## Some aspects on:

# LHC Global Aperture Measurements

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with input from:
R. Jones, S. Redaelli, J. Wenninger and others

see also:
link LHCCWG, Classification and Detection of LHC BPM Errors and Faults, 2007-10-23
link MPWG #53, Closed Orbit and Protection, 2005-12-16

# Motivation

- Motivation for aperture scans:
  - Machine Protection : combined failure mode: bump + other fast failure
  - LHC Cleaning System: settings dependence on aperture model assump.
  - BPMs alignment and calibration: detection of spurious offsets
  - Optics verification for regular LHC operation

- Two applicable methods:
  - Aperture scans: free Betatron-oscillations, controlled emittance blow-up
  - Magnet surveillance: main dipoles (done), CODs, quadrupoles,

# Machine Protection: Closed Orbit drifts...

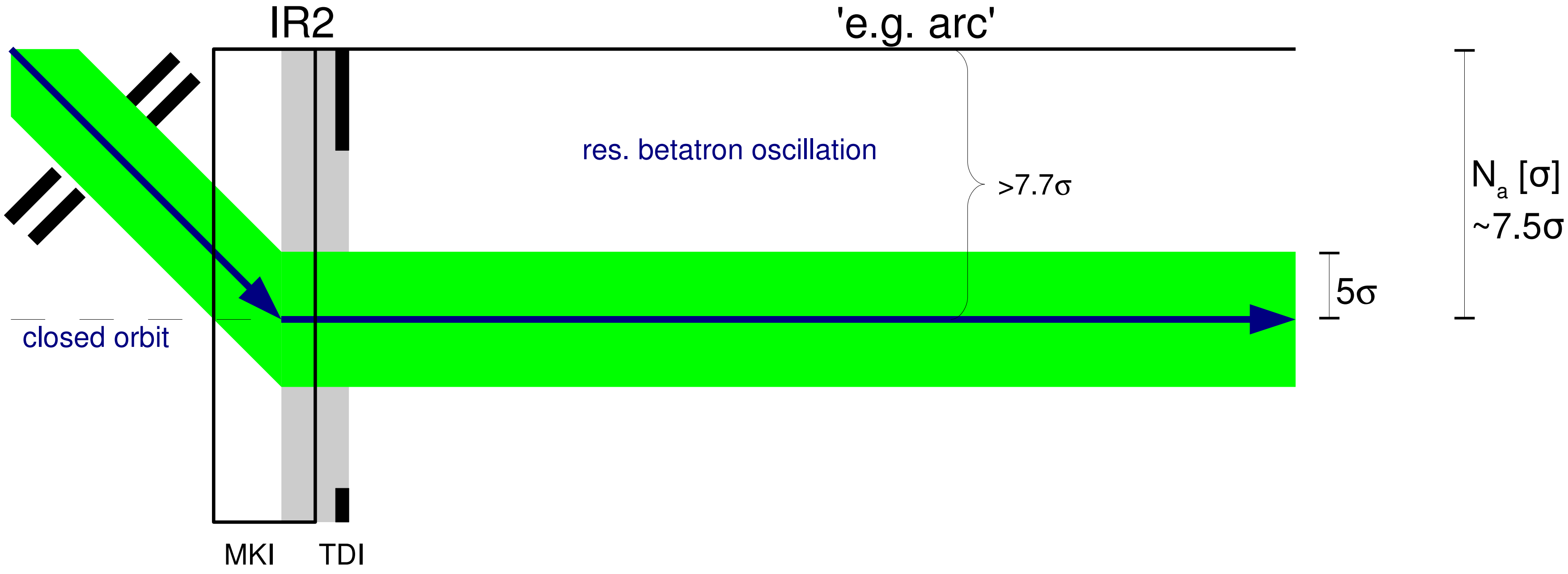
- alone are unlikely to cause damage to the machine
  - Expected drift velocities are slow: < 2 σ/s
  - Easily detectable and captured through beam loss monitors
    - independent on whether they are local or global drifts

- However, combined failures are an issue:
  - "local orbit bump" + fast other failure, e.g.:
    - Single turn failure involving injection, extraction or aperture kicker
    - fast magnet field decays
  - reduction of alignment margin at local protection devices
    - TDIs, TCDQs, Collimators etc.

- Local orbit bumps may compromise passive protection properties of absorbers and collimators for machine protection!

# Example: Protection against Single Turn Failures

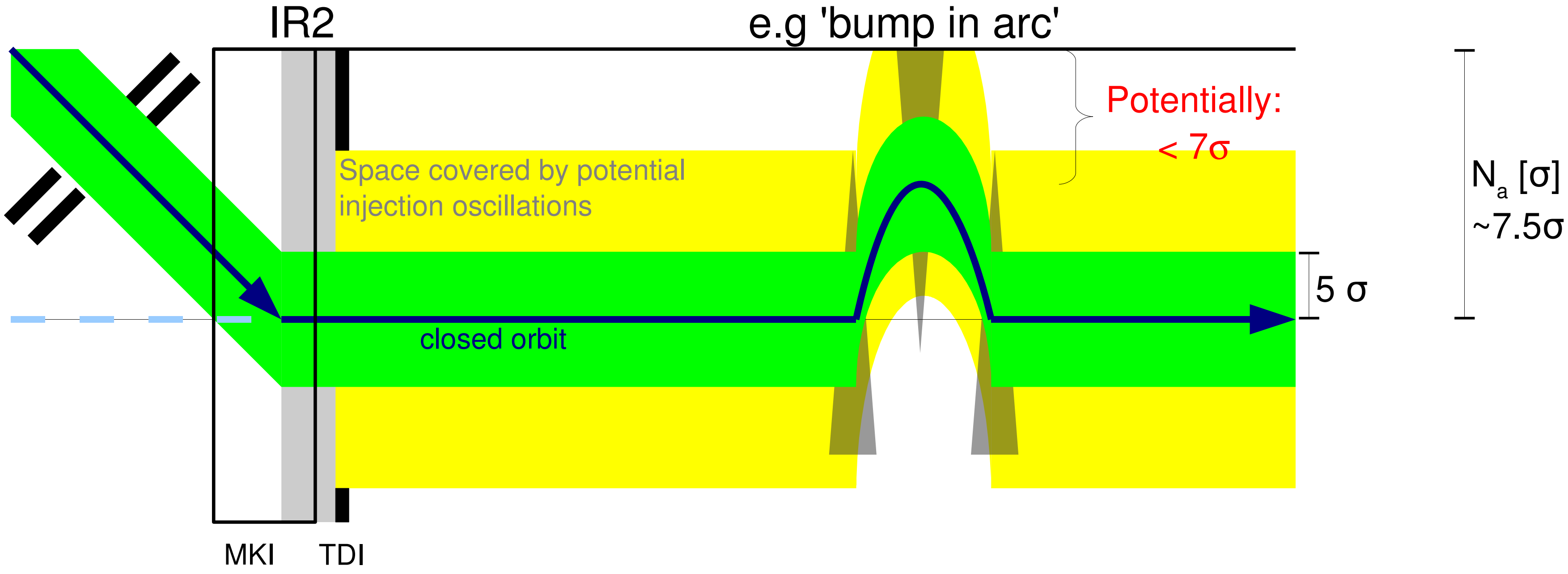
- Combined failure: (Pilot) Injection with perfect closed orbit



- TI8/TI2 collimators limits $|x_\beta(s)|_{max} < 5\ \sigma$, TDI (locally) limits $|x_\beta(s)|_{max} < 7\ \sigma$
- Perfect matching: beam circulates on closed orbit & $\varepsilon_{TI8/TI2} = \varepsilon_{ring}$
- $\Delta x, \Delta x'$/optics mismatch: → oscillation around $x_{co}$ & filamentation $\varepsilon_{ring} > \varepsilon_{TI8/TI2}$
  - But: $\sigma_{ring} < 7\ \sigma$ globally (if proper TDI setup)
  - TDI shadows critical machine aperture
- “Ring aperture is safe”, assuming only single turn (injection) failures.

# Example: Compromised Protection through Orbit Bumps

- Combined failure: Local orbit bump and injection of nominal beam:

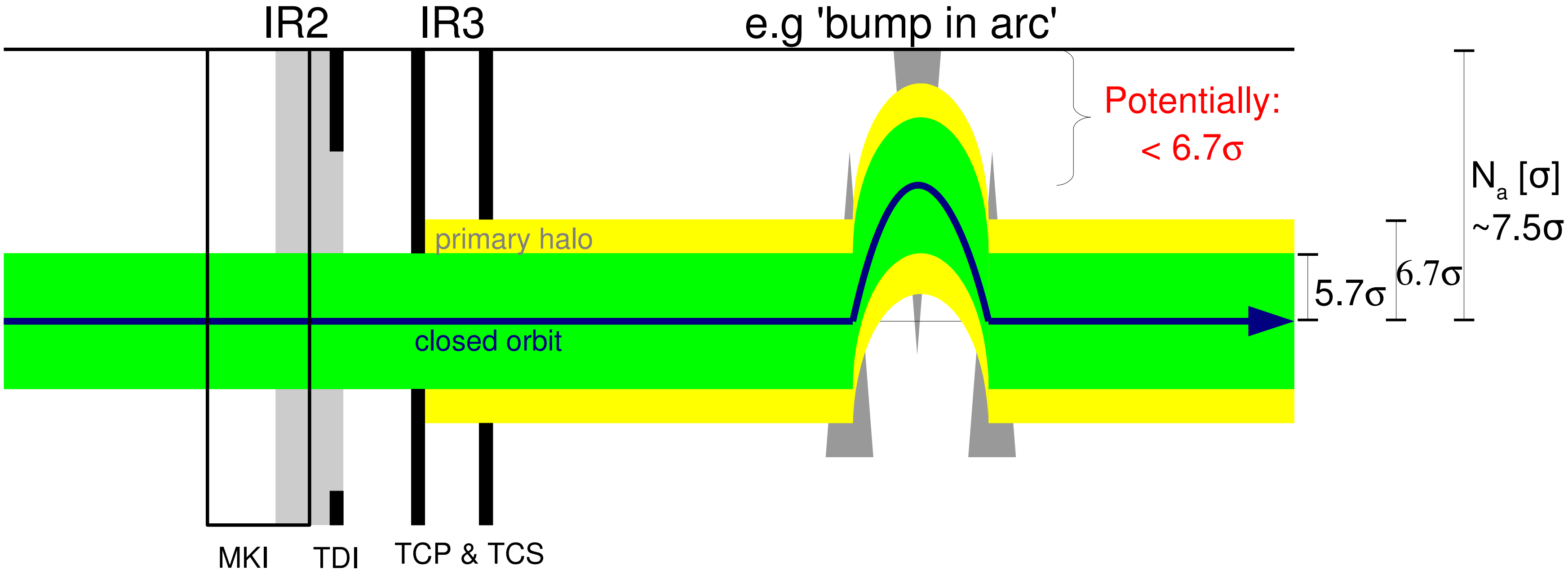


- TI8/TI2 collimators limits $|x_\beta(s)|_{max} < 5\ \sigma$, TDI (locally) limits $|x_\beta(s)|_{max} < 7\ \sigma$
  - TDI does potentially not shadow sensitive equipment

  → Orbit bumps may compromise function of absorbers for protection if beam is closer to the aperture than to TDI

# Example: Compromised Protection through Orbit Bumps

- Combined failure: Local orbit bump and collimation efficiency (/kicker failure):



- Primary collimator (TCP) limits $|x_\beta(s)|_{max}$ locally to <5.7σ, secondary collimator (TCS) at~ 6.7σ
- To guarantee two stage cleaning efficiency/machine protection:
  - Local: TCP must be >0.7σ closer than TCS w.r.t. the beam → Orbit FB
  - Global: no other object (except TCP) closer to beam than TCS

→ Orbit bumps may compromise function of collimation if beam is closer to the aperture than to jaws!

# BPM Functionality Test Procedure

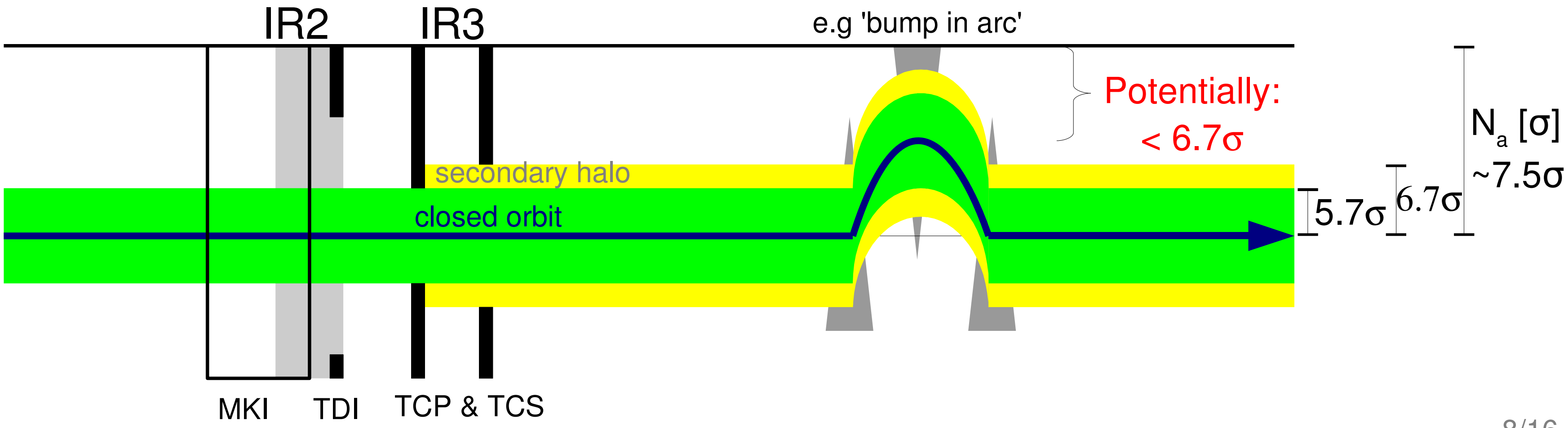
- Three main lines of defence against BPM errors and faults:
  1. Pre-checks without beam using the in-build calibration unit
     - eliminates open/closed circuits, dead circuits/element candidates
  2. Pre-checks with Pilot and Intermediate beams
     - verifies calibration offset (guarantee) and slope (golden orbit)
     - verifies/guarantees proper function of machine protection
  3. Continuous data quality monitoring through Orbit Feedback
     - detects spikes, steps and BPMs that are under verge of failing

- (k-modulation can for a few (insertion) BPMs provide some additional limited cross-checks for BPM misalignments w.r.t. magnetic quadrupole limits. However: no hard limits!)

# 2.Pre-checks with Pilot and Intermediate beams I/III

- Two simple functional tests to check whether BPMs are working.
Idea: “Every non-moving position reading indicates a dead BPM”.
  1 free betatron oscillation with rotating phase
    - non-moving BPM readings → faulty BPM
    - tests calibration factor and/or optics

  2 aperture scan to checks abs. BPM offsets and insures proper machine protection functionality:
    - 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.)*



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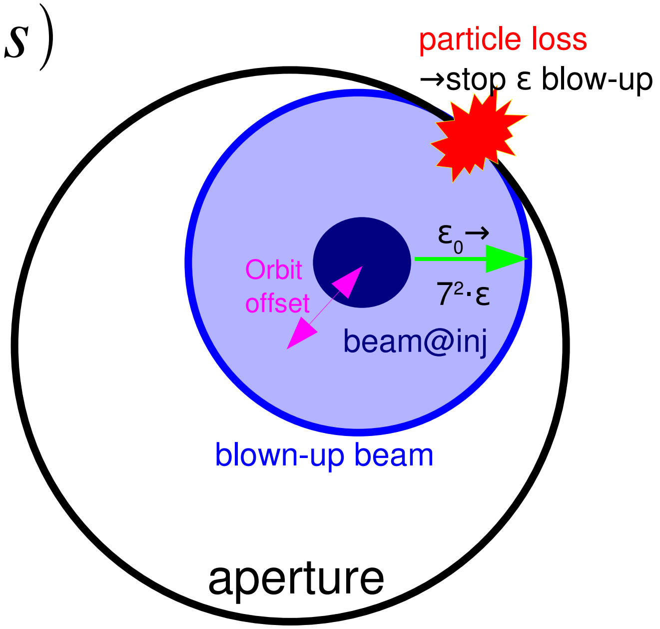
[1] R. Steinhagen, “Closed Orbit and Protection”, MPWG #53, 2005-12-16

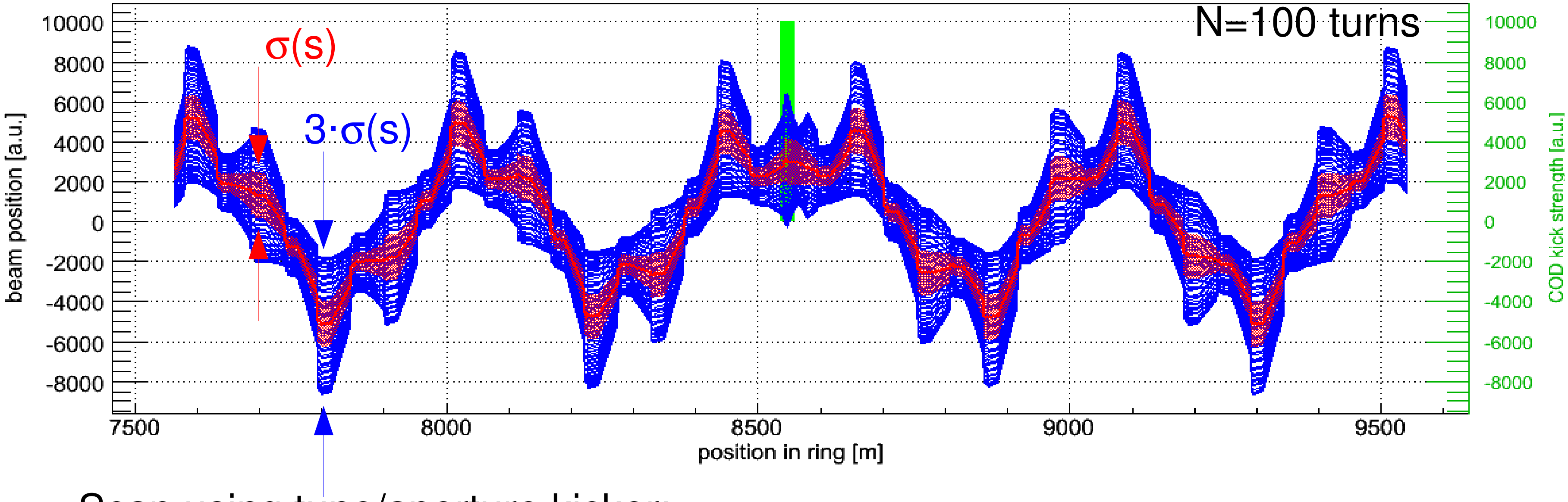
# Aperture Measurement  using controlled Emittance Blow-Up

Three methods to establish whether the closed orbit is within 6.7σ of the available mechanical resp. dynamic aperture:

- Scan using emittance blow-up: $\sigma(s)=\sqrt{\varepsilon\beta(s)}$
  - Increase beam size in a controlled way while measuring the beam size.
    (e.g. using transverse damper and synchrotron light monitor/IPM)
  - Once particle loss above given threshold:
    → store last beam size measurement
  - “Is beam size ≥ 6.7 $\sigma_0$ ?” ($\sigma_0$: beam size at injection)
    - Yes: → mechanical aperture ≥ 6.7 σ → orbit is safe
    - No: → mechanical aperture ≤ 6.7 σ → orbit is un-safe
      - rework orbit reference (compare with old reference....)



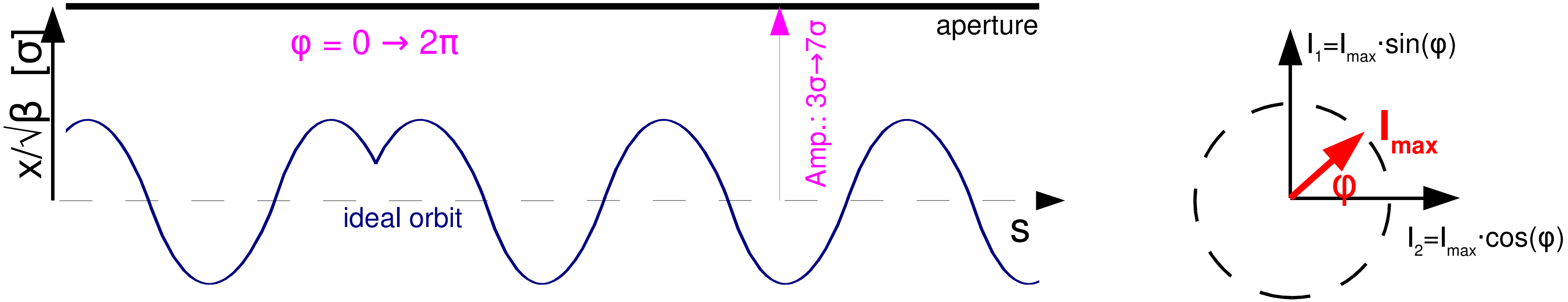
# Aperture Measurement using Tune/Aperture Kicker Magnet



- Scan using tune/aperture kicker:
  - likely to create larger beam loss transients (easy BLM detection)
  - indicates aperture location assuming "hitting aperture → losses at down-stream quadrupole" dependence
  - filamentation → emittance blow-up → need to dump and re-fill beam
  - tune kicker provides only 1 σ oscillations @ 450 GeV (⇄ 3 kV)
  - aperture kicker:
    - intrinsically dangerous/un-safe
    - not and ad-hoc instrument

# Aperture Measurement using closed orbit dipole magnets

- Scan using two COD magnets (currents: $I_1$ & $I_2$) with $\pi/2$ phase advance:



  - Scan (assuming global aperture of ~ 7.5σ):
    - φ = 0→2π requires ~25 seconds @7σ, per transverse angle
    - propose to measure at four transverse angles: 0°, 45°, 90°, 125°
  - Increase amplitude (COD currents) till orbit shift ≈ 6.7σ
  - Loss does not exceed predefined BLM threshold if COD settings@ 6.7σ:
    - Yes: → mechanical aperture ≥ 6.7 s → orbit is safe
    - No: → mechanical aperture ≤ 6.7 s → orbit is un-safe
  - additional feature: compare measured with reference BPM step response ($x_{co}$= 0-3σ)

    → rough optics check (phase advance and beta-functions)

# Intermediate Summary:

## Controlled e-blow-up/kicker scan:

- may check both planes at the same time
- relatively fast measurement
- reliability/robustness of beam size measurement/blow-up is an issue
- no information on injection optics
- Tests rather dynamic than mechanical aperture if $a_{dyn} < a_{mech}$
- Destructive measurement
  - beam has to be dumped after scan
  - cannot be used for collimator setup
  - increased beam loss during extraction

## COD Betatron oscillation scan:

- non-destructive measurement

  (could be done to check during each injection)
- rough information on injection optic
- Independent information on planes
- checks only one plane at a time
- What to do if on COD is down?
  - spares: longer measurement
- requires ~30 s for a scan at $7\sigma$
- Required:
  - inhibit injection during scan
  - COD setting reset after scan

- All three methods:
  - Determine the available aperture
  - should be performed with low-intensity beams
  - need time and exclusive control of the machine
- in order to minimise the need for too frequent aperture scans:

  → perform above checks only when exceed given window

# Indicators whether Aperture Scan is required I/II
# BPM orbit surveillance

- Propose to perform two procedural steps for each fill:

A: Initial check whether Orbit is safe:

1. After Pilot injection: scan aperture with retracted collimators till either the assumed mechanical aperture is reached or beam loss is triggered
   - eliminates “dead”, calibration, wrong gain mode BPMs for 'HIGH-SENSITIVITY'
   - estimates BPM offsets and tests safe aperture model with an accuracy of better than one r.m.s beam width.
   - verification of correct injection optics (orbit response)
2. After intermediate beam injection: collimators in nominal positions w.r.t. above measured global aperture and scan till a pre-defined beam loss (pattern) is reached
   - eliminates “dead”, calibration, wrong gain mode BPMs for 'LOW-SENSITIVITY'
   - verifies that primary collimators/absorbers are set correctly → Partial assurance that we setup the system properly....
     - Potential bump scans to determine location of aperture
3. save “safe BPM reference” current settings → $x_{ref}$ = “SAFE SETTING”

B: Continuous Monitoring: $\text{if } ( |x_{meas.} - x_{ref}| < \Delta x_{tol}) \{...\}$

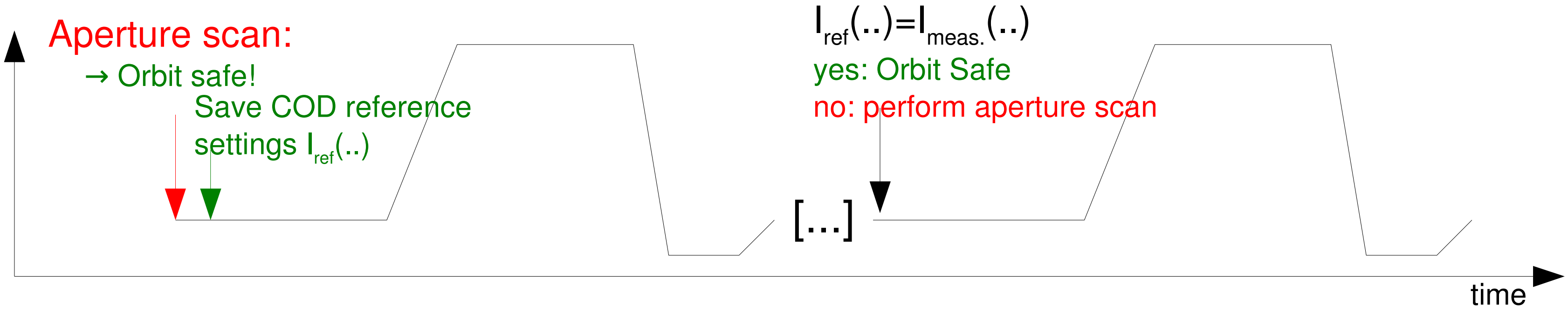
- FALSE: potential orbit bump detected

no

- TRUE: Orbit is safe

yes

# Indicators whether Aperture Scan is required I/II
# Magnet Current Surveillance



Aperture scan:

→ Orbit safe!

Save COD reference settings $I_{ref}(..)$

[...]

$I_{ref}(..)=I_{meas.}(..)$

yes: Orbit Safe

no: perform aperture scan

time

- Proposed Procedure:

A: Initial check whether Orbit is safe:

  - aperture scan (ε blow-up, betatron-oscillation)
    - Potential bump scans to determine location of aperture
  - Save “safe COD reference” current settings → $I_{ref}(...)$ = “SAFE SETTING”

B: Each cycle:

  - Compare with actual current reference $I_{meas}(..)$:

$$\text{if } (|I_{meas}(..) - I_{ref}(...)| < \Delta I_{tolerances}) \{...\}$$

no

- FALSE: Orbit may contain potential bumps → State A
- TRUE: Orbit can be considered to be safe → State B

yes

# Summary

- Current Surveillance:

Pro's

- Can be used to check before first injection
- Can run in parallel to orbit FB operation

Con's

- Less sensitive to complicated orbit bumps
- No precise & simple 'ΔI → Δx' transfer function available
- depends on machine optic, energy
- CODs create not only bumps but compensate, ground motion, decay & snap-back, multipole field errors, ..

- Aperture scans + BPM Surveillance:

Pro's:

- Easy to check with circulating beam
- Less dependent on machine optics
- Sensitive to most orbit manipulations

Con's:

- erroneous BPMs
- No information before injection
- affected by systematic BPM uncertainties
- Potential cross-talk with orbit feedback

N.B. Tolerance levels ("SAFE SETTINGS") should include margin for:

- Compensation of closed orbit and optics uncertainties = "natural effects"
- BPM system uncertainties
- OFB operation (crossing/separation bump, injection/extraction steering, ...)

additional slides

# Machine Protection: Closed Orbit Uncertainties at Injection

| | |
|---|---|
| LPR501 specification[1]: | |
| – nom.: $(\Delta p/p)_{max} \approx 10^{-4}$ | 0.25 σ (MD: max ≈ 3.7 σ) |
| – $b_2+b_3 \cdot \Delta x$ decay: $(\Delta\beta/\beta)_{3\sigma} \approx 2.5\%$ | 0.03 σ |
| Moon/sun tides[2] ($\Delta p/p \leq 5.0 \cdot 10^{-5}$) | 0.14 σ |
| Main Bends, random $b_1 \approx 0.75$ units[34] (dipole kick) | 0.11 σ |
| Random ground motion[5] (10 hours) | ~0.3 – 0.5 σ |
| Systematic ground motion drifts: | ~?? σ |
| MCB hysteresis[6] | 0.01 σ |
| MCB ±8V/±60A PC stability[7] (16bit ADC) | 0.10 σ |
| Total (abs): | ~0.9 - 1.1 σ (max: 4.6 σ) |

→ May become an issue for (close to) nominal operation

[1] M. Giovannozzi: FQWG Meeting on 8th of March 2005
[2] J. Wenninger: "Observation of Radial Ring Deformation using Closed Orbits at LEP"
[3] M. Haverkamp, "Decay and Snapback in Superconducting Accelerator Magnets", CERN-THESIS-2003-030
[4] FQWG-Homepage: http://fqwg.web.cern.ch/fqwg/
[5] RST: "Analysis of Ground Motion at SPS and LEP, implications for the LHC", AB note to be published
[6] W. Venturini: "Hysteresis measurements of a twin aperture MCB orbit corrector", 19th October 2005
[7] Q. King, L. Ceccone: private communications

# Example: Tolerance and COD Constraints

- Mechanical aperture: $N_a = n\,\sigma$ (e.g. n=7.5)
- Deductions:
  - Collimation: 6.7 σ
  - Momentum correction
  - Known uncertainties: 1.1 σ
  - Unknown: ~?? σ
- safe window for dynamic closed orbit modifications: ~ "- 0.3 σ"???
  - Evident: aperture check required!

- Possible MCB tolerance levels:
  - ... 1 σ orbit excursion using CODs one needs e.g.:
    - All CODs with a r.m.s. kick of ~ 1.4 µrad ↔ ≈ 0.07 A@450 GeV
    - 3COD bump: 2x ~12 (-0.1) µrad ↔ ≈ 0.5 (0.05)A@450 GeV

  → Vicious bump: smaller strengths and larger local displacement possible!

  - ... 1 σ orbit excursion through dispersion one needs ($\Delta p/p \approx 4\cdot10^{-4}$):
    - Coherent shift of all MCBH CODs ≈ 0.5 A@450 GeV

→ MCB current change of 0.5 A is likely to cause a orbit bump/shift of 1 σ.

# Continuation of Interlock Scheme through Ramp

- Scheme may be extended through the ramp till squeeze:
  - Similar effects as in injection that perturb the orbit dynamically:
    - Snapback (= inverse of Decay), ground motion,...
  - But: effect of each dipole (deflections) depends on energy:
    - Interlock window and its centre has to be scaled with energy:
      - 0.5 A/$\sigma_{orbit}$ @450 Gev → 7.8 A/$\sigma_{orbit}$ @7 TeV
- Continuation through β*-Squeeze seems to be tricky:
  - CODs do not compensate only ground motion/decay
  - Squeeze induced orbit shifts due to systematic (mis-)alignment of the orbit inside the insertion quadrupoles. If not corrected:
    - Squeeze induced orbit drift up to 30 mm ↔ 100 σ!

→ No simple window to subtract squeeze induced COD changes from those creating bumps.

# Known Error Sources: BPM dependence on

- bunch length $\sigma_b$, intensity $n_b$ ($\sigma_f$: filter time constant) and integrator temperature changes ΔT, filling pattern, ...:

$$\Delta x_{error} \sim \frac{\sigma_{eff}^3}{n_b^{1.5}} + \approx 15-20\frac{\mu m}{^oC}\cdot\Delta T$$

$$with \quad \sigma_{eff} \approx \sqrt{(\sigma_b^2+\sigma_f^2)}$$