Beam Profile Monitors
Based on Residual Gas Interaction
Peter Forck, Alexander Bank, Tino Giacomini, Andreas Peters
Gesellschaft für Schwerionenforschung, Darmstadt
DIPAC 2005, Lyon

Basics on physics, technical realizations and some applications for:

1. Beam Induced Fluorescence BIF
2. Ionization profile monitor IPM (equivalent to Residual Gas Monitor RGM)
3. Comparison between BIF and IPM

Methods are mainly used at proton and ion accelerators.
Non-intercepting Profile Measurement based on Energy Loss

Standard monitors: SEM-Grid, Wire-Scanner, Scintillation Screen, OTR-Screen…

Disadvantage: intercepting,
problems for time-varying processes

**Non-intercepting** profile measurement:

- Large beam power can destroy the material
- **Synchrotron**: Monitoring during **full** cycle
- **LINAC**: Monitoring at different locations,
  variation during the macro-pulse

**Physics**: electronic stopping power

Bethe-Bloch formula:

\[-\frac{dE}{dx} = const \cdot \frac{Z_t \rho_t}{A_t} \cdot \frac{Z_p^2}{1/\beta^2} \cdot \left( \ln(const \cdot \gamma^2 \beta^2 / I) - \beta^2 \right)\]

Target e⁻-density
Strong dependence on projectile charge
⇒ Profile determination from ionization and excitation of *residual* gas.

M. Plum et al.:
\[p\text{ in } N_2\text{ at CERN-PS}\]
Physics of fluorescence for $\text{N}_2$ residual gas:

- Excitation of residual gas molecules by beam’s energy loss
- Decay of $\text{N}_2^+$ levels generate light, blue light $390 \text{ nm} < \lambda < 470 \text{ nm}$, lifetime $\tau = 60 \text{ ns}$.

Realizations at Los Alamos, CERN, Orsay/Saclay, UNI-Frankfurt, GSI, COSY …

Fluorescence of 200 keV p in $\text{N}_2$ (1961)

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>391.4</th>
<th>0–0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu' - \nu''$</td>
<td>upper—low vib.</td>
<td></td>
</tr>
</tbody>
</table>

$\text{N}_2^+$ transitions:

$B \Sigma_u^+ (\nu') \rightarrow X^2 \Sigma_g^+ (\nu'')$

Spectrum confirmed at CERN-PS/SPS from 1 to 450 GeV.
Technical realization of image intensifier at GSI:

- Photo cathode S20 UV: $\gamma$-e$^-$ conversion, 15 to 25 % efficiency, 200 nm < $\lambda$ < 650 nm
- **Two** step MCP (25 mm diameter): $10^6$ fold amplification
- P 46 phosphor: e$^-$-$\gamma$ conversion, 300 ns decay, 500 nm < $\lambda$ < 600 nm
- Minifying taper coupling to CCD chip (1/2''): 7% transmission
- Digital camera (Basler A302fs): Firewire interface
Compact chamber with 150 mm insertion:

Installation behind Alvarez at 11 MeV/u

Horizontal BIF
- camera
- image intensifier
- lens
- gas inlet

Vertical BIF
- pulse generator

Image Intensified CCD for horizontal profile
- remote controlled lens
- gas inlet valve
- vacuum gauge
- Ima. I. CCD vert. profile
- beam
- 100 mm flange
- 150 mm chamber length
- support
- to turbo-pump
**Example at GSI-LINAC:**

4.7 MeV/u Ar$^{10+}$ beam

$I=2.5$ mA equals to $10^{11}$ particle

**One single** macro pulse of 200 $\mu$s

Vacuum pressure: $p=10^{-5}$ mbar ($N_2$)

bump restricted $\sim 1$ m,

$\rightarrow$ no influence to beam detected

**Features:**

- Single photon counting
- High resolution (here 0.3 mm/pixel), can easily be matched to application
- Low background (sometime larger contribution by neutrons and $\gamma$)
Application of Beam Induced Fluorescence

Signal treatment
Statistics offers ‘offline’ optimization
statistics ↔ integration time ↔ resolution

Special application
Variation during the macro pulse detectable:
Switching of image intensifier
→ Exposure window during macro-pulse

Beam parameter:
Ar^{10+} at 11 MeV/u with 8 mA
**Example:** CERN SPS and PSB,PS (R. Jung, M. Plum et al.)
Photon yield scales like Bethe-Bloch energy loss $\Delta E$ for $p$ with $100 \text{ MeV} < E_{\text{kin}} < 450 \text{ GeV}$

<table>
<thead>
<tr>
<th>Gas</th>
<th>$N_2$</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E$/photon</td>
<td>3.6 keV</td>
<td>46 keV</td>
</tr>
<tr>
<td>lifetime</td>
<td>$58 \pm 0.3 \text{ ns}$</td>
<td>$59 \pm 1 \text{ ns}$</td>
</tr>
</tbody>
</table>

**Method:** fluorescence decay by $\sim 5$ ns long bunches

Comparison to wire scanner at SPS
Choice of fluorescence gas:

- High fluorescence yield at optical wave-length
- Short lifetime of excited level
- Good vacuum pumping

Results:

⇒ Profile is independent of gas

Care:

- Long life (ions only) →
  broadening by beam space charge
- Light emitted by primary ions
  e.g. \( p + N_2 \rightarrow H^* + N_2^+ \)
  (only important for \( E_{\text{kin}} < 1 \text{ MeV} \))
- At large \( N_2 \) density (\( p > 10^{-3} \text{ mbar} \)): Two-step processes e.g. \( N_2 + e^- \rightarrow N_2^* + e^- \) possible

Example: Ion source 100 keV, 100 mA protons
P. Ausset et al. (Orsay/Saclay)
Technical Realization Possibilities for BIF

**Double MCP:**
- + single photon, $10^6$-fold amp.
- resolution limited (MCP-channels)

Example: GSI-LINAC (300 μm/pixel)

**Single MCP:**
- lower $10^3$-fold amp.
  + higher resolution

Example: CERN-SPS (160 μm/pix), R. Jung et al.

---

Photo-cathode: Only for required wavelength interval to avoid dark currents, e.g.

**S20UV:** $200<\lambda<650$ nm $\Rightarrow$ dark rate $500 \text{ e}^-/\text{cm}^2/\text{s}$, **S25red:** $300<\lambda<900$ nm $\Rightarrow$ 30000 $\text{ e}^-/\text{cm}^2/\text{s}$

Phosphor: Fast decay $\leftrightarrow$ lower sensitivity e.g. P47: $\tau = 0.1 \mu$s, P43: $\tau = 1000 \mu$s $\Rightarrow I_{P43} \sim 4 \cdot I_{P47}$

Problem: Radiation hardness of CCD camera
**IPM**: All products are detected ‘4\(\pi\)-geometry’, energy loss \(\approx\) 50 eV per ion-e\(^-\) pair

**BIF**: Solid angle only \(\Delta\Omega/\Omega \approx 10^{-4}\), \(\approx\) 5 keV per photon

Signal generation:
- Secondary e\(^-\)/ions accelerated by E-field (\(E\approx\) 50 V/mm)
- MCP as \(10^6\)-fold amplifier

High resolution mode:
⇒ CCD readout

Turn-by-turn mode:
~100 photo-diodes or multi-anode PM
Realization at GSI-SIS

Ion detection:
⇒ E-field in-homogeneity $\Delta E/E < 1\%$

New design for phosphor readout:

- IPM with 175 x 175 mm clearance
- HV-electrode
- MCP: 100 x 30 mm$^2$
- 63 wires, 2 mm spacing
- 300 mm flange
Technical Challenges for IPM

- **Electric field** for secondary ion/electron acceleration
  - large homogeneity required ⇒ complex vacuum installation
  - for e\(^{-}\) detection: suppression of surface-emitted e\(^{-}\) from HV-plate opposite to MCP
- **Magnet field** with \(\sim 0.1\) T required with large clearance (up to 400 mm)
- **MCP**: large dynamic range required due to low/high current operation, MCP switching, decrease of efficiency ⇒ MCP test device required: filament, UV-lamp etc.

<table>
<thead>
<tr>
<th>Anode type</th>
<th>Wire array</th>
<th>Phosphor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanics</td>
<td>variable</td>
<td>require window access</td>
</tr>
<tr>
<td>Resolution</td>
<td>(\sim 1) mm</td>
<td>(\sim 0.1) mm</td>
</tr>
<tr>
<td>Slow readout ((\sim 10) ms)</td>
<td>extensive ((\sim 100) ch)</td>
<td>facile by CCD</td>
</tr>
<tr>
<td>Turn-by-turn readout</td>
<td>possible by ac-amplifier</td>
<td>complex by PM or PD</td>
</tr>
<tr>
<td>Bunch image charge</td>
<td>problematic</td>
<td>optically de-coupled</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>not problematic</td>
<td>problematic</td>
</tr>
</tbody>
</table>

⇒ Various realization at different laboratories
**Ion detection:** for intense beams 
⇒ broadening due to space charge

**Electron detection:**
B-field required for e⁻ guidance toward MCP.

Effects: • 3-dim start velocity

\[ E_{\text{kin}}(90\%) < 50 \text{ eV}, \theta_{\text{max}} \approx 90^\circ \]
⇒ \( r_{\text{cyl}} < 0.1 \text{ mm if } B \approx 0.1 \text{ T} \)

• \( E \times B \)-drift only for high intensities

**Monte-Carlo simulation:**
Ion versus e⁻ detection

10¹⁰ U⁷⁺ injection at SIS
⇒ Only e⁻ scheme gives correct image
**Magnet Design**

A magnetic field is required to guide the electrons:

Maximum image distortion:

5% of beam width ⇒ $\Delta \frac{B}{B} < 3\%$

(particle tracking required)

**Challenge:**

→ Large clearance of ~ 400 mm

*and* compact design required

Example: RHIC-type *permanent* magnet (R. Connolly et al.)

B = 140 mT, pole clearance 12 cm, length 30 cm
Electro-magnet with phosphor readout: *Example:* CERN-SPS type (C. Fischer et al.)

Hole in pole face for light transmission

- Compact E-field box
- Prism for light reflection

**Magnet parameter:**
- $B_{\text{max}} = 240$ mT,
- Pole clearance 200 mm
- Total magnet length 0.68 m
- Total chamber length 1.6 m

---

Peter Forck (GSI), DIPAC 2005, Lyon

Profile Monitors based on Residual Gas Interaction
**Example:** Stacking by electron cooling of U^{73+} beam at GSI.

**IPM:** Profile recording every 10 ms (0.5 ms integration) within one cycle.

**Horizontal Profiles:**

- 1st injection and cooling
  - Graph showing distribution with coordinates [mm] and integral/current [arb. units].

- 2nd injection
  - Graph showing similar data as 1st injection.

**1st to 5th injection and cooling:**

- Graphs showing changes in horizontal and vertical profiles over time [s].

- 5th cooling period & acc.
  - Graphs showing final stages of cooling and acceleration.
Injection has to be well aligned to prevent emittance blow-up

⇒ Turn–by-turn measurement

Example: orientation mis-match

<table>
<thead>
<tr>
<th>phase space</th>
<th>third turn</th>
<th>second turn</th>
</tr>
</thead>
<tbody>
<tr>
<td>forth turn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>first turn</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example: CERN-SPS (C. Fischer et al.):
Anode-technology:
Phosphor + Photomultiplier, 1.2 mm resolution

Example: matched

Example: mis-matched
Comparison BIF versus IPM

**Beam Induced Fluorescence BIF:**

*Advantage:* • simple mechanics (nothing installed in the vacuum), compact installation  
• adjustable resolution, high resolution possible (limited by focal depth)  
• commercial hardware and data acquisition system

*Disadvantage:* • low signal: for ‘single particle scheme’ → generation of photons/ion ~ 1/100,  
  solid angle $\Delta \Omega/\Omega \sim 10^{-4}$ and 30% detection eff. ⇒ BIF/IPM ~ $10^{-5}$  
  • local pressure bump required

*Application:* Mainly at LINACs

**Ionization Profile Monitor IPM:**

*Advantage:* • large signal strength due to ‘4π geometry’  
• high resolution possible down to 100 μm, limited by MCP and field quality

*Disadvantage:* • complex installation inside vacuum for E-field and MCP-detector  
  • compact magnet with large B-field homogeneity required  
  • limited resolution compared to wire-scanner (?)

*Application:* Mainly at synchrotrons
Thanks to all colleagues for discussion, release of results and figures.

Thank you for your attention!
Example:
Wanted vertical-horizontal emittance exchange by skew quadrupoles.
Within 10 ms the beam is rotated by 90° in real space!
Monitoring of wanted manipulation to reach the maximum ion currents!
⇒ turn-by-turn readout down to 1 μs
⇒ MCP switching 1μs to 10ms necessary to overcome regular count-rate limitation (10^6 1/s continuous rate limit)
High current setting at SIS:
Resonance crossing for $10^{10}$ Kr$^{36+}$ ions:
Injection $Q_H=4.15$
$\rightarrow$ Slow extraction $Q_H=4.31$
Blow-up during resonance crossing
Important measurements for any manipulations

Example: Resonance crossing at GSI-SIS

Profile Monitors based on Residual Gas Interaction
Realization at GSI-SIS

MCP detector: active area 100x30 mm²

Ion detection:
⇒ E-field in-homogeneity $\Delta E/E < 1\%$
Digital Interface for Firewire

Digital camera offers:
no loss of data-quality due to cable, versatile trigger, variable exposure time
CCD-camera: Basler A311f featuring 649x494 pixels, 12 bit, 50 frames/s, IEEE 1394b
Iris/MCP-gain variation: Remote controlled iris by local, ethernet based DAC
Readout: HUB → optical fiber → real-time controller on RT-LabVIEW (NI)
Software: RT-LabVIEW and data transfer to LINUX for data presentation

LabVIEW Software:
MCP-phosphor combination
→ High resolution down to 100 μm
→ Fast turn-by-turn readout
   with photo diode array
\( e^- \) detection: B-field of 100 mT by window frame
Example: Stacking by electron cooling of U^{73+} beam at GSI.

IPM: Profile recording every 10 ms (0.5 ms integration) within one cycle.

Horizontal Profiles:

- 1st injection and cooling
- 2nd injection
- 3rd injection
- 4th injection
- 5th injection

5th cooling period & acc.

Profile Monitors based on Residual Gas Interaction