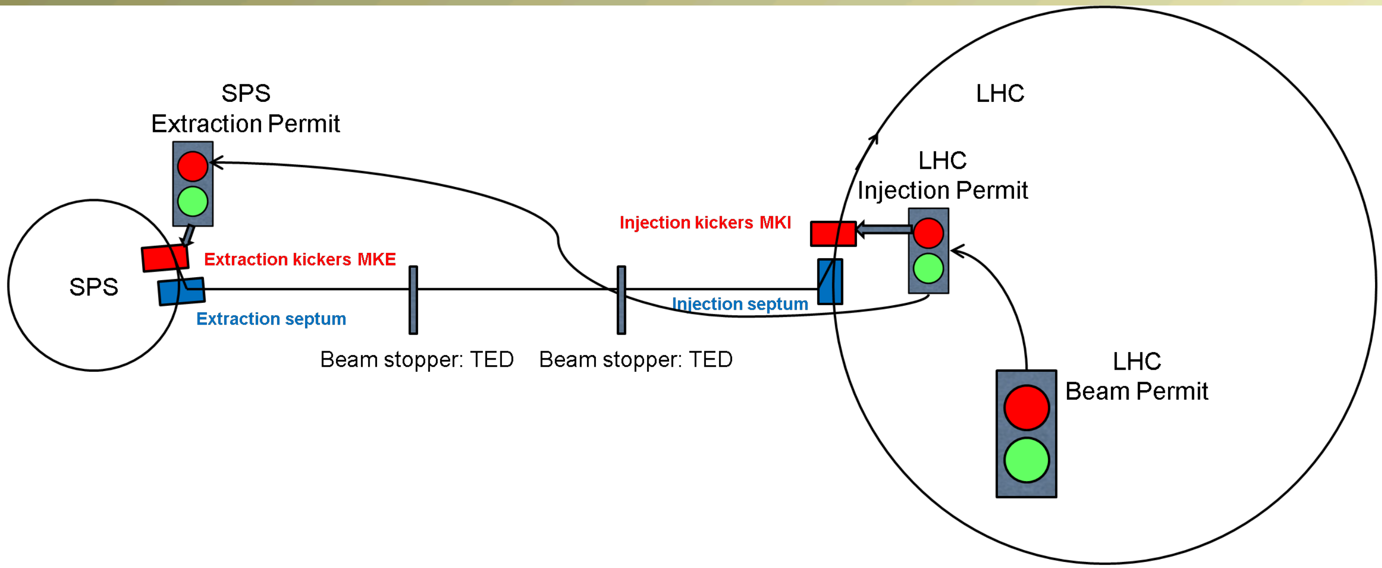
As soon as transfer has started, cannot be stopped anymore. Stop beam in previous machine.



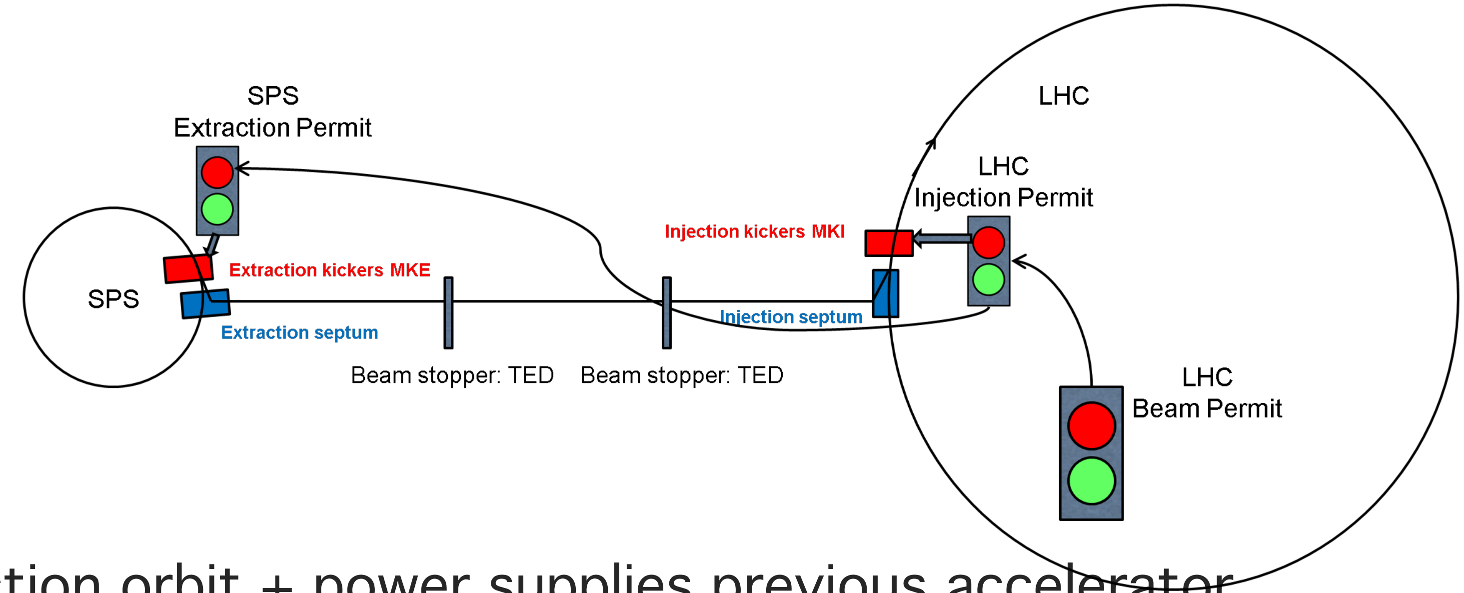
Monitoring, permit and kickers

Interlocking hierarchy: LHC ➔ LHC Injection ➔ SPS Extraction





Which systems are typically interlocked for transfer of dangerous beams?



- Extraction orbit + power supplies previous accelerator.
- Extraction elements: septum current, kicker strength
- All transfer line power supplies: correctors, bends, quadrupoles
- Vacuum valves, screens
- Settings of passive protection devices
- Beam Loss Monitors – to stop next injection
- Trajectory
- Through injection permit: injection equipment and next accelerator through next accelerator permit.

Example SPS to LHC Transfer

TT40 is the first part of
LHC transfer line TI 8

Warm magnet interlock

Extraction kickers

Extraction septa

Fast Magnet Current
Change Monitors

First commissioning of transfer with beam

The concept of “disabling" certain interlock inputs under certain conditions must be possible: “Masking”

SPS/LHC: masking allowed for “setup intensity”

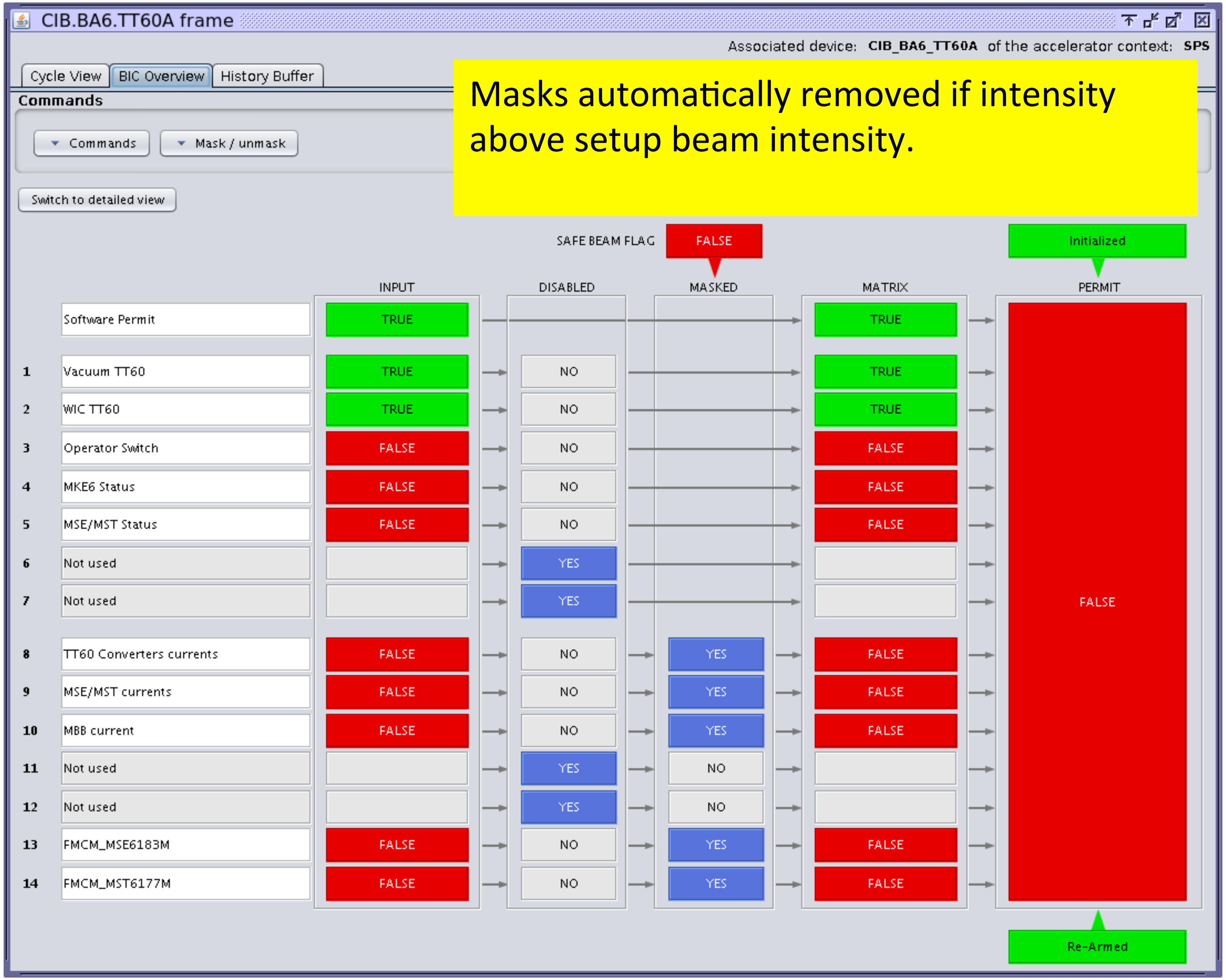
Setup intensity is derived from the SPS or LHC beam current transformer measurements and distributed across the machines in the form of the “setup intensity flag”.

This flag (and others) is distributed by a dedicated system: **Safe Machine Parameter System.**

Safe Machine Parameter System: https://ab-div-bdi-bl-blm.web.cern.ch/ab-div-bdi-bl-blm/Specification/LHC-CI-ES-0004-10-00.pdf

After the commissioning the interlock thresholds are adjusted and masks removed.

Example SPS to LHC transfer



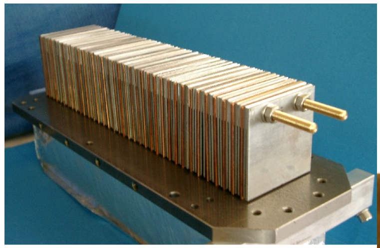
Masks automatically removed if intensity above setup beam intensity.

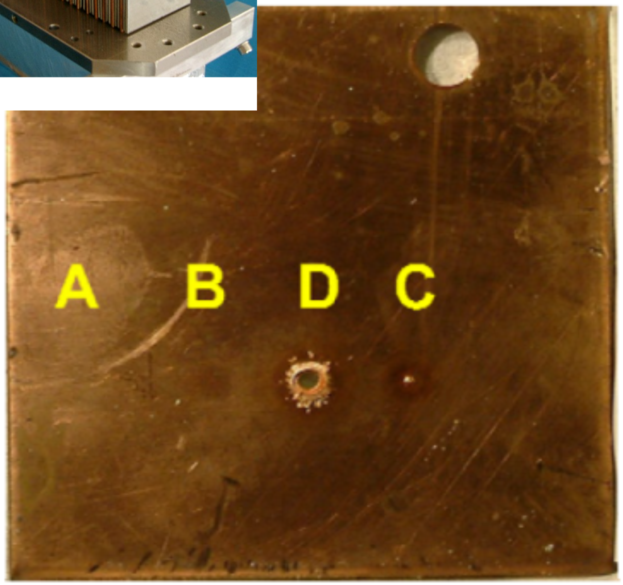
Ad "Setup Intensity"

The setup intensity must be reasonably high to be able to test under representative beam conditions.

The setup intensity should be below damage limit (quench limit).

The knowledge of the accelerator equipment damage limit is of importance. Test result at 450 GeV with LHC beam:





Intensity	# protons	Comments
A	1.2e12	No effect
B	2.4e12	Decolouration
C	4.8e12	Melting
D	7.2e12	Fragment ejection

Definition of LHC Setup Beam Flag

$$\left(\frac{E\left[GeV\right]}{450\left[GeV\right]}\right)^{1.7} \times I\left[p\right] \leq 1\times10^{12}$$

Another important concept: Beam Presence Flag

Not all systems are connected to the beam interlock system.

Final check of receiving machine is “circulating beam”

Before sending high intensity a very, very low intensity bunch is injected into the LHC.
Probe beam intensity: ~ 5 x 10^9 p^+ per bunch

If it circulates ➔ beam presence flag is generated

High intensity injection only allowed under condition:

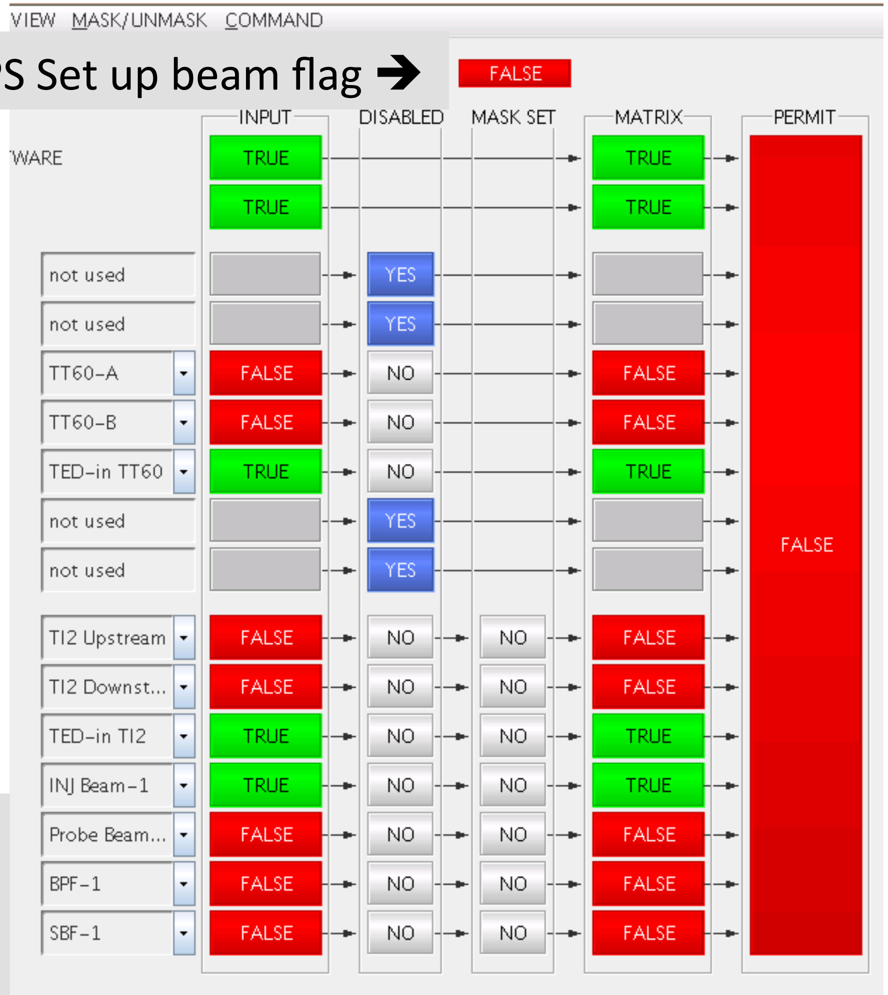
SPS Probe Beam Flag ||
[Beam Presence && (NOT.(LHC Set-up Beam Flag) || SPS Set-up Beam Flag)]

All flags are generated by the “Safe Machine Parameter System"

Another important concept: Beam Presence Flag

This is not just a recommendation. The evalution of the combination of the flags is hardcoded into the SPS extraction permit.

SPS Set up beam flag ➔



SPS Extraction Permit for extraction into LHC transfer line TI 2

SPS Probe Beam Flag ➔

LHC Beam Presence Flag ➔

LHC Set up Beam Flag ➔

Post Operational Checks

Automatic post operational check software.

E.g. after each injection data collection from BLMs, BPMs, kickers, wall current monitors etc., SPS scraping is triggered.

Automatic analysis with respect to reference shot + tolerance.

If outside tolerance: next injection ➔ next extraction blocked.

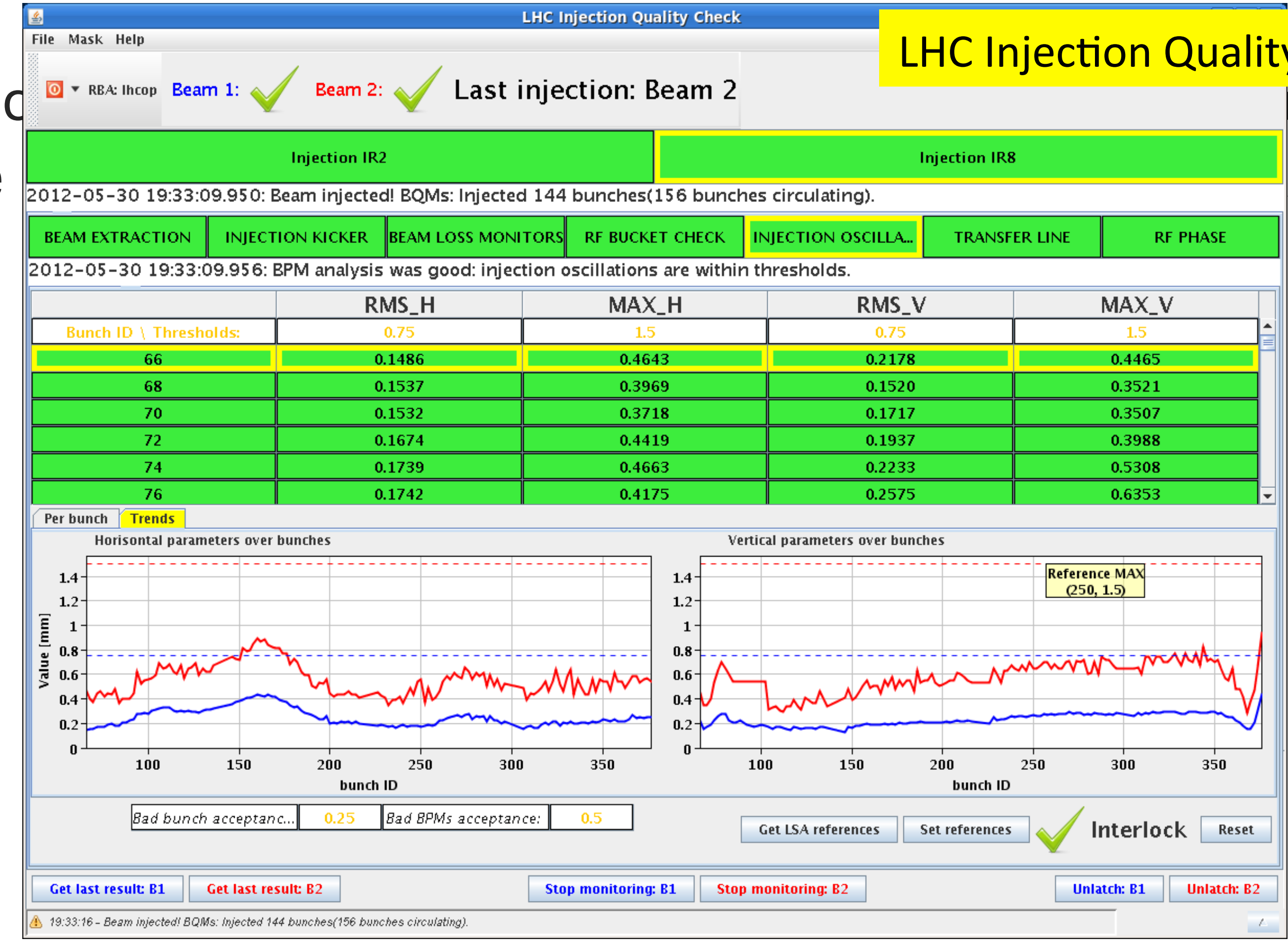
Post Operational Checks

Automatic post operational check software.

E.g. after each injection data collection from BLMs, BPMs, kickers, wall current monitors etc., SPS scraping is triggered.

Automatic ... ice.

If outside ... ed.



LHC Injection Quality Check (IQC)

Required time constants for power supply surveillance

Pulsed transfer lines. Only current value at extraction time counts. Currents are verified before the extraction occurs. SPS to LHC: ~ 1 ms before extraction.

Magnet Family	Time constant ms	Time for 1 σ ms
Family TI 2		
Extraction septum MSE	23	0.03
Extraction septum MST	41	0.27
Injection septum MSI	950	0.48
Main dipoles MBI	773	0.11
MBIAV1	2772	0.62
MBB	1241	0.75
MPLH	100	1.93
MBIBH	1295	2.66
MBIAV3	1959	3.69
MBIAV2	2522	6.50
Family TI 8		
Extraction septum MSE	23	0.02
Injection septum MSI	1100	0.69
Main dipoles MBI	894	0.25
MBIBV	1296	0.77
MBHC	1010	0.91
MPLH	100	1.28
MCIBH	391	1.43
MBIAH	2631	1.50
MBHA	2607	1.58
MBIAV	2453	5.84
MCAIV(x3)	487	18.50

Time constants of circuits in case of failure: power converter trip...

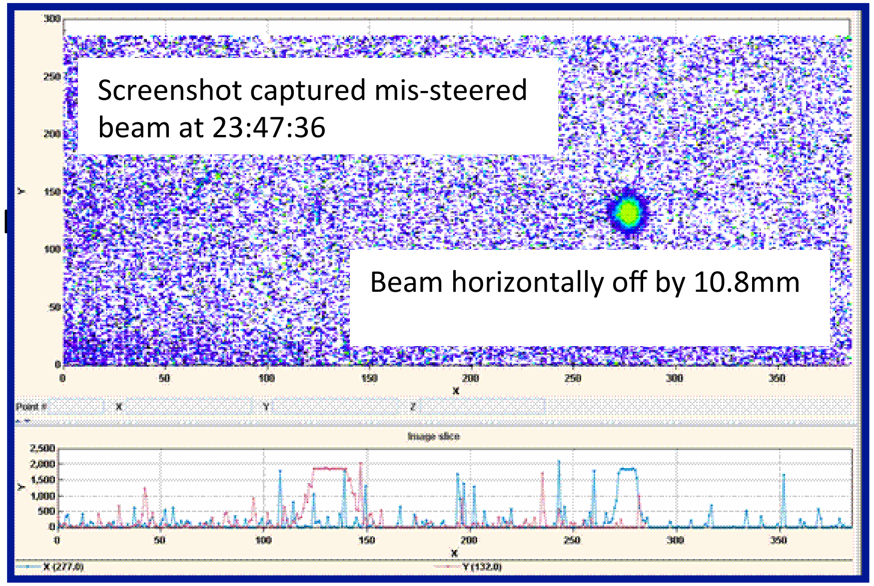
SPS Extraction septa particularly fast

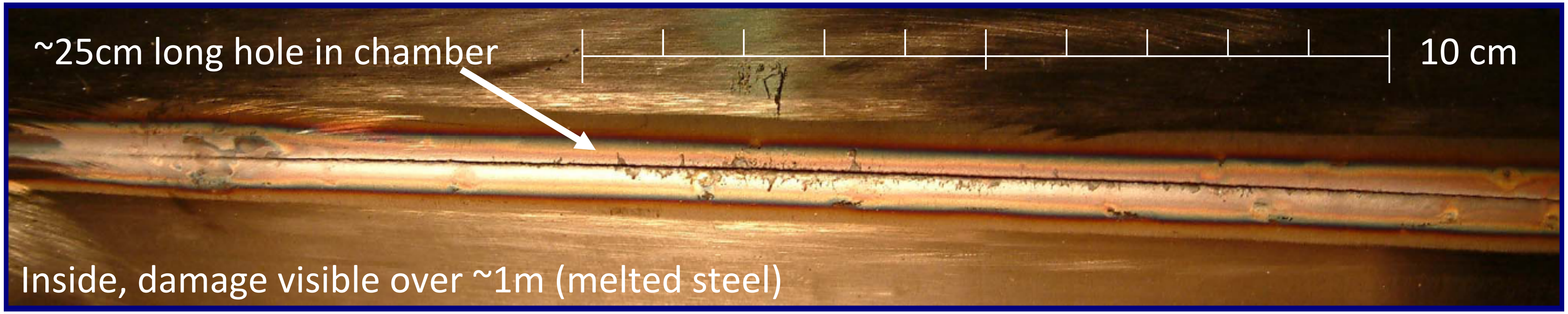
- Moves beam by 40 σ in 1 ms

Aperture ~ 10 σ

Example – Famage from LHC type beam, Extracted from SPS

- Failure in SPS during setting-up of LHC beam (25/10/04)
- Extraction septum supply tripped due to EMC from the beam
- In 11ms the field dropped 5%
- $3.4{\times}10^{13}$ p+ @ 450GeV were wrongly extracted onto aperture
- Chamber and quadrupole magnet were damaged and had to be replaced





Additional protection for very fast power supply failures

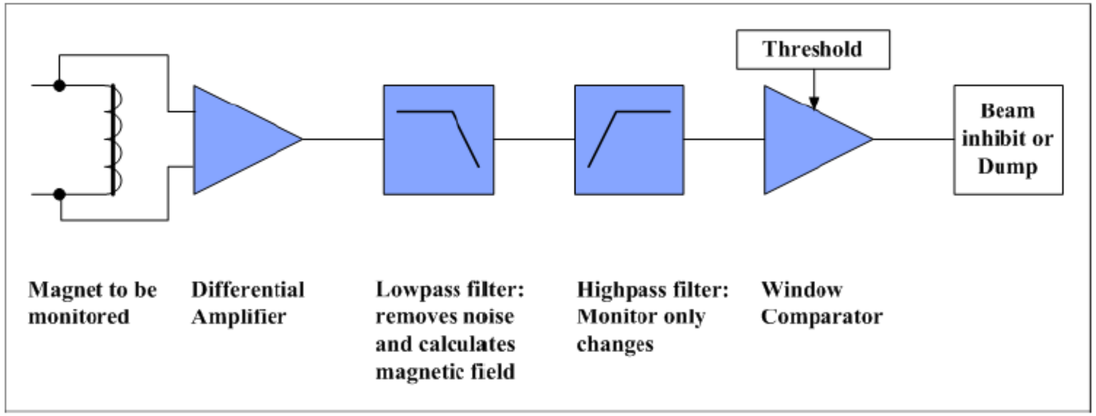
- Interlocking on fast current changes

  FMCM: Fast Magnet Current Change Monitor.

  Instead of measuring small current changes, it measures changes of the voltage of a critical magnet or powering system.

  Can detect current changes of 10^{-4} in less than 1 ms.

  Developed by DESY and successfully used at CERN.



E.g. Extraction septum

Reaction time 50 μs
for current change of 0.1%

Reference: M. Werner et al., A Fast Magnet Current Change Monitor for Machine Protection in HERA and the LHC, proceedings ICALEPS 2010

Passive Protection

We have seen that there are many options to ensure the correct settings of the magnets during beam transfer, before beam transfer occurs.

Beam transfer can be inhibited in the very last moment in case of failures.

The only exception are failures of kicker magnets.
Not all kicker failures can be actively avoided.

Dealing with mis-kicked beam has to be designed into the protection system:

PASSIVE PROTECTION – absorbers, collimators, dumps

Passive Protection Devices

When designing a passive protection system, the following questions have to be answered:

- Protection against which failure?
    - Where to put protection (how many)?

- What is the damage level/quench level/allowed radiation level of downstream equipment? Defines required attenuation.

- What is the maximum particle density that can impact the protection devices? At which repetition rate? Robustness versus material density. Defines length for given attenuation

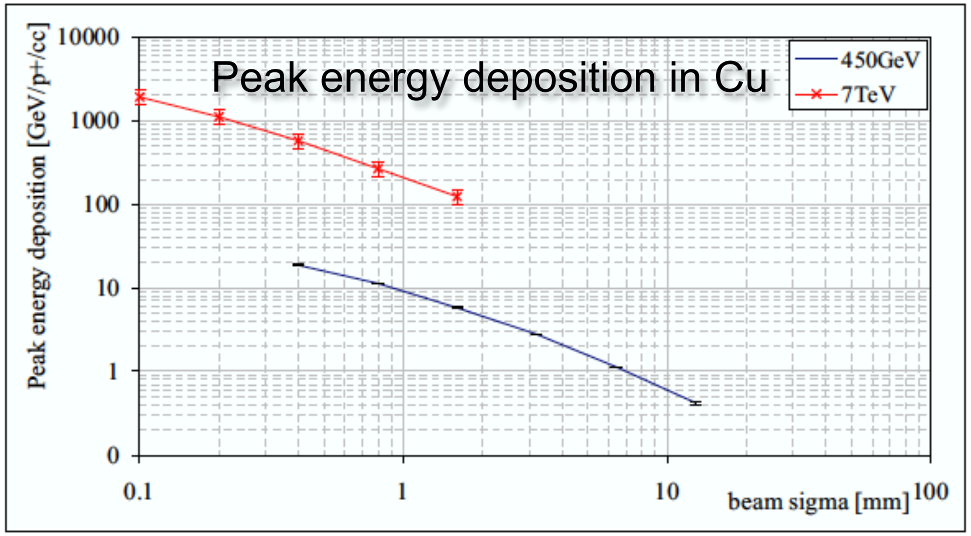
- What is the aperture to be protected? Moveable devices? Which transverse setting?

Design of protection devices: between accelerator physics and material science. Simulations for particle tracking, energy deposition and thermo-mechanical response are required.

Energy deposition as function of intensity and emittance

The damage potential of a beam does not only depend on the total intensity

Energy deposition for a given energy as function of spot size $\sigma_x \times \sigma_y$



$$\Delta E \propto \frac{I_{beam}}{\sigma_x \cdot \sigma_y}$$

$$\Delta E \propto \frac{I_{beam}}{\varepsilon}$$

Assumed round beams in this context

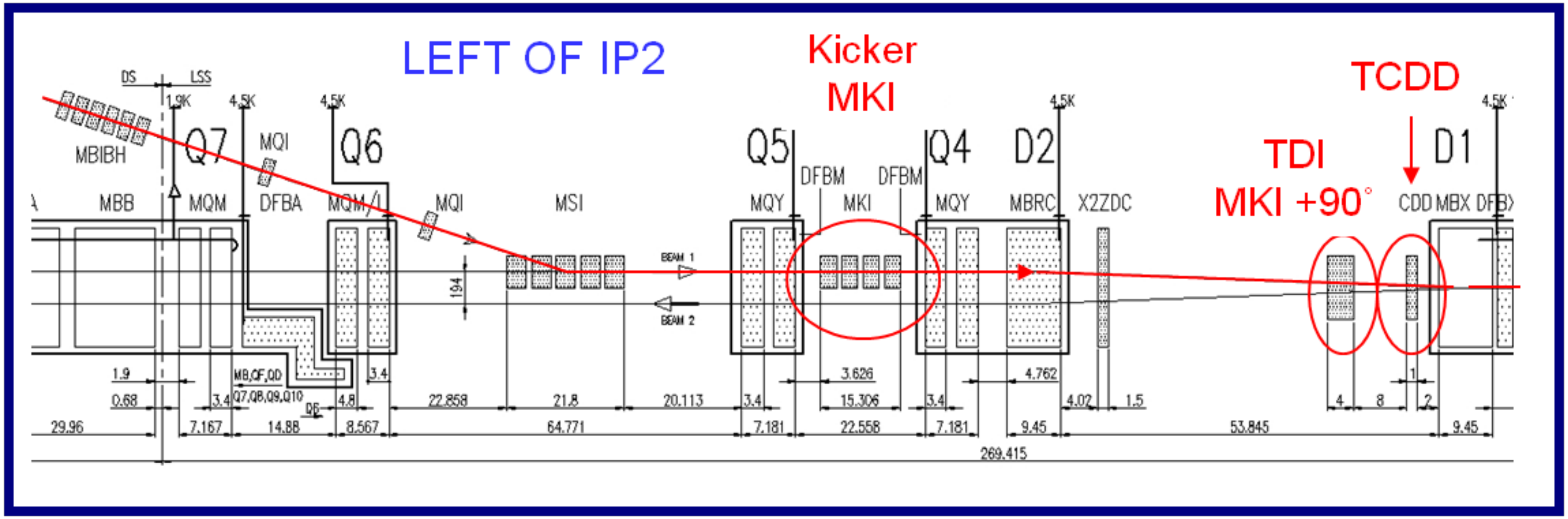
Protection devices: more attenuation for higher brightness

Example: Passive Protection against LHC Injection Kicker Errors

Injection energy 450 GeV

Passive protection device TDI: 90° phase advance downstream of injection kickers. Vertical absorber. Mask TCDD.

Designed for 288 bunches with 1.7e+11 p^+ per bunch.



LHC Injection Stopper TDI

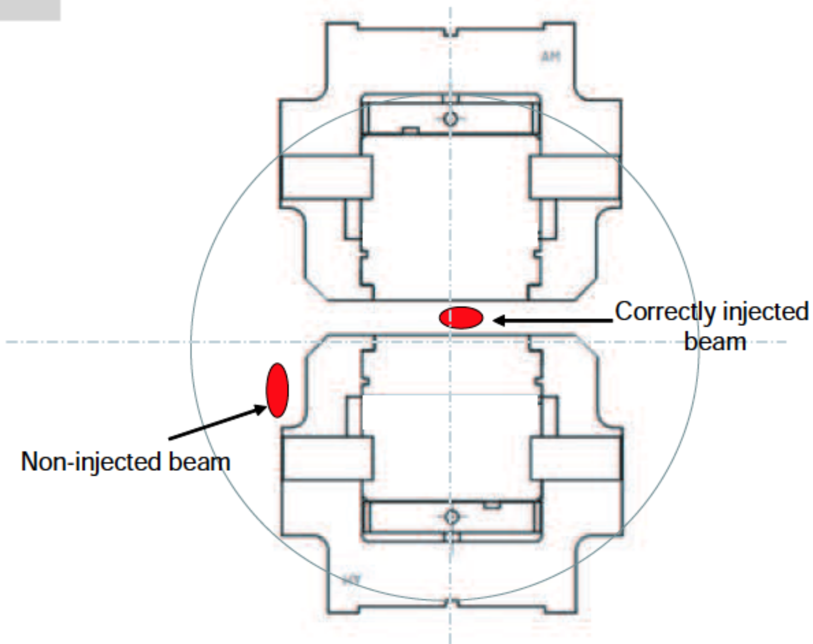
Roughly 4 m long vertical absorber

Device	Materials	Density	Active length
TDI	BN5000	$1.92\,g/cm^3$	2.85 m
	Al	$2.67\,g/cm^3$	0.6 m
	Cu-Be	$8.96\,g/cm^3$	0.7 m
TCLIA	Graphite R4550	$1.83\,g/cm^3$	1 m
TCLIB	C/C AC150	$1.67\,g/cm^3$	1 m

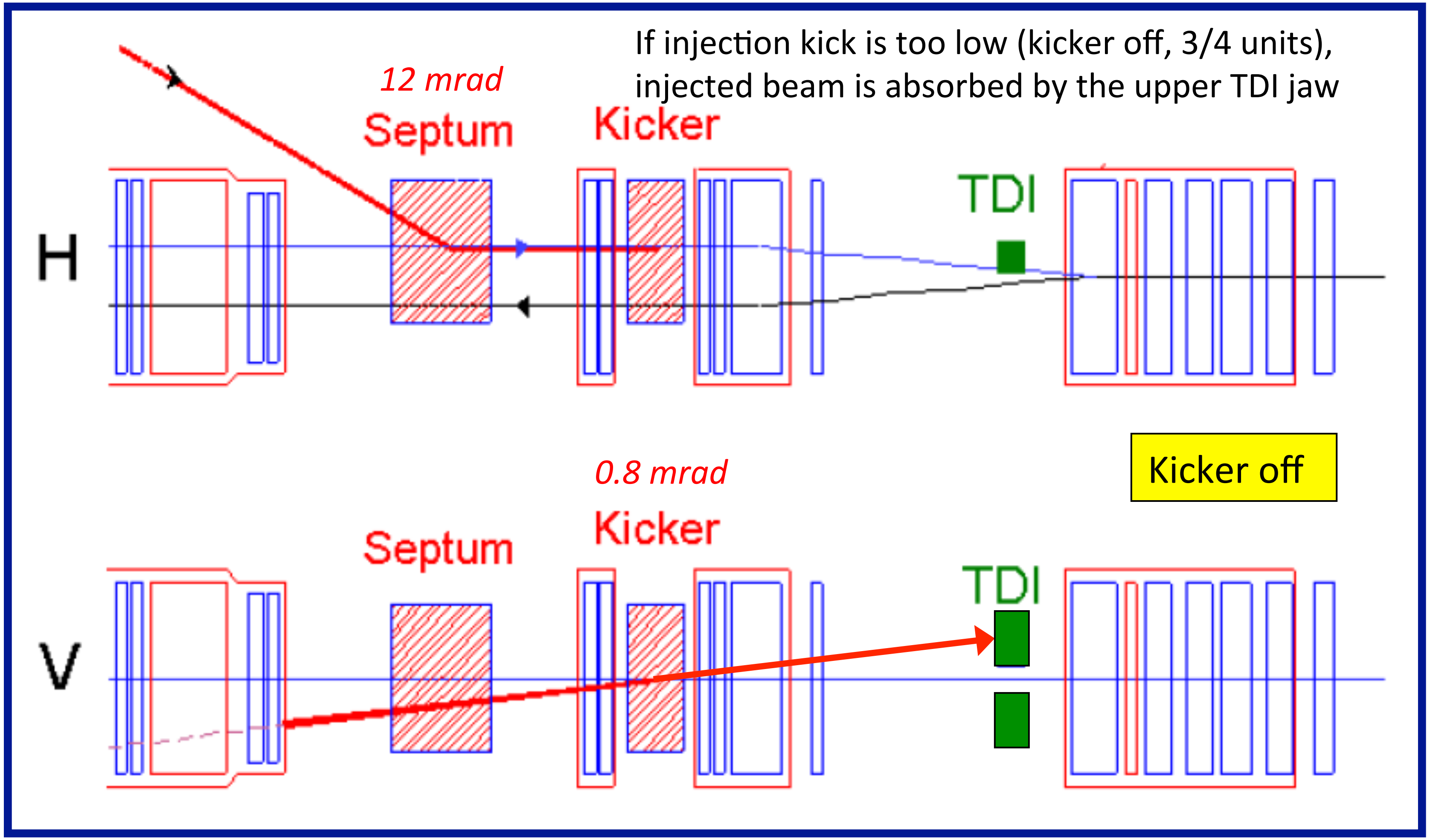
← Injection stopper

← Auxiliary collimators

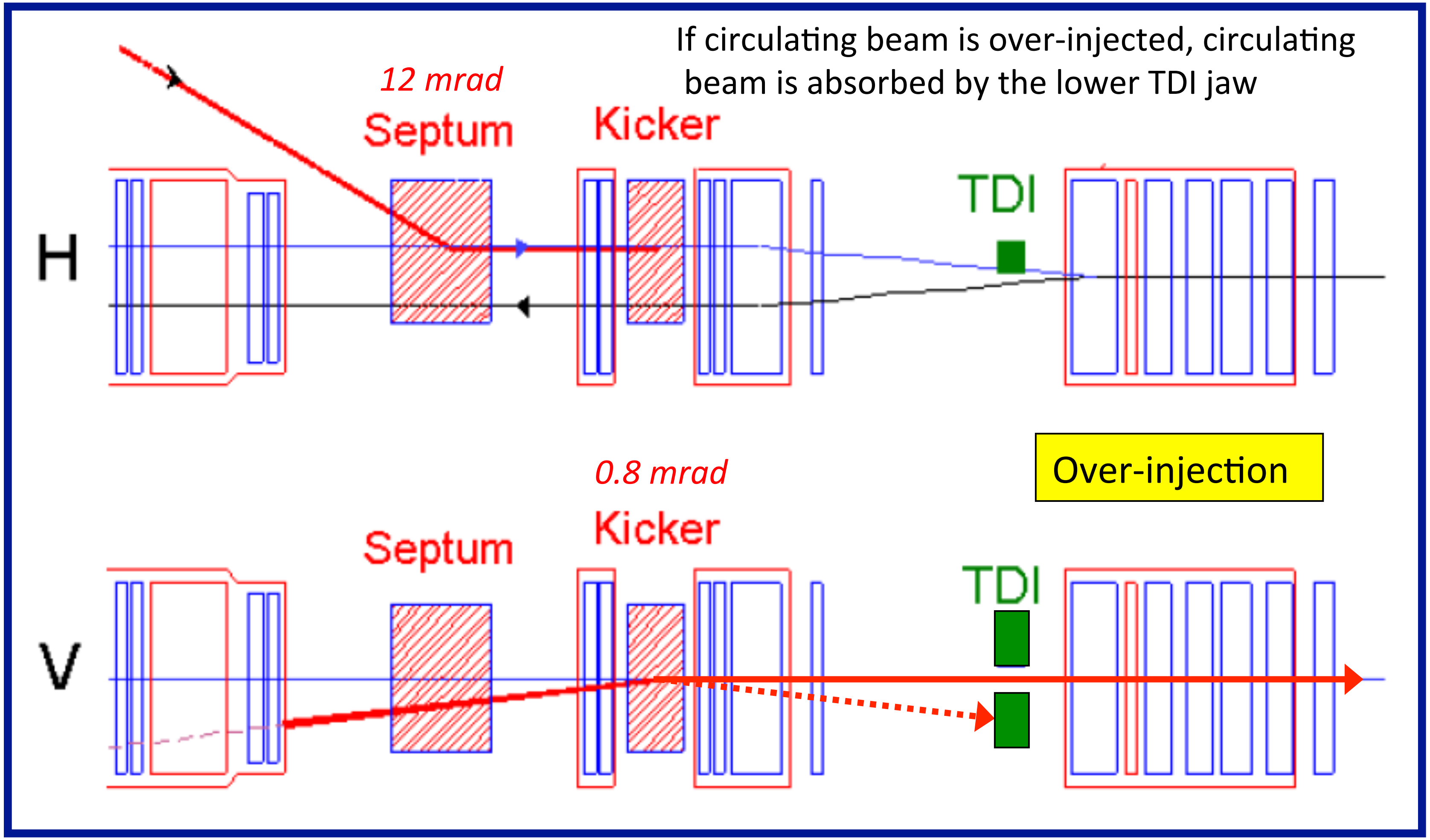
Two vertical jaws for the TDI



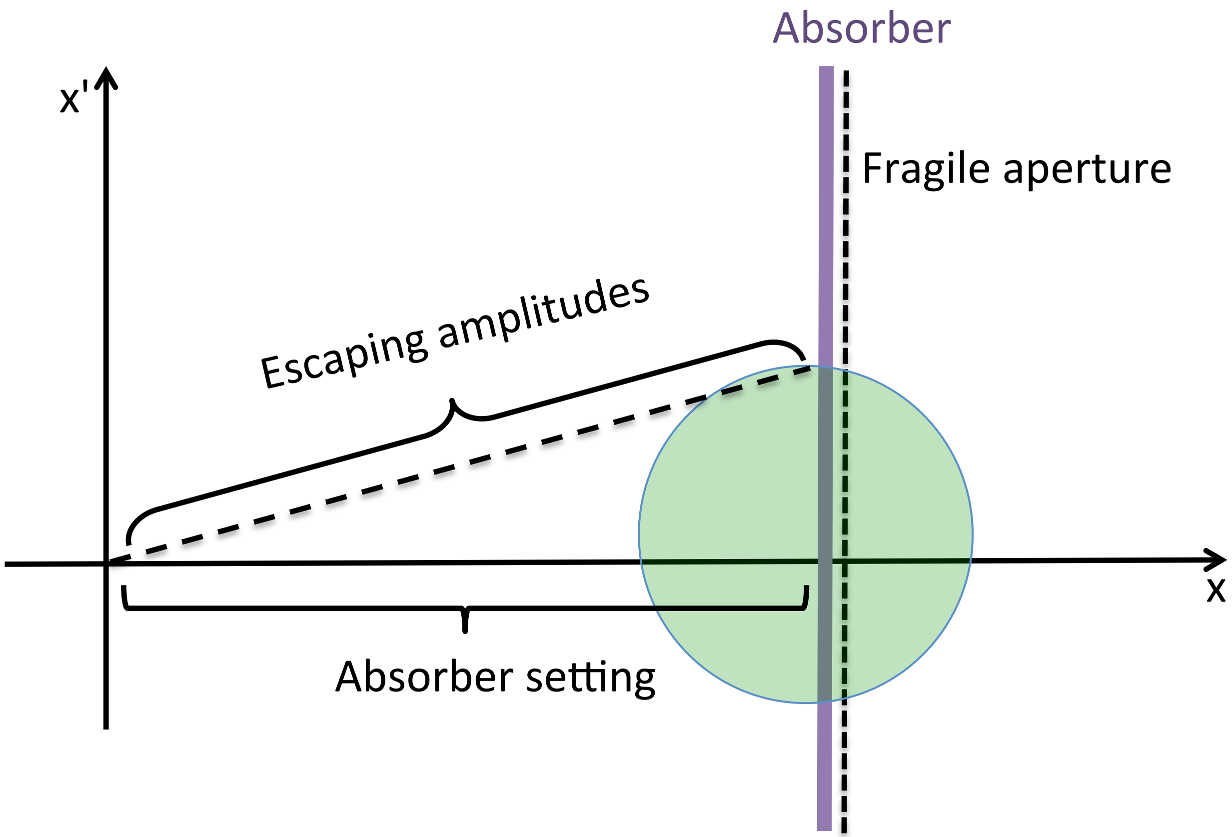
2 Jaws for the Injection Absorber



2 Jaws for the Injection Absorber



Which setting for the passive absorber?

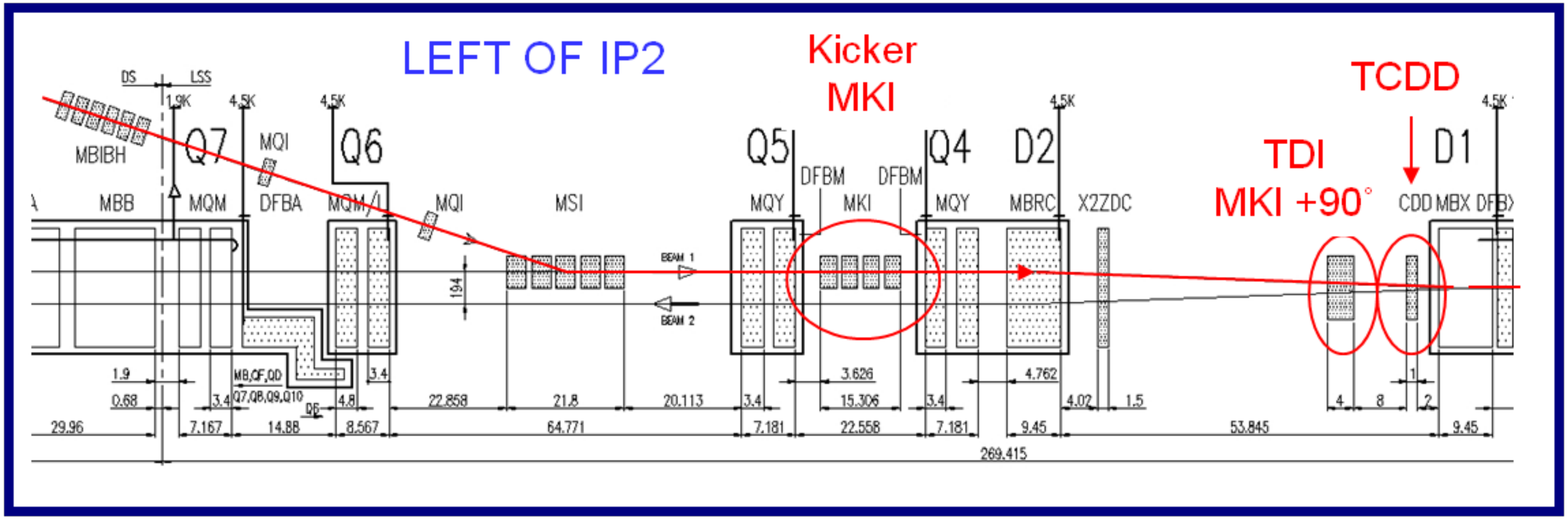


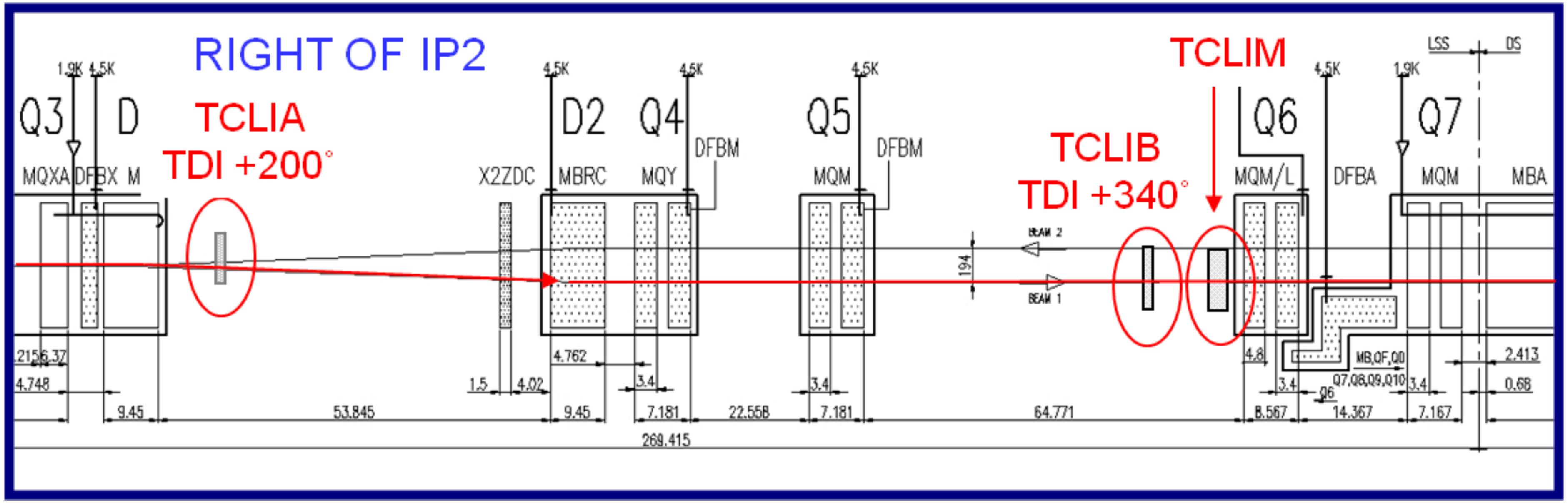
➔ Absorber setting < (fragile aperture – margin)

➔ Not single location with absorber.

Example Injection LHC: TDI + 2 auxiliary collimators +/- 20° from TDI.

Passive Passive Protection against LHC Injection Kicker Errors – Auxiliary Collimators

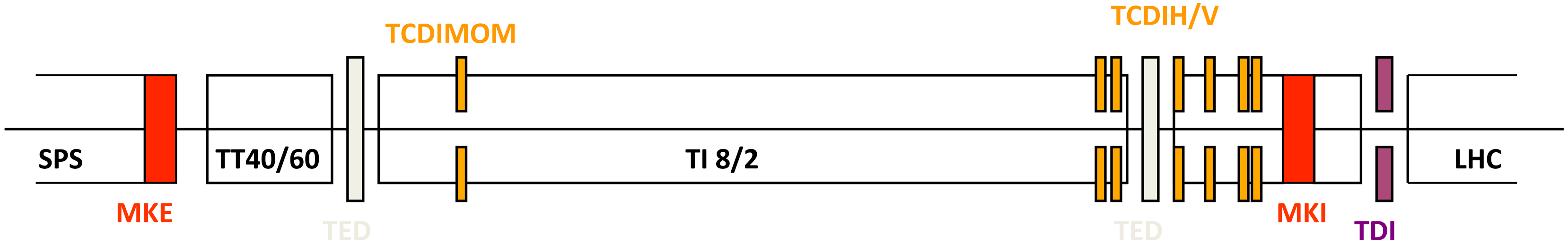




Passive Protection in a Transfer Line

Protection against ANY failure during extraction, transfer:

Generic protection system ➔ full phase-space coverage.



In single pass for a generic protection/collimation system:

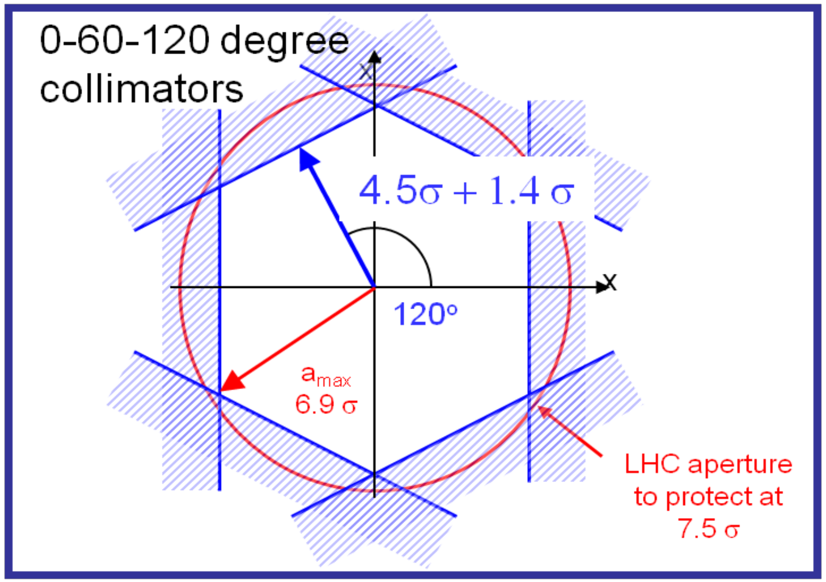
Collimators at several phase locations are needed.

Often: three collimators with 60 degrees in between.

LHC Transfer Lines:
3 collimators per plane

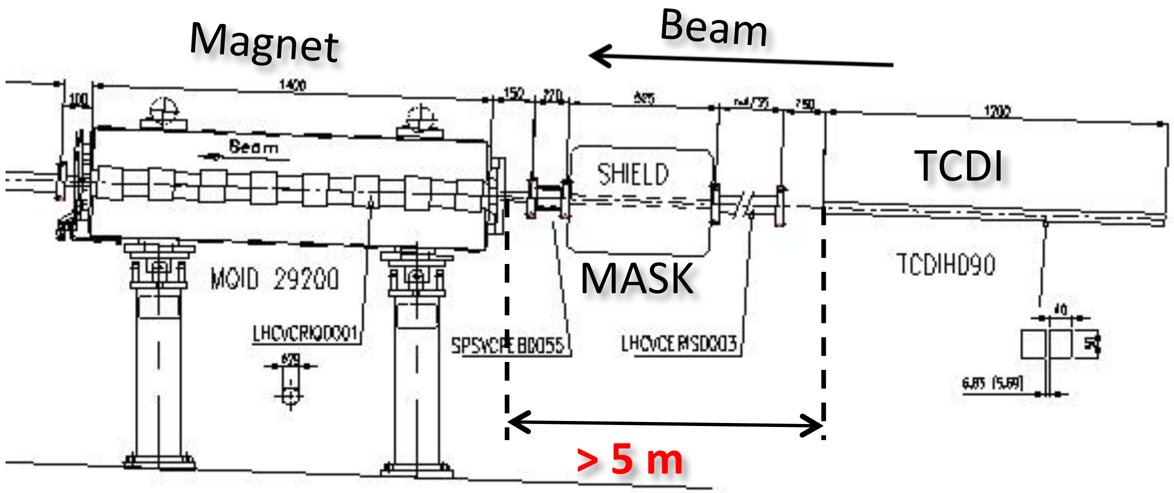
Maximum amplitudes for setting n:

$$a_{max}[\sigma] = \frac{n[\sigma]}{\cos(60^\circ/2)}$$



SPS TO LHC Transfer Line Collimators

1.2 m long graphite (1.83 g/cc) moveable absorbers.
Attenuate intensity by ~ factor 20. Setting 4.5 – 5 σ.



Concern for future upgrades with high brightness beams:
Materials such as graphite, hBN, CfC are not necessarily robust for shock impact.

Solution: larger beta functions at collimator locations ➔ lower particle density at block front-face.

Operation with moveable passive protection devices

Moveable protection devices need to be set up with beam.

Beam loss monitors need to be installed close by. Absorber jaws centered around beam.

The absorbers can only be set up when the optics is corrected and reference trajectory/orbit established.

Interlock thresholds for jaw position measurement systems are then defined and applied. E.g. injection is not allowed if the jaws are not at the correct location.

System qualification tests have to be carried out. E.g. simulate failure case and verify phase space coverage.

Before qualification finished operation with high intensity is not allowed.

BEAM DUMPING

Beam Dump System

The beam dump system is one of the main components of the machine protection system.

It is connected to the machine's beam permit.
It is triggered when the beam permit disappears.

Equipment involved: kicker magnets, (septa), beam dump block.

- Internal beam dump
- Extraction line to beam dump block

Requirement for beam dump system:

- LHC/SPS: Has to always work, must "never" fail
    - No missing beam dump requests, no "bad" beam dumps
    - Failure with very low probability: SIL 3 level; failure rate of 10^{-7}/h to 10^{-8}/h
- Has to work for all energies and beam types
- Beam dump system failures and consequences have to be evaluated. Design accordingly.

Energy Tracking

Charging of PFNs “long” – ms time scales. Want to be able to dump beam within a few turns.

Thus for beam dump system:

Dump kicker PFNs are always charged – with the correct voltage for a given energy.

System to derive energy from synchrotron is required.

System to survey correct tracking of PFNs and other involved equipment (septa currents,...) is required.

If a tracking error occurs, the beam dump is triggered immediately.

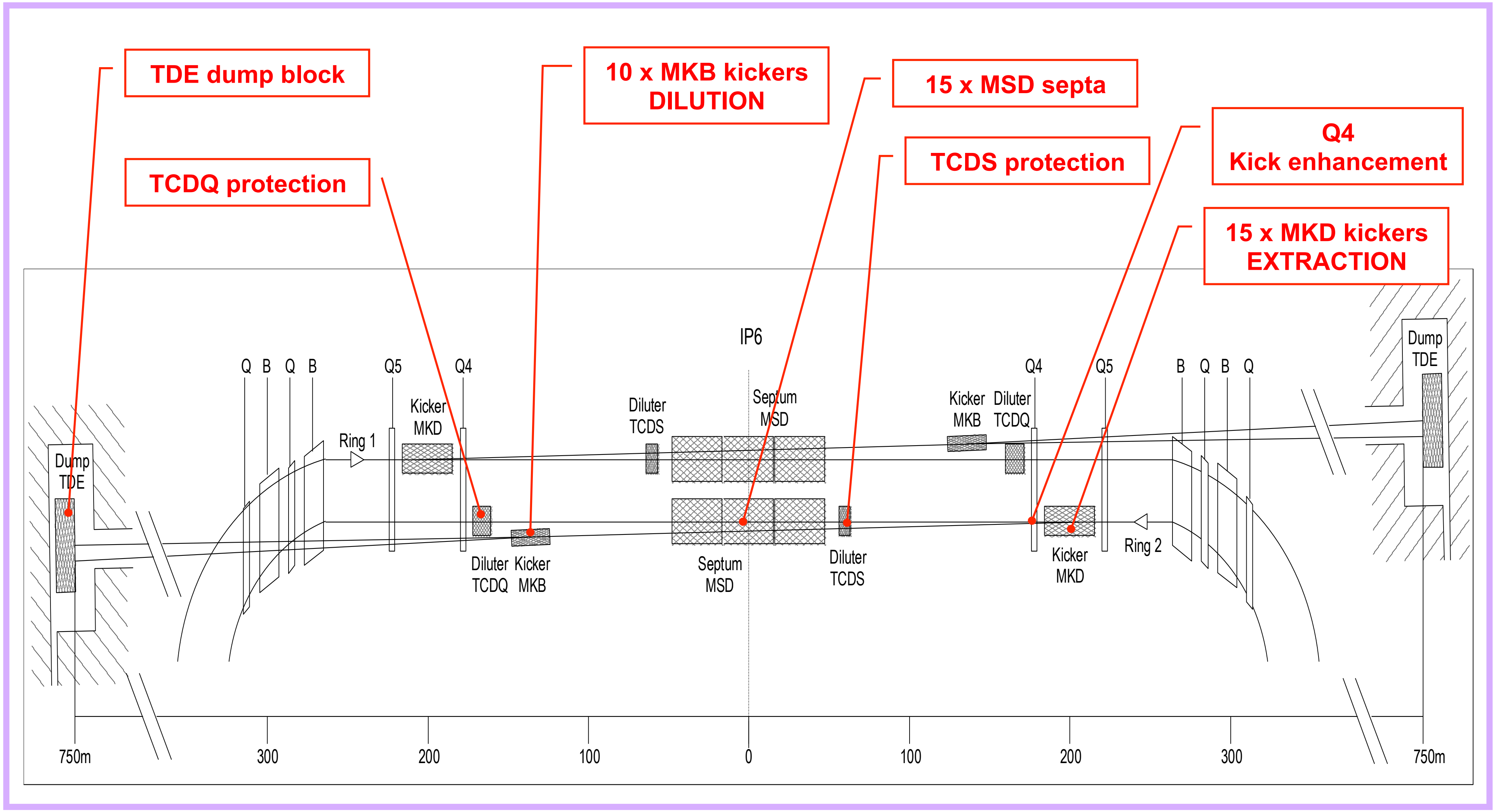
LHC/SPS: BETS = Beam Energy Tracking System.

Reference: E. Carlier et al. ,The Beam Energy Tracking System of the LHC Beam Dumping System, ICALEPS 2005

Layout of the LHC Beam Dump System

Beam dump system in Long Straight Section 6 of the LHC.

975 m from dump kickers to dump block.



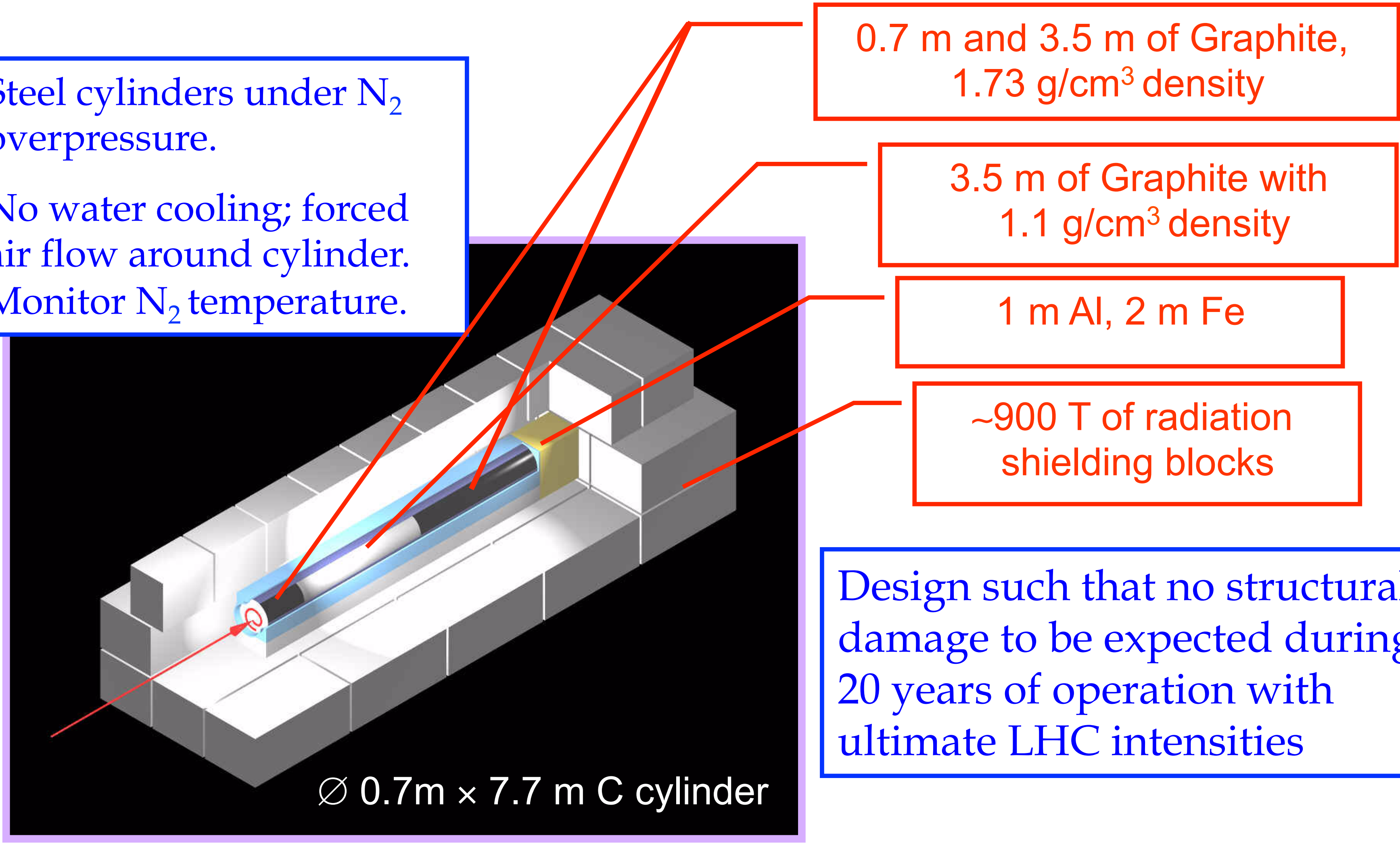
LHC Beam Dump Block

Dump block design take into account: robustness, dump repetition rate,...

E.g. LHC: only sufficient robustness with dilution.

Steel cylinders under N_2 overpressure.

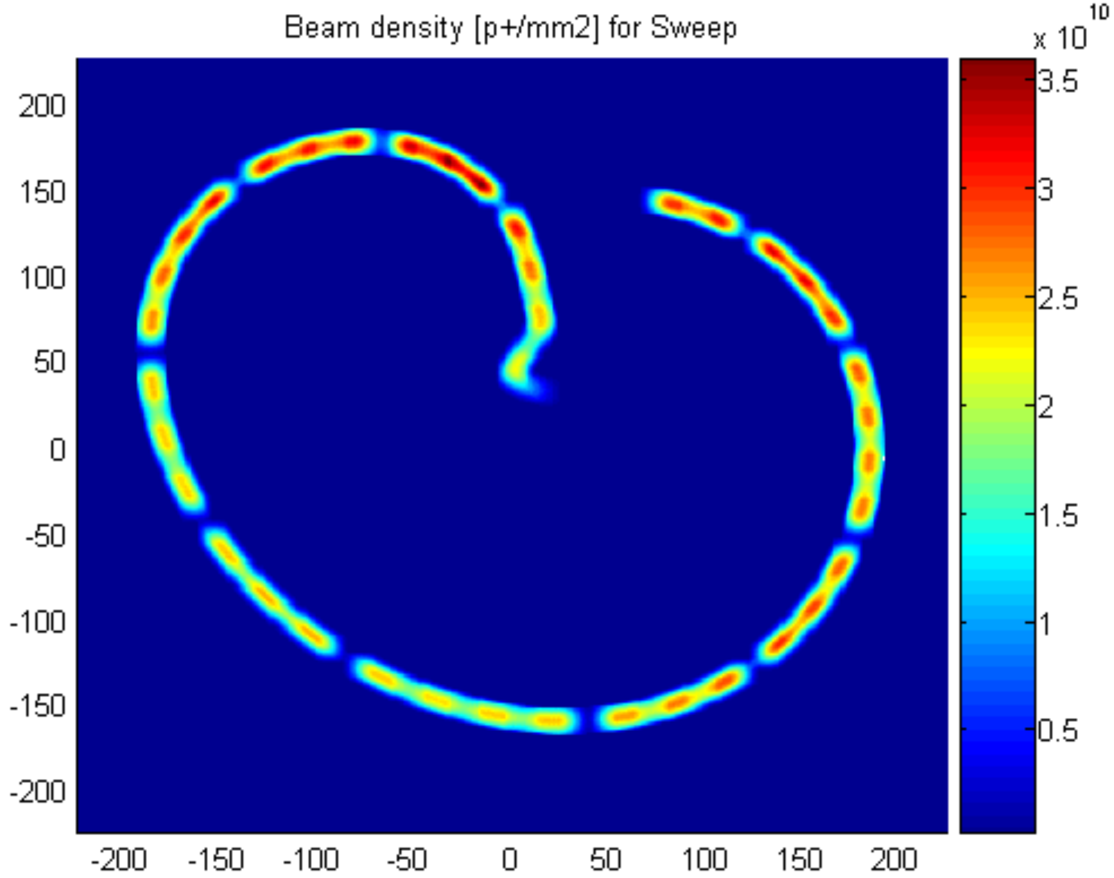
No water cooling; forced air flow around cylinder. Monitor N_2 temperature.



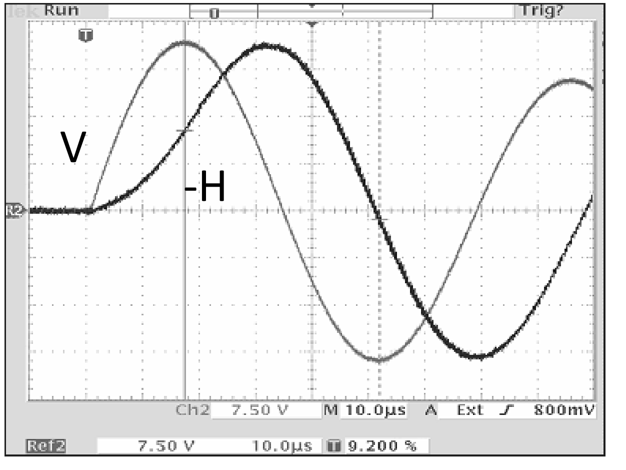
Design such that no structural damage to be expected during 20 years of operation with ultimate LHC intensities

Dilution

A set of vertical and horizontal dilution kickers in the extraction channel sweep the beam onto the dump block.



Waveform of H and V
Dilution kickers



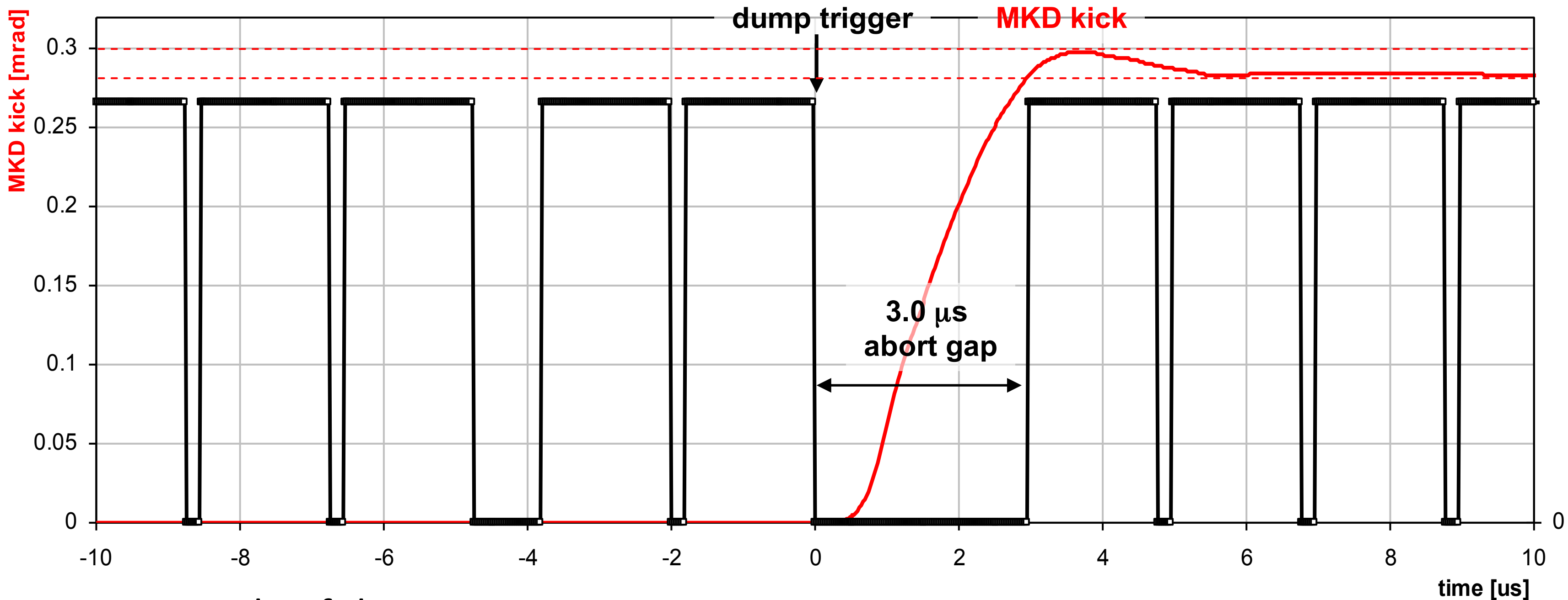
Failure Scenarios of beam dump system

Beam dumping system involves kicker system.

And kickers can spontaneously trigger, asynchronously trigger,...

No particles are allowed in the abort gap: filled with debunched beam.

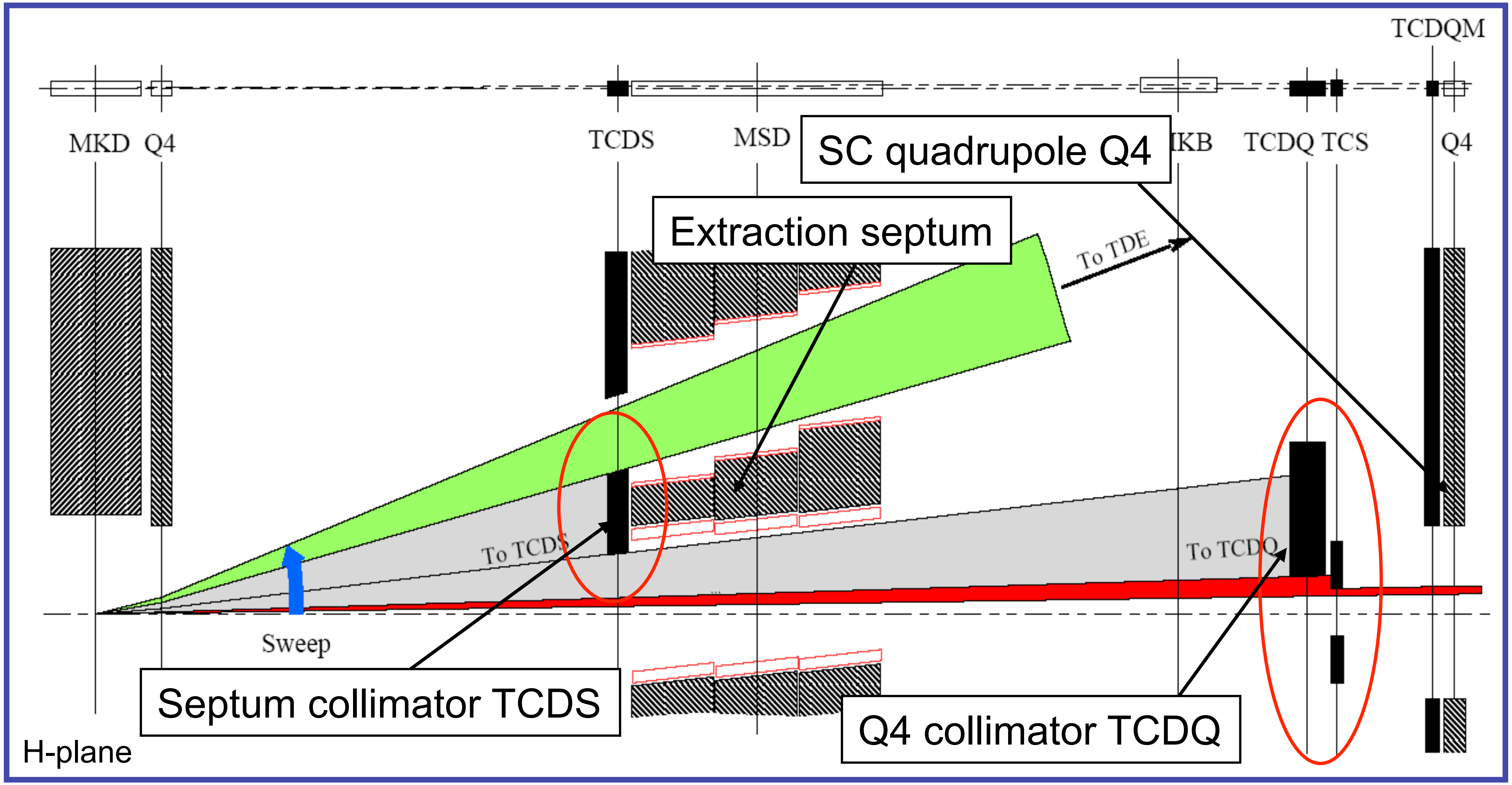
Moveable absorber: 90° downstream against swept beam.



Example of the LHC

Asynchronous Beam Dump: LHC

Protection of the LHC: moveable TCDQ absorber made of CfC, graphite: 9 m long



Failure Classes – LHC Beam Dump

1. Should not happen in the LHC lifetime ("beyond design")
   - Not receiving trigger from Beam Interlock System after failure in LHC
   - Failure of beam energy tracking
   - < 14 / 15 extraction kickers
   - < 3 / 10 dilution kickers

2. Protected against by surveillance and interlocking (dump while conditions still ~ok) - majority
   - Failures of general services (electricity, vacuum, cooling, Ethernet, ...)
   - Bad beam position (BPM, BLM)
   - Magnet powering failure
   - Large abort gap population

3. Cannot be prevented by surveillance (kicker faults associated with dump action)
   a) Can be tolerated without damage
   - Missing extraction kicker magnet
   - Missing dilution kicker magnet
   - Erratic dilution kicker magnet

   b) Cannot be tolerated: rely on passive protection devices
   - Extraction kicker erratic (spurious asynchronous trigger)

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