11th meeting of the

LHC Commissioning Working Group

July 26nd, 2006

LHC Aperture Measurements at Injection Energy

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with

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Acknowledgments: SPS-OP team, K. Cornelis, B. Goddard, V. Kain, R. Schmidt, J. Wenninger, F. Zimmermann, ...

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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

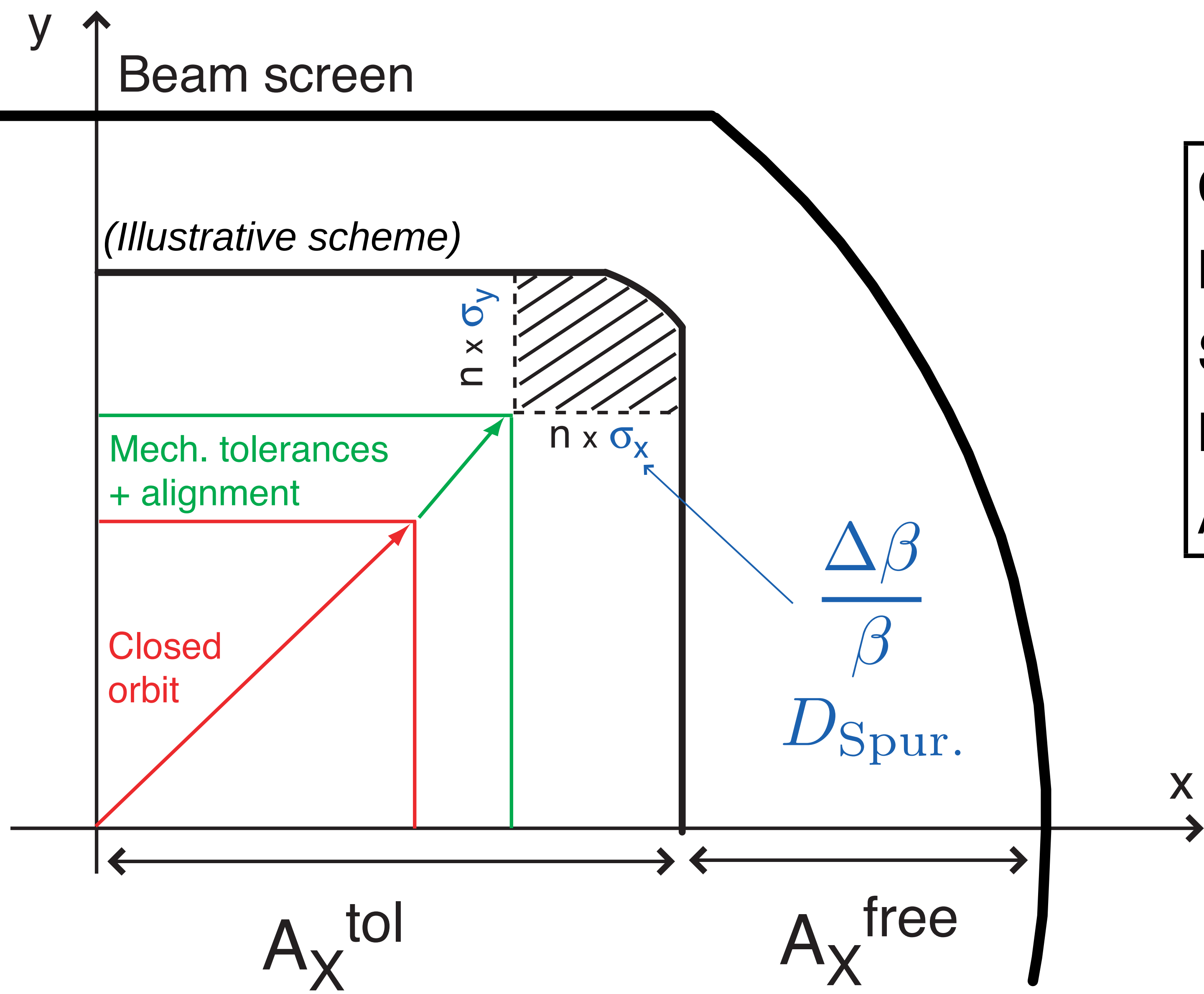
- Cross-check tools and assumptions used so far

  → 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



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

$$A_x^{\mathrm{Available}} = \frac{(A_x^{\mathrm{mech}} - A_x^{\mathrm{tol}})}{\sigma_x}$$

$$\sigma_i = \sqrt{\beta_i \epsilon}$$

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

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

⇨

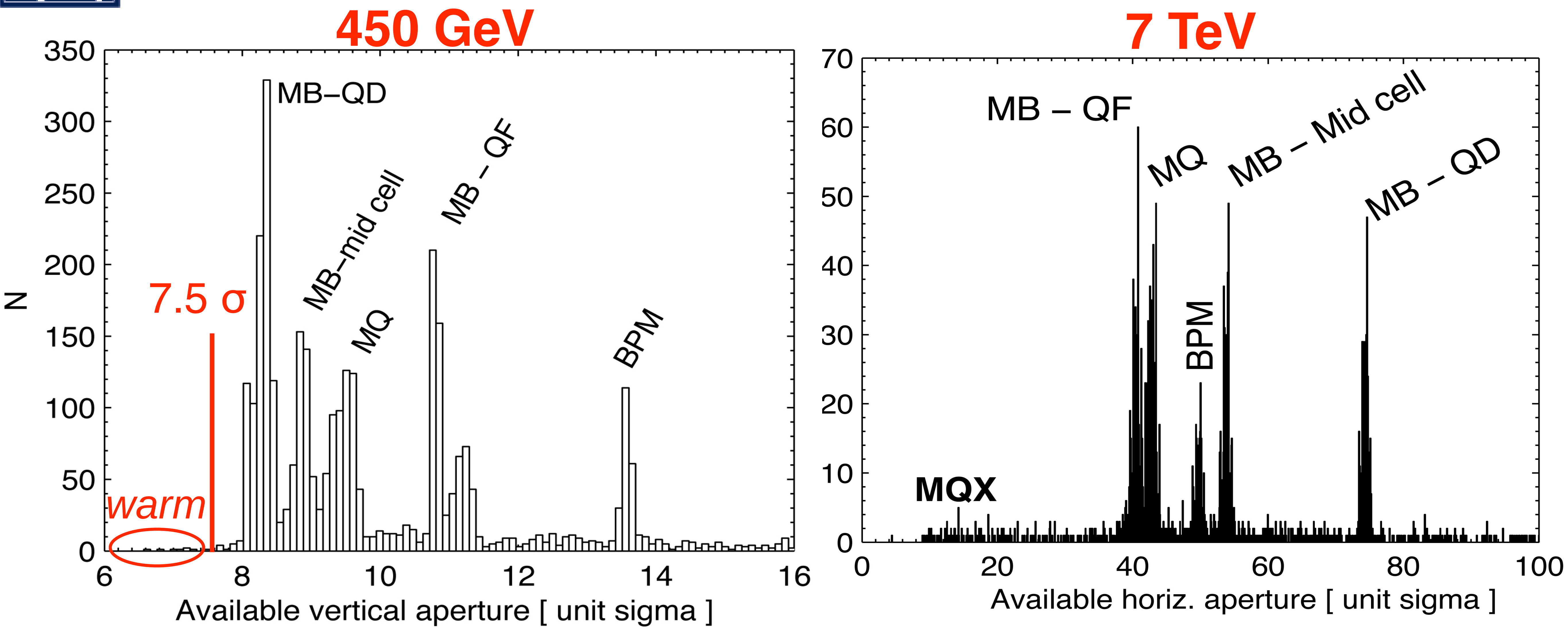
n_1

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

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

Design → $n_1 > 7$

The LHC aperture



Arc aperture only critical at injection (4x bigger than at 7 TeV)

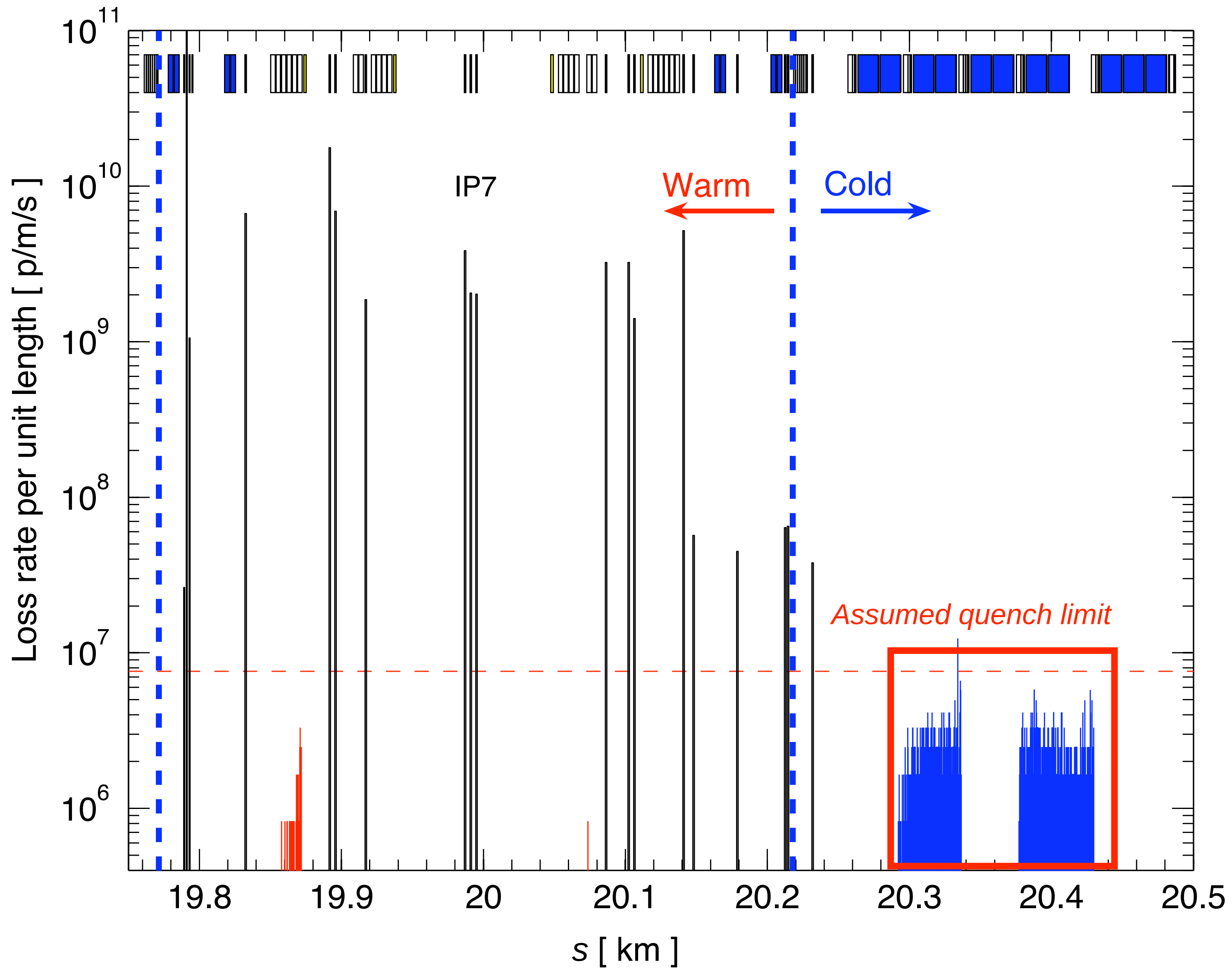
Minimum cold aperture at injection: **≈ 7.5 σ** (few elements below specs!)

A_{mech} = 7.5 σ: *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

Table 4: Critical loss locations at injection optics.

Element	Location
Q11	right of IR3
DFBA @ Q5	right of IR6
Q11	right of IR7
Q13	right of IR7
Q23	right of IR7
Q27	right of IR7
Q31	right of IR7
Q33	left of IR8
Q29	left of IR8
Q25	left of IR8
Q2	right of IR8
Q6	right of IR8

Critical loss locations at injection and at 7 TeV identified for various optics errors (orbit, beta-beat, ...)
G. Robert-Demolaize, Chamonix2006

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}~$5\text{x}10^9$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 $1x10^9$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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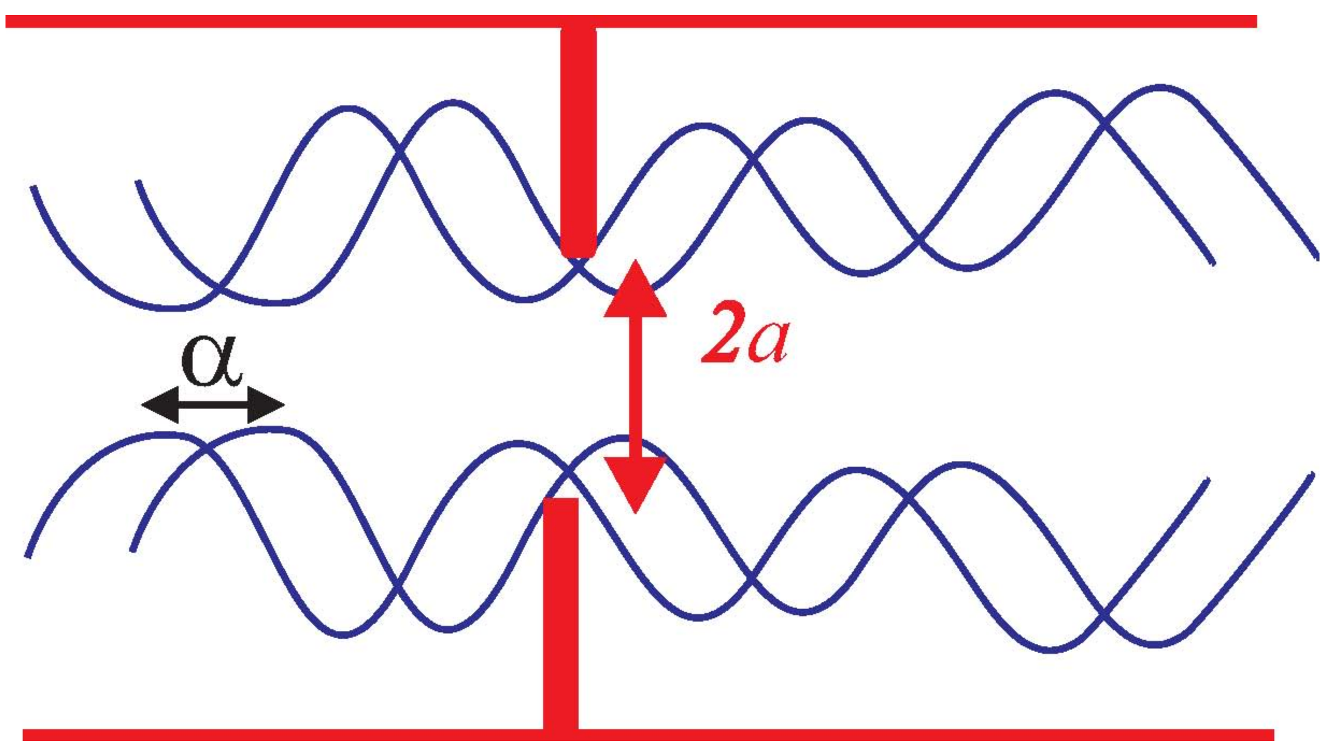
Closed orbit scans

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

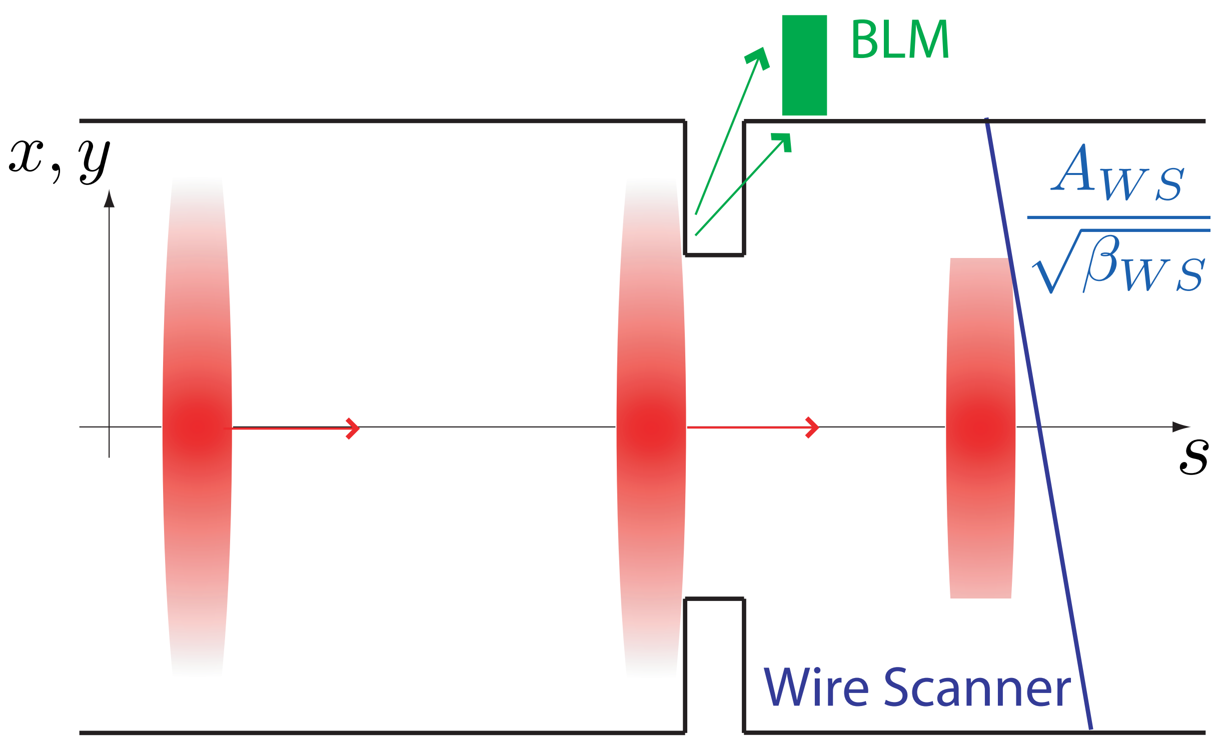


Frank, LHCCWG of April 5th, 2006

- 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 ~2-3 h / ring

Drawbacks — At least two measurements per scan
Need full beam scraping

Emittance blow-up + wire scans



Normalized coordinates around CO

- 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?)

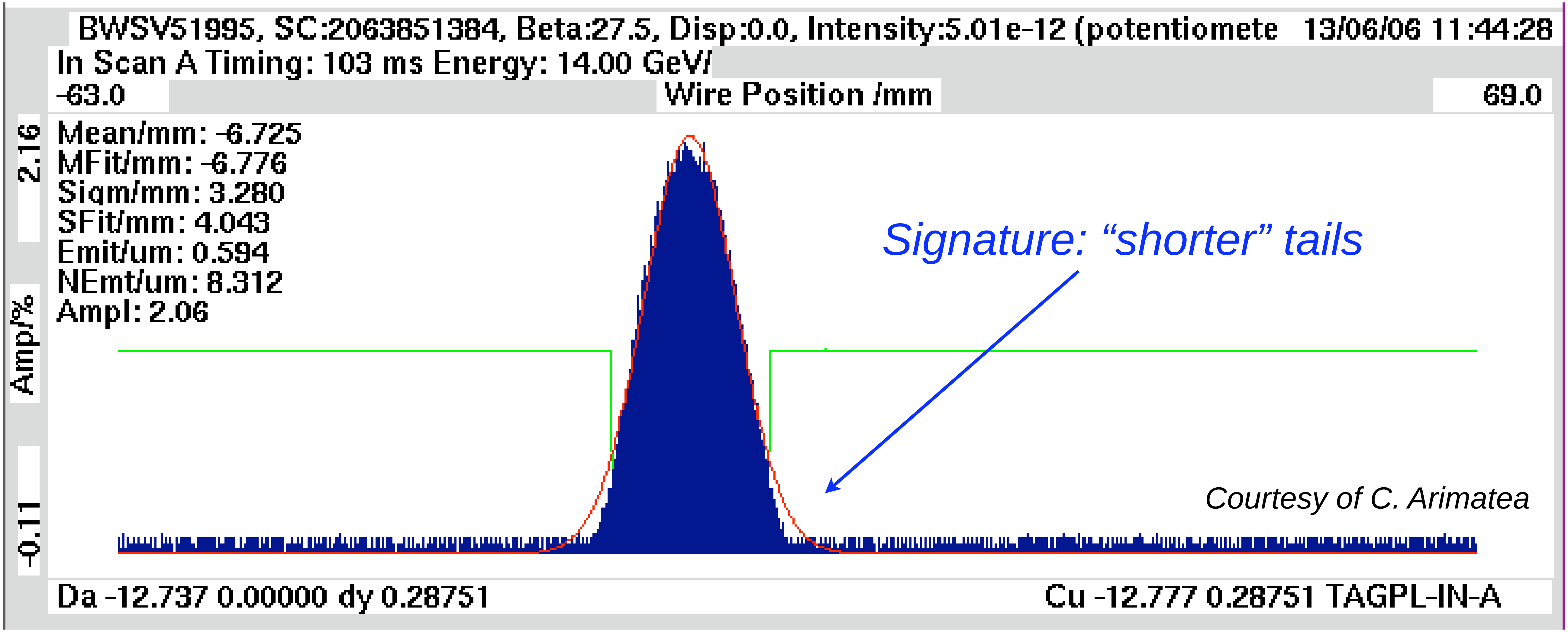
Relies entirely on wire scan calibration (no redundancy: 1 per plane/ring)

What for skew plane?

Depending on $\Delta\varepsilon$ rate, can be difficult to identify the loss locations with low-intensity pilot beams

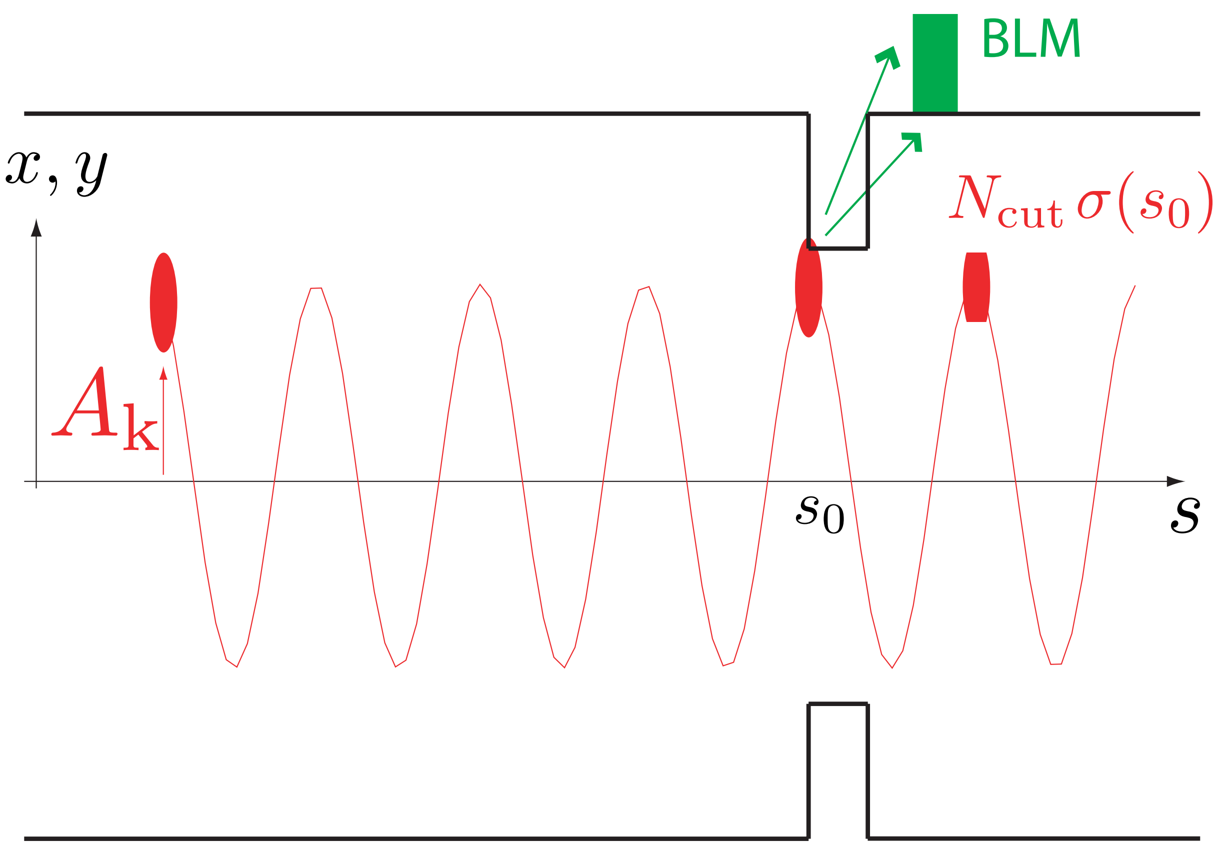
This list of drawbacks might change if IPM or wiggler are available

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.

Kick combined to BCT measurements



Normalized coordinates around CO

- Kick the beam until you loose a significant fraction of particles
- Infer *Ncut* from assumption on beam distribution (measure it with WS!)
- Calculate normalized aperture as:

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

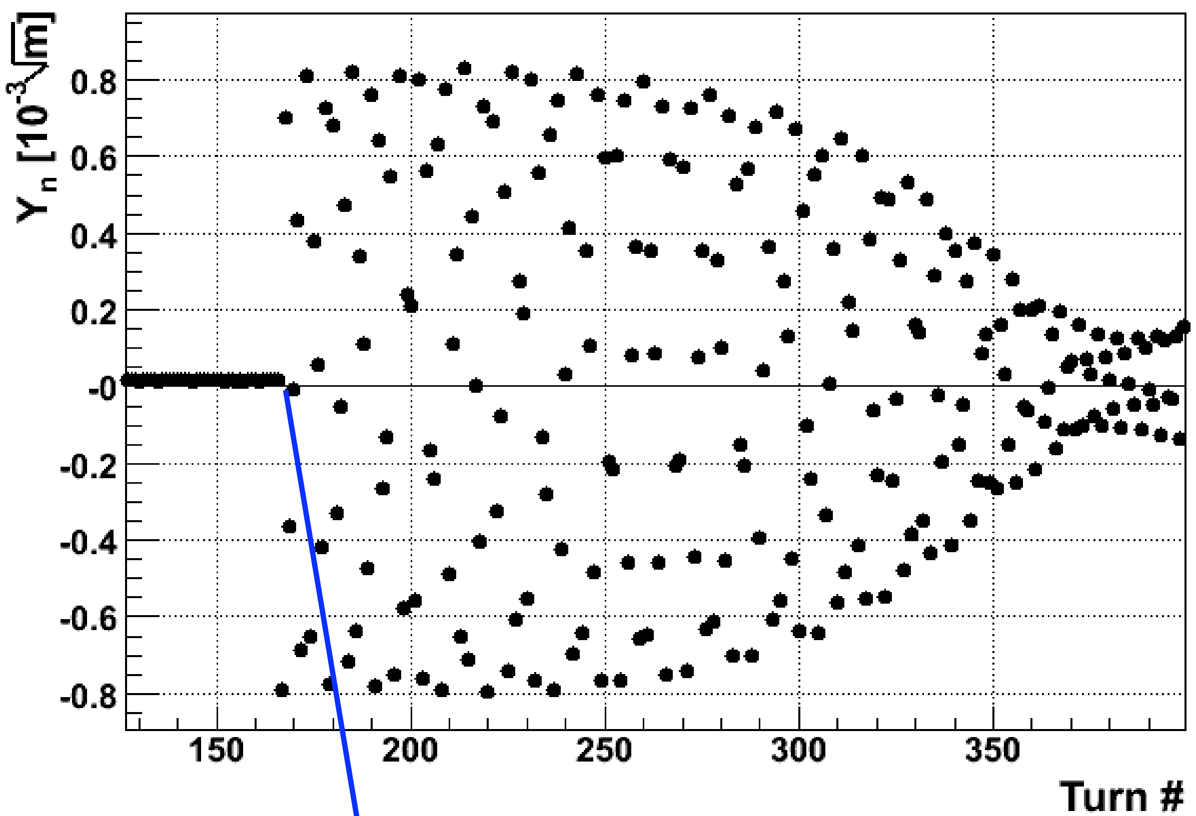
- Identify loss location with BLM's and/ or BPM sum signal

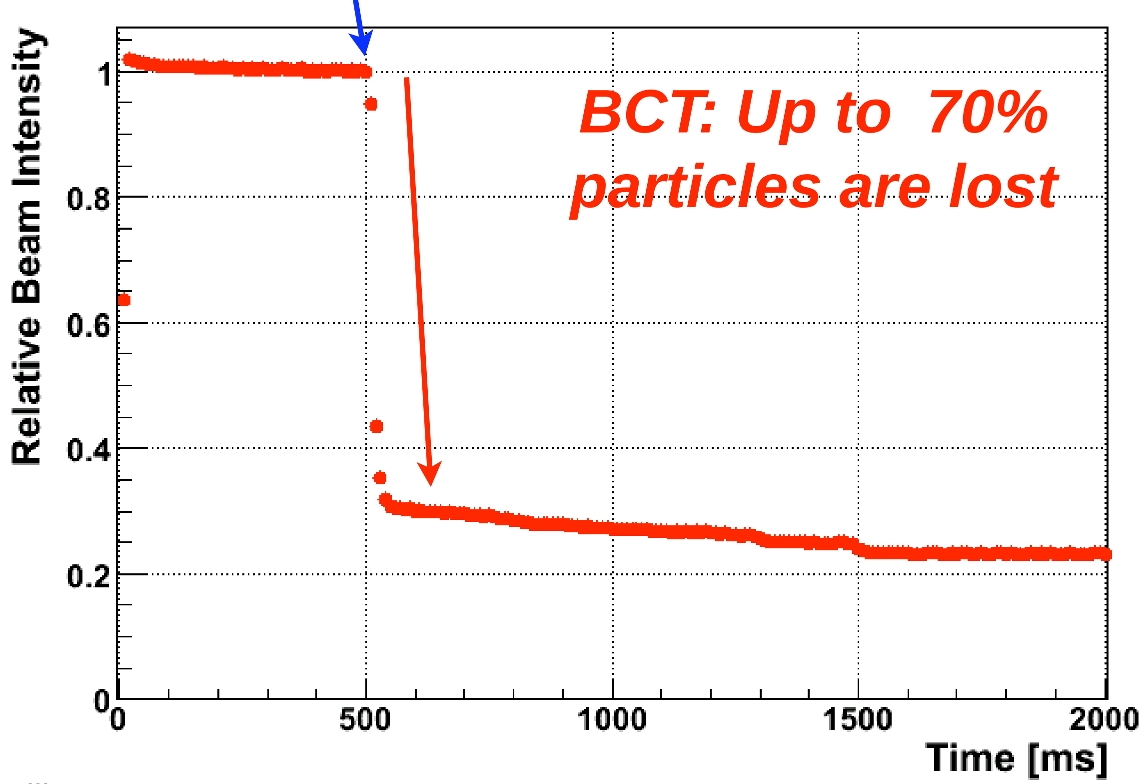
Advantages	Fast and potentially accurate method (see SPS examples)
	All phases in one kick. Minimum required hardware
	Redundant "calibration" (kick amplitude, BPM's, wires)
	Experience + tools from the SPS
Drawbacks	Can keep oscillation constant for tens of turns? (?AC dipole?)
	Need to refill after every measurement
	Absolute measurements limited by BCT accuracy with pilot

Example: SPS measurements

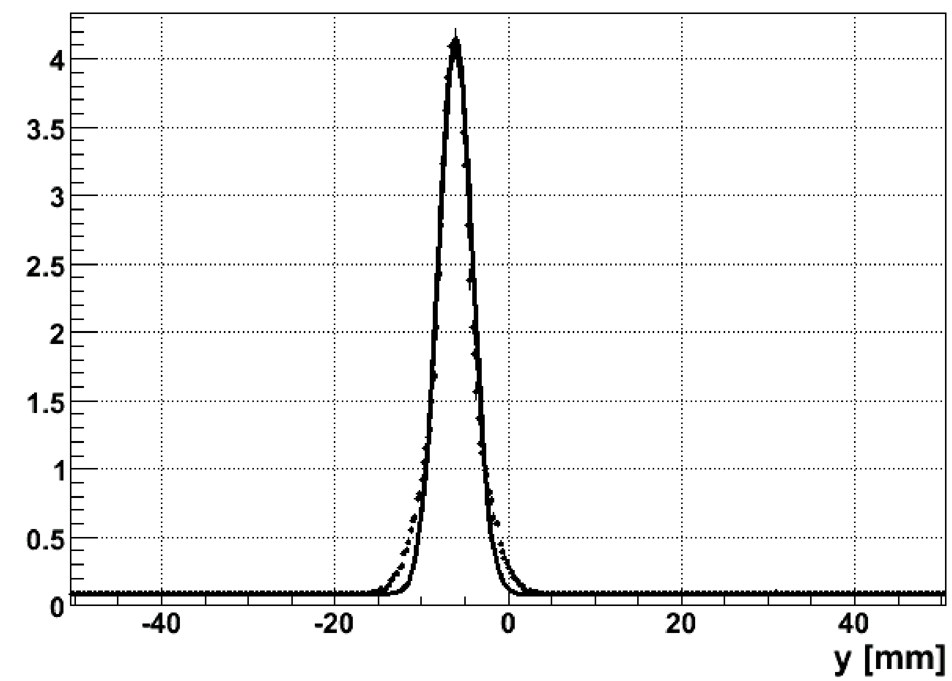
(July 2006 - Analysis by F. Roncarolo)

Kick applied with the Q meter (5 kV)

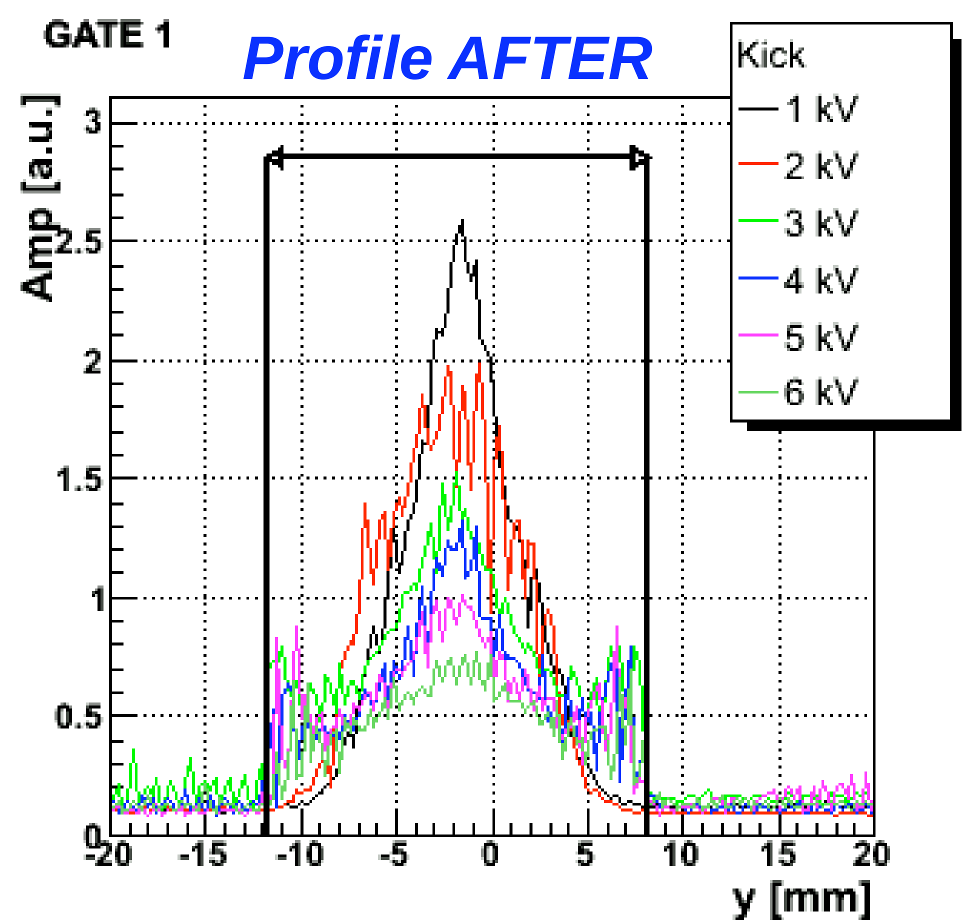




Profile BEFORE

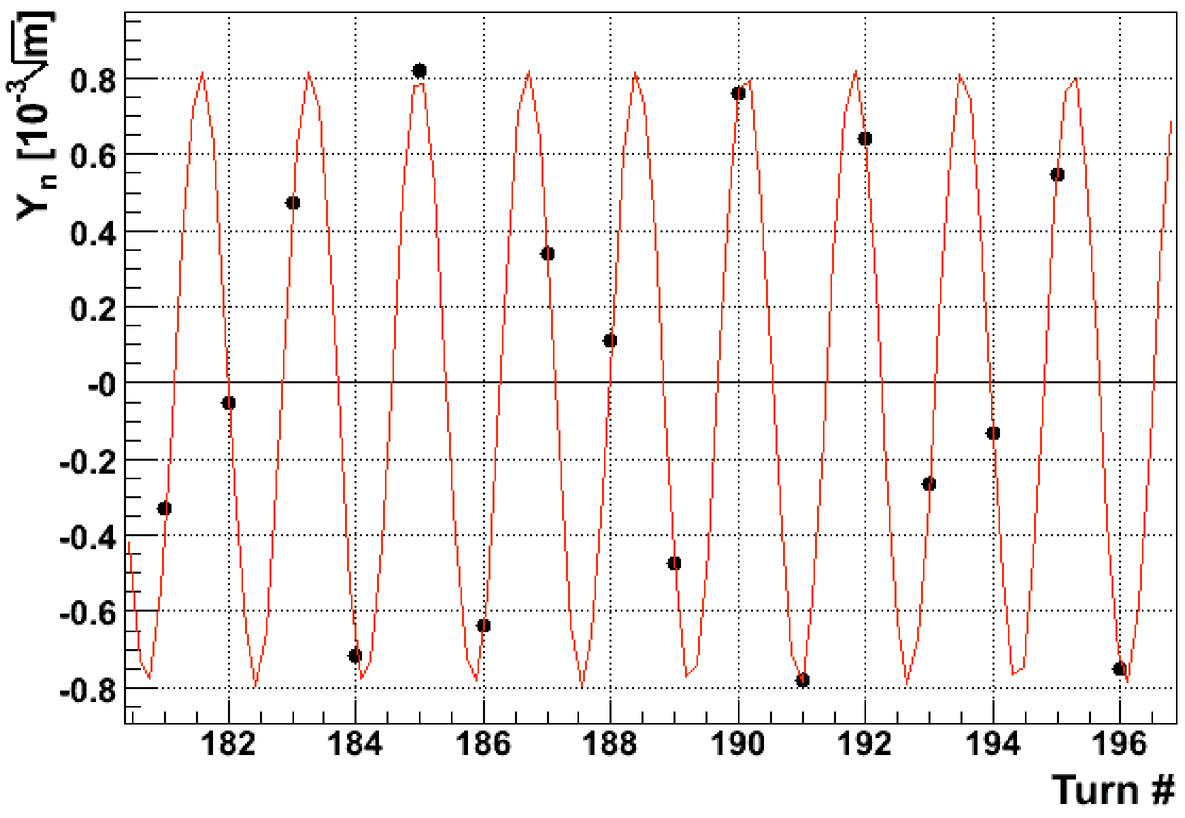


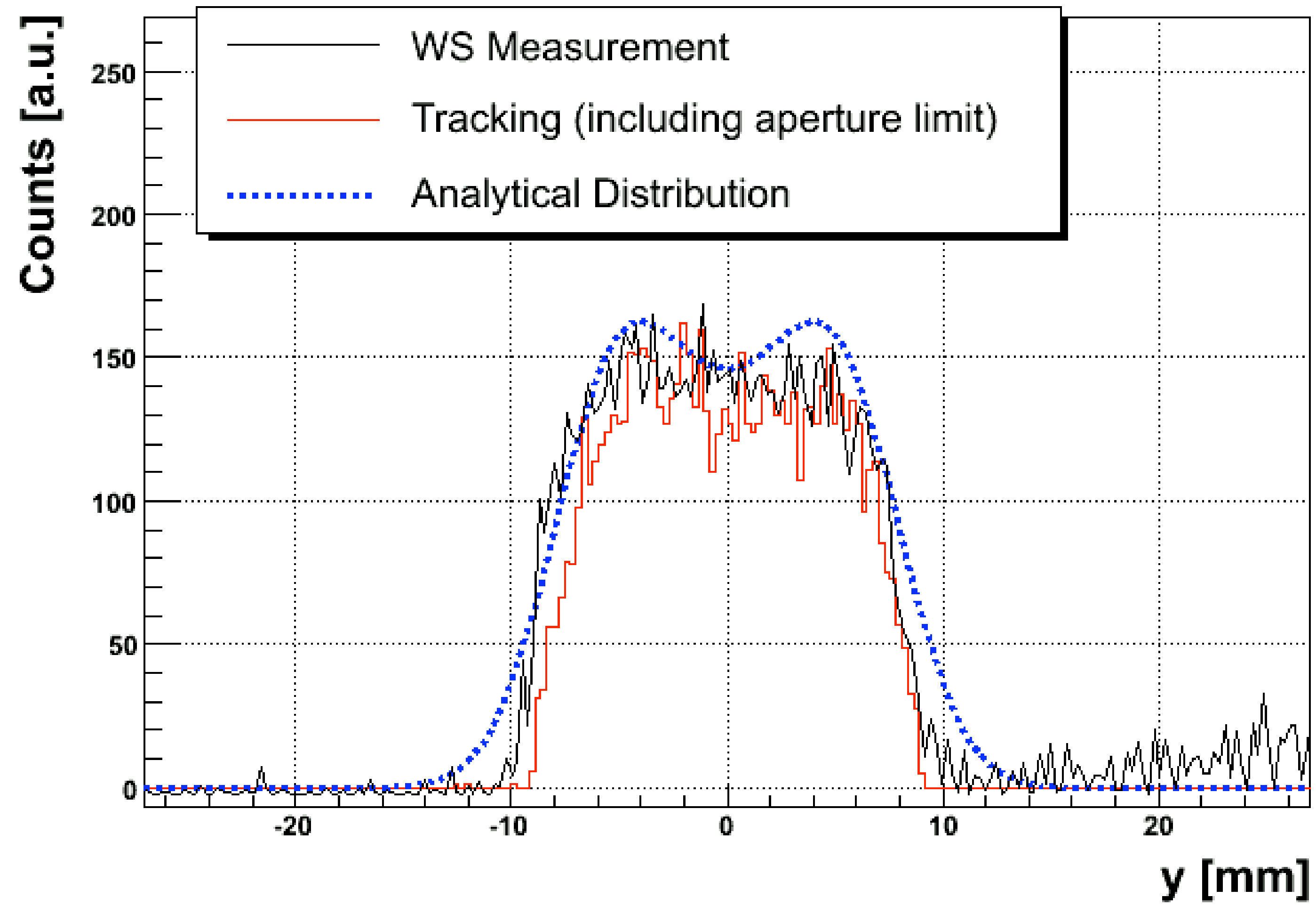
Profile AFTER



SPS measurements (cont'd)

(July 2006 - Analysis by F. Roncarolo)





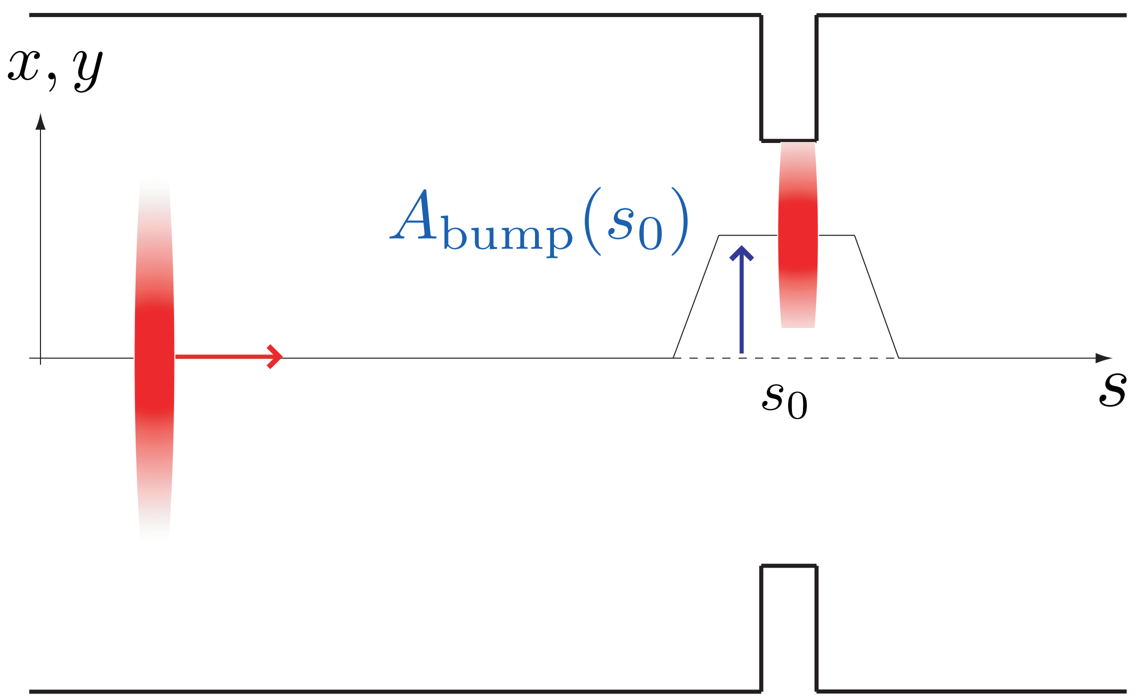
SPS: Good understanding of the measurements. **Accuracy ≈ 20%**, limited by kick calibration (aperture calculated with wires is different)

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!

Local measurements: Sliding bumps

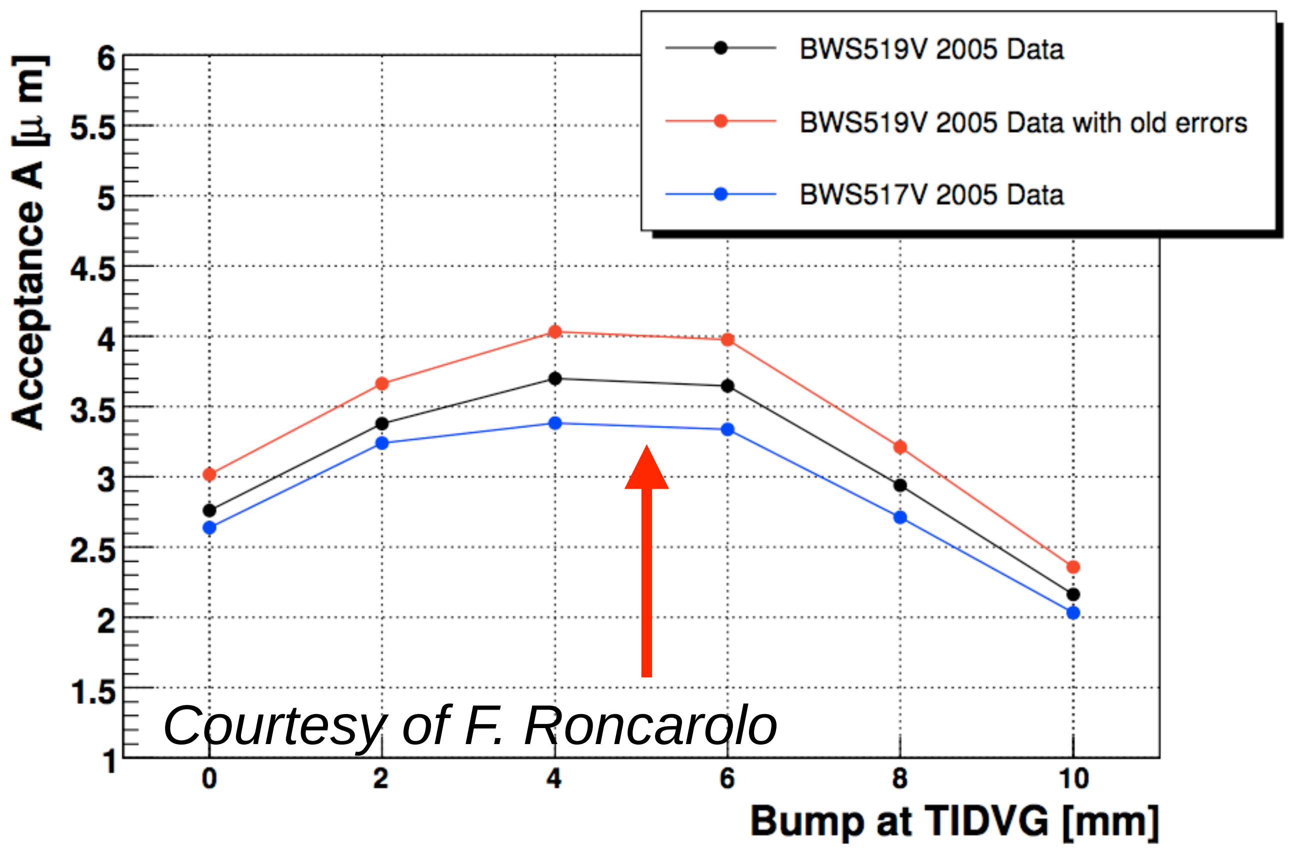


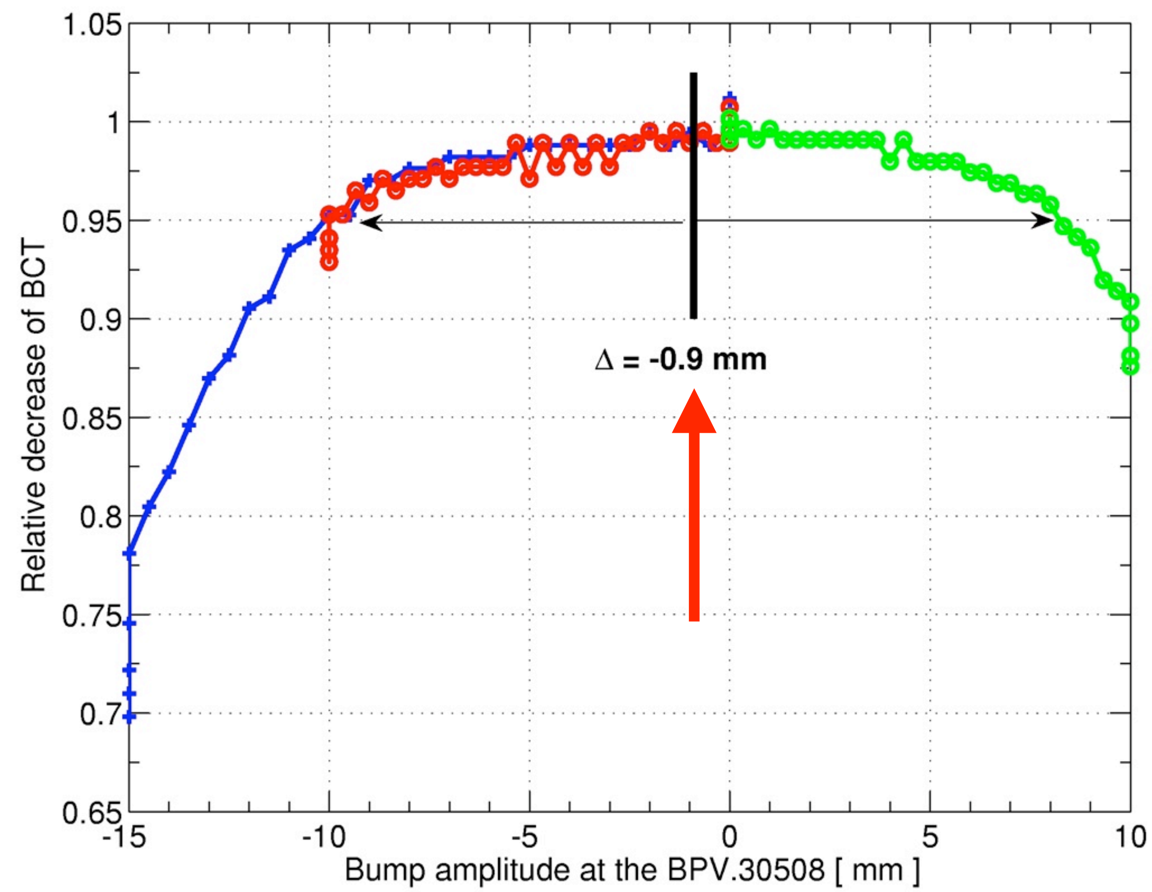
Each method discussed is suitable for **global** and **local** measurements

Scan vs. amplitude of a closed-bump!

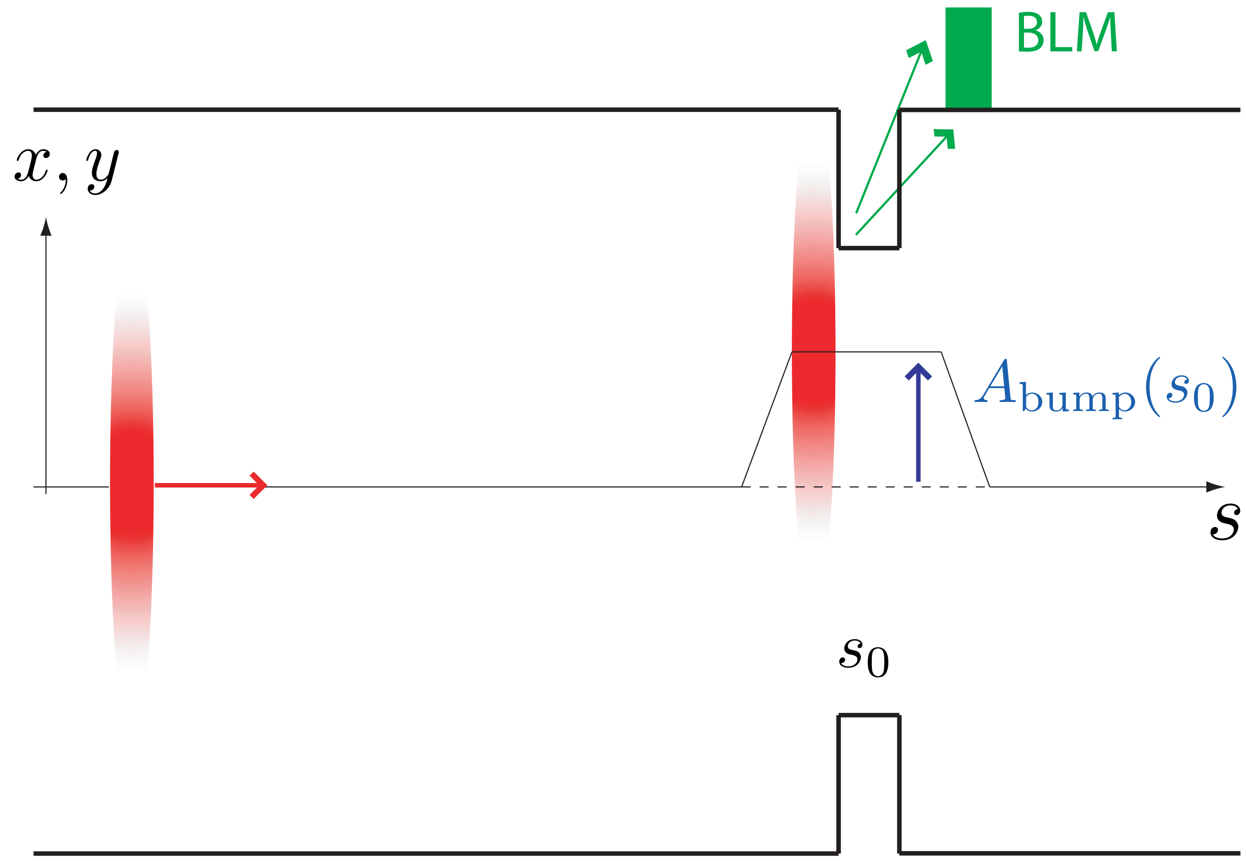
Good to optimize *known* bottlenecks (change orbit), not to find them (27km!)

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





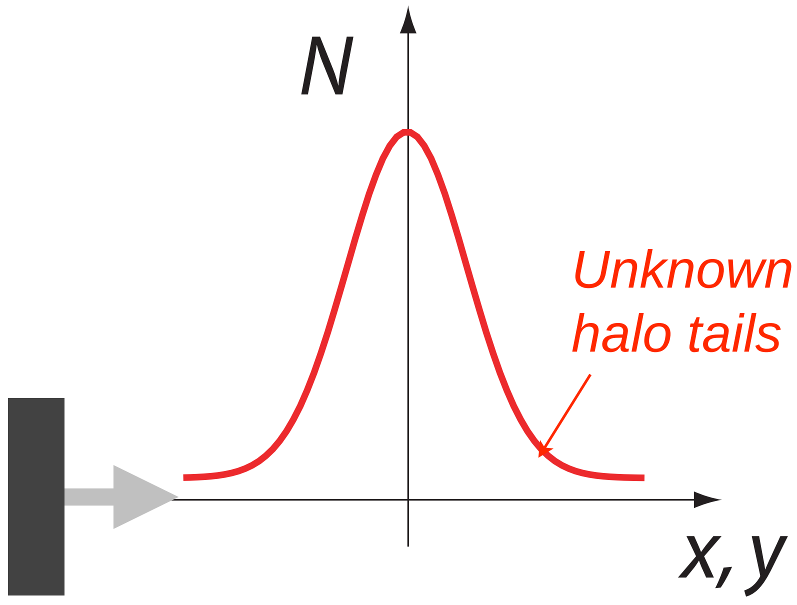
Aperture measurements with BLM's

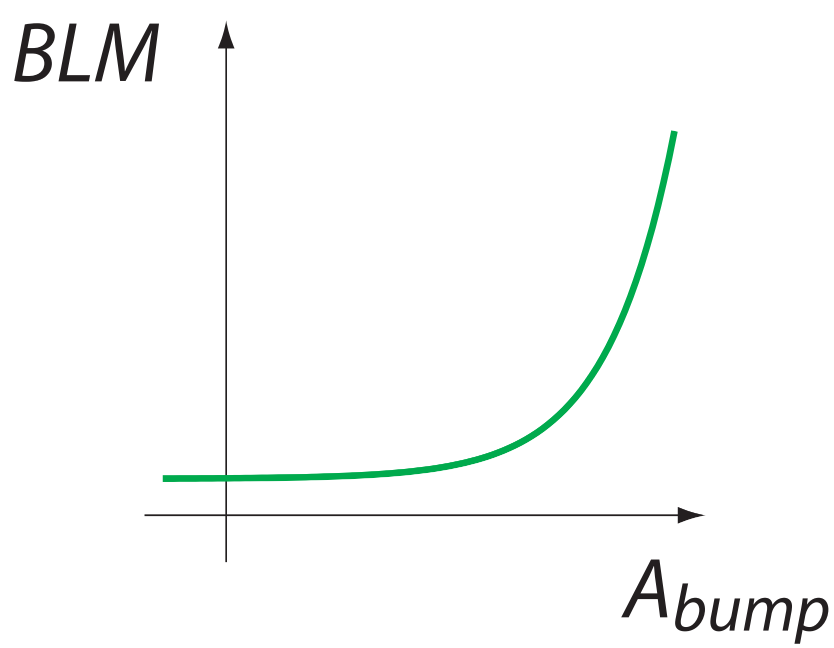


Can we use the (many) BLM for absolute aperture measurements?

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

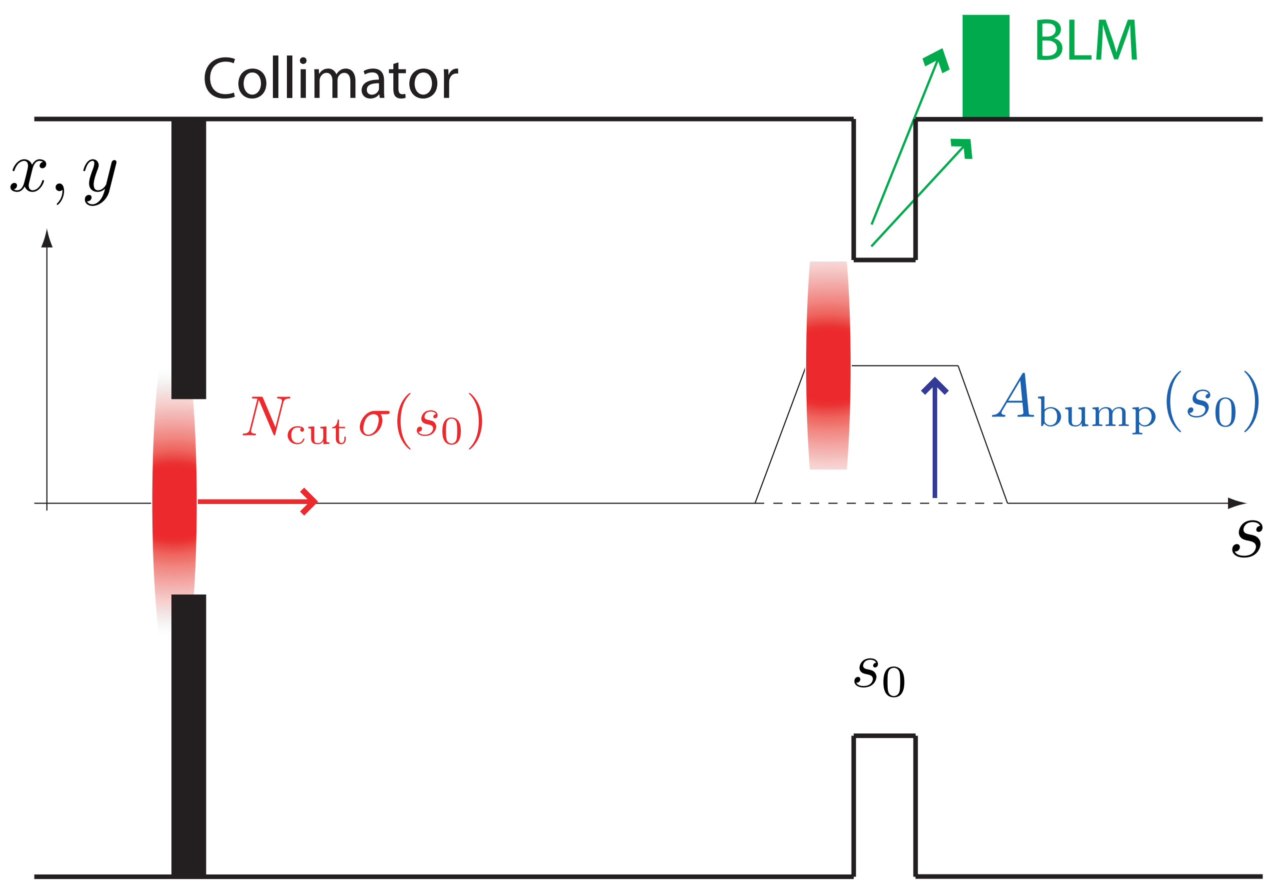
Halo population, response vs. exact location of losses, different response for different magnet types, dependence of readout on loss rate, etc.





2004 collimator at the SPS: BLM's show signal at > 15 σ from the beam core!

Touch the aperture with scraped beams

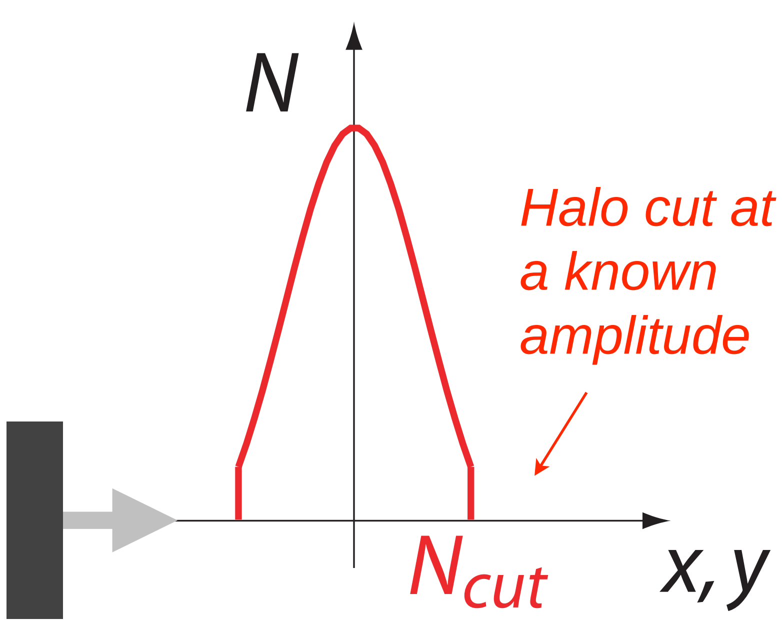


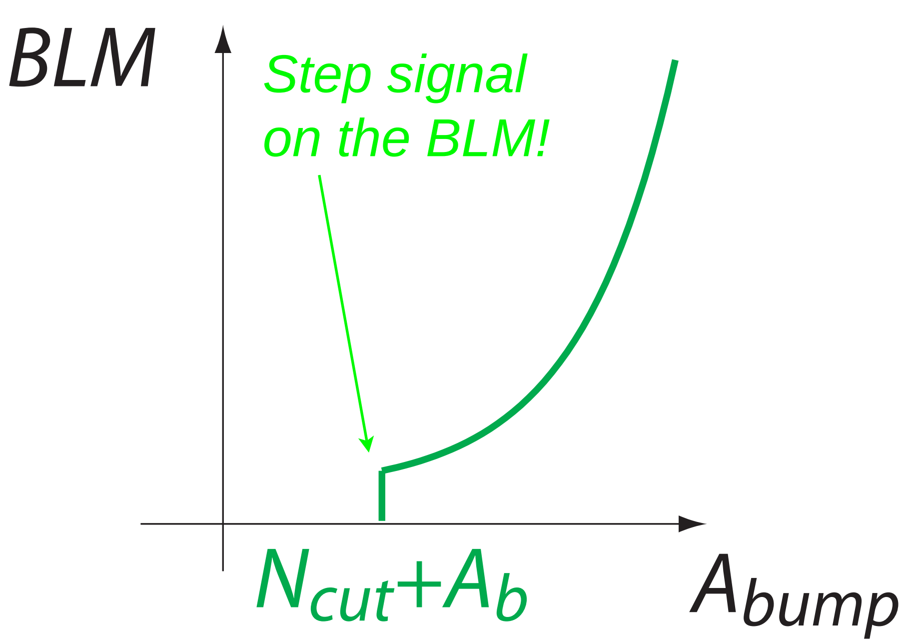
New method proposed for local aperture scans (Ralph, Stefano):

We can use the BLM's for scans with scraped beams!

SPS experience: with the collimator we control precisely N_{cut}.

Bump must be closed (obvious!)

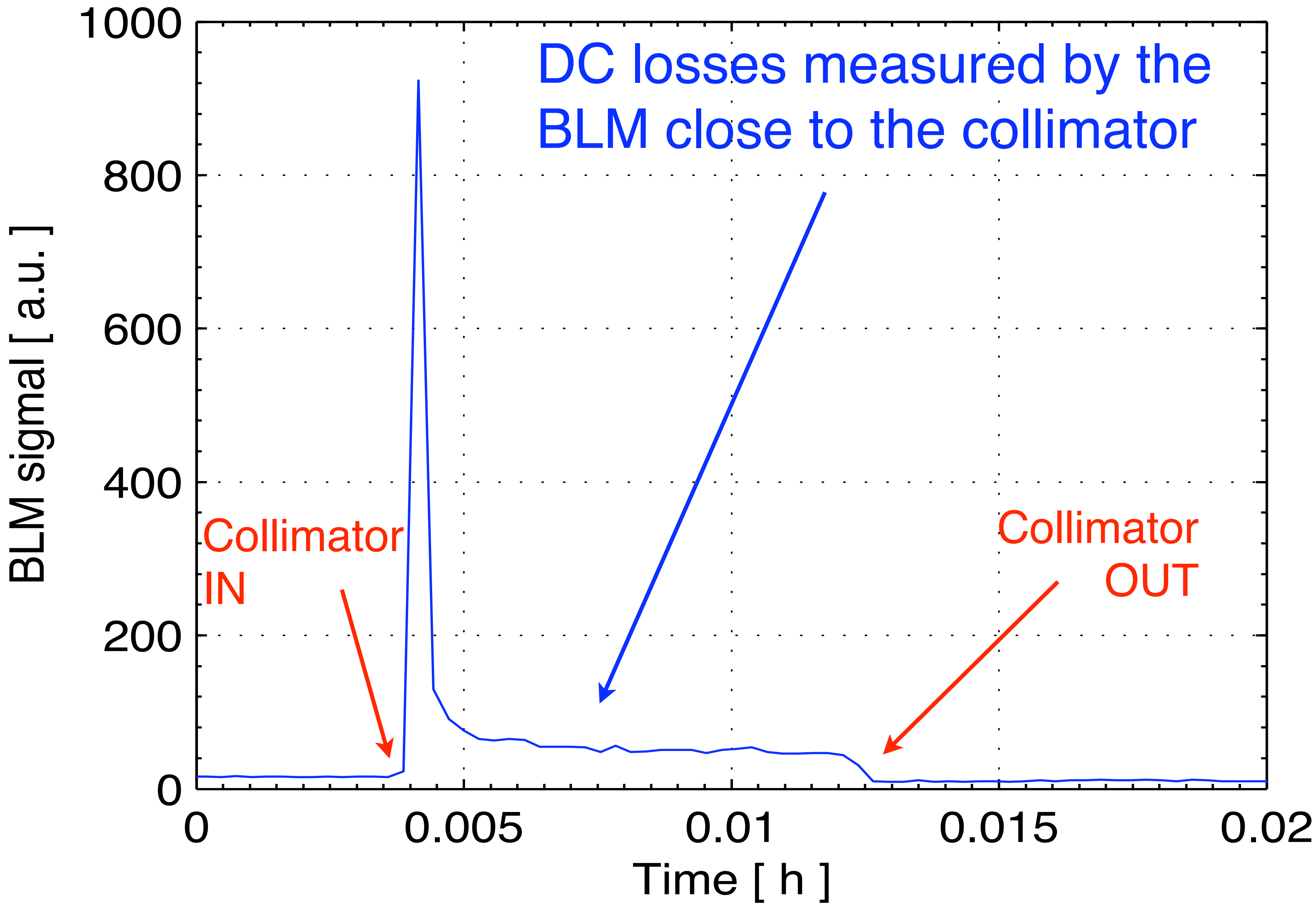


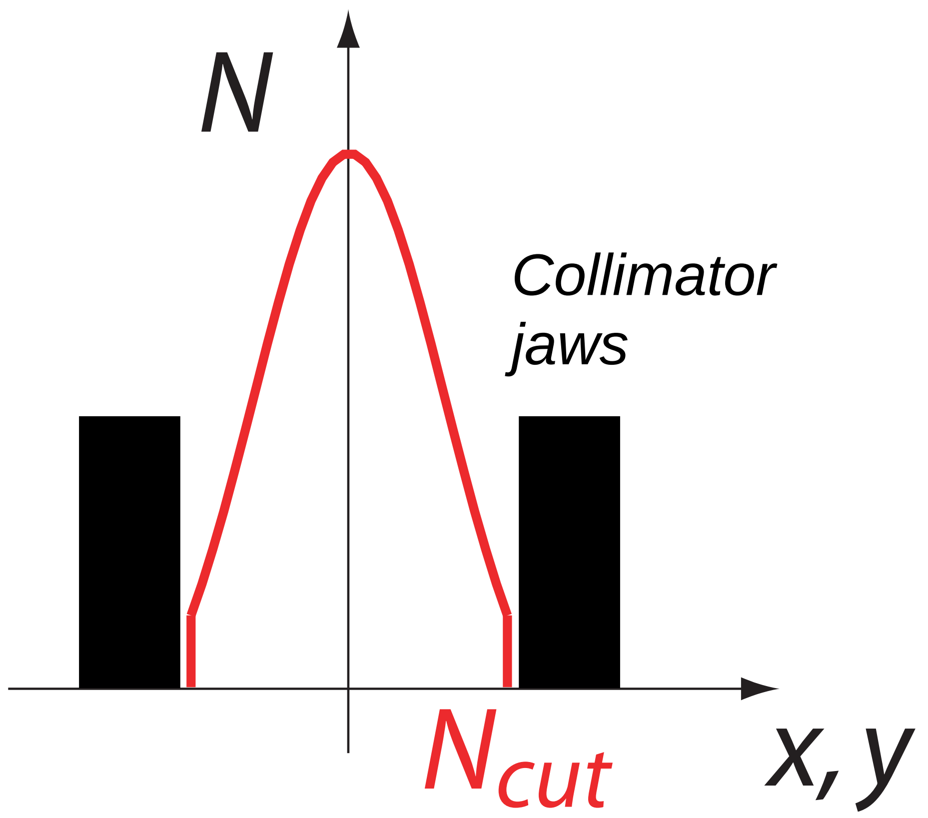


Advantages:

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

Idea from the results of the 2004 SPS test





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.

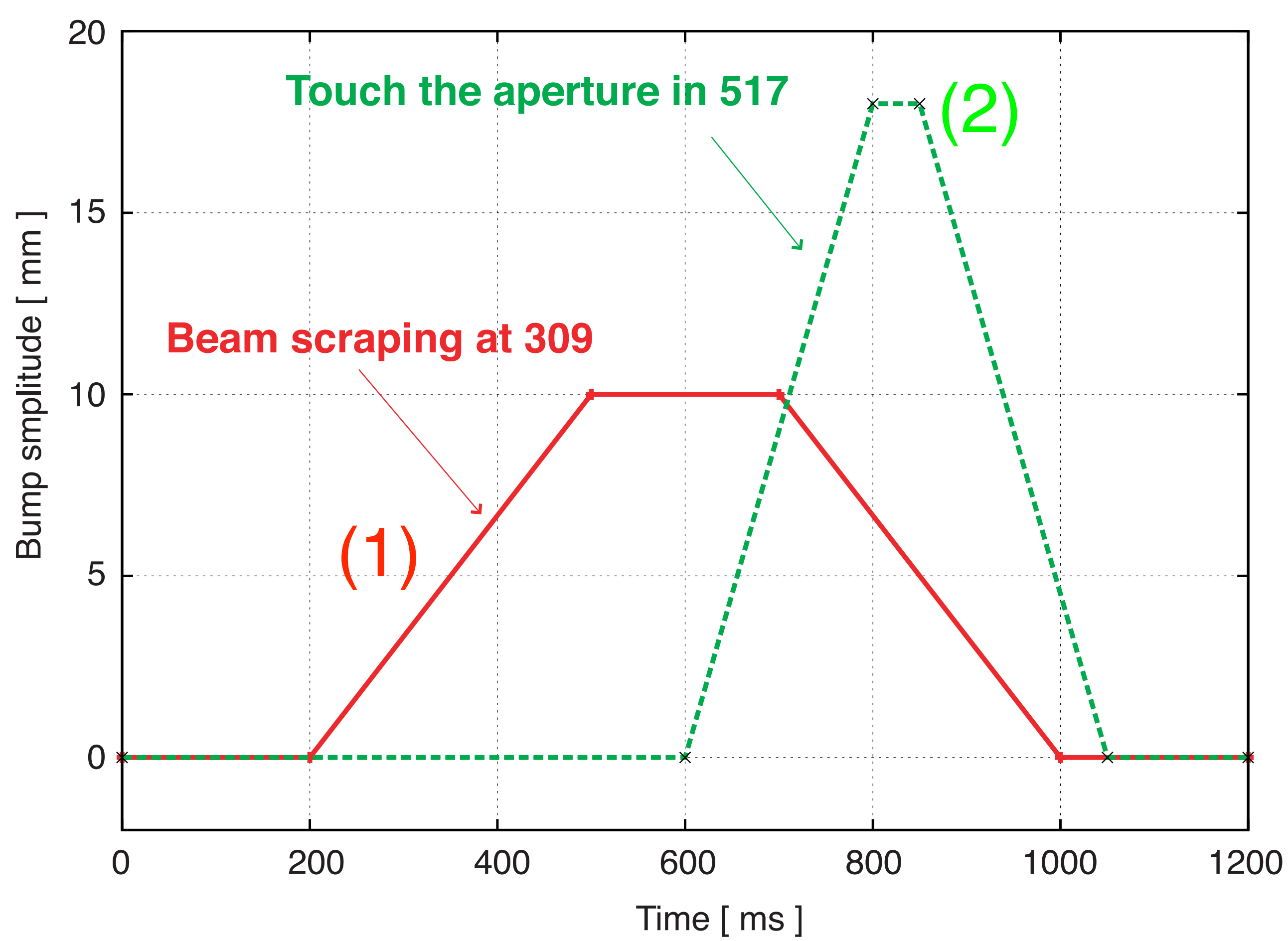
No collimator available - beam scraping done on the aperture!

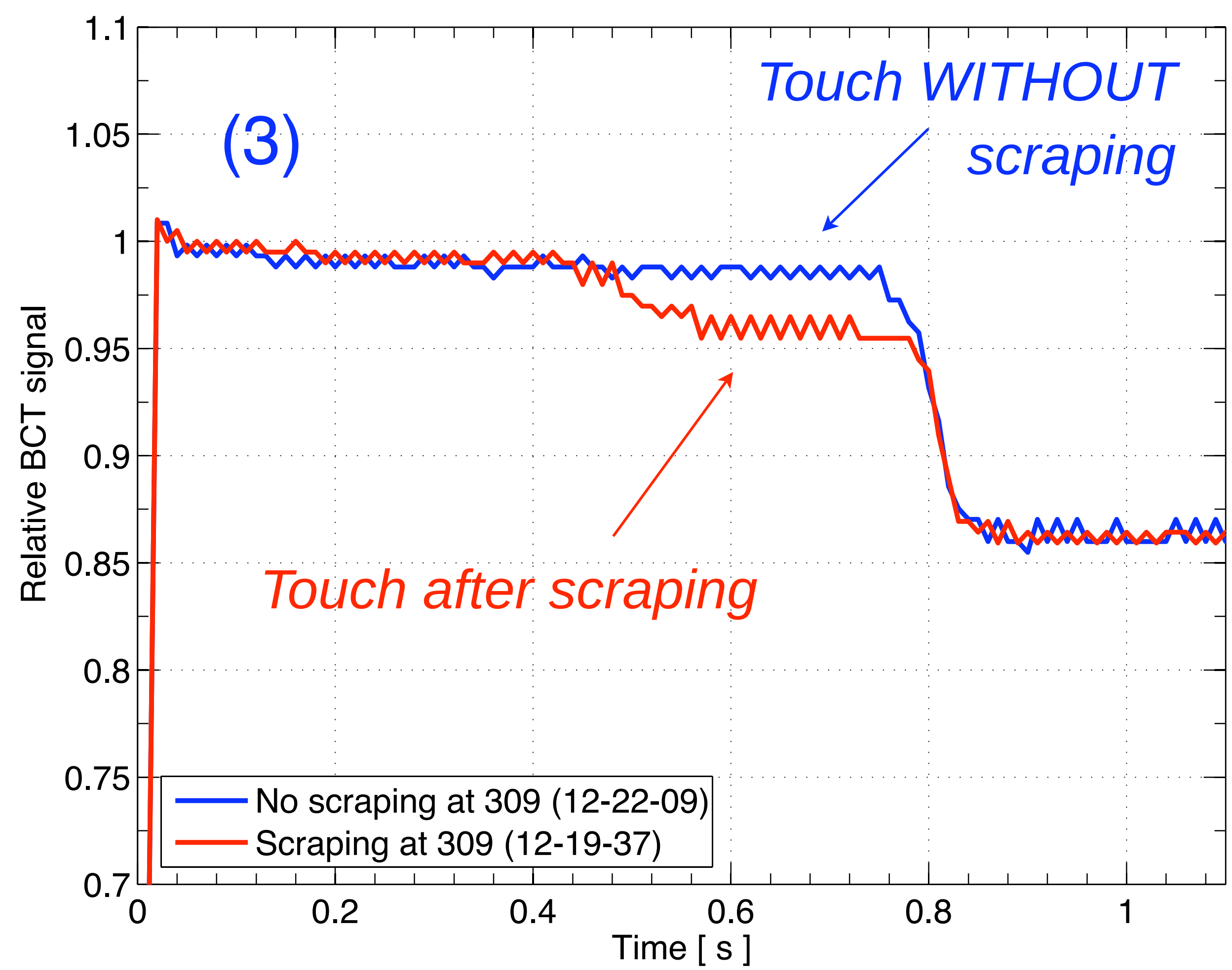
Procedure-Within one cycle (flat bottom~1.2 s), apply closed bumps at two locations:

(1) Scrape the beam by a few percent at a know bottleneck → $N_{cut} \sim 3\sigma$

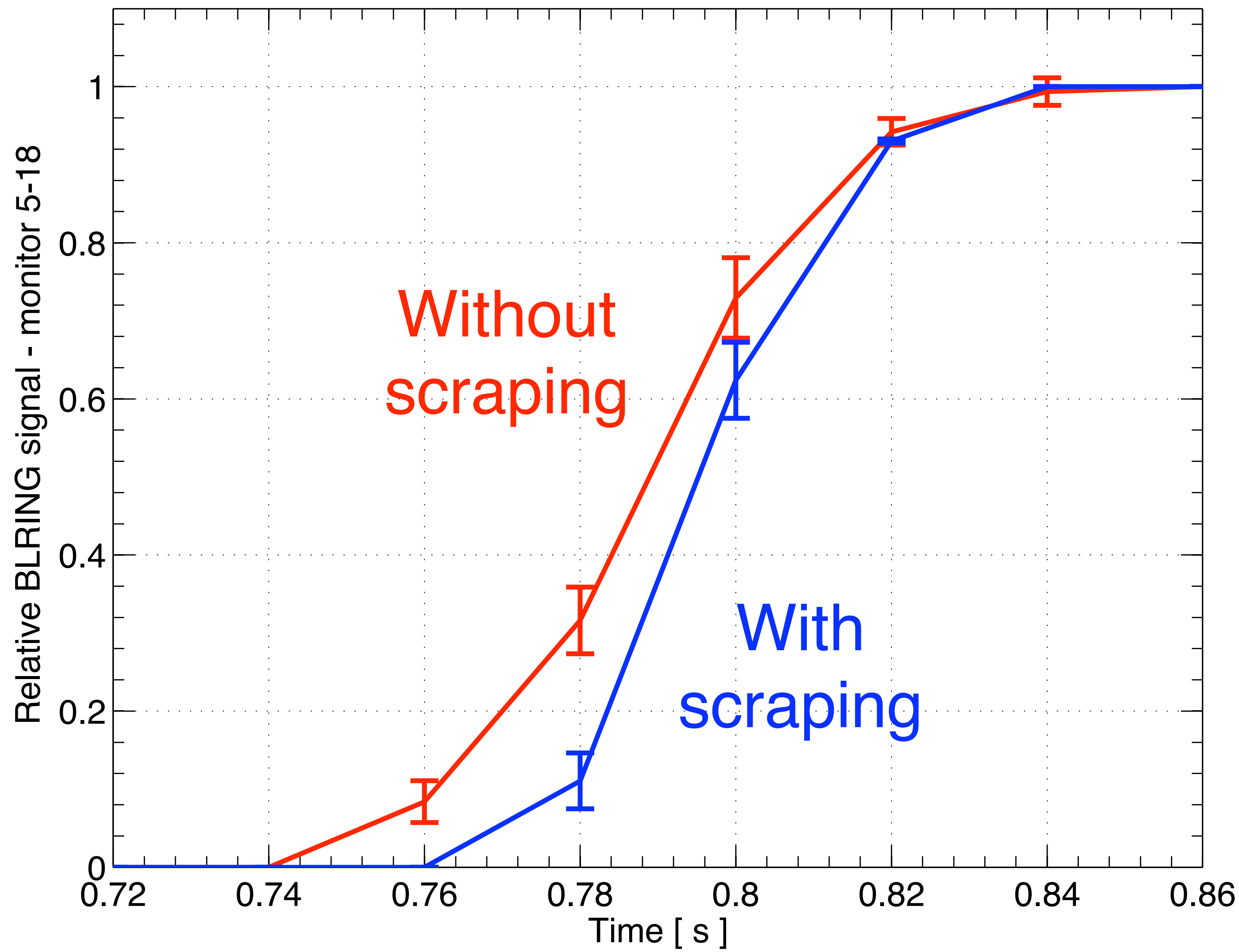
(2) After scraping, start another closed bump to touch the aperture elsewhere

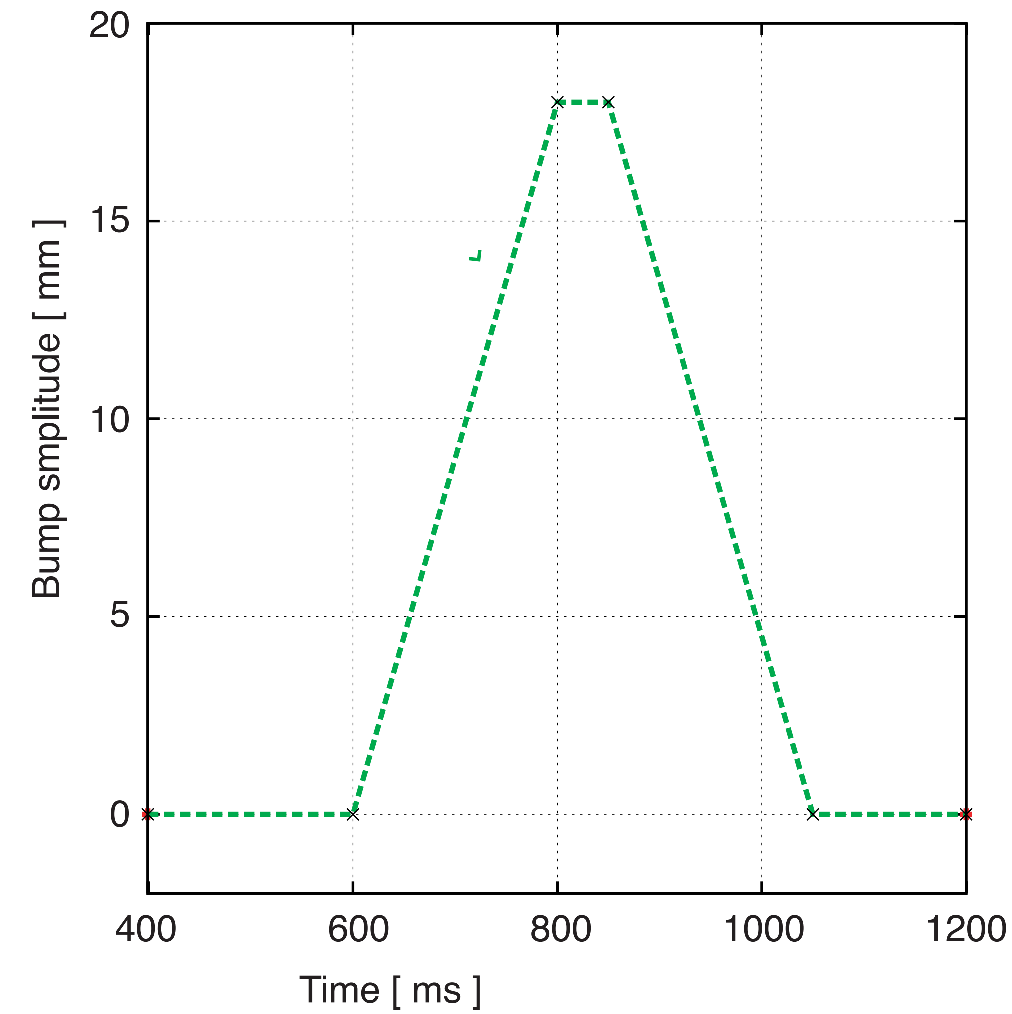
(3) Compare the BLM signal versus bump amplitude with and without scraping





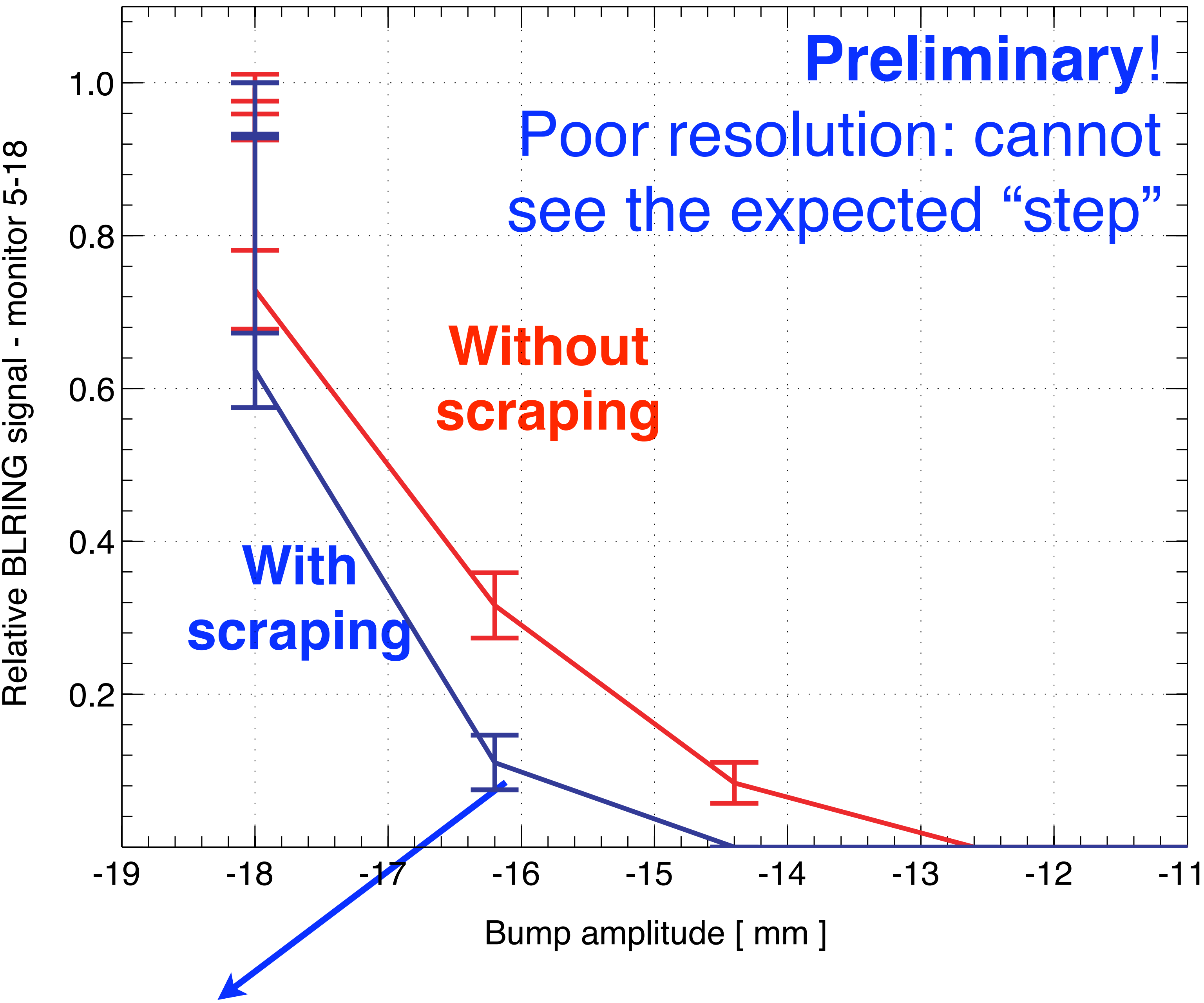
Preliminary measurement results



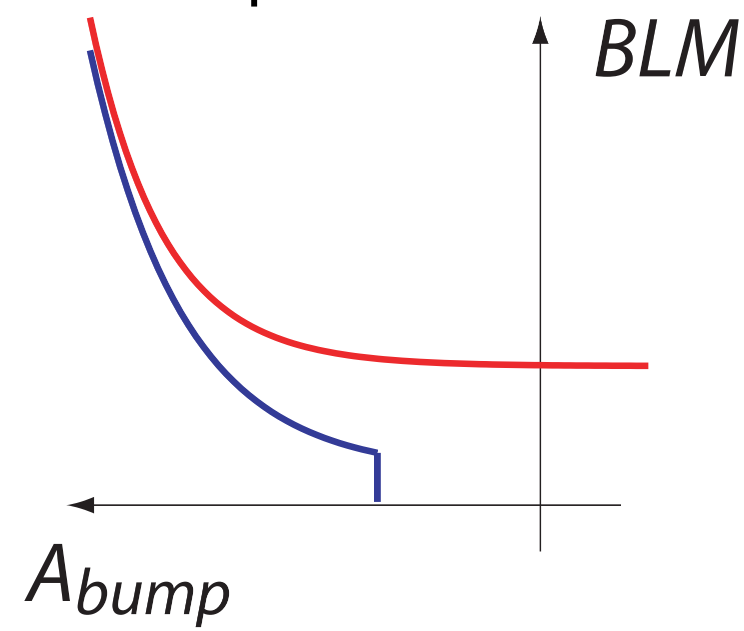


Thanks to F. Follin for setting up a fast acquisition (20ms) of the SPS BLRING!

Preliminary measurement results (cont'd)



Expected:



<u>No scraping</u>: don't know the distance from the beam centre

<u>Scraping</u>: 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

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_{mech} **~ 0.3 h**
  - $A_{mech} > 7.5\ \sigma$ ⇒ STOP!
  - $A_{mech} < 7.5\ \sigma$ ⇒
    - 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:

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

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 BLM > BLM_0"
  - Spatial resolution: $\Delta = 0.1\ \sigma_{inj}$ (move faster below 6σ)
  - Find centre position and set CO there!
- Efficient on-line data analysis (e.g.: plot BLM or BCT vs. A_{bump})

Accuracy of measurement and correction

"Reasonable" goal: **0.2 x σ** [can we relax this at startup?]

Remember that the nominal TCP setting is 5.7σ!

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

Bad for BCT with pilot - Good for scraped beams

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

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

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

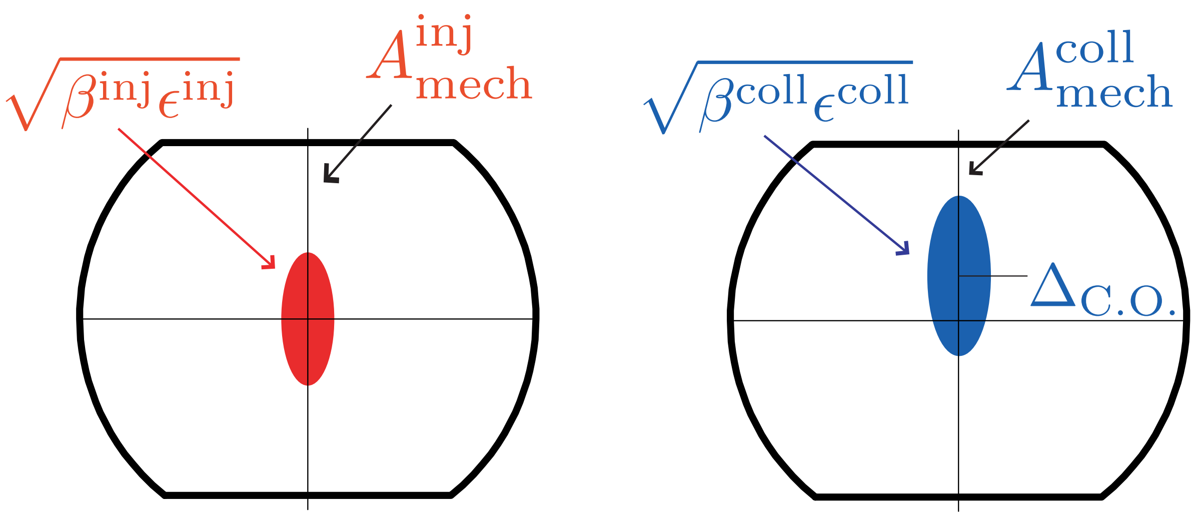
Discuss here a **prioritized list of critical locations**!

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 7 TeV



Ex.: Simplified case with dispersion

$$n_1^{\mathrm{inj}} > \frac{1}{\sqrt{\beta^{\mathrm{inj}}\epsilon^{\mathrm{inj}}}}(7 + \Delta_{\mathrm{C.O.}})\sqrt{\beta^{\mathrm{coll}}\epsilon^{\mathrm{coll}}}$$

$$\Delta_{\mathrm{C.O.}} \approx \frac{2\ \mathrm{mm}}{1.22 \times 1.2 \times \sqrt{\beta^{\mathrm{coll}}\epsilon^{\mathrm{coll}}}}$$

Budget for change during squeeze ~ 2 mm

Additional critical elements should be identified for the various β* + crossing!

Additional measurement locations (cont'd)

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: $\Delta p/p = \pm 1.5\ 10^{-3}$

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

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

Changes up to a few kHz should be possible BUT we have to disable an interlock: |Δf/f |<200Hz. Ok pilot. (Andy, J. Tuckmantel)

Proposed method

Use low-intensity (I ~ 10^9 p) “pencil” beams

Scrape the beams at 1-2σ_H at the SPS or with TCP-H

Scrape Δp/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 ~ 10^9p) "pencil" beams
Scrape the beams at 1-2σ 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 ~ 0.2 σ 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 ...