Beam Loss Monitors: 

Overview of BLM Technology

1. Introduction
2. Dynamic range, sensitivity
3. Limitations in
   a) time and/or
   b) spatial resolution
4. Challenges associated to measurements of losses (in different machine types)
5. Radiation hardness
6. A comprehensive summary of the current state-of-the-art methods
7. Needs for further development

Kay Wittenburg
3rd oPAC Topical Workshop on Beam Diagnostics
Vienna, 8-9 May 2014
Beam loss monitor systems are designed for measuring beam losses around an accelerator or storage ring. **A detailed understanding of the loss mechanism**, together with an **appropriate design of the BLM-System** and an **appropriate location of the monitors** enable a wide field of very useful **beam diagnostics and machine protection** possibilities.

- **Regular (controlled, slow) loss**
  Those losses are **typically not avoidable** and are localized on the collimator system or on other (hopefully known) aperture limits. They might occur continuously during operational running and correspond to the lifetime/transport efficiency of the beam in the accelerator. **The lowest possible loss rate** is defined by the theoretical beam lifetime limitation due to various effects.

- **Irregular (uncontrolled, fast) losses**
  The irregular losses may be distributed around the machine and not obviously on the collimation system. Can be avoided and should be kept to low levels but may reach very high levels in case of an accident.

**It is clearly advantageous to have a BLM System which is able to deal with both loss modes. But this means -> High Dynamic Range System!**
2. Dynamic Range, Sensitivity

In these two references one can find a lot of details on various BLM types!

K. Wittenburg, Beam loss monitors, CAS2008
Specialised Beam Diagnostics School in Dourdan, France, CERN-2009-005

Lars Fröhlich, Beam Loss Monitors
ERL Instrumentation Workshop, Cornell University, 2-3 June 2008

<table>
<thead>
<tr>
<th>Detector Material</th>
<th>energy to create one electron [eV/e]</th>
<th>number of [e / (cm MIP)] (depends on dE/dx, resp. density)</th>
<th>Sensitivity S (for MIPs) [nC/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Scintillator</td>
<td>250 – 2500</td>
<td>$10^3 - 10^4$</td>
<td>$\approx 17 \cdot 10^3 \cdot (\text{PMT}_\text{gain})$ (1 ltr.)</td>
</tr>
<tr>
<td>Inorganic Scint.</td>
<td>50 - 250</td>
<td>$10^4 - 10^5$</td>
<td>$\approx 100 \cdot 10^3 \cdot (\text{PMT}_\text{gain})$ (1 ltr.)</td>
</tr>
<tr>
<td>Gas Ionization:</td>
<td>22 – 95</td>
<td>$\approx 100$ (Ar, 1 atm., 20°C)</td>
<td>$\approx 500 \cdot (\text{Elec}_\text{gain})$ (1 ltr.)</td>
</tr>
<tr>
<td>Semiconductor (Si):</td>
<td>3.6</td>
<td>$10^6$</td>
<td>$\approx 50 \cdot (\text{Elec}_\text{gain})$ (1 cm$^2$ PIN-Diode)</td>
</tr>
<tr>
<td>Secondary emission:</td>
<td>2-5%/MIP (surface only)</td>
<td>0.02-0.05 e/MIP</td>
<td>$\approx 2 \cdot 10^{-3} \cdot (\text{PMT}_\text{gain})$ (8cm$^2$)</td>
</tr>
<tr>
<td>Cherenkov light</td>
<td>$10^5 - 10^6$</td>
<td>$\approx 10$ (H$_2$O) - 200 (fused silica)</td>
<td>$\approx 270 \cdot (\text{PMT}_\text{gain})$ (1 ltr.)</td>
</tr>
</tbody>
</table>

Including Gain and 1 Gy = 100 rad

$\approx 0.2 \cdot 10^{-3} \cdot (\text{PMT}_\text{gain})$ for 1 m Cherenkov fiber

>10$^8$ Difference in Sensitivity between different types
2. High dynamic loss monitoring by

**Different BLM types/materials**

- **FLASH**

- **FLASH**

- **LHC**

---

**SNS**

<table>
<thead>
<tr>
<th>Area</th>
<th>IC</th>
<th>ND</th>
<th>PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTL</td>
<td>11</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>CCL</td>
<td>50</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>SCL</td>
<td>76</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>HEBT, LDmp, IDmp</td>
<td>59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring</td>
<td>71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTBT</td>
<td>40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Kay Wittenburg | 3rd oPAC Topical Workshop on B
2. High dynamic loss monitoring by

Different BLM types/materials
Diamond and Sapphire

![Graph showing signals vs bunch charge for Diamond and Sapphire sensors.]

Figure 5.4.5: Fits for the maximal average signal for a diamond and sapphire sensors.

<table>
<thead>
<tr>
<th>Diamond (UR)</th>
<th>Sapphire (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low charges &lt;50 pC</td>
<td>Low charges &lt;90 pC</td>
</tr>
<tr>
<td>(6.6e-02)*x + (3.1e-16)</td>
<td>(1.4e-02)*x + (3.5e-02)</td>
</tr>
<tr>
<td>Medium charges &gt;50 pC &amp; &lt;113 pC</td>
<td>Medium charges &gt;90 pC &amp; &lt; 690 pC</td>
</tr>
<tr>
<td>(2.0e-06)*x + (-6.7e-04)*x2 + (6.99e-02)*x + (1.27e+00)</td>
<td>(2.5e-09)*x3 + (-8.7e-06)*x2 + (9.0e-03)*x + (5.5e-01)</td>
</tr>
<tr>
<td>High charges &gt;113 pC</td>
<td>High charges &gt; 690 pC</td>
</tr>
<tr>
<td>(0)*x + (3.62e+00)</td>
<td>(0)*x + (3.47e+00)</td>
</tr>
</tbody>
</table>

Table 5.4.1: Parameters for the resulting fit functions.

Figure 5.2.1: View to the BHM module from the dump. The pick-ups of the magnetic-coupled BPM can be seen in front of the cups with sapphire sensors.

Alexandr Ignatenko
Thesis, 2014
Brandenburgische Technische Universität Cottbus-Senftenberg
2. High dynamic loss monitoring by

Small and Large

FLASH

HERA

Note that the flux density of photons into the light guide is “incompressible”!

=> The cross section of the scintillator should not be larger than the cross section of the light guide -> I did not proof this rule, any experience with that?
2. High dynamic loss monitoring by

Noise to saturation

**Detector:**

**PMTs:**
- Noise at max Gain ≈ 1 mV
- Saturation ≈ 1 V
- **Active** gain variation ≈ 10³
⇒ Dynamic range ≈ 10⁶

**Ionization chamber (LHC):**
- Leakage current < 1 pA
- Saturation ≈ 1 mA
⇒ Dynamic range ≈ 10⁹

**Electronic:**

**RF Amplifiers**
- Dynamic range ≈ 10⁴
- Log Amp. ≈ 10⁵

**ADC**
- 12 bit ≈ 4 x 10³
- 16 bit ≈ 6 x 10⁴
- 24 bit ≈ 2 x 10⁷ (SNS: VME ADC but 10 bits noise)

**Counting**
- Dark count rate ≈ 1 Hz
- Signal: Bunch rep. rate ≈ 10 MHz
⇒ Dynamic range > 10⁹ (averaging!)
3a. Limitations in time resolution
3a. Limitations in time resolution

> Typical reaction time of

- **Rings:** 1 - few turns -> \( \approx 10 \ \mu s \) -> Defines the detector time response
- **Linac:** Bunch distance (\( \approx 100 \ \text{ns at bunch train or } \approx \text{ms at single bunch} \)) but important:
  - Bunch by Bunch resolution -> Defines the detector time response
  - Integration over bunch train
  - Integration over some bunch trains
3a. Limitations in time resolution

≥ turn by turn:

- Ionization chambers
- Low bandwidth ADC allows high dynamic range
- Counting (many bunches)

Allows super high dynamic range

Pin Diodes at HERA

(4) Experience at the J-PARC MR

Response

rise time ~ 100ns

Integrated Zin = 500Ω, gain = 10, HV = -1.6 kV

downstream of 1st collimator

T. Toyama et al., HB2008

Counting circuit for LHC Ion Chamber

\[ f = \frac{i_m}{I_{ref} \Delta T} \]
3a. Limitations in time resolution

> < 100 ns:

- PMT (or APD) + Cherenkov or Scintillator
- SEM + GHz Amplifier (or SEM-PMT)
- Solid State Detectors + GHz Amplifier
+ GHz ADC (limited dynamic range)!!!

The signal width from the R5900 PMT is as short as 20 ns, even after 50m twisted pair cable.

Signals from 3 bunches at FLASH:

BLM #1 (top, BC-408, HV=500V) and BLM #3 (quartz fibers, HV=700V).
3a. Limitations in time resolution

Loss signal

Diamond signal

Ionisation chamber
(40 us integration time)

Time

B. Dehning
Beam Loss: New Developments, Detectors and Electronics;
7th DITANET Topical Workshop on
Beam Loss Monitoring
December 7, 2011
3b. Limitations in spatial resolution (where to put BLMs)
3b. Limitations in spatial resolution (where to put BLMs)

Electron beam = small shower

Beam direction
3b. Limitations in spatial resolution (where to put BLMs)

**Trajectory of Electrons after Energy Loss**

Figure 3: Deviation of the electron orbit with momentum difference from 1% to 10%.

**Electron Beam Loss Monitors for HERA**
F. Ridoutt, W. Bialowons, K. Wittenburg; EPAC 1994

**A New Theoretical Design of BLM System for HLS II**
Yukai Chen, Lijuan He, Juexin Li, Wei-min Li, Yuxiong Li
IPAC 2013

Important:
- Beam Optics!
- Tracking Codes

Beam direction
3b. Limitations in spatial resolution (where to put BLMs)

A local orbit distortion creates losses at high beta (in general at aperture limitations)

High Energy Proton Beam = Large Shower

Important:
Particle Shower
Monte Carlo Codes

Secondary at surface

Proton losses

QF cell

beta [m]

middle of QF

Position

0 (cm)

500 1000 1500 2000

dE/dx (arb. units)

shower maximum @ 11360 cm

beam2

loss@ 11448 cm

Beam direction

Figure 2: Proposed beam loss monitor locations around the quadrupoles.
3b. Limitations in spatial resolution (where to put BLMs)

Low Energy Proton Beam = Shielded Shower

Loss in the middle of first quadrupole magnet, in xz plane, with 150 MeV energy.

Loss in the middle of first quadrupole magnet, in xz plane, with 200 MeV energy.

Loss in the middle of first quadrupole magnet, in xz plane, with 1 GeV energy.

Loss in the middle of first quadrupole magnet, in yz plane, with 2 GeV energy.

Loss location = middle of first quadrupole
Loss angle = 1.5 mrad
Loss intensity = $10^{12}$ protons/sec

Important:
Loss signal has to be calibrated by energy Monte Carlo Codes

Technical Note ESS/AD/0032
3b. Limitations in spatial resolution (where to put BLMs)

Local measurement
Vs.
Do losses appear somewhere?

Neutrons are everywhere in the accelerator tunnel in case of losses:

Few neutron detector BLMs are sufficient
3b. Limitations in spatial resolution (where to put BLMs)

**Neutron Detector**

- 35 mm poly moderator
- Li (n, alpha)
- Scintillator detects the alphas
- PMT
- $10^4 - 10^8 n/cm^2/s$
- 0.03 eV - 3 MeV
4) Challenges associated to measurements of losses

Just a small selection:

a. Very low energy machines
b. High background
4a) Challenges associated to measurements of losses at low energies

The problem: No or very few secondaries outside the vacuum chamber

Solutions:
• Differential current measurement
  • Limited position resolution
  • LINAC/transport only
• BLMs very close to beam pipe
  • Risk of wrong position
• BLMs sensitive to neutrons
  • Limited position resolution
• Very sensitive BLMs
• Use of BLMs at collimators
4a) Challenges associated to measurements of losses at low energies

The problem: No or very few secondaries outside the vacuum chamber

Solutions:
- Differential current measurement
  - Limited position resolution
  - Linac/transport only
- BLMs very close to beam pipe
  - Risk of wrong position
- BLMs sensitive to neutrons
  - Limited position resolution
- Very sensitive BLMs
- Use of BLMs at collimators

that complements ionization chambers. A specifically designed device, the halo monitor ring (HMR), is implemented upstream of each cryomodule to detect beam loss directly. Together

-> Also: Cryogenic BLMs (not at low energy)
4a) Challenges associated to measurements of losses at low energies

The problem: No or very few secondaries outside the vacuum chamber

Solutions:
- Differential current measurement
  - Limited position resolution
  - Linac/transport only
- BLMs very close to beam pipe
  - Risk of wrong position
- BLMs sensitive to neutrons
  - Limited position resolution
- Very sensitive BLMs
- Use of BLMs at collimators

that complements ionization chambers. A specifically designed device, the halo monitor ring (HMR), is implemented upstream of each cryomodule to detect beam loss directly. Together with fast response neutron scintillators, the new integrated BLM system satisfies both machine protection and sensitivity requirements.
4a) Challenges associated to measurements of losses at low energies

The problem: No or very few secondaries outside the vacuum chamber

Solutions:
- Differential current measurement
  - Limited position resolution
  - Linac/transport only
- BLMs very close to beam pipe
  - Risk of wrong position
- BLMs sensitive to neutrons
  - Limited position resolution
- Very sensitive BLMs
- Use of BLMs at collimators

Challenges: Low energy part of linac
- Low energy beam (<20MeV)
  - IC not sensitive enough
  - ND sensitive, but hard to calibrate (no sufficient experimental data for reliable simulation)
  - Still the biggest issue

![Loss Waveform](Image)
4a) Challenges associated to measurements of losses at low energies

The problem: No or very few secondaries outside the vacuum chamber

Solutions:
- Differential current measurement
  - Limited position resolution
  - Linac/transport only
- BLMs very close to beam pipe
  - Risk of wrong position
- BLMs sensitive to neutrons
  - Limited position resolution
- Very sensitive BLMs
- Use of BLMs at collimators

Challenges: Low energy part of linac

- Low energy beam (<20MeV)
  - IC not sensitive enough
  - ND sensitive, but hard to calibrate (no sufficient experimental data for reliable simulation)
  - Still the biggest issue
  - PMTs are supposed to help

Loss Waveform

Warm linac PMTs
4a) Challenges associated to measurements of losses at low energies

The problem: No or very few secondaries outside the vacuum chamber

Solutions:
- Differential current measurement
  - Limited position resolution
  - Linac/transport only
- BLMs very close to beam pipe
  - Risk of wrong position
- BLMs sensitive to neutrons
  - Limited position resolution
- Very sensitive BLMs
- Use of BLMs at collimators
  - Known loss location
  - Aperture limit
  - Highest loss rate (hopefully)
  - Machine + Collimator Protection

- “Tails” in distributions are from the beam.
- BLM signal is linear with proton intensity.
- Left-right asymmetry of the shower depends on the collimator gap size and gap position.
- Slight top-bottom asymmetry?
- BLM signal depends on the impact position on the jaw.
- Compares ~ OK with simulations (TT40).
4a) Challenges associated to measurements of losses at low energies

The problem: No or very few secondaries outside the vacuum chamber

Solutions:
- Differential current measurement
  - Limited position resolution
  - Linac/transport only
- BLMs very close to beam pipe
  - Risk of wrong position
- BLMs sensitive to neutrons
  - Limited position resolution
- Very sensitive BLMs
- Use of BLMs at collimators
  - Known loss location
  - Aperture limit
  - Highest loss rate (hopefully)
  - Machine + Collimator Protection

Figure 4. Benchmark of the beam loss pattern for a single minipulse of beam collimated in a two-stage system. The pink boxes are the measured BLM readings, converted to energy deposition, and the blue diamonds are the ORBIT simulation results.
4b) Challenges associated to measurements of losses at high background

The problem: Limits the dynamic range

1. EM Noise

Reasons:
- Shielding
- Ground loops
- RF
- PS ripple (from magnets, from HV)
- Kickers, septum
- Magic
- Ghosts
- Sabotage
- …

Solutions:
Blame the others!
(not very useful, I know…)
4b) Challenges associated to measurements of losses at high background

The problem: Limits the dynamic range

2. X-ray from cavities

Reasons:
- Released electrons from cavity
- Magic
- Ghosts
- Sabotage
- …

Solutions:
- Subtraction by software
- Use of a x-ray insensitive detector

Figure 4: BLM signals from a single bunch and dark current at FLASH (April 2012): BLM with SQ1 synthetic fused silica (top, HV=700 V) and BLM with a scintillator (HV=550 V).

XFEL Beam Loss Monitor System
A. Kaukher, I. Kroupchenkov, D. Noelle (D. Nölle), H. Tiessen, K. Wittenburg
IPAC12
The problem: Limits the dynamic range

2. **X-ray from cavities**

**Reasons:**
- Released electrons from cavity
- Magic
- Ghosts
- Sabotage
- ...

**Solutions:**
- Subtraction by software
- Use of a x-ray insensitive detector

![Image of oscilloscope trace showing signals from a gas proportional monitor (green) and plastic scintillation monitor (magenta) at SDTL13 section, during beam operation with chopped beam. The beam current signal with a current transformer is also shown (yellow).]

Figure 5: Signals from a gas proportional monitor (green) and plastic scintillation monitor (magenta) at SDTL13 section, during beam operation with chopped beam. The beam current signal with a current transformer is also shown (yellow).

Beam Loss Detected by Scintillation Monitor
Akihiko Miura, et al.
IPAC’11
4b) Challenges associated to measurements of losses at high background

The problem: Limits the dynamic range

3. X-ray from Synchrotron radiation

Reasons:
- SR is unavoidable

Solutions:
- Subtraction by software
- Use of a x-ray insensitive detector: Cherenkov material: Quartz
- Coincidence

K. Scheid, ESRF, 7th DITANET Topical Workshop on Beam Loss Monitoring; 2011

S.L. Krameer NSLS II, 7th DITANET Topical Workshop on Beam Loss Monitoring; 2011

L. Fröhlich, FERMI, 7th DITANET Topical Workshop on Beam Loss Monitoring; 2011

J. Perry, Jlab, PAC93
The problem: Limits the dynamic range

3. X-ray from Synchrotron radiation
   **Reasons:**
   - SR is unavoidable

   **Solutions:**
   - Subtraction by software
   - Use of a x-ray insensitive detector: Cherenkov material: Quartz
   - **Coincidence: Counting**

   Coincidence technique: SR-Photons stop in one or the other PIN diode and are not counted!

---

**The Beam Loss Monitoring System at ELSA**
Dennis Proft, IPAC12

**Installation and Test of a Beam Loss Monitor System for the S-DALINAC**
Robert Stegmann, IPAC12

**Beam Loss Monitors for the HERA Proton Ring**
DESY HERA 90-11
5) Radiation hardness
5) Radiation hardness

Reviewing relevant papers is an essential

<table>
<thead>
<tr>
<th>Sample name</th>
<th>By $\gamma$-ray [kGy]</th>
<th>By proton beam loss [kGy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Scintillator</td>
<td>1100</td>
<td>230</td>
</tr>
</tbody>
</table>

The radiation Dose which makes $1/e$ reduction of the original transparency

the time and place of observation! The literature on radiation damage in detectors could well lead to an equally valid conclusion.
6) A comprehensive summary of the current state-of-the-art methods
6) A comprehensive summary of the current state-of-the-art methods

- Cannot be answered since all kind of methods are in use (as seen from previous slides)
- There is no “best method” since a useful method depends on various accelerator parameters
- Therefore: Don’t trust on “state of the art”, often a well established method can be the best (Ion chambers and Scintillators+PMT are the most common BLMs)
- However, new problems need new solutions: e.g. x-ray background-> Cherenkov rods and fibers, PIN-Coincidence
- Still searching for a fast and sensitive detector with high dynamic range and high radiation damage threshold -> Diamonds?
- Simulations are important to understand losses and the BLM response
6) A comprehensive summary of the current state-of-the-art methods

a) Simulation:
IBIC2013
Beam Delivery Simulation (BDSIM): A Geant4 Based Toolkit for Diagnostics and Loss Simulation
Monte Carlo Simulations of Beam Losses in the Test Beam Line of CTF3
Simulation for Radiation Field Caused by Beam Loss of C-ADS Injector II
Beam Loss Monitoring at the European Spallation Source
IPAC11
Comparative Studies into 3D Beam Loss Simulations
Monte Carlo Simulation of the Total Dose Distribution around the 12 MeV UPC Race-track Microtron and Radiation Shielding Calculations
Beamloss Study at J-PARC Linac by using Geant4 Simulation

b) Fiber based BLMs
IBIC13
Update on Beam Loss Monitoring at CTF3 for CLIC
Optical Fiber Based Beam Loss Monitor for Electron Storage Ring
Cherenkov Radiation for Beam Loss Monitor Systems
BIW12IBIC12
Development of Optical Fiber Beam Loss Monitor System for the KEK Photon Factory
Simulation and Measurement of Beam Loss in the Narrow-Gap Undulator Straight Section of the Advanced Photon Source Storage Ring

c) Diamond BLMs
IBIC12/13
Operation of Silicon, Diamond and Liquid Helium Detectors in the Range of Room Temperature to 1.9 Kelvin and After an Irradiation Dose of Several Mega Gray
A Prototype Readout System for the Diamond Beam Loss Monitors at LHC
Performance of Detectors using Diamond Sensors at the LHC and CMS
IPAC12
Advances in CVD Diamond for Accelerator Applications
BEAM HALO MONITOR FOR FLASH AND THE EUROPEAN XFEL
Investigation of the Use of Silicon, Diamond and Liquid Helium Detectors for Beam Loss Measurements at 2 Kelvin
7) Needs for further development:
7) Needs for further development:

• Calibration of BLM signal in terms of lost particles

• Dealing with saturation, avoiding, detecting

• Extending the useful dynamic range and speed of loss measurements

Quite often, BLMs are used just to minimize losses. Mainly in superconducting hadron accelerators a calibration of the loss signal was done to define thresholds for quenches.

There is a need to calibrate the losses in terms of dose at high intense hadron accelerators to avoid activation, checking the 1W/m rule. -> Reliable integration of BLMs into MPS

Beam lifetime measured by current and loss monitors agreed by factor 2 in HERAp. I’ve heard about the same at LHC.
7) Needs for further development:

- Calibration of BLM signal in terms of lost particles
- **Dealing with saturation, avoiding, detecting**
- Extending the useful dynamic range and speed of loss measurements

It is not always obvious if your detector, amplifier, ADC circuit is saturating. PMTs behave crazy at saturation. It’s known, but how to deal with it in operation? Not much in literature available.
7) Needs for further development:

- Calibration of BLM signal in terms of lost particles
- Dealing with saturation, avoiding, detecting
- Extending the useful dynamic range and speed of loss measurements
7) Needs for further development.

My final message:

One BLM System is not enough for

your accelerator!!!

Thanks for attention, questions?