LHC Aperture Measurements
at Injection Energy

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with
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R. Schmidt, J. Wenninger, F. Zimmermann, ...
Questions from the chairman

• What do we need to measure?
• How will we do it?
• Who will do it?
• How will we correct?
• What facilities do we need available?
• How long will it take?
• What is the measurement resolution?
• What is the accuracy of correction?
Milestones

☑ In order to proceed with the next commissioning steps (detailed set-up of protection + collimators, then energy ramp):
  ➔ Find out / correct major aperture bottlenecks
  ➔ Achieve the design LHC aperture
  ➔ Reduce the risk of damage for higher intensities / energies
  ➔ IR apertures (separation, crossing, squeeze)

☑ Understand aperture locations that become critical at 7 TeV

☑ Measure loss locations for relevant injection failures

☑ Measure the LHC momentum aperture

☑ Cross-check tools and assumptions used so far
  ➔ Understand better the machine
Outline

• Introduction - LHC aperture
• Requirements (beam, optics, HW, SW..)
• Aperture measurements
• Proposed procedure
• Additional required measurements
• Measuring the momentum aperture
• Aperture for injection failures
• Conclusions
• Web procedures
Introduction

**Design criteria** for LHC aperture:
The secondary halo should not touch the beam pipe!

J.B. Jeanneret, LHC-Project-Note 111

### Tolerance table

|                  | 
|------------------|------------------|
| Closed orbit     | ± 4 mm           |
| Beta-beat        | ± 20 %           |
| Spurious dispersion | 27% $D_{nom}^{Arc}$ |
| Mechanical tolerance | 1-2.5 mm       |
| Alignment        | 1.0.-1.6 mm      |

### Illustrative scheme

- $A_x^{tol}$
- $A_x^{free}$
- $n \times \sigma_y$
- $n \times \sigma_x$
- $\Delta \beta \over \beta$
- $D_{Spur}$

### Design

\[
A_{x,y}^{Available} = \left( A_{x}^{mech} - A_{x}^{tol} \right) \over \sigma_x
\]

\[
\sigma_i = \sqrt{\beta_i \epsilon}
\]

$A_{x,y}^{Avail} > 1.22 \times 7 \times \sigma_{x,y}$

$A_{skew}^{Avail} > 1.4 \times 7 \times \sigma_{skew}$

Design $\rightarrow n_1 > 7$
The LHC aperture

Arc aperture only critical at injection (4x bigger than at 7 TeV)
Minimum cold aperture at injection: ≈ 7.5 σ (few elements below specs!)

$A_{\text{mech}} = 7.5 \sigma$: Assumption for setting up cleaning and protection at injection
Here, used as a goal the aperture optimization at injection

Many critical locations at injection. “Only” MQX’s + IR’s at 7 TeV
Warm magnets below 7.5σ ⇒ find / correct before measuring cold aperture!
Additional constraints from collimation

Systematic loss locations in the DS downstream of the cleaning insertions

Critical loss locations at injection and at 7 TeV identified for various optics errors (orbit, beta-beat, ...)

G. Robert-Demolaize, Chamonix2006

Table 4: Critical loss locations at injection optics.

<table>
<thead>
<tr>
<th>Element</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q11</td>
<td>right of IR3</td>
</tr>
<tr>
<td>DFBA @ Q5</td>
<td>right of IR6</td>
</tr>
<tr>
<td>Q13</td>
<td>right of IR7</td>
</tr>
<tr>
<td>Q23</td>
<td>right of IR8</td>
</tr>
<tr>
<td>Q27</td>
<td>right of IR8</td>
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<tr>
<td>Q2</td>
<td>right of IR8</td>
</tr>
<tr>
<td>Q6</td>
<td>right of IR8</td>
</tr>
</tbody>
</table>
Optics and beam requirements

Stable machine

Closed-orbit and beta-beat stable
Injected emittance reproducible (measured at each cycle)
“Detailed” measurements of linear optics (β, dispersion)
Chromaticity under control

Beams

Single bunch, \( I_b \leq 10^{10} \) p [can lose ~30% in 1 magnet - \( Q_{lim} \sim 5 \times 10^9 \) p]

Assess soon what is the maximum intensity before quenching

“Pencil” beams for dedicated measurements
“Nominal” emittance (the same agreed for ramp)
Required beam instrumentation

**BPM:** Commissioning of full system (polarity/offset/calibration)
Measurements in sum mode (available?)
Turn-by-turn acquisition (sum: simultaneous for B1 and B2?)

**BLM:** Commissioning of full system
“Moveable” monitors available and ready to use
Acquisition faster than 1s will speed-up procedure

**Wire scanners / IPM:** Absolute calibration

**BCT:** Fastest acquisition that we can get at this stage
*Can we improve the resolution to better than $1 \times 10^9 p$?*
Required hardware and software

**Hardware:**

- Kickers (tune kickers) / COD’s (absolute calibration)
- Collimators (TCP’s) / scrapers for beam scraping
- “Some” partial commissioning of protection + dump
- Setup the inject&dump mode + coast beams
- SPS scrapers

**Software** *(more details later):*

- Control of the above systems + of required BI
- Steering program (YASP) - 3C- and 4C-bumps
- “On-line” optics model of whole machine
- Dedicate application for sliding bumps?

*Aperture database: bottlenecks + bumps that optimize*
Outline

• Introduction - LHC aperture
• Requirements (beam, optics, HW, SW..)

• **Aperture measurements**
  - Closed orbit scans
  - Emittance blow-up
  - Kick + BCT
  - Sliding bumps
  - Scans with scraped beams (new)

• Proposed procedure
• Additional required measurements
• Measuring the momentum aperture
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Closed orbit scans

\[ A = \frac{a^2}{\beta_a} = \frac{1}{4} \left( \frac{\sin^{-2}(\pi Q) \theta_1^2 \beta_1 \theta_2^2 \beta_2}{\theta_1^2 \beta_1 + \theta_2^2 \beta_2 - 2 \theta_1 \theta_2 \sqrt{\beta_1 \beta_2} \cos \alpha} \right) \]

Frank, LHCCWG of April 5th, 2006

- determine global transverse aperture using pairs of orthogonal correctors (minimum 8 measurements with beam loss, per ring); center beam inside aperture for each corrector
- estimated minimum time \( \sim 2-3 \) h / ring

Drawbacks

At least two measurements per scan
Need full beam scraping
Emittance blow-up + wire scans

- Blow-up the emittance (transverse noise) until you touch the aperture
- Measurements of scraped beam profile give the machine acceptance
- Get local aperture bottleneck if you know the loss location

Drawbacks
Requires more time (commission the emittance blow up)
Define how we want to increase the emittance (transverse noise?)
Relies entirely on wire scan calibration (no redundancy: 1 per plane/ring)
What for skew plane?
Depending on \( \Delta \varepsilon \) rate, can be difficult to identify the loss locations with low-intensity pilot beams
This list of drawbacks might change if IPM or wiggler are available
Example: SPS measurement

Emittance blow up: insert all the screens of the transfer line!
Used as a preliminary cross-check to exclude major obstacles, rather than for detailed measurements.

Signature: “shorter” tails

Courtesy of C. Arimatea
Kick combined to BCT measurements

**Advantages**

- Fast and potentially accurate method (see SPS examples)
- All phases in one kick. Minimum required hardware
- Redundant “calibration” (kick amplitude, BPM’s, wires)
- Experience + tools from the SPS

**Drawbacks**

- Can keep oscillation constant for tens of turns? (?AC dipole?)
- Need to refill after every measurement
- Absolute measurements limited by BCT accuracy with pilot

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- Kick the beam until you lose a significant fraction of particles
- Infer $N_{cut}$ from assumption on beam distribution (measure it with WS!)
- Calculate normalized aperture as:

$$A_{mech}(s_0) = A_{kick} + N_{cut} \times \sigma(s_0)$$

- Identify loss location with BLM’s and/or BPM sum signal
Example: SPS measurements
(July 2006 - Analysis by F. Roncarolo)

Kick applied with the Q meter (5 kV)

Profile BEFORE

Profile AFTER

BCT: Up to 70% particles are lost
SPS: Good understanding of the measurements. **Accuracy \( \approx 20\% \)**, limited by kick calibration (aperture calculated with wires is different)

LHC: We must achieve a **better accuracy**. Problem: decoherence / filamentation

Certainly a good method to **FIND aperture bottlenecks** **IF** we can rely on a good BLM system or turn-by-turn BPM-sum acquisition!

Need detailed **local bumps** for precise measurements and corrections!

S. Redaelli, LHCCWG, 26-07-2006
Local measurements: Sliding bumps

Each method discussed is suitable for global and local measurements.

Scan vs. amplitude of a closed-bump!

Good to optimize known bottlenecks (change orbit), not to find them (27km!)

Need to lose a significant fraction of beam → refill for each scan!

Courtesy of F. Roncarolo
Aperture measurements with BLM’s

Can we use the (many) BLM for absolute aperture measurements?

BLM’s cannot easily be used because their response cannot be calibrated w.r. to distance from the beam core.

Halo population, response vs. exact location of losses, different response for different magnet types, dependence of readout on loss rate, etc.

2004 collimator at the SPS: BLM’s show signal at > 15 σ from the beam core!
**Touch the aperture with scraped beams**

New method proposed for local aperture scans (Ralph, Stefano):
We can use the BLM’s for scans with scraped beams!

SPS experience: with the collimator we control precisely $N_{\text{cut}}$.
Bump must be closed (obvious!)

Advantages:
- Minimum additional hardware (use primary collimators or scrapers)
- Can do many scans with one coasted beam
- Precise for local scans of bottlenecks

Halo cut at a known amplitude

Step signal on the BLM!
Idea from the results of the 2004 SPS test

DC losses measured by the BLM close to the collimator

If we touch the aperture elsewhere, the collimator is no longer the bottleneck ⇒

(1) We see a sharp spike on the BLM’s at the location of the new bottleneck
(2) We see a drop of the DC noise at the collimator BLM’s

Beam tests required!!!
Try a “proof of principle” at the SPS

**Preliminary** beam tests carried out at the SPS with a 14 GeV beam.

No collimator available - beam scraping done on the aperture!

**Procedure**-Within one cycle (flat bottom~1.2 s), apply closed bumps at two locations:

1. Scrape the beam by a few percent at a know bottleneck → $N_{cut} \sim 3\sigma$
2. After scraping, start another closed bump to touch the aperture elsewhere
3. Compare the BLM signal versus bump amplitude with and without scraping
Thanks to F. Follin for setting up a fast acquisition (20ms) of the SPS BLRING!
Preliminary measurement results (cont’d)

- Without scraping: don’t know the distance from the beam centre
- Scraping: From one step to the next, we know that we touch at 3σ!

Touch at ~ 15-16 mm
Ncut ~ 3σ = 12-15 mm
Mech. Aperture r = 30 mm
Resolution: ~ 2 mm (bump too fast)
fast rise-time to fit it within flat bottom

Expected:

Good indication - not yet a proof!
More detailed tests with the LHC collimator at the SPS!
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Aperture measurements

Methods to use

→ Kick + BCT + wires to measure global aperture
→ Scraped beams for detailed local scans + correction

1) Set-up kicker(s) (synchronization) and sensor acquisition (BCT, BPM, WS, BLM) > 1 h
2) Set-up beam scraping with the collimator(s) + local bumps. > 1 h
3) Measurement loop:
   - Global aperture meas. with kick (inj+dump) ⇒ \( A_{\text{mech}} \) ~ 0.3 h
     - \( A_{\text{mech}} > 7.5 \sigma \) ⇒ STOP!
     - \( A_{\text{mech}} < 7.5 \sigma \) ⇒
       a. Identify loss location with BLM + BPM sum [need to use moveable BLM’s?] ~ 0.5 h
       b. Local bump at bottleneck with scraped beams
       c. Centre the orbit with a local bump
Approximate time estimate

If we believe the previous time estimates, we will need a total time of:

$$T_{\text{total}} = (1h + 1h + N_{\text{bottleneck}} \times 0.8h) \times 3 \times 2$$

- Set-up time (reduced after experience is gained?)
- Identify and correct the bottleneck
- $H$, $V$ and $S$
- $B1$ and $B2$

Remarks: Time estimates are very difficult! How many? → ABP-LOC?
Important to assess the LHC skew aperture!
Required time becomes much longer if orbit bumps cannot improve the global orbit! Change the optics?
Required time becomes much longer if bottlenecks occur at locations that are invisible for BLM and BPM systems!
How can we save time?

- Can we reduce the set-up time at next iterations?
- Can we do B1 and B2 in parallel? Cross talk of BLM’s? BPM-sum for both?
- Good BLM coverage essential from day 1 to find bottleneck locations!
- Faster acquisition of the BLM’s and BCT as soon as possible!
- Automatic procedures for sliding bumps would be of great help!

Use the proposed method with scraped beams (faster, less fills)

Ideas for specs: Scan each element with a 3C-bump (±)

“Move until $\text{BLM} > \text{BLM}_0$”

Spatial resolution: $\Delta = 0.1 \sigma_{\text{inj}}$ (move faster below $6\sigma$)

Find centre position and set CO there!

- Efficient on-line data analysis (e.g.: plot BLM or BCT vs. $A_{\text{bump}}$)
Accuracy of measurement and correction

“Reasonable” goal: $0.2 \times \sigma$ [can we relax this at startup?]
Remember that the nominal TCP setting is $5.7\sigma$!

$$A_{\text{mech}}(s_0) = A_{\text{kick}} + N_{\text{cut}} \times \sigma(s_0)$$

$$\frac{\delta A_{\text{mech}}}{A_{\text{mech}}} = \sqrt{\left(\frac{\delta A_{\text{kick}}}{A_{\text{kick}}}\right)^2 + \left(\frac{\delta N_{\text{cut}}}{N_{\text{cut}}}\right)^2 + \left(\frac{\delta \sigma}{\sigma}\right)^2} < 10 - 20\%$$

$$\frac{\delta \sigma}{\sigma} = \sqrt{\left(1 + \frac{D^2 \delta^2}{\beta \epsilon}\right)^{-1} \left[\frac{1}{2} \frac{\delta \beta}{\beta}\right]^2 + \left(1 + \frac{\beta \epsilon}{D^2 \delta^2}\right)^{-1} \left[\left(\frac{\delta \delta_p}{\delta_p}\right)^2 + \left(\frac{\delta D}{D}\right)^2\right]}$$

Optics only. Uncertainty on emittance on top of this!!

Keys for success: Good knowledge of optics
Detailed calibration of kickers and BPM’s!

Can we achieve 20% ?? We need realistic estimates…
Additional aperture measurements

Discuss here a **prioritized list of critical locations**!

**Sliding bumps** with scraped beams to investigate / optimize additional aperture restrictions!

Same time estimates apply: **0.5-1 h** per additional location.

1) Elements that become critical at 7 TeV (Stefano, Stephane)

450 GeV

$\sqrt{\beta_{inj} \epsilon_{inj}}$

$A_{mech}^{inj}$

7 TeV

$\sqrt{\beta_{coll} \epsilon_{coll}}$

$A_{mech}^{coll}$

$\Delta_{C.O.}$

Ex.: Simplified case with dispersion

\[
n_{1}^{inj} > \frac{1}{\sqrt{\beta_{inj} \epsilon_{inj}}} (7 + \Delta_{C.O.}) \sqrt{\beta_{coll} \epsilon_{coll}}
\]

$\Delta_{C.O.} \approx \frac{2 \text{ mm}}{1.22 \times 1.2 \times \sqrt{\beta_{coll} \epsilon_{coll}}}$

**Budget for change during squeeze ~ 2 mm**

Additional critical elements should be identified for the various $\beta^* +$ crossing!
2) IR commissioning with crossing and separation schemes
   A whole study on its own… (discussed at a future LHCCWG)
   Do we want aperture scans independently of the IR bumps?
   Triplet aperture to setup the TCT protection! Extrapolate it to 7 TeV?

3) Critical beam losses locations?
   See talk by G. Robert-Demolaize at Chamonix2006
   Quench-wise, can we improve the cleaning performance by
   optimizing the aperture at critical loss locations? (Collimation team!)

4) Additional measurements during commissioning of dedicated systems
   Collimation, dump, injection, …: done by “system commissioners”

5) Other locations? “Known”/suspected locations of obstacles? Alignment errors?

6) Repeat (some) aperture scans with a different energy: $\frac{\Delta p}{p} = \pm 1.5 \times 10^{-3}$
   Assess contribution of spurious dispersion!
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Momentum aperture measurements

Measurements of momentum aperture: **Radial steering**
*(Change frequency until beam is lost, also suggested by Frank)*

**Requirements**

\[ \frac{\Delta p}{p} = \pm 1\% \Rightarrow \frac{\Delta f}{f} = \eta \frac{\Delta p}{p} = 3.182 \times 10^{-4} \frac{\Delta p}{p} \approx 1.275 \text{kHz} \]

Changes up to a few kHz should be possible BUT we have to disable an interlock: \( |\frac{\Delta f}{f}| < 200 \text{Hz} \). Ok pilot. (Andy, J. Tuckmantel)

**Proposed method**

Use low-intensity \((I \sim 10^9\ p)\) “pencil” beams
Scrape the beams at 1-2\(\sigma_H\) at the SPS or with TCP-H
Scrape \(\Delta p/p\) distribution with TCP-IR3? SPS Gymnastic?
Change the RF frequency until the beam is lost
Identify the loss location with BLM’s

**Required time**

1 h per beam per scan (+ / -) (include identify loss)
Need to repeat for vertical plane with crossing?
Injection failure losses

Goal
Find loss locations for injection failure scenarios

Proposed method
Use low-intensity ($I \sim 10^9 p$) “pencil” beams
Scrape the beams at 1-2$\sigma$ at the SPS
Inject in the LHC and see loss locations with BLM’s Measurements with all collimators OPEN (also TL’s)

Failures
Wrong SPS extraction kicker - all TL collimators out
Wrong SPS energy (SPS radial steering)
Failures of the LHC injection kickers

Required time
~ 1-2 h per case seems reasonable (optimistic?)
Implications of collision run at 450 GeV

- Method discussed here apply likewise if we don’t ramp
- Need to investigate updated tolerance for a relaxed 450 GeV engineering run (collimation, dump, inj, ABP-LOC, ... )
  However, goal of 7.5 sigma will not be much relaxed (protection)
- IR commissioning must be reviewed for the 11m optics
- No need of investigating early on the expected critical loss locations only at 7 TeV
- ?
Who does aperture measurements

- Interest from the collimation project!
- Support / interest from ABP-LOC needed!
- Hardware commissioners responsible for “their” regions
  
  Collimation, dump and injection project must work together!
- IR’s: ABP
- Could not verify interest from colleagues outside CERN
- Issue: Software to speed up the procedure?
  Software for the on-line analysis?
  Off-line understanding of the all information available!
Conclusions

• Measuring the LHC aperture will be extremely critical!

• Ambitious measurement program proposed
  Global and local procedures for getting above design value
  Additional critical loss locations
  Losses of off-momentum beams
  Loss locations for injection errors

• Reviewed of available methods for aperture measurements

• New method proposed - Promising but needs experimental proof

• Measurements potentially time-critical - depends on $N_{bottleneck}$

• Achieving accuracy of $\sim 0.2 \sigma$ is challenging - more studies

• Web procedures to be updated according to this LHCCWG
Open issues

• Assess **quench limits** for fast losses and set pilot intensity to improve accuracy (BCT resolution) without quenching
• Estimate **source of error** of the aperture measurement
• What do we do in case of **MANY solvable bottlenecks** at ~ 7σ?
• What do we do if we **cannot** bring the aperture within tolerance with local orbit bumps? Change the optics?
• Implications on machine performance of an aperture << 7σ?
• When do we stop? Safety margin? Global aperture > 10σ?
• Set-up an “**aperture database**” with the relevant information
  ➞ “Golden orbit” optimized for aperture
  ➞ Link/compare with other DB’s, e.g. aperture model, intentionally displaced magnets to optimize aperture ...