Beam Induced Fluorescence Monitors

BIF®, FPM®, BPL®, SPM®, OBPM®, VPM®, RGM®...
Outline

- Motivation & Introduction
  - Benefit of non-intercepting profile measurement
  - Detection principle, components and functionality

- Physics – Results of Research
  - Estimation of the photon yield
  - Parameters to be optimized
  - Limiting factors (yield, radiation, displacement)

- Overview of Realizations
  - Transport & LINAC installations
  - Synchrotron installations

- Conclusion
Gas-Based Detectors

- $N_2$-dominated for $p \geq 10^{-8}$ mbar, $H_2$-dominated for lower $p$

- Atomic collisions drive $-dE/dx \rightarrow$ electronic stopping

- Processes to be observed: ionization and fluorescence...
Gas-Based Detectors

- $N_2(X^1\Sigma) + \text{Ion}$
- $N_2^+(B^2\Sigma_u^+) + e^- + \text{Ion}(\Delta E)$
- $N_2^+(X^2\Sigma_g^_) + \gamma$

- $N_2$-dominated for $p \geq 10^{-8}$ mbar, $H_2$-dominated for lower $p$
- Atomic collisions drive $-dE/dx \rightarrow$ electronic stopping
- Processes to be observed: ionization and fluorescence...
### Ionization Profile Monitor

- Gas-ions accelerated in homogeneous E-field vs. spatially resolving sensor
- ±6 kV accelerating voltage → $E = 70 \text{ kV/m}$
- TOF $\text{N}_2^+$ ions $\sim 100 \text{ ns}$
- $4\pi$-acceptance → all ions
- MCP-amplification $\sim 10^6$
- Stripline/optical readout

Sensitive profile monitor suitable for synchrotrons

[DIPAC: TUPD51, Giacomini]
Beam Induced Fluorescence

N₂ gas equally distributed at high vacuum

vaccum-gauge

25 cm black chamber walls

ION-BEAM

lens, image intensifier, CCD-camera

leak valve
How a Beam Profile is Obtained
How a Beam Profile is Obtained

200 MeV Xe$^{48+}$, 20 pulses of $10^9$ Ions in $5 \cdot 10^{-4}$ mbar N$_2$

BIF- and SEM-profiles in accordance with each other, $\Delta \sigma / \sigma \leq 10\%$
Beam Profile Comparison

4.8 MeV Ca^{10+}, 100 pulses of 10^{10} Ions in 1 \cdot 10^{-5} mbar N_2

Limits: -5 mm to 15 mm

\sigma_{IPM} = 4.72 mm
\sigma_{BIF} = 4.73 mm

BIF- and SEM-profiles in accordance with each other, \Delta \sigma/\sigma \leq 10\%
BIF- and IPM-profiles agree very well [DIPAC: WEOA03 Egberts]
Detachment Principle

Solid angle limited by view-port/iris opening

GAS (N₂) BEAM

Atomic collisions beam ions ↔ N₂
dE/dx → excitation optical fluorescence
N₂⁺: 391, 427 nm, ...

Lens system

Image plane

Sensitive Photon Detector

Photon

Photon
Solid angle limited by view-port/iris opening

GAS (N₂) BEAM

Atomic collisions heavy ions ⇔ N₂
dE/dx → excitation fluorescence trans.
N₂⁺: 391, 427 nm,...

Lens system

Photon

Low noise CCD/CMOS sensors with active cooling.
State of the art ADCs and digital interfaces GigE, FireWire, ...
Detection Principle – Slit with PMT

Solid angle limited by view-port/iris opening

GAS (N₂) BEAM

Atomic collisions heavy ions ⇔ N₂
dE/dx → excitation fluorescence trans.
N₂⁺: 391, 427 nm,...

Photon

Lens system

Slit

ADC

Photomultiplier tube
HV ⇔ amplification ~10⁶
Single photon counting!

18/05/2011 | DIPAC2011 @ HH Cap San Diego | WEOD01 | Frank Becker | GSI Beam Diagnostics | 12
Detection Principle – PMT Array

Solid angle limited by view-port/iris opening

GAS (N₂)

BEAM

Atomic collisions
heavy ions ↔ N₂
dE/dx → excitation
fluorescence trans.
N₂⁺: 391, 427 nm,...

Lens system

Photon

Multi anode PMT array
HV ↔ amplification ~10⁶
Single photon counting!

Multi channel ADC
Solid angle limited by view-port/iris opening

UV-enhanced S-20 total QE ~15%

Fast P-46 phosphor screen (green light)

Detection Principle – 2 Dimensional

GAS (N₂) BEAM

Lens system

Fiberoptical taper 13:7

Atomic collisions heavy ions ⇔ N₂ dE/dx → excitation fluorescence trans. N₂⁺: 391, 427 nm,...

„V-Stack“- MCP HV ⇔ amplification ~10⁶ Single photon counting!
Benefit of the BIF-monitor

- Short insertion-length
- No mechanical parts inside the vacuum
- Gas pressure adjusts signal strength
- Optical system can be tailored to application

**Components of the shelf**
- Lens with motorized iris
- V-stack image intensifier single photon counting
- Digital 12-bit VGA-cam with FireWire-interface
Benefit of the BIF-monitor

- Short insertion-length
- No mechanical parts inside the vacuum
- Gas pressure adjusts signal strength
- Optical system can be tailored to application

Components of the shelf
- Lens with motorized iris
- V-stack image intensifier single photon counting
- Digital 12-bit VGA-cam with FireWire-interface
What is next:

- Motivation & Introduction
  - Benefit of non-intercepting profile measurement
  - Detection principle, components and functionality

- Physics – Results of Research
  - Estimation of the photon yield
  - Parameters to be optimized
  - Limiting factors (yield, radiation, displacement)

- Overview of Realizations
  - Examples – Transport & LINAC installations
  - Examples – synchrotron installations

- Conclusion
Number of Detected Photons

\[ Y_{\text{photon}} = \sigma_{\text{photon}}(E, \bar{q}) \, N_{\text{Ion}} \, \Delta s \, \Omega \, P_{\text{Det}} \, \rho \]
The Given Parameters

\[ Y_{\text{photon}} = \sigma_{\text{photon}}(E, \bar{q}) N_{\text{Ion}} \Delta s \Omega P_{\text{Det}} \rho \]

- Cross sections experimentally determined at PS-Booster/PS:
- dE/dx energy dependency but more data points required...
- Source, LINAC/Cycl., Synchr.
- Yield scales with \( \bar{q}^2 \)
- Gas species determines light yield and energy loss

We like to have the maximum number of photons per dE/dx

[M.A. Plum et al. NIM A 2002]
S\textsuperscript{6+} Ions @ 5 AMeV in 10\textsuperscript{-3} mbar gas:

- Fluorescence for rare gases and N\textsubscript{2}:
  - near UV to green
- Intensive lines and highest Y for N\textsubscript{2}

<table>
<thead>
<tr>
<th>Gas</th>
<th>Y to p</th>
<th>Y to p/ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>86 %</td>
<td>22 %</td>
</tr>
<tr>
<td>Kr</td>
<td>63 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Ar</td>
<td>38 %</td>
<td>30 %</td>
</tr>
<tr>
<td>He</td>
<td>4 %</td>
<td>26 %</td>
</tr>
<tr>
<td>N\textsubscript{2}</td>
<td>100 %</td>
<td>100 %</td>
</tr>
</tbody>
</table>

- Gas electron density $n_e \propto dE/dx$

N\textsubscript{2}\textsuperscript{+} and Xe\textsuperscript{+} are recommended!

[F. Becker et al. BIW 2010]
**Results Spectroscopy – Profile Reading**

S\(^{6+}\) Ions @ 5 AMeV in 10\(^{-3}\) mbar gas:

- Fluorescence for rare gases and N\(_2\): near UV to green
- Intensive lines and highest Y for N\(_2\)

Profile reading is equal for all gases except for He. N\(_2^+\) and Xe\(^+\) are recommended!

[F. Becker et al. BIW 2010]
Parameters to be Optimized

\[ Y_{\text{photon}} = \sigma_{\text{photon}}(E, \bar{q}) N_{I\text{on}} \Delta s \Omega P_{D\text{et}} \rho \]
Parameters to be Optimized

\[ Y_{\text{photon}} = \sigma_{\text{photon}}(E, \bar{q}) \, N_{\text{Ion}} \Delta s \, \Omega \, P_{\text{Det}} \, \rho \]

\[ \Delta d \] should cover the beam width \( \rightarrow \) \( \Omega \) is limited due to \( \kappa_{\text{min}} \)
Parameter free to Choose

\[ Y_{photon} = \sigma_{photon}(E, \tilde{q}) \, N_{Ion} \, \Delta s \, \Omega \, P_{Det}(\rho) \]

\( \kappa = \frac{f}{D} \)

\( \Delta d \) should cover the beam width \( \rightarrow \) \( \Omega \) is limited due to \( \kappa_{\text{min}} \)
Pressure-Variation

UNILAC (4,5 AMeV)

- Statistical error
- Average value

Signal amp. [arb.] vs. pressure [mbar]

- Fit: $y = ax^b$
- $b = 1.08(5)$

profile FWHM [mm]

LINAC: $10^{10} \text{N}_2^6^+ \oplus 4.54$ AMeV und
$p = 10^{-6}$ mbar bis $p = 10^{-3}$ mbar

SIS-18 (200 AMeV)

- Single sequence
- Average value

Signal amp. [arb.] vs. pressure [mbar]

- Fit: $y = ax^b$
- $b = 1.02(5)$

profile FWHM [mm]

HEBT: $2 \times 10^8 \text{Xe}^{48+} \oplus 200$ AMeV und
$p = 10^{-3}$ mbar bis $p = 3$ mbar

Light yield $\sim p$ and $\sigma = \text{constant} \rightarrow p$ is a free parameter
Gas Dosing Systems

Wide range gauge and motorized needle valve

+ controller

Controller + HV-pulse supply

Bending element

Linear stack

Time scale: minutes ↔ ms pulses

Graph showing time scale in minutes and microseconds.
Limiting Factors

- Photon Yield shotnoise, statistics

- Radiation induced noise & damage

- Displacement process, lifetime, particle mass...
### Limiting Factors

- Photon Yield
  - shot noise, statistics

- Radiation induced
  - noise & damage

- Displacement process, lifetime, particle mass...

### Improvements

- Optimized Geometry + Optics
  - and single photon counting
Limiting Factors  →  Improvements

- Photon Yield shotnoise, statistics  →  Optimized Geometry + Optics and single photon counting

- Radiation induced noise & damage  →  Radiation tolerant components and sufficient shielding

- Displacement process, lifetime, particle mass...
<table>
<thead>
<tr>
<th>Limiting Factors</th>
<th>Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon Yield shotnoise, statistics</td>
<td>Optimized Geometry + Optics and single photon counting</td>
</tr>
<tr>
<td>Radiation induced noise &amp; damage</td>
<td>Radiation tolerant components and sufficient shielding</td>
</tr>
<tr>
<td>Displacement process, lifetime, particle mass...</td>
<td>Ionized gas particles reduce excitation by electrons, heavy species with short lifetime, e.g. Xe⁺</td>
</tr>
</tbody>
</table>
Shielding-Concept with Image-Guide

- Shielding walls or blocks
  $1m^3 \rightarrow \geq 90\%$ reduction

- Image transport with relay optics or image guide

- Radiation hard components and optics are recommended: ICID, CMOS, quartz fibers...

[C. Zamantzas, DIPAC]
[F. Senée, DIPAC-09]
[F. Becker, BIW-08]
Diagnostics with the Eye :-)
Decreasing Kr-Pressure 1000 – 1 mbar

3.75 MeV/u Ø 4 mm 100 nA S\textsuperscript{7+} beam in 1000 – 1 mbar Krypton @ TU–Munich
What is next:

- Motivation & Introduction
  - Benefit of non-intercepting profile measurement
  - Detection principle, components and functionality

- Physics – Results of Research
  - Estimation of the photon yield
  - Parameters to be optimized
  - Limiting factors (yield, radiation, displacement)

- Overview of Realizations
  - Examples – Transport & LINAC installations
  - Examples – synchrotron installations

- Conclusion
PSI Cyclotron and LEBT

- Monitor commissioned 1987 @ PSI
- 9-14 mA protons at 870 keV in $10^{-6} - 10^{-5}$ mbar H$_2$ and N$_2$ gas
- 720 steps with 2-32 ms int. time each
- Successfully operated at 10 LEBT locations since installation

[Courtesy of R. Doelling, PSI]
Measurement of 10 luminescent profile monitors along the transport section. 870 keV, 13 mA DC proton beam in $\leq 10^{-5}$ mbar residual gas.

[Courtesy of R. Doelling, PSI]
BIF Setup at GSI-UNILAC

- Single pulse operation
- Typical gating times μs-ms
- 4 systems in operation
- 2 Systems in preparation
- Profile-View software for online monitoring in the controls room

[DIPAC 2009 R. Haseitl]

[DIPAC: MOPD60 C. Andre]
IFMIF EVEDA – Prototype Testing

ICID-Camera

15 μA D⁺ beam at 9 MeV/u in 7 × 10⁴ mbar N₂ gas (125 mA is intended)

PMT-Array

τ=20ms

τ=5ms

[Courtesy of J.M. Carmona]
1.5 \cdot 10^{10} \text{ protons at } 2.6 \text{ GeV/c cooler storage synchrotron, low } p

- Pulsed piezo leak valve to minimize gas load \( t_{\text{min}} \sim 1 \text{ ms} \)
- \( p_{\text{base}} \sim 2 \cdot 10^{-9}, \ p_{\text{measure}} \sim 4 \cdot 10^{-8} \text{ mbar} \)
- Integration time counteracts low p

[DIPAC: MOPD51 V. Kamerdzhiyev]
- 450 GeV SPS proton beam
- In 10^{-7} – 10^{-5} mbar N_2 gas
- Beam size monitoring during ramp in agreement with wire scanner
- Fluorescence CS from 14-450 GeV
- Spectral mapping agrees with 200 keV

- 450 GeV SPS proton beam
- In $10^{-7} - 10^{-5}$ mbar $N_2$ gas
- Beam size monitoring during ramp in agreement with wire scanner
- Fluorescence CS from 14-450 GeV
- Spectral mapping agrees with 200 keV and 5 MeV data (GSI)

BNL – RHIC Injected Gas Jet

Supersonic atomic H-jet

density: \(10^{12}\) atoms/cm\(^2\)
Velocity 1560 m/s (Mach-5)

- Directed jet provides \(p \leq 10^{-3}\) mbar
- Integration \(\sim 10^{19}\) 100 GeV protons
- Online emittance measurement

[PAC’11: paper MOP210 T. Tsang]
IAP Frankfurt – Tomography

Tomography: 181 profile projection measured with rotating chamber:

- 2-dimensional density distributions
- High res. scanning, radon transform
- Non-invasive emittance determin.
- 120 keV, 200 mA H+, 5·10^{-5} mbar N₂

Reconstructed density distribution [DIPAC: TUBD60 & TUPD52 H. Reichau/C. Wagner]
CEA Saclay – Tomography

- 2-dimensional density distributions
- Iterative Algebraic reconstruction technique (ART)
- Installed at BETSI source test bench
- 50 keV, 5 mA H\(^+\) beam, 5 \cdot 10^{-5} \text{ mbar H}_2

Projections and reconstruction (bottom) Diagnostic chamber with 6 equally spaced viewports for CCDs

[DIPAC: TUPD58 C.M. Mateo]
Conclusion

- **Remarkable developments for:**
  - Synchrotrons & transport to characterize intensive ion beams

- **Results of research:**
  - Signal-amplitude $\rightarrow$ linear with $p$, $dE/ds$ with $E \rightarrow f = \text{const.}$
  - Profile-width $\rightarrow$ does not depend on $p \rightarrow p$ free parameter
  - Radiation-induced background $\rightarrow \sim E^2 \rightarrow$ shielding is mandatory
  - Rare gases (Kr, Xe) can replace $N_2 \rightarrow$ reduced profile errors
  - $N_2$ has highest fluorescence-efficiency per energy loss

- **Successful implementation of BIF-monitors:**
  - In the energy-range of 7.5 AkeV – 450 AGeV
  - In transport sections and synchrotrons
  - Many innovative installations are in operation
  - The story goes on...
Acknowledgements

Thank you for supporting this contribution:

P. Ausset (Orsay Paris-Sud), J.M. Carmona (CIEMAT), J. Dietrich (FZ-Jülich), R. Doelling (PSI), D. Gilpatrick (LANL), V. Kamerdzhiev (FZ-Jülich), C-M. Mateo (CEA-Saclay), O. Meusel (IAP-Frankfurt), M. Sapinski (CERN), T. Tsang (BNL)

Thanks’ to my colleagues:

C. Andre (GSI), F.M. Bieniosek (LBNL), P. Forck (GSI), T. Giacomini (GSI), R. Haseitl (GSI), D.H.H. Hoffmann (TUD), A. Hug (GSI), T. Milosic (GSI), P.A. Ni (LBNL), H. Reeg (GSI), A. Ulrich (TUM), B. Walasek-Hoehne (GSI)

Thank you for your attention! 😊