Calorimeter Issues and Possible Directions for R&D

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Argonne National Laboratory

R&D Opportunities for the LC: WS at FNAL on April 5, 2002
Outline of talk

Requirements on calorimeter
- EM calorimeter
- Had calorimeter
- Lumi calorimeter

Simulations
Conclusions

This talk assumes we have a few years time for R&D
Basic Requirements on Calorimeter (I)

**Hermeticity:** Barrel and Endcaps  
Very forward detectors

**Speed of readout**

\[ s_{\text{tot}}(500 \text{ GeV}) = 4 \text{pb} \]
\[ L_{\text{NL C/TESLA}} = 0.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]

\[ \rightarrow 1 \text{ event / 50 sec} \]

**Not a concern!**  
Unless: Surprises  
Running at Z pole

April 5, 2002  
J Repond: Calorimeter R&D
**Basic Requirements on Calorimeter (IIa)**

*(Jet) Energy Resolution:* Many ‘interesting’ final states involve 2-10 jets

Benchmark process: $e^+e^- \rightarrow VV$?
Separation of WW and ZZ $\rightarrow$ 4 jets

Requires excellent resolution: $O(30%/vE)$

→ Has never been achieved before
→ Best so far: ZEUS with $\sim 50%/vE$

New Approach

From H. Videau
### Basic Requirements on Calorimeter (IIb)

**Energy Flow Algorithm (EFA)**

<table>
<thead>
<tr>
<th>Components of Jets</th>
<th>Fraction of Energy in %</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged particles</td>
<td>60</td>
<td>Tracker</td>
</tr>
<tr>
<td>Photons</td>
<td>20</td>
<td>EM calorimeter</td>
</tr>
<tr>
<td>Neutral Hadrons (K^0_L,n)</td>
<td>10</td>
<td>EM and HAD calorimeter</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>10</td>
<td>Lost</td>
</tr>
</tbody>
</table>

**Requirements on Detector:**

- **Tracker:** large volume, high B-field (~4T)
- **E-Cal:** resolution of O(10%/vE), fine segmentation
- **H-Cal:** fine segmentation, compensation?

**Thick coil: calorimeter inside!**

Plot by S Kuhlmann

![Photon + Jet P_t Balancing in CDF Data](image)
Basic Requirements on Calorimeter (III)

**Space:** current designs of LC detectors

<table>
<thead>
<tr>
<th></th>
<th>TESLA</th>
<th>SD</th>
<th>LD</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_I</td>
<td>1.68</td>
<td>1.27</td>
<td>2.00</td>
</tr>
<tr>
<td>R_O</td>
<td>1.90</td>
<td>1.43</td>
<td>2.50</td>
</tr>
<tr>
<td>?_EM</td>
<td>0.22</td>
<td>0.16</td>
<td>0.50</td>
</tr>
<tr>
<td>HAD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_I</td>
<td>1.90</td>
<td>1.43</td>
<td>2.50</td>
</tr>
<tr>
<td>R_O</td>
<td>3.00</td>
<td>2.48</td>
<td>3.70</td>
</tr>
<tr>
<td>?_HAD</td>
<td>1.10</td>
<td>1.05</td>
<td>1.20</td>
</tr>
</tbody>
</table>
Basic Requirements on Calorimeter (IV)

**Cost:** Not a constant with time
  
e.g. Price for silicon dropped significantly in past years

Affordable
EM Calorimeter (I)

Review of possible technologies

Requirements: excellent EM energy resolution
fine segmentation (both laterally and longitudinally)
small Molière Radius: $R_M$

Silicon – Tungsten Sandwich Calorimeter

Preferred choice of

<table>
<thead>
<tr>
<th></th>
<th>TESLA</th>
<th>NLC (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of layers</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Thickness of W</td>
<td>1.4 ? 4.2 mm</td>
<td>2.5 mm</td>
</tr>
<tr>
<td></td>
<td>0.4 ? 1.2 $X_0$</td>
<td>0.7 $X_0$</td>
</tr>
<tr>
<td>Thickness of EM</td>
<td>24 $X_0$</td>
<td>21 $X_0$</td>
</tr>
<tr>
<td>Calorimeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area of silicon</td>
<td>3300 m$^2$</td>
<td>1200 m$^2$</td>
</tr>
<tr>
<td>(barrel and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>endcaps)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td>10x10 mm$^2$</td>
<td>5x5 mm$^2$</td>
</tr>
<tr>
<td>segmentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td># of channels</td>
<td>33x10$^6$</td>
<td>50x10$^6$</td>
</tr>
</tbody>
</table>
**EM Calorimeter (II)**

- Energy resolutions: EM ~ 10%/vE  
  (HAD: non-compensating)

- Lateral density:  
  \( R_{M(W)} = 9 \text{ mm} \)  
  Including gap of 2.5 mm:  
  \( R_{M(EM)} = R_{M(W)}(1 + t_{gap}.t_{W}) \approx 18 \text{ mm} \)

- Effort in US: Oregon, SLAC

**Issues with Silicon/Tungsten**

**Cost:** Driven by Silicon wafer (~70% of cost)  
Assume $4/cm^2? \quad $132M (TESLA)

**Gap size:** Minimize to preserve small \( R_M \)  
Possibly 2.5 mm? 1.5 mm?

![Graph showing cost vs. wafer size over the years](Image)  
Cost/Area of Single-sided Silicon Strip Detectors  
(double-sided factor 2.5 higher)

(Guestimates by HFWS)
EM Calorimeter (III)

Development of readout electronics:
Full integration of readout on Silicon wafer

6" Wafer
1027 (5 mm) cells

Plots by M. Breidenbach

TESLA effort

Note:
$ t_{\text{total}} = 3 \text{ mm} $
EM Calorimeter (IV)

Shashlik Calorimeter

Second choice of TESLA TDR

Pb (1mm) with scintillator (1mm): e/h > 1
140 layers corresponding to 25 $X_0$
Beam tests: $s_{EM/E} = 14.2\%/\sqrt{E} + 0.6\%$
No known effort in US

Transverse segmentation: 3x3 cm$^2$
use of larger scintillator pads with groves

Longitudinal segmentation: 3 ideas
- Silicon pad detectors inserted at various depths
- Insertion of photodiodes at various depths
- Use of scintillator with different decay times

Issues with Shashlik calorimeter

Lateral segmentation: enough for EFA?
Longitudinal segmentation: enough for EFA?
Cost estimate: $14M

Plot from Atoian et al.

Plot from A C Benvenuti et al.
**EM Calorimeter (V)**

**Lead-Scintillator Sandwich Calorimeter**

LD design in US, similar efforts in Europe and Japan

- 4 mm Pb with 1 mm Scintillator: \( e/h \sim 1 \)
- 40 Layers corresponding to 29 \( X_0 \)
- Molière Radius: \( R_M = 20 \) mm
- Tiles: 50x50 mm²

**JLC Test Beam Results**

**Issues with Pb-scintillator**

- Longitudinal segmentation: None?  
  Good enough for EFA?  
  Shower maximum detectors?
- Lateral segmentation: Good enough for EFA?
- EM resolution: Good enough for EFA?  
  Compromise other physics, e.g. \( H^0 \) ? ??
- Magnetic field: Readout?
## EM Calorimeter (VI)

### Crystal Calorimeter

Advantages: Best achievable EM resolution
Some crystals with short $X_0, R_M$
Effort in US: Caltech

Table from R Y Zhu

<table>
<thead>
<tr>
<th></th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF$_2$</th>
<th>BGO</th>
<th>PbWO$_4$</th>
<th>LSO(Ce)</th>
<th>GSO(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^2$)</td>
<td>3.67</td>
<td>4.51</td>
<td>4.51</td>
<td>4.89</td>
<td>7.13</td>
<td>8.3</td>
<td>7.40</td>
<td>6.71</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>651</td>
<td>621</td>
<td>621</td>
<td>1280</td>
<td>1050</td>
<td>1123</td>
<td>2050</td>
<td>1950</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.85</td>
<td>1.85</td>
<td>2.06</td>
<td>1.12</td>
<td>0.9</td>
<td>1.14</td>
<td>1.37</td>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>4.8</td>
<td>3.5</td>
<td>3.5</td>
<td>3.4</td>
<td>2.3</td>
<td>2.0</td>
<td>2.3</td>
<td>2.37</td>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>41.4</td>
<td>37.0</td>
<td>37.0</td>
<td>29.9</td>
<td>21.8</td>
<td>18</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>Refractive Index $^a$</td>
<td>1.85</td>
<td>1.79</td>
<td>1.95</td>
<td>1.50</td>
<td>2.15</td>
<td>2.2</td>
<td>1.82</td>
<td>1.85</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>Yes</td>
<td>Slight</td>
<td>Slight</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Luminescence $^b$ (nm) (at peak)</td>
<td>410</td>
<td>560</td>
<td>420</td>
<td>310</td>
<td>300</td>
<td>480</td>
<td>560</td>
<td>420</td>
</tr>
<tr>
<td>Decay Time $^b$ (ns)</td>
<td>230</td>
<td>1300</td>
<td>35</td>
<td>6</td>
<td>630</td>
<td>300</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Light Yield $^{b,c}$ (%)</td>
<td>100</td>
<td>45</td>
<td>5.6</td>
<td>2.3</td>
<td>21</td>
<td>9</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>$d$(LY)/dT $^b$ (%/°C)</td>
<td>~0</td>
<td>0.3</td>
<td>-0.6</td>
<td>-2</td>
<td>-1.6</td>
<td>-1.9</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Volume Price ($/cm$^2$)</td>
<td>1 to 2</td>
<td>2</td>
<td>2.5</td>
<td>2.5</td>
<td>7</td>
<td>2.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*a. at peak of emission; b. up/low row: slow/fast component; c. measured by PMT of bi-alkali cathode.*
EM Calorimeter (VII)

Plot by R Y Zhu

Recent developments: increased light output for PbWO$_4$, PbF$_2$, LSO(Ce), GSO(Ce)

Issues with Crystals

Segmentation: lateral, longitudinal

Magnetic field: readout

Space: $25 \times 0$ in say 20cm

compromising EFA
**EM Calorimeter (VIII)**

**General issues for ECAL**

**Dynamic range:** Assume 1 cm² pads
- 250 GeV e⁺ → 340 MeV (at shower max)
- MIP → 0.16 MeV

2.1x10³ ~ 12 bits

Significant reduction in pad size needed to reduce dynamic range

**Calibration:** Absolute

**Intercalibration:** important!

**Timing information:** What is needed?

**Performance in magnetic field?**

**Other technologies?**
HAD Calorimeter (I)

Review of possible technologies

Consensus: sandwich calorimeter

Requirements: depth: $= 4 \ell_i$ at $90^\circ$ for $R = 1.2$ m
fine segmentation
compensation?

Ratio of $\frac{\ell_i}{X_0}$:
advantageous for Fe, Cu
Active gap size $\ell$; 1 cm

Active medium?

Choices for Absorber

<table>
<thead>
<tr>
<th>Material</th>
<th>A/Z</th>
<th>$\ell_i$ [cm]</th>
<th>$X_0$ [cm]</th>
<th>$\frac{\ell_i}{X_0}$</th>
<th>$t_{\text{passive}} = 4 \ell_i$ [cm]</th>
<th>Number of layers assuming $1X_0$ sampling</th>
<th>$t_{\text{active/layer}}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>56/26</td>
<td>16.8</td>
<td>1.8</td>
<td>9.3</td>
<td>67</td>
<td>38</td>
<td>8.7</td>
</tr>
<tr>
<td>Cu</td>
<td>64/29</td>
<td>15.1</td>
<td>1.4</td>
<td>10.8</td>
<td>42</td>
<td>60</td>
<td>9.5</td>
</tr>
<tr>
<td>W</td>
<td>184/7 4</td>
<td>9.6</td>
<td>0.35</td>
<td>27.4</td>
<td>38</td>
<td>110</td>
<td>5.6</td>
</tr>
<tr>
<td>Pb</td>
<td>207/8 2</td>
<td>17.1</td>
<td>0.56</td>
<td>30.5</td>
<td>68</td>
<td>122</td>
<td>2.6</td>
</tr>
<tr>
<td>U</td>
<td>238/9 2</td>
<td>10.5</td>
<td>0.32</td>
<td>32.8</td>
<td>42</td>
<td>181</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Assuming $R = 100$ cm
HAD Calorimeter (II)

Gas Electron Multipliers GEM

**Advantages:**
- Low HV: few 100V/GEM layer
- Thin layer: ~6 mm
- On-board readout possible
- Flexible pad readout segmentation
  - Printed circuit
- Either digital or semi-analog readout
- Cheap

**Effort:** University of Texas

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**Issues with GEMs**

**Effects of**
- stray particles
- heavily ionising particles

**Long term performance**

**Cross talk**

**Calibration**

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April 5, 2002  J Repond: Calorimeter R&D  17
Resistive Plate Chambers RPCs

Advantages: Thin layer possible
   On-board readout possible
   Flexible pad readout segmentation
   Printed circuit
   Either analog, semi-analog, digital readout
   Reliable
   Underlying physics mostly understood
   see http://www.coimbra.lip.pt/~rpc2001/talks.html
   Cheap
Effort: Argonne; Russia, France, Korea
HAD Calorimeter (IV)

Choices: Resistive plates: Glass (preferred) Bakelite (needs to be coated)
Operation: Avalanche mode
Faster
Lower HV
Smaller signal (~1pC)

Streamer mode
Slower
Higher HV
Large signals (~100pC)

Mechanical: gap size
glass thickness
number of gaps
or completely new design

Cosmic ray tests at ANL

Plots by A Bamberger

Plots by V Amassov
HAD Calorimeter (V)

**Issues with RPCs**

**Safety with HV:** using up to 10kV can be reduced with smaller gaps in avalanche mode

**Cross talk between pads:** significant charge on neighboring pad reduced with higher resistivity ink 40kΩ/? 200kΩ/? signal shape very different easy to discriminate!

**Long term operation:** significant experience elsewhere

**Calibration:** probably not needed in streamer mode
HAD Calorimeter (VI)

Scintillator

First choice in TESLA TDR

Lateral size: 5x5 cm² ? 25x25 cm²
Longitudinally: 38 (53) layers in barrel (endcap)
9 (12) cells ganged together
gap: total t = 7.5 mm
scintillator 5.0 mm
Absorber: 20mm Fe
corresponding to 1.15 X₀
Effort: NIU-NICCAD; DESY, Russia, Prag

Plot by V Rykalin

Cosmic ray test
Realistic set-up with fibers etc.

Readout: has to work in B-field

Avalanche photodiodes: low gain
Hybrid photodiodes: complicated readout
VLPC: Visual Light Photon Counters
Quantum efficiency: 60 – 80 %
Gain: 10⁵ – 10⁶
Operates at 7 °K
MRS: Metal Resistor Semiconductor Photodiodes
Recent development
Quantum efficiency: ~30 %
Operates at room temperature
HAD Calorimeter (VII)

Issues with Scintillator

- **Thickness of Scintillator:** enough light for individual readout?
- **Fiber routing:** light loss
- **Segmentation:** readout of all tiles separately versus ganging together? good enough for EFA?
- **Choice of Photodetector:** high gain and quantum efficiency
- **Calibration**
HAD Calorimeter (VIII)

General issues for HCAL

Compensation versus EF optimization?
  or can you have both?

Tail catcher?
  ever used before?

Timing information?
  what is needed?
  suppress noise

Dynamic range?
  analog versus hybrid versus digital

Performance in magnetic field?

Other technologies?
Luminosity Calorimeter

**Measure:** forward Bhabhas for luminosity determination
tag e+e- for 2-? physics
measure beamstrahlung to optimize machine setting

**Technology:** PbWO₄ with fiber readout
Silicon/Tungsten
Diamond/Tungsten

**Effort:** no US effort; DESY, DESY-Zeuthen, Milan, UC London

**Issues with LCAL**

Design of IR
Geometry of detector
Synchrotron Radiation
Radiation hardness

Plot by A Stahl
Simulations (I)

Overview

Europe

Simdet:
- fast simulation of TESLA TDR detector
- no flexibility with geometry
- (realistically) parameterized detector response should not be used to fine tune detector design

Brahms:
- GEANT3 (fortran based)
- full simulation of TESLA TDR detector
- no flexibility with geometry

Mokka:
- GEANT4 (C++ based)
- flexible geometry (modifications in C++)
- package ready for use (CAL only)

America

Fast MC:
- smearing/libraries
- should not be used to fine tune detector design

LCD full simulation:
- Gismo (EGS/Geisha)
  Simulation of SD and LD designs
  Flexible geometry (user friendly!)

Transition to GEANT4
- First results available
- Flexible geometry (user friendly!)
- Code, tutorials, examples, documentation in http://www-sldnt.slac.stanford.edu/nld/new/analysis.htm
Simulations (II)

Tools needed for calorimeter design studies

Clustering of CAL energies:
- Cluster cheater (uses ‘truth’)
- Simple cluster builder (adjacent cells)
- Radial cluster builder (1st layer ? cone)
- Inverse (outer layer ? front)

Track-cluster matching algorithm

Tracking algorithm for calorimeter: \( \mu \)

Identification of ?’s: \( e = 85\% \) with \( p = 84\% \) (Algorithm by M Iwasaki)

Identification of neutral hadrons

Plot from F Badaud et al.
Simulations (III)

**ECAL Studies**

Comparison of Si/W, Pb/scintillator, Crystal
- EM resolution
- Ability to separate different components of jets
- Jet energy resolution

**HCAL Studies**

Matrix of studies for Jet Energy Resolution
- Different absorbers (material and thickness)
- Different segmentation: from 1 cm$^2$ to 25 cm$^2$
- Different size of active gap ($R_m$)
- Analog versus digital readout

**Common Studies**

Need for compensation or reweighting
- Energy flow algorithms
Simulations (IV)

Validation of Simulations

Recently discovered bugs in Geisha package!

Large differences between Gismo and GEANT4

Can’t afford to design detector based on faulty simulations!!!

Test beams: measure single particle resolutions shower characteristics simulate jets with event overlays

Study of existing detectors?

Current efforts in US

SLAC  T Abe, G Bower, R Cassell, N Graf …
ANL  S Kuhlmann, S Magill
NIU-NICCAD  D Chakraborty, A Maciel, R McIntosh, V Zutshi…
Oregon  R Frey, M Iwasaki

Maximum hit energy in a cluster

Plots by M Iwasaki

Maximum hit energy [GeV]
Conclusions

Design of calorimeter: driven by need for excellent jet energy resolution
  goal: \(\frac{s}{E} = 30\%/\sqrt{E}\)

Technologies: several choices for both ECAL and HCAL
  none completely established/accepted
  some technologies not (yet) pursued in US

→ major effort needed to substantiate case for any choice

Design issues: segmentation of readout required for optimum Energy Flow Algorithms
  need for compensation

→ major simulation effort needed to address these issues

All listed efforts could profit from more manpower