Transverse emittance measurement and preservation in the LHC chain

CARE-ABI emittance workshop
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F. Roncarolo
Cockcroft Institute and University of Manchester, CERN AB-ABP

Acknowledgements:
Contents

- Introduction
- Transverse emittance instrumentation
- Characterization of LHC beams in all the acceleration chain

Will not cover:
- LHC ion beams
- analysis strategies
- ....
INTRODUCTION
INTRODUCTION

CERN rings and transfer lines
evidenced the ones treated in this presentation
INTRODUCTION

LHC beams transverse emittance

- Proton source
- Initial transverse emittances
  - On purpose emittance manipulation (e.g. shaving, induced blowup)
  - Bunching
    - Acceleration
    - Beam transfer
    - Bunch splitting
- LHC beams emittance at collision
- Lifetime
  - Beam-beam
INTRODUCTION

Sources of (undesired) emittance increase

- various mismatches (injection, betatron, dispersion): any difference between the ‘as-seen-by-the-beam’ and the nominal optics.
- multiplicative (betatron, dispersion mismatch)
- additive (injection mismatch) \(\Rightarrow\) relative effect enhanced at high energies (i.e. low emittance)

Mismatch sources are:
- hardware errors (magnetic errors, misalignment…). Detectable by measuring the elements of the transfer matrix (often linked to profile monitors operation)
- Uncertainties on the ‘initial conditions’ and their dependence on the extraction parameters
- ‘Wrong’ beam energy \(\Rightarrow\) Mismatch between energy setting of the line and beam energy

- beam - residual gas scattering
- collective effects (intra-beam scattering, wake fields, electron clouds, beam-beam) and related instabilities
- working point and resonance crossing
- noise in accelerator systems like transverse damper
- Operation of interceptive diagnostics (!!)
Emittance measurement methods

INTRODUCTION

Geometrical Transverse Emittance

Beam Optics studies providing the transverse emittance as one of the output parameters
Multi-profile measurements, etc...

Other Methods
Schottky detectors...
INTRODUCTION

Typical Machine Development day

PROBLEMS
- The emittance in the accelerator X is:
  - larger than expected
  - larger than in the accelerator X-1

QUESTIONS
- anything wrong in the injection into X
- anything wrong in the extraction from X-1
- anything wrong in the transfer line X-1 to X
- is the emittance constant along the bunch trains
- is the measured emittance correct

ACTIONS
- check machine(s) settings, verify optics
- check instabilities and injection errors (mis-steering)
- measure mismatch
- perform detailed emittance scans
- CHECK DIAGNOSTICS

CHECK DIAGNOSTICS
- parameters setup
  - e.g. gain settings for different beams
    - absolute if measuring a well known beam or probe signal
  - relative to
    - other instruments
    - change in beam parameters
INTRODUCTION

LHC beams parameters

Basic way to assess the dynamic range necessary for the LHC beam types in over all the accelerator chain:

Parameters of probe and nominal beams in all the rings:

<table>
<thead>
<tr>
<th></th>
<th>PS Booster</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inj</td>
<td>Extr</td>
<td>Inj</td>
<td>Extr</td>
</tr>
<tr>
<td>$p$ [GeV/c]</td>
<td>0.31</td>
<td>2.14</td>
<td>2.14</td>
<td>26</td>
</tr>
<tr>
<td>$K$ [GeV]</td>
<td>0.050</td>
<td>1.4</td>
<td>1.4</td>
<td>25.08</td>
</tr>
<tr>
<td>$T_{\text{rev}}$ [µs]</td>
<td>1.67</td>
<td>0.572</td>
<td>2.29</td>
<td>2.1</td>
</tr>
<tr>
<td>Bunches/ring</td>
<td>1</td>
<td>6</td>
<td>72</td>
<td>2-4×72</td>
</tr>
<tr>
<td>$N_b$ [$10^{11}$ p]</td>
<td>NOMINAL</td>
<td>13.8</td>
<td>13.8</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>PROBE BUNCH</td>
<td>0.05 - 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta T_{\text{bunch}}$ [ns]</td>
<td>-</td>
<td>-</td>
<td>326.88</td>
<td>24.97</td>
</tr>
<tr>
<td>$T_b$ [ns]</td>
<td>571</td>
<td>190</td>
<td>190</td>
<td>4</td>
</tr>
<tr>
<td>$\varepsilon_{H,V}$ normalized at 1 sigma [µm]</td>
<td>NOMINAL</td>
<td>&lt;2.5</td>
<td>&lt;3</td>
<td>&lt;3.5</td>
</tr>
<tr>
<td></td>
<td>PROBE BUNCH</td>
<td>&lt;1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Moreover: during LHC operation a number of other beams will be accelerated: pilot bunch, 50ns and 75ns bunch spacing beams, TOTEM beam, beam for MDs etc...
### Requirements for LHC beams

#### Profile measurements in transfer lines

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Reason</th>
<th>Adequate Monitors</th>
<th>Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D profiles</td>
<td>coupling</td>
<td>OTR screens</td>
<td>TT2, TT10, TI2, TI8</td>
</tr>
<tr>
<td>batch and bunch mode</td>
<td>instabilities</td>
<td></td>
<td>TT2, TT10, TI2, TI8</td>
</tr>
<tr>
<td>low energies</td>
<td>profile, emittance</td>
<td></td>
<td>TT2, TT10</td>
</tr>
</tbody>
</table>

#### Profile measurements in rings

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Reason</th>
<th>Adequate Monitors</th>
<th>Rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D profiles</td>
<td>coupling</td>
<td>OTR screens, SyncLight</td>
<td>LHC mainly</td>
</tr>
<tr>
<td>batch and bunch mode</td>
<td>instabilities</td>
<td>OTR screens</td>
<td>SPS, LHC</td>
</tr>
<tr>
<td>single turn</td>
<td>matching</td>
<td>OTR screens</td>
<td>SPS, LHC</td>
</tr>
<tr>
<td>multi-turn (1-20ms)</td>
<td>emittance-matching</td>
<td>WS, IPM, SyncLight, OTR</td>
<td>PSB, PS, SPS, LHC</td>
</tr>
<tr>
<td>Non intercepting</td>
<td>TL and RING simultaneously</td>
<td>IPM, SyncLight</td>
<td>SPS, LHC</td>
</tr>
</tbody>
</table>
### INTRODUCTION

Profile monitoring in transfer line - general

<table>
<thead>
<tr>
<th></th>
<th>pros</th>
<th>cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OTR</strong></td>
<td>2D profile</td>
<td>blow-up depends on thickness</td>
</tr>
<tr>
<td></td>
<td>good resolution</td>
<td>aging, finite lifetime</td>
</tr>
<tr>
<td></td>
<td>no dependence on thickness</td>
<td>not available at low energies</td>
</tr>
<tr>
<td></td>
<td>good linearity</td>
<td>background filtering / calibration</td>
</tr>
<tr>
<td><strong>SEM wire/ grids</strong></td>
<td>good at low energies</td>
<td>damaging for high intensities</td>
</tr>
<tr>
<td></td>
<td>in general less blow-up than screens</td>
<td>resolution (wire or grid distance)</td>
</tr>
</tbody>
</table>

I'll list similar remarks on profile monitoring for rings in the LHC overview
### Profile monitors park - from PSB to SPS

$v=$wire speed, $d=$wire diameter (or strips/screen thickness), $b=$wire (or strips) distance, $s=$strips width

<table>
<thead>
<tr>
<th>MONITOR</th>
<th>FEATURES</th>
<th>USE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PSB Rings (1 to 4)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 WS (1 /ring/plane)</td>
<td>$v = 10-20 \text{ m/s}$, $d=30\mu m$</td>
<td>emitt. of PSB bunches during ramp and before transfer to the PS</td>
</tr>
<tr>
<td><strong>Measurement line</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 SEM grids (3 /plane)</td>
<td>wires, $d=40\mu m$ (b=1-1.5 \text{ mm})</td>
<td>cross calibration of WS</td>
</tr>
<tr>
<td><strong>PS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 WS (2 /plane)</td>
<td>$v = 10-20 \text{ m/s}$ (d = 30 \mu \text{m})</td>
<td>emittance before and after splitting, monitor blow-up during acceleration</td>
</tr>
<tr>
<td>8 SEM grids (4 /plane)</td>
<td>wires, $d=40\mu m$ (b=1-2 \text{ mm})</td>
<td>cross calibration of WS, matching at injection</td>
</tr>
<tr>
<td><strong>TT2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 SEM grids (3 /plane)</td>
<td>wires, $d=40\mu m$, $b=0.5 \text{ mm}$ (s=1-2 \text{mm}, b=2.5 \text{ mm})</td>
<td>monitor blowup during ramp in PS, bunch rotation, matching (not for nom. beam, see spare slides)</td>
</tr>
<tr>
<td>1 OTR</td>
<td>$Ti d=12 \mu m$ or $C d=100 \mu m$</td>
<td>matching</td>
</tr>
<tr>
<td><strong>TT10</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 SEM grids (3 /plane)</td>
<td>strips, $d=7\mu m$, $s=0.7 \text{mm}, b=1.8 \text{ mm}$</td>
<td>matching</td>
</tr>
<tr>
<td>4 OTRs</td>
<td>$Al d=1 \text{mm}, Ti d=12 \mu m$, $Mylar d=25 \mu m$</td>
<td>matching</td>
</tr>
<tr>
<td><strong>SPS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 OTR screens</td>
<td>$Al d=1 \text{mm}, Ti d=12 \mu m$, $Mylar d=25 \mu m$</td>
<td>single turn and multi turn matching (filamentation)</td>
</tr>
<tr>
<td>10 WS (5 /plane)</td>
<td>$v=0.4 \text{ m/s (linear)}, 6\text{m/s (rotational)}$ (d=30\mu m)</td>
<td>emittance before and after acceleration</td>
</tr>
<tr>
<td>IPM</td>
<td>CCD camera 20ms, data storage 40 ms</td>
<td>continuous measurement during long cycles, blow-up during ramp</td>
</tr>
</tbody>
</table>
Predictable emittance increase

- mismatch
- operation of diagnostics - Multiple Coulomb Scattering
EMITTANCE BLOW-UP SOURCES

Mismatch

During injection, any difference between the nominal (expected) optics and what seen by the particles in reality causes an emittance increase due to filamentation.

Injection mismatch

\[
\frac{\Delta \varepsilon*_{af}}{\varepsilon*} = \frac{\Delta X^2 + \Delta X^2}{2\varepsilon*} \beta \gamma
\]

- static errors can be corrected by adequate monitoring and correction
- transverse feedback -if available- is used for minimizing cycle-by-cycle variations
- the effect increases with the beam energy (factor $\beta \gamma$)

$\Delta = \text{orbit and angle deviation from model}$

$X_n, X'_n = \text{normal phase space coordinates}$

Betatron mismatch

\[
\frac{\Delta \varepsilon*_{af}}{\varepsilon*} = \frac{1}{2} \left[ \frac{\beta_0}{\beta_m} + \frac{\beta_m}{\beta_0} + \left( \alpha_0 \sqrt{\frac{\beta_m}{\beta_0}} - \alpha_m \sqrt{\frac{\beta_0}{\beta_m}} \right)^2 \right]
\]

- uncertainty on the Twiss parameters at the beginning of a transverse line and errors along the line translate into ‘wrong’ optics at the downstream accelerator injection

$0 = \text{MODEL}$

$m = \text{MEASURED}$

Dispersion mismatch

\[
\frac{\Delta \varepsilon*_{af}}{\varepsilon*} = \left( \frac{\Delta D^2_n + \Delta D^2_n}{2 \varepsilon*} \right) \beta \gamma
\]

- this is a term particularly critical for LHC beams with small transverse emittance and relatively large momentum spread

$\Delta = \text{difference between model and measured}$

Proper measurement of transverse emittance along transfer lines and at injection is fundamental for trying to attribute mismatch sources
EMITTANCE BLOW-UP SOURCES

Multiple Coulomb scattering

Scattering of charged particles traversing a material is dominated by Coulomb scattering

\[ \theta_{rms} = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{\frac{d}{L_{\text{rad}}}} \left[ 1 + 0.038 \ln \left( \frac{d}{L_{\text{rad}}} \right) \right] \]

Scattering angle (RMS) of a particle with momentum \( p \) traversing a material with characteristic radiation length \( L_{\text{rad}} \) and thickness \( d \)

Better than 11% for:

\[ 10^{-3} < \frac{d}{L_{\text{rad}}} < 100 \]

But e.g.: SPS wire scanners carbon wires and protons, for which

\[ \frac{d}{L_{\text{rad}}} \approx 1.5 \times 10^{-4} \]

N.B.: the logarithmic term is not negligible!

In their publication Lynch and Dahl also propose another approximation (apparently less popular) where RMS scattering angle is calculated as

\[ \theta'_{rms} = 2.557 \chi_{cc} \frac{\sqrt{d}}{p c \beta^2} \]

\[ \chi_{cc}^2 = (0.3961 \cdot 10^{-3})^2 \frac{Z}{A} \frac{p}{[\text{GeV}^2 \text{cm}^{-1}]} \]

Used for WS studies in the SPS and for predicting emittance increase in all CERN screens

Starting from Moliere’s theory (1947)

- V.L. Highland, Nucl. Instr. and Meth. 129 (1975)
Experimental measurements of mismatch and blow-up
MISMATCH EXAMPLES

TT2-TT10 Dispersion mismatch  Courtesy of E. Benedetto

Horizontal dispersion measurements 31-7-2007

Changes in the optics were needed in order to extract form the PS without QKE58

Mismatched optics

Optics re-matched from fit on the measurements

Theor disp in the SPS

Measured points

Theoretical value in the SPS
MISMATCH EXAMPLES

TT10-SPS injection mismatch

Case of injection mismatch at the SPS injection, as measured by multi-turn OTR acquisition

Emittance blow-up after filamentation

Courtesy of E. Benedetto
MISMATCH EXAMPLES

TT10-SPS betatron mismatch

During multi-turn acquisition the measured blow-up (accounting for uncertainty on the screen foil thickness) is well in agreement with predicted

\[ \text{blow-up from mismatch} + \]
\[ \text{blowup from MC scattering} \]

\( H = \frac{\Delta \varepsilon}{\varepsilon} \)

\( \text{due to mismatch} \)
\( \text{due to MC scattering} \)
EMITTANCE BLOW-UP SOURCES

Multiple Coulomb scattering - WS in the SPS

- BWS517V
- LHC Pilot bunch
- P=26 GeV

![Graphs showing data and predictions](image)

<table>
<thead>
<tr>
<th>Predictions from:</th>
<th>( \theta_{\text{max}} = \frac{13.6 \text{ MeV}}{\beta p} \sqrt{\frac{d}{L_{\text{rad}}}} \left[ 1 + 0.038 \ln \left( \frac{d}{L_{\text{rad}}} \right) \right] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>- (1)</td>
<td></td>
</tr>
<tr>
<td>- (2)</td>
<td></td>
</tr>
<tr>
<td>- (3)</td>
<td>( \theta_{\text{max}} = 2.557 \sqrt{\frac{d}{\beta p \gamma_0}} )</td>
</tr>
</tbody>
</table>

N.B.:
- blow-up 48 nm \( \approx \) 20 % of the initial emittance!
Emittance diagnostics

- Quick review about (some of) the used profile monitors
**DIAGNOSTICS**

**Wire Scanners**

- **Linear** movement (SPS)
- **Rotational** to Linear Movement (PSB, PS, SPS)
- 30 μm carbon wires
- speeds from 0.4 to 20 m/s
- wire position: motor encoders (PSB, PS, SPS), potentiometers (SPS)
- Signal amplitude PM, SEM grids
DIAGNOSTICS

Ionization Profile Monitor

- Profits from the ionization–induced by the beam of the residual gas

Primary electrons accelerated by high voltage
- MCP plate
- Phosphor
- Optical system
- CCD camera

- One image can be acquired every 20ms
- 1 IPM in the SPS (+1 in 2006)
- 4 IPMs will installed in LHC
  - 1 per plane per beam

Beam Profile by summing the lines
BTV

Scintillating screens or OTR screens

TV camera detector

= 2D beam image

**DIAGNOSTICS**

**Requirement/issue** | **Need** | **Equipment**
--- | --- | ---
interceptive, limited lifetime | inserted only during dedicated measurement periods | actuator
calibration, inspection | images without beam | illumination system
cover dynamic range | sensitivity with different beam size and intensity | neutral optical filters

... and the LHC started
Characterization of emittance measurement diagnostics

- Accuracy and reproducibility studies
Diagnostics
PSB Wire Scanners calibration
Ring1, measurements with new (LHC type) electronics

<table>
<thead>
<tr>
<th>Good reproducibility</th>
<th>Reproducibility studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>No wire speed/beam size dependence</td>
<td>Beam intensity =3.5e12 p</td>
</tr>
<tr>
<td>Measured beam pos. moving with wire speed</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Center (hor. scan)</td>
<td>15.213 ± 0.084</td>
</tr>
<tr>
<td>Sigma (hor. scan)</td>
<td>3.840 ± 0.025</td>
</tr>
<tr>
<td>Center (vert. scan)</td>
<td>7.464 ± 0.036</td>
</tr>
<tr>
<td>Sigma (vert. scan)</td>
<td>2.722 ± 0.010</td>
</tr>
</tbody>
</table>

Accuracy studies: comparison w.r.t. SEM grids, on the same bunch

<table>
<thead>
<tr>
<th>Vertical:</th>
<th>Beam intensity =8.5e12 p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central agreement with SEM grid (Dx correct?)</td>
<td>Hor. emittance (WS)</td>
</tr>
<tr>
<td>10 m/s</td>
<td>6.3</td>
</tr>
<tr>
<td>15 m/s</td>
<td>5.2</td>
</tr>
<tr>
<td>20 m/s</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Courtesy of B. Mikulec

see also: minutes of the CERN-APC Meeting, November 14th, 2008
PS Wire Scanners

Comparison between old (FWSV85) and new (BWS65W) LHC type electronics

New system not fully calibrated yet
1-systematic difference between old and new system: ~ 27 %

assuming:
- stable beam during the measurements
- perfect optics (same at the two locations)

2-much better reproducibility on beam pos, almost equal on beam size

<table>
<thead>
<tr>
<th></th>
<th>BWS65V</th>
<th>FWSV85</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>sigma</td>
<td>Position</td>
</tr>
<tr>
<td>m1</td>
<td>-2.937</td>
<td>0.454</td>
</tr>
<tr>
<td>m2</td>
<td>-2.880</td>
<td>0.462</td>
</tr>
<tr>
<td>m3</td>
<td>-2.930</td>
<td>0.531</td>
</tr>
<tr>
<td>m4</td>
<td>-2.910</td>
<td>0.520</td>
</tr>
<tr>
<td>m5</td>
<td>-2.900</td>
<td>0.525</td>
</tr>
</tbody>
</table>

Average: -2.911, 0.498, 2.790, 0.636
std dev.: 0.023, 0.037, 0.228, 0.053

Reproducibility: 7.5 %, 8.3 %

Normalized emittances for LHC beams of different intensities

using old electronics, see also: minutes of the CERN-APC Meeting, s Jun 20th and Nov 14th, 2008
SPS WS calibration via beam based measurements

**LINEAR WIRE SCANNERS:** comparison of 2 monitors

- Measurements with low emittance beam, vertical plane
- 3 measurement periods during which the theoretical emittance increase was compared to the experimental results

  **Period 1:** Two monitors used **simultaneously**
  **Period 2:** Two monitors used **individually** (few minutes after Period 1)
  **Period 3:** Two monitors used **individually** (several weeks before Period 1 and 2)

<table>
<thead>
<tr>
<th>Period</th>
<th>Monitor 1</th>
<th>Monitor 2</th>
<th>$\Delta \varepsilon_m$ [nπm]</th>
<th>$\Delta \varepsilon_m - \Delta \varepsilon_{mc}$ [nπm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Entries</td>
<td>$\mu$</td>
<td>$\sigma/\sqrt{N}$</td>
<td>$\sigma/\sqrt{2}$</td>
</tr>
<tr>
<td>Period 1</td>
<td>BWS517V</td>
<td>19</td>
<td>79</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>BWS521V</td>
<td>19</td>
<td>73</td>
<td>3</td>
</tr>
<tr>
<td>Period 2</td>
<td>BWS517V</td>
<td>9</td>
<td>37</td>
<td>3</td>
</tr>
<tr>
<td>Period 3</td>
<td>BWS517V</td>
<td>25</td>
<td>39</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>BWS521V</td>
<td>26</td>
<td>41</td>
<td>2</td>
</tr>
</tbody>
</table>

Repeatability in terms of beam size

- 10 μm for BWS517V
- 6 μm for BWS521V

**SYSTEMATIC ERROR**

$$\Delta \varepsilon_m - \Delta \varepsilon_{mc} = -1 \pm 4 \text{nπm}$$

**ROTATIONAL WIRE SCANNERS:** comparison of 3 monitors w.r.t. LINEAR (used as reference)

<table>
<thead>
<tr>
<th>Relative Emittance Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before IN/OUT Correction</td>
</tr>
<tr>
<td>After IN/OUT Correction</td>
</tr>
<tr>
<td>Scans at t=0.5 s</td>
</tr>
<tr>
<td>Scans at t=1.5 s</td>
</tr>
</tbody>
</table>

Repeatability in terms of beam size

- 33 – 42 μm

**SYSTEMATIC ERROR**

- 4 – 37 %
SPS WS versus IPM

YEAR 2003: 
- CIRCULATING BEAM, p=26 GeV, Beam losses along time --> emittance decrease

YEAR 2004: 
- START OF ACCELERATION
- PULSED BEAM, ACCELERATION FROM 26 TO 450 GeV
- < 2 %
- &gt; 175 %

Wrong IPM settings for the initial high intensity
Proper IPM settings, good agreement with WS for all intensities
Transverse emittance of LHC beams
LHC BEAMS EMITTANCES
PSB Ring-by-Ring emittances

**Ring-by-Ring variation**
- bunch-by-bunch variation in the LHC
  - Max ~ 50% (RING4-RING1 Hor)
  - Possible reasons:
    - Beam
    - Optics
    - Wire scanner calibration
    - Data treatment

**WS - SEM GRIDS difference**
- Max ~ 50% (RING4)
  - (assuming reproducible beam as proved by statistics)
  - Possible reasons:
    - Wire scanner calibration
    - SEM grids calibration
    - Data treatment

**LHC 25ns beam, half of nominal intensity**

**Transverse emittance measurements**

<table>
<thead>
<tr>
<th>YEAR 2008</th>
<th>Transverse emittance measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary table on 1/2 of nominal intensity (WS and SEM)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ring</th>
<th>$\epsilon_x$ ($\mu$m)</th>
<th>$\epsilon_y$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>1.2</td>
<td>0.95</td>
</tr>
<tr>
<td>Ring 2</td>
<td>1.1</td>
<td>0.95</td>
</tr>
<tr>
<td>Ring 3</td>
<td>1.8</td>
<td>1.35</td>
</tr>
<tr>
<td>Ring 4</td>
<td>1.15</td>
<td>1</td>
</tr>
</tbody>
</table>

**SEM grids in extraction line** (extract 1 ring at a time)

<table>
<thead>
<tr>
<th>Ring</th>
<th>$\epsilon_x$ ($\mu$m)</th>
<th>$\epsilon_y$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ring 2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ring 3</td>
<td>0.9</td>
<td>1</td>
</tr>
<tr>
<td>Ring 4</td>
<td>1.15</td>
<td>1</td>
</tr>
</tbody>
</table>

WS shows values about (1.5, 1.35) higher than SEM grids: suspect wrong calibration of the WS

**Courtesy of G. Rumolo**

see also: minutes of the CERN-APC Meeting, August 15th, 2008
Emittance evolution in the LHC injectors

Measurement of a LHC batch \((N_{\text{bunch}}=1.3 \times 10^{11} \text{p})\) from the PSB to the SPS

![Graphs showing horizontal and vertical emittance](image)

Vertical error bars: error on the mean
Horizontal error bars: just the histogram beam width (should take them out)

These measurement bars, dedicated to verify the emittance preservation was performed with WS in all rings and gave very consistent results \(\text{(not always the case!)}\)

Same data analysis tools \(\text{(not always the case!)}\)
LHC BEAMS EMITTANCES

LHC beam at SPS extraction

WS Measurements of LHC nominal beam at SPS extraction energy, while injecting multiple batches of 72 bunches

Almost within specs
Beams other than nominal - as measured in 2004

Pilot bunch is low intensity and very small. These results prove that

- Betatron and dispersion mismatch
- Injection errors (more important for small beams)

are well under control
LHC BEAM EMITTANCE

Beams other than nominal - as measured in 2004

75 ns BEAM HORIZONTAL

75 ns BEAM VERTICAL

Beam prepared for early runs for reducing electron cloud effects and for delivering appropriate non-uniform luminosity at the 4 LHC experiments

May be replaced by a 50ns bunch spacing beam
<table>
<thead>
<tr>
<th>Monitor</th>
<th>Main features</th>
</tr>
</thead>
<tbody>
<tr>
<td>xx OTR screens</td>
<td>Matching, 2D images</td>
</tr>
<tr>
<td>LHC RING</td>
<td></td>
</tr>
<tr>
<td>OTR screen</td>
<td>Matching, 2D images, equipped with fast camera for turn-by-turn acquisition</td>
</tr>
<tr>
<td>8 Wire Scanners</td>
<td>reference method, linear devices at 1m/s (upgrade to 2 m/s foreseen)</td>
</tr>
<tr>
<td>2 /plane /beam (operational)</td>
<td>at 1m/s, can be used with 25% (inj energy) and 6% (collision energy) of total</td>
</tr>
<tr>
<td>2 spare /plane /beam</td>
<td>intensity</td>
</tr>
<tr>
<td>8 Wire Scanners (installed)</td>
<td>bunch-by-bunch acquisition</td>
</tr>
<tr>
<td>4 IPM monitors</td>
<td>primarily designed for LHC Ion runs, used forseen with protons (gas injection)</td>
</tr>
<tr>
<td>1 /plane / beam</td>
<td>needs calibration w.r.t. WS at low intensity</td>
</tr>
<tr>
<td>2 synchrotron light monitors</td>
<td>non perturbative, 2D images</td>
</tr>
<tr>
<td>1 / plane</td>
<td>works with undulator below ~1TeV and light from D3 dipole above</td>
</tr>
<tr>
<td>4 Schottky monitors</td>
<td>needs calibration w.r.t. WS at low intensity</td>
</tr>
<tr>
<td>1 / beam /plane</td>
<td>non-perturbative</td>
</tr>
<tr>
<td>4 Schottky monitors</td>
<td>tune, chromaticity and emittance at the same time</td>
</tr>
<tr>
<td>1 / beam /plane</td>
<td>need calibration w.r.t. WS or other beam based methods</td>
</tr>
</tbody>
</table>
One final remark

Tevatron Sync.Light - WS calibration:
many studies performed, tens of notes in the FNAL ‘Beams DocDB’

- last public document I found:
Randy M Thurman-Keup, Beams-doc-1975-v2 (revised in Jan 2008),


shows discrepancies between the two monitor systems that were reduced during the years but remain well above 10% in many cases.
SPARE
WS Measurements with stored beam

- Example of Wire Scanner measurements with low emittance beam in “coast”

![Graph showing correlation between emittance increase and number of scans]

- Correlation between emittance increase and number of scans
- Almost 100% of the blow-up can be attributed to the operation of the WS monitor

These studies have been selected by an international committee for an oral presentation at the Particle Accelerator Conference in Knoxville, Tennessee, June 2005.
Silicon Carbon wires

With laboratory measurements we verified that SiC wires are less sensible to EM coupling, two wire were installed and ....

Wire scan measurement: wire broke during the scan !!
Carbon wire breaking to RF coupling is reported in the thesis
UNCERTAINTIES

Momentum spread and dispersion
UNCERTAINTIES

Wrong IPM settings for high intensity beam
Figure 3. Transverse beam profile from a Secondary Emission Monitor in the PS to SPS transfer line vs. bunch length. Top: nominal LHC beam with bunch rotation (full bunch length = 4 ns). Bottom: LHC beam without bunch rotation (full bunch length = 16 ns).
MISMATCH EXAMPLES

TT10-SPS betatron mismatch

- during multi-turn acquisition the measured blow-up (accounting for uncertainty on the screen foil thickness) is well in agreement with predicted

  blow-up from mismatch
  +
  blowup from MC scattering

VERTICAL

\[ H = \Delta \varepsilon / \varepsilon \]

Courtesy of E. Benedetto

Emittance

\[ \sigma_y \]

\[ x \times 10^{-3} \]

\[ 2 \times 10^{-3} \]

\[ 2 \]

\[ 1.9 \]

\[ 1.8 \]

\[ 1.7 \]

\[ 1.6 \]

\[ 1.5 \]

\[ 0 \]

\[ 20 \]

\[ 40 \]

\[ 60 \]

\[ 80 \]

\[ 0 \]

\[ 10 \]

\[ 20 \]

\[ 30 \]

\[ 40 \]

\[ 50 \]

\[ 60 \]

\[ 70 \]

\[ 80 \]
WS BPM calibration

Monitors in: v519, LHC Beam

- Mean_IN
- Mean_DATA_IN
- Mean_OUT
- Mean_DATA_OUT

Expected Pos. at WS [mm]

WS/BPM

- FT BEAM
- LHC BEAM
- TOTEM BEAM
EMITTANCE MEASUREMENT METHODS
Profile monitors park - LHC

<table>
<thead>
<tr>
<th>SPS to LHC</th>
<th>MONITOR</th>
<th>MAIN FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TI2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TI8</td>
<td></td>
</tr>
</tbody>
</table>

| LHC | XX WS |                |
|     | XX IPM|                |
|     | SincLight |           |

See also SLIDES #34-35