Luminometers for future $e^+e^-$ collider experiments

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What’s all this “collider luminosity” stuff, anyhow?

• The instantaneous luminosity of a collider is the quotient between the rate of a certain event or group of events and the effective cross section of the processes involved

\[ L = \frac{1}{\sigma} \frac{dN}{dt} \left[ b^{-1} s^{-1} \right] \]  

\( \text{e.g. } L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)

• Luminosity is a **machine parameter** related to the **beam features** such as size and intensity
  – Luminosity is **process-independent**
  – Can be **inferred** from measured event rate and its known event cross section
  – Need a **well understood and measurable process**

• **Integrated luminosity** is \( L \) accumulated over the experiment data taking period

\[ L_{\text{int}} = \int L dt \left[ b^{-1} \right] \]

• Integrated luminosity is related to the **total data** produced by an experiment
L and $L_{\text{int}}$ are very important (!)

- $L$ is necessary to monitor the accelerator performance
- The higher $L_{\text{int}}$, the higher the number of unlikely events to show up in the experiment
  - E.g., for 7TeV LHC, only one Higgs is produced every 10G events!
- $L_{\text{int}}$ is necessary to measure the process cross section

http://cerncourier.com/cws/article/cern/67435
Luminosity in $e^+e^-$ colliders

- Luminosity measurements are crucial in a collider physics program
- Luminosity precision goals in $e^+e^-$ colliders are more ambitious than in hadron colliders
- **One luminosity instrument** concept for **two linear colliders** under study
  - ILC (SCRF cavities)
  - CLIC (conventional cavities)
Outline of this talk

- Luminosity measurements
- LumiCal and BeamCal design
- Recent testsbeam results
- Thin detector planes development
- ASIC development
So what’s next?

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**Precision luminometry in e\(^+\) e\(^-\) colliders**

Small-angle elastic e\(^+\) e\(^-\) scattering (Bhabha process) is used for precision luminosity measurements

- High production rate
  - Almost pure QED
- Theoretically well understood

\[ \begin{align*}
\text{annihilation} & \quad \text{scattering} \\
e^+ & \rightarrow e^+ + \gamma \\
e^- & \rightarrow e^- + \gamma
\end{align*} \]
How precise?

- Required precision: $10^{-3}$ for initial design, $10^{-2}$ for scaled design

- The differential cross section of Bhabha scattering can be calculated from theory:

\[
\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s} \frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s} \frac{1}{\theta^3}
\]

- Then the luminosity can be estimated:

\[
L = \frac{N_B}{\sigma_B}
\]

Luminometers for future collider experiments
**Instantaneous luminometry in e\(^+\) e\(^-\) colliders**

- **Instantaneous luminosity measurement** based on e\(^+\)e\(^-\) pairs originating from beamstrahlung
  - Depends on beam-beam alignment at interaction point
- Smaller polar angles than those for Bhabha scattering
- **Fast**, but not as precise as estimations from Bhabha process

Distribution of the energy deposited by beamstrahlung pairs after one bunch crossing in a the sensor covering small angle.
Luminometry requirements and challenges for future linear colliders

• Precise measurements
  – Precision better than $10^{-3}$ for 500-GeV CME
    • Challenges in electronics, mechanics and position control; non-trivial luminosity spectrum due to beam-beam effects
  – Small spread of shower for better reconstructability

• Instantaneous measurements
  – High occupancy
  – High radiation environment (~MGy per year) due to beamstrahlung
  – Shield tracker by reducing backscattering

• These requirements call for two complementary instruments in the collider forward region:
  – **Lumical** for precise luminosity measurements
  – **BeamCal** for instantaneous luminosity measurements
Example of forward calorimeters: layout for ILD detector @ILC

[Update of DD4hep implementation of FCAL for ILD, Pawlik and Schuwalow, FCAL Workshop 2017]
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LumiCal design

- Sampling (sandwich) Si-W calorimeter
- **30 precise** layers at ILC (40 at CLIC), one radiation length each
- 42–67 mrad at ILC (38–110 mrad at CLIC)
- **Compactness** for transverse size of shower around ~1 cm

http://inspirehep.net/record/1386724/files/v46p1297.pdf
BeamCal design

- Sampling W calorimeter
  - Thorough research on Sapphire, CVD diamond and GaAs as possible candidates
- 30 precise layers at ILC (40 at CLIC), one radiation length each
- 5–45 mrad at ILC (15–38 mrad at CLIC)
- High radiation tolerance
- Fast bx-by-bx readout
FCAL sensor planes

LumiCal sensor plane sector

BeamCal segmentation options

BeamCal sensor plane sector example

[Optimization of the BeamCal Design, L. Bortko, LCWS 2014]
**BeamCal sensor planes – Sapphire option**

For comparison 2 designs of BeamCal models are considered:

- **baseline**
  - PCB ~0.2 mm
  - 30 layers
  - Sensors
  - Transverse view: 150 x 150 mm
  - pads 7.5 x 7.5 mm

- **new**
  - PCB 2 mm
  - 12 layers
  - Sensors
  - Sensor strip in depth: 7.5 x 150 mm
  - pads 7.5 x 7.5 mm

[Optimization of the BeamCal Design, L. Bortko, LCWS 2014]

- Sapphire is cheap and less sensitive to radiation; smaller signals
- New design is more sensitive to MIPs, less DR required
- Non-standard assembly procedure
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CERN PS accelerator, T9 beam 2014

• Beam parameters:
  – Particles (mainly $e^-$ and $\mu$) with $\sim$5GeV energy
  – 400ms spills every 33.6s

• Objectives:
  – Demonstrate multiplane W-Si operation
  – Study EM shower and estimate Molière radius

Experimental setup

- 4-layer tracker using MIMOSA-26 chips
  - Custom DAQ based on NI PXI crate
- Scintillation counters for trigger
- Few electrons per second were recorded
- 4-layer detectors, 32 channels/layer
  - FPGA-based DAQ
Results: distribution of radial shower position

Distribution of radial shower position – Lumical vs. tracker

Results: Energy per layer

\[ \langle E_{\text{layer}} \rangle \text{[MIP]} \]

\[ \langle E_{\text{layer}} \rangle \text{[MIP]} \]

arXiv:1705.03885

Luminometers for future collider experiments
What’s all this “Molière radius” stuff, anyhow?

- Radius of a cylinder that contains 90% of the energy deposition of the shower
  - A small $R_M$ facilitates reconstruction of high energy $e^-$
- It is a **constant of the material** or target **stack**
  - E.g., an air gap in the stack increases $R_M$

Example: EM shower simulation, 10GeV $e^-$ on opal, https://goo.gl/Vb38eZ
Molière radius results

\[ R_M = 24.0 \pm 0.6\text{(stat.)} \pm 1.5\text{(syst.)} \text{ [mm]} \]

Air gaps in detector assembly explain the results
Molière radius results, TB2016

Comparison of transverse shower in TB2016 with TB2014

Luminometers for future collider experiments
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Luminometers for future collider experiments
Design of the thin Lumical module

- Envelope: 120µm
- Kapton HV: 65µm
- Kapton Fan out: 120µm
- Sensor: 360µm
- Glue: 10-20µm
- Carbon fiber support
- Araldite epoxy and ultrasonic wire bonding
  - Conductive glue
- Lumical Silicon sensor
- High voltage kapton
- Kapton-copper fanout

Luminometers for future collider experiments
Wedge wire-bonding for FE contact

Achievable size of the bonding loops is in the range 50 $\mu$m - 100$\mu$m.

Bonding loop measured with 3D laser scanning confocal microscope at DESY Zeuthen.

Luminometers for future collider experiments
TAB technology for FE contact

Search for long-term stable contact between sensor and readout electronics which meets LumiCal geometrical (compactness) requirement.

Single point Tape Automated Bonding (TAB):
- No wire loop, the bond can be covered by the glue for better protection;
- One LumiCal module is assembled and tested using TAB technology.
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Prior art:
FCAL-related ASICs overview

Why do we need a dedicated readout for our luminometers?

Luminometers for future collider experiments
Bean V1 and fast readout

DOI: 10.1109/TNS.2012.2194308
Recent development

- For **very compact calorimeter** we need an **ultra low-power** SoC
- FLAME: 16-channel readout ASIC in 130nm CMOS, includes FE & ADC, fast SER and Data Tx

[FLAME: FcaL Asic for Multiplane rEadout]

[LumiCal Readout, M. Idzik, 31st FCAL WS 2017]
FLAME and Serializer ASIC

- Prototype 8-channel FE+ADC ASIC
- Prototype serializer ASIC

130-nm CMOS process
First tests performed
- PCB produced
- Front-end: OK
- ADC: OK
- Serializer: OK
- Ongoing work...

[LumiCal Readout, M. Idzik, 31st FCAL WS 2017]
Concluding remarks

• Luminosity numbers are important
• Two luminosity concepts presented
  – Precise estimation from Bhabha scattering
  – Fast estimation from Beamstrahlung pairs
• Current development includes
  – ASICs
  – Thin sensor planes
• Testbeam results show promising results
  – Verified functionality of existing setup
  – Performance of EM shower reconstruction is in excellent agreement with MC simulations

Major components for a luminometer to be used at a future experiment at CLIC or ILC, developed by the FCAL collaboration, can be operated as a system.
THANKS FOR YOUR ATTENTION
BACKUP SLIDES
ILC layout

[ILC TDR 2013]

Luminometers for future collider experiments

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>500 GeV</td>
</tr>
<tr>
<td>Length</td>
<td>31 km</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$1.8 \times 10^{34} \text{ cm}^2\text{s}^{-1}$</td>
</tr>
<tr>
<td>Repetition</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Beam Pulse Period</td>
<td>0.73 ms</td>
</tr>
<tr>
<td>Beam Current</td>
<td>5.8 mA (in pulse)</td>
</tr>
<tr>
<td>Beam size ($\gamma$) at FF</td>
<td>5.9 nm</td>
</tr>
<tr>
<td>SRF Cavity G. $Q_0$</td>
<td>31.5 MV/m</td>
</tr>
<tr>
<td></td>
<td>$Q_0 = 1 \times 10^{10}$</td>
</tr>
</tbody>
</table>
Luminosity formula

\[ \mathcal{L} = F \frac{k_b N_b^2 f_{\text{rev}} \gamma}{4\pi \epsilon_n \beta^*} = F \frac{N_1 N_2 f_{\text{rev}} N_b}{4\pi \sigma_x \sigma_y} \quad (12.7) \]

where \( k_b \) is the number of bunches per ring, \( N_b \) the number of protons per bunch, \( f_{\text{rev}} \) the revolution frequency, \( \epsilon_n \) the normalized r.m.s. transverse emittance (assumed to be the same in both planes), \( \beta^* \) the beta-function at the collision point, and \( F \leq 1 \) is a reduction factor caused by the finite crossing angle \( \Phi \).

[Induction Accelerators, Takayama and Briggs (editors), Springer 2011]
DESY-II Synchrotron 2011

e$^-$ beam 2-4.5GeV, 100’s particles per second

https://doi.org/10.1088/1748-0221/10/05/P05009
Results: shower development, Si sensor

- Full functionality of sensor planes
- SNR between 20 and 30
- Next step: multiplane tests

Luminometers for future collider experiments
LumiCal FE and multichannel ADC

Served both TB campaigns mentioned earlier

https://doi.org/10.1016/j.nima.2009.06.059

Served during the first TB campaign mentioned earlier

JINST, 6 P01004, 2011

Luminometers for future collider experiments
Prufpilo: Low power ADC and nonlinear ADC

DOI: 10.1016/j.mejo.2015.06.005

Luminometers for future collider experiments
Bean V2: arbitrary weighting function generation

Luminometers for future collider experiments
Pulse at output of shaper \( v(t) \) is convolution of input signal (current from sensor – \( s(t) \) ) and impulse response of readout chain \( h(t) \):

\[
v(t) = \int_{-\infty}^{+\infty} h(t-x)s(x) \, dx
\]

Using data from continuously running ADC and taking advantage of known pulse shape one can perform invert procedure – deconvolution – to get information about event time and amplitude.
Deconvolution for CR-RC shaping - Theory

\[ d_i = s_i + w_1 s_{i-1} + w_2 s_{i-2} \]

- Only two multiplications and three additions (very fast and light!)
- Deconvolution produces non-zero data only when one or two first samples are on baseline, and second/third is on pulse
- **Initial time** of pulse is found from ratio of those samples
- **Amplitude** is found from sum of those samples, multiplied by time dependent correction factor
- Deconvolution reduces (infinite number) of CR-RC pulse samples to 1 or 2 non-zero samples!

CR-RC, \( T_{\text{smp}} = T_{\text{peak}} = 1 \), amp = 1

Synchronous sampling (\( t_0 = \text{int} \times T_{\text{smp}} \))

Asynchronous sampling (\( t_0 = \text{int} \times T_{\text{smp}} \))

Look Up Tables used Can be done off-line
Deconvolution for CR-RC shaping
Real, averaged, FE pulses

- Real pulse (1 MIP) deconvoluted for various phase shift \( t_0 \) between the Front-End pulse and ADC sampling
- Deconvolution done for different sampling periods (12.5, 25 and 50 ns are presented)
  - **Amplitude reconstruction** (top plot) – deconvoluted to real pulse amplitude ratio
    - Error is below 2% except 12.5 ns sampling period
  - **Time reconstruction** (bottom plot) – difference between reconstructed and real pulse peak position
    - Constant offset of around 2 ns except 50 ns sampling period
- **S/N** after deconvolution still to be measured...