Machine protection and closed orbit

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- Aperture limits and orbit stability requirements
- Interlocking requirements
- Fast position interlock system
- Failures with bumps
- Summary

Acknowledgements :
R. Jones, B. Goddard, R. Schmidt, R. Assmann, R. Steinhagen
and many others

Machine apertures at injection

Mech. aperture of LHC ring defines the scale $a_{ring} \approx 8\sigma$

➔ *tight aperture*

Protection devices protect ring aperture $a_{prot} < a_{ring}$

➔ *protect against injected beam*

Secondary collimators tighter than protection $a_{sec} < a_{prot}$

➔ *limit the amount of halo hitting protection devices*

Primary collimators tighter than secondary $a_{prim} \approx 5\text{-}6\sigma < a_{sec}$

➔ *primary collimators define the aperture bottleneck in the LHC for cleaning of the circulating beam!*

- These conditions must always be fulfilled :

  ➔ *orbit tolerances are at the level of* $0.1\text{-}0.5\sigma \approx 100\text{-}500\ \mu m$.

  ! long distance correlations : some objects are separated by kms !
- The aperture definition includes tolerances for beta-beat (20%), orbit (4 mm), energy offsets, spurious dispersion…

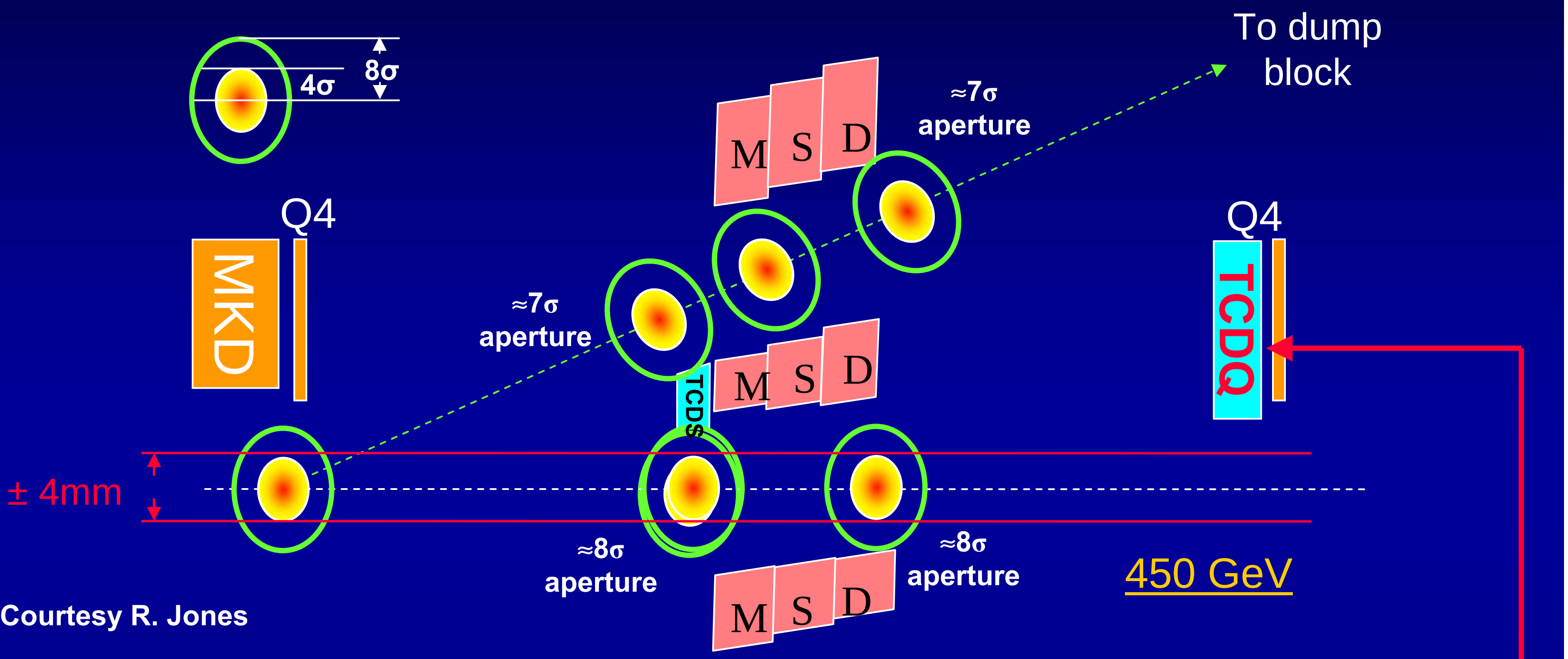
Machine aperture at 7 TeV

Settings at 7 TeV for fully squeezed beams ($\beta^* = 0.5$ m IR1/5)

Low-beta triplet aperture defines the scale	$a_{triplet} \approx 9\sigma$
Protection devices must protect aperture ➔ *protect against asynchronous beam dump*	$a_{prot} < a_{triplet}$
Secondary collimators tighter than protection ➔ *minimize halo hitting protection devices*	$a_{sec} < a_{prot}$
Primary collimators tighter than secondary ➔ *primary collimators define the aperture!*	$a_{prim} \approx 5\text{-}6\sigma < a_{sec}$

- Operation at nominal intensity requires excellent beam cleaning.
  ➔ *orbit tolerance around collimators is in the range $\sigma/3 \sim 70\ \mu m$.*

Beam dump region : orbit tolerances



Courtesy R. Jones

- Dump channel protection : orbit excursion must be smaller than ±4 mm.

  Prevent damage to extraction channel

- Protection against asynchronous dump : orbit excursion < 0.5-2σ at TCDQ absorber downstream of the beam dump (depends on energy, β*…)

  Limit number of bunches escaping to collimators and other machine elements.

Orbit stabilization

For nominal performance the orbit tolerances are very tight.

The relative position of collimators, absorbers.. must be maintained.

➔ The orbit is not a 'play-parameter' for operation, except at low intensity.

'Playing' with the orbit will result in quasi-immediate quench at high intensity.

At the LHC the orbit must always be very well controlled, but perturbations during various phases (snapback, ramp, squeeze) can be large and fast.

➔ *Stabilization by a real-time orbit feedback system*

Stabilization of both beams around the rings

Maintain orbit at critical collimators, absorbers and aperture limits

Long distance correlations are important !

Operation of the FB limits the operational freedom of operators

Orbit feedback

Some FB system details :

- Fully digital feedback.
- Centralized control with high performance (multi-processor) PCs.
- System involves over 100 VME front-end crates.

  Data is collected from ~ 70 BPM crates → central control → fan out to PC crates.

- Max. operation frequency is estimated to be ~ 25 Hz.
- Algorithms will aim to minimize impact of faulty BPMs → wrong steering.

  Optimization of correction performance versus robustness.

A proto-type system (using the LHC BPM acquisition system) has been operated very successfully at the SPS, albeit with only … 6 BPMs (1000 at the LHC).

This FB system :

→ plays a critical role to maintain relative alignments of protection elements.

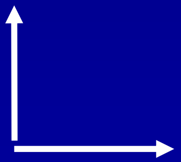
→ is not able to counteract orbit changes due to the most critical powering failures.

→ <u>is not a fail-safe system, since it is much too complex. Not part of MP system.</u>

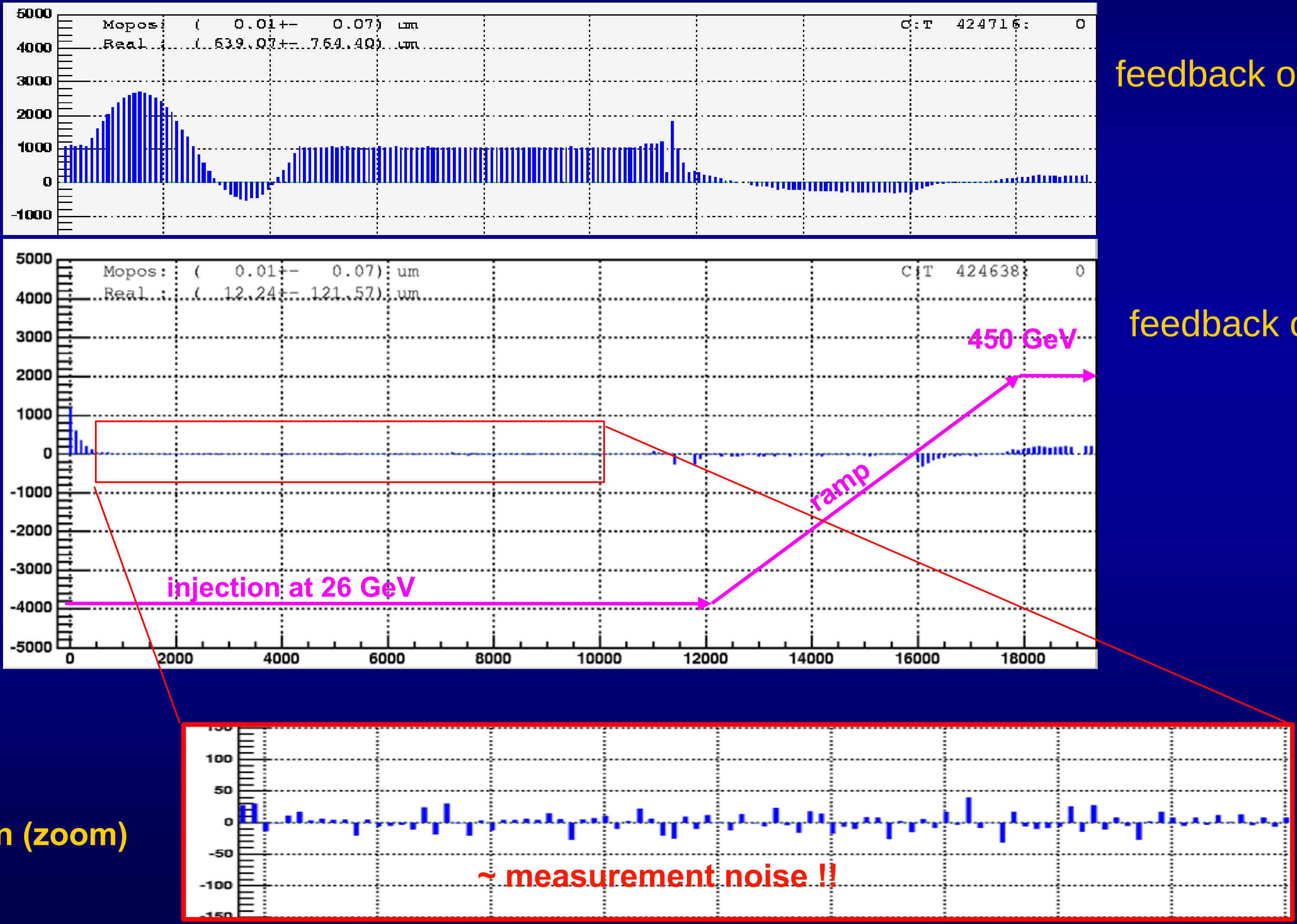
FB proto-type at the SPS

Steering example with external noise over one SPS cycle

BPM
Reading
(µm)



Time
(milliseconds)



feedback off

feedback on

feedback on (zoom)

Fast orbit changes

A large number of failures imply:

- Fast *global* orbit drifts, up to ≈ 1 mm/ms in some locations (1 ms ~ 10 turns)
  - ***PC failures…***
- Fast amplitude growth of oscillations
  - ***Transverse damper failure or incorrect input, instabilities…***

Such orbit changes sooner of later lead to beam loss

- BLMs at aperture limiting collimators see the loss first.
  - ***Critical condition: the collimators must really define the aperture !***
- BLM reaction time depends on shape of the halo.
  - ***Halo is sensitive to machine details (non-linearity, beam-beam…)***

→ interlock on fast orbit drifts as complement the BLM system.

Beam position interlocking

To be protected :

- Beam dump channel (±4 mm).
- Magnets & collimators from asynchronous beam dump.

  beam position relative to TCDQ absorber needs to be maintained

  slow drifts → software interlock ….
- Collimators (and of course all the rest…) from fast orbit changes.

  redundancy for the BLM system !

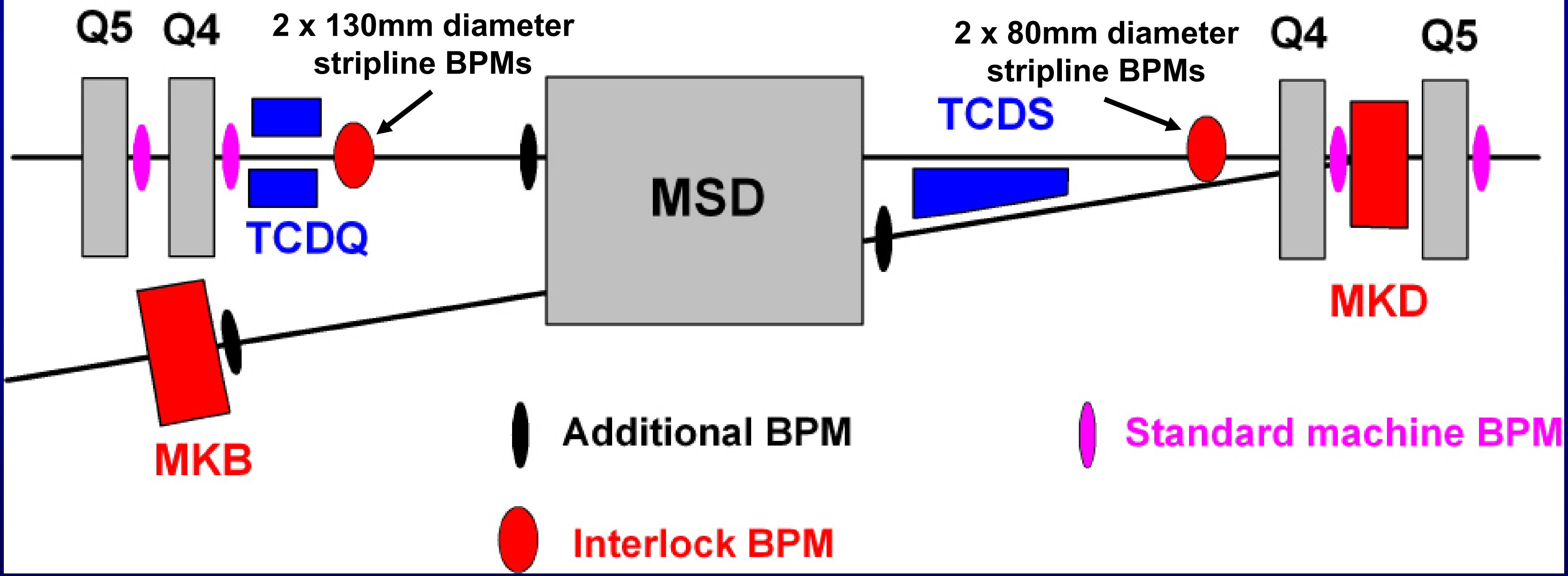
Implementation issues :

- We cannot HW interlock the entire LHC orbit

  → *select 'strategic' position*
- Concentrate on beam dump requirements and fast position changes.
- 'Slow' (< 1 Hz) orbit 'drifts' surveyed by a software interlock system.

Beam position interlock layout

- IR6 (beam dump IR) has now 4 interlock BPMs per beam
  - 2 redundant BPMs added near TCDQ and 2 near preceding Q4.
  - 90° phase advance to cover all betatron phases.
  - large betatron function ~ 600 m → sensitivity.
  - combined protection of dump channel and protection against fast orbit changes.



Interlock thresholds : beam dump channel

To define effective tolerances we must look at a ‘bad’ case:

◆ Warm D1 separation dipole failure @ 7 TeV gives ~ 60 µm/turn:

Response time: 1 turn (detection) + 2 turns (BIC delay & abort gap synchronization)

⇒ 200 µm movement between detection and dump.

◆ For a single pilot bunch of 5×10^9 protons the BPMs have a single shot (turn) resolution of ~1.5% of half radius:

~ 300 µm for 80 mm diameter BPM (at Q4)

~ 500 µm for 130 mm diameter BPM (at TCDQ)

→Interlock threshold:

Set to 4 - 0.2 - 0.5 = 3.3 mm to give an effective threshold of 4mm.

◆ Damper failures @ injection ~ 1σ / 4 turns ~ 400 µm / turn.

Requires similar threshold if trigger on a few bunches (for nominal bunches).

Interlock thresholds : collimator protection

Injection (450 GeV) :

- Arc mech. aperture at ≈8σ.
- TCDQ (asynch. dump protection) sits at ≈7σ & collimators at 5-6σ
- 4 mm beam position tolerance corresponds to < 2σ

→ Protected by 4mm beam position interlock

Allows Q-meter kicks at max kicker strength of 1.75σ for a centred beam.

Provides some margin for injection oscillations.

7 TeV :

- Primary collimators sit at ≈5-6σ with respect to the beam.
- D1 failure may result in collimator damage after ~3 ms ~ 30 turns.

loss of around 10^{12} protons

- Orbit only moves by ~2 mm over 3 ms at interlock BPMs

→ must be sensitive to fast 1 mm changes.

Beam position interlock design

BDI group implementation proposal :

System is based on a modified LHC orbit digital acquisition card

- Bunch-by-bunch acquisition system
- Direct comparison of positions & thresholds performed inside a FPGA
  - ⇒ no dependence on external software
- Auto-triggered system
  - ⇒ no dependence on external timing
- For fast orbit changes, observe only relative change wrt preceding closed orbit
  - ⇒ no dependence on external orbit references
- Two output signals to beam interlock system
  - ⇒ 1 signal for the beam dump aperture, 1 signal for fast changes

Beam position interlock design issues

◆ Issues : dump channel protection

- Spurious triggers, latency
  - ***How many bunches must be out of limit before dumping?***
  - ***For single or few bunches this will imply an increased latency, but risk is lower***
- Alignment and position offsets
  - ***Do we measure these with the beam or reduce the threshold to include them?***

◆ Issues : fast orbit changes

- Limited to relative orbit changes
  - ***1 mm offset wrt stable orbit***
- Comparison of current position to last orbit
  - ***Local orbit reference updated every 20ms***
  - ***Can compare single bunch position (for oscillations) & /or 1 turn orbit***
- Only valid for nominal bunch intensity
  - ***BPM single bunch resolution < 100μm***

Some of the issues may be determined by operational experience…

Bumps

The position interlock can only intercept failures that lead to an orbit change at the beam dump IR,

→ The BPM interlock system does not protect against local bumps

We must consider the following situations :

- Local orbit bumps with a circulating beam.
- Local orbit bumps during injection.

Bumps on circulating beam

◆Bump growth / arcs

	Max. Speed	Max. amplitude	Arc aperture	
450 GeV	3σ / s	~ 240 σ	~ 8 σ	(>)> arc aperture
7 TeV	0.8σ / s	~ 50 σ	~ 40 σ	

If the strength margin for orbit correction is taken into account,

→ cannot reach the *ARC* aperture at 7 TeV.

The ramp speed will be limited in practice to ~ ½ the quoted figure (PC control).

◆ BLM sampling times

- Arcs : < 2.5 ms ~ 25 turns
- Collimators & critical locations : 1 turn

→ BLM system can detect a beam loss due to a bump before damage occurs.

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Bumps with injected beam

Principle for safe injection →

If no beam is circulating
→ must inject a safe beam

→ no problem for injection of the safe beam.

Boundary conditions for injection of unsafe beam :

- Beam must be circulating.
  - ***A 'bumped' beam must be at least $\approx$ 2-3σ away from aperture (low int.)***
  - ***For a pilot bunch, this will not lead to a quench.***
- Injection oscillations are limited to ~ 5σ by transfer line collimators.

Failure scenario :

Low intensity beam
bumped close to aperture

⊕

Nominal injection of 3×10^{13}p
with 3σ inj. oscillation

↓

Loss of ~ 10^{13} protons at the bump → could lead to damage !!!

Protection against a ‘bumped beam failure’

- Survey the orbit and corrector settings at injection by software interlock
  - *1 Hz surveillance should be sufficient*
  - *Reference obtained from average readings/settings over few days*
- Freeze orbit during injection, i.e. no changes by operators.
  - *But the feedback will be active !*
  - *FB algorithm must not produce bumps from false BPM readings*
- Limit bump amplitude range & speed by control system
  - *Limitation on corrector ramp rate*
  - *Can we implement this fully consistently ?*
- Enforce rigorous operation procedures
  - *Never ‘jump’ to many orders of magnitude in intensity in one step*
  - *pilot → intermediate intensity (few 10^{12} p) → nominal injection (few 10^{13} p)*

We have no solution based on HW interlocks, but the measures proposed above could be sufficient.

Summary

- A fast beam position interlock system at the LHC is foreseen to :
  - protect the beam dump channel against damage.
  - protect the LHC against fast global orbit movements.
  - provide redundant protection with respect to the BLM system.
- The technical realization is feasible and the tolerances of this interlock system are acceptable.
- Local bumps at injection cannot be detected by this interlock system :
  - combined failures (large bump + large injection oscillations) can lead to damage.
  - counter-measures must implemented for such cases :
    - SW interlocks.
    - Protection by the control system
    - Rigorous OP procedures