History (Part I)

**1988 - 1993:** INFN Scientific Committee V has funded:

- **SPACAL** (Generic R&D on scintillating fibre compensating Calorimetry)
  - (Cagliari, CERN, CERN-LAA, Lisbon, Napoli, NIKHEF, Paris VI&VII, Pavia, Rio de Janeiro, Weizmann)

- **RD1** (Scintillating Fibre Calorimetry for LHC)
  - (CERN, Clermont-Ferrand, Ecole Polytechnique, Lisbon, Marseille, Napoli, Orsay, Paris VI&VII, Pavia, Rio de Janeiro, Weizmann)

1. “Results Of Prototype Studies For A Spaghetti Calorimeter”
   D. Acosta et al.

2. “Electron - Pion Discrimination With A Scintillating Fiber Calorimeter”
   D. Acosta et al.

3. “Localizing particles showering in a Spaghetti calorimeter”
   D. Acosta et al.

4. “Electron, pion and multiparticle detection with a lead / scintillating - fiber calorimeter”
   D. Acosta et al.

5. “On muon production and other leakage aspects of pion absorption in a lead / scintillating fiber calorimeter”
   D. Acosta et al.

6. “The Performance of a lead / scintillating fiber calorimeter at LHC / SSC compatible gate widths”
   D. Acosta et al.

7. “Laterally shower profiles in a lead / scintillating fiber calorimeter”
   D. Acosta et al.

8. “Detection of muons with a lead / scintillating fiber calorimeter”
   D. Acosta et al.

9. “Test Results of an electromagnetic calorimeter with 0.5-mm scintillating fibers readout”
   J. Badier et al. [RD1 Collaboration]

10. “Test Results of a fully projective lead / scintillating fiber calorimeter”
    J. Badier et al. [RD1 Collaboration]
History (Part II)

- **1992:**
  - Scintillating Fibre calorimeter option in the ATLAS Letter of Intent
  - Ansaldo - INFN Feasibility study for a Sci-Fi Hadron calorimeter for ATLAS

- **2006 - ........**
  - DRC: **Dual Read-out Calorimetry.** High resolution (hadron) Calorimetry
  - US name: DREAM **Dual READ-out Method**

*CERN 95-02*
28 February 1995

*SCINTILLATING-FIBRE CALORIMETRY*

Michele Livan, Valerio Vercesi
*Università di Pavia and INFN Sezione di Pavia, Pavia, Italy*

and

Richard Wigmans
*Texas Tech University, Lubbock TX 79409-1051, USA*
Institutions

✦ Cagliari
  ✦ A. Cardini

✦ Cosenza
  ✦ L. La Rotonda, E. Meoni, A. Policicchio, G. Susinno

✦ Pavia
  ✦ C. Conta, R. Ferrari, S. Franchino, M. Fraternali, M. Livan (Responsabile Nazionale)

✦ Pisa
  ✦ F. Bedeschi, R. Carosi, M. Incagli, F. Scuri

✦ Roma I
  ✦ G. Ciapetti, F. Lacava, D. Pinci, C. Voena

✦ UCSD
  ✦ H. P. Paar et al.

✦ Iowa State
  ✦ J. Hauptman et al.

✦ Texas Tech
  ✦ R. Wigmans (Project Leader) et al.
Design goal ILC: separate $W, Z \rightarrow q\bar{q}$

**LEP-like detector**

**ILC design goal**

<table>
<thead>
<tr>
<th>$M_{jj}$</th>
<th>$M_{jj}$</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Graph 1" /></td>
<td><img src="image2.png" alt="Graph 2" /></td>
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</table>

- No kinematic constraints as in LEP (Beamstrahlung)
High resolution hadron spectroscopy

- High-resolution Hadron Calorimetry (for jet spectroscopy) very relevant for Linear high-energy $e^+e^-$ Colliders
  - Small uncertainties due to jet algorithms/underlying event
  - No constrained fits as in LEP (beamsstrahlung)
    - $\Rightarrow$ Intrinsic detector properties limiting factor

- High-resolution Electromagnetic and high-resolution Hadronic calorimetry are mutually exclusive:
  - Good jet energy resolution $\Rightarrow$ Compensation $\Rightarrow$ very small sampling fraction ($\sim 3\%$) $\Rightarrow$ poor electron, photon resolution
  - Good electromagnetic resolution $\Rightarrow$ high sampling fraction (100% Crystals, 20% LAr) $\Rightarrow$ large non compensation $\Rightarrow$ poor jet resolution
High-resolution hadron calorimetry

- Common problems in hadron calorimetry
  - Energy scale different from electrons, in energy dependent way
  - Hadronic non-linearity
  - Non-Gaussian response function
  - Poor energy resolution

- Why?
  - Electromagnetic calorimeter response ≠ non-em response \((e/h ≠ 1)\)
  - Large event-to-event fluctuations in em shower content \((f_{em})\)

- Solutions
  - Compensating calorimeters \((e/h=1)\), e.g. Pb/plastic scintillator
  - Measure \(f_{em}\) event-by-event
Measuring the electromagnetic shower content

- Measure $f_{\text{em}}$ event-by-event
  - Pioneered by WA1 around 1980
  - Used characteristics of energy deposit profile to disentangle em/non-em shower components
  - Works better as energy increases
  - Does not work for jets (collection of $\gamma$s, $\pi$s showering simultaneously in the same area)
The first DREAM prototype

Basic structure:
- 4x4 mm² Cu rods
- 2.5 mm radius hole
- 7 fibers
- 3 scintillating
- 4 Čerenkov

DREAM prototype:
- 5580 rods, 35910 fibers, 2 m long (10 \( \lambda_{\text{int}} \))
- 16.2 cm effective radius (0.81 \( \lambda_{\text{int}} \), 8.0 \( \rho_M \))
- 1030 Kg
- \( X_0 = 20.10 \text{ mm}, \rho_M = 20.35 \text{ mm} \)
- 19 towers, 270 rods each
- hexagonal shape, 80 mm apex to apex
- Tower radius 37.10 mm (1.82 \( \rho_M \))
- Each tower read-out by 2 PMs (1 for Q and 1 for S fibers)
- 1 central tower + two rings
The DREAM principle

✦ Quartz fibers are only sensitive to em shower component!

✦ Production of Čerenkov light ⇒ Signal dominated by electromagnetic component

✦ Non-electromagnetic component suppressed by a factor 5 ⇒ e/h=5 (CMS)

✦ Hadronic component mainly spallation protons \( E_k \sim \) few hundred MeV ⇒ non relativistic ⇒ no Čerenkov light

✦ Electron and positrons emit Čerenkov light up to a portion of MeV

✦ Use dual-readout system:

✦ Regular readout (scintillator, LAr, ...) measures visible energy

✦ Quartz fibers measure em shower component \( E_{em} \)

✦ Combining both results makes it possible to determine \( f_{em} \) and the energy \( E \) of the showering hadron

✦ Eliminates dominant source of fluctuations
The (energy independent) $Q/S$ method

$$R(f_{em}) = E \left[ f_{em} + \frac{1}{e/h}(1 - f_{em}) \right]$$

$$e/h = 1.3(S), 5(Q)$$

$$S = E \left[ f_{em} + \frac{1}{(e/h)_S}(1 - f_{em}) \right]$$

$$Q = E \left[ f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em}) \right]$$

$$\frac{Q}{S} = \frac{R_Q}{R_S} = \frac{f_{em} + 0.20(1 - f_{em})}{f_{em} + 0.77(1 - f_{em})}$$
DREAM: Effect of corrections (200 GeV “jets”)

NIM A 537 (2005) 537

![Graph showing the effect of corrections on Čerenkov signal](image)
DREAM: Energy resolution “jets”

- After corrections the energy resolution is dominated by leakage fluctuations
- Calibrated only with electrons!
- Calorimeter radius \(.8 \lambda_{int}\)!
- Total weight only 1 ton!
How to improve DREAM?

- Build a larger detector → reduce effects of side leakage
- Increase Čerenkov light yield
  - DREAM: 8 p.e./GeV → fluctuations contribute 35%/√E
  - Homogeneous detector? Crystals?
- Need to separate Čerenkov and scintillation contributions
- Ultimate hadron calorimetry (15%/√E)
  - Measure also “nuclear binding energy losses” with a third active component or using time structure of signals
3 Papers from the 2006 test beam

Measurement of the Contribution of Neutrons to Hadron Calorimeter Signals

Dual-Readout Calorimetry with Lead Tungstate Crystals

Contributions of Čerenkov Light to the Signals from Lead Tungstate Crystals

N. Akchurin\textsuperscript{a}, L. Berntzon\textsuperscript{a}, A. Cardini\textsuperscript{b}, R. Ferrari\textsuperscript{c}, G. Gaudio\textsuperscript{c}, J. Hauptman\textsuperscript{d}, H. Kim\textsuperscript{a}, L. La Rotonda\textsuperscript{e}, M. Livan\textsuperscript{c}, E. Meoni\textsuperscript{e}, H. Paar\textsuperscript{f}, A. Penzo\textsuperscript{g}, D. Pinci\textsuperscript{h}, A. Policicchio\textsuperscript{e}, S. Popescu\textsuperscript{i}, G. Susinno\textsuperscript{e}, Y. Roh\textsuperscript{a}, W. Vandelli\textsuperscript{c} and R. Wigmans\textsuperscript{a,1}

\textsuperscript{a} Texas Tech University, Lubbock (TX), USA
\textsuperscript{b} Dipartimento di Fisica, Università di Cagliari and INFN Sezione di Cagliari, Italy
\textsuperscript{c} Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN Sezione di Pavia, Italy
\textsuperscript{d} Iowa State University, Ames (IA), USA
\textsuperscript{e} Dipartimento di Fisica, Università della Calabria and INFN Cosenza, Italy
\textsuperscript{f} University of California at San Diego, La Jolla (CA), USA
\textsuperscript{g} INFN Trieste, Italy
\textsuperscript{h} Dipartimento di Fisica, Università di Roma “La Sapienza” and INFN Sezione di Roma
\textsuperscript{i} CERN, Genève, Switzerland

Papers available on arXiv:
0707.4013
0707.4019
0707.4021
Identifying Čerenkov component I

- Results from 2006 test beam with PWO$_4$ crystals
- Č contribution up to 13%. Smaller asymmetry for “late showers” (isotropic component)
- PWO$_4$ crystals not ideal: not transparent below 350 nm and decay time too short (10 ns)
Identifying Čerenkov component II

- Average time structure of the signals in the L and R PMTs produced by 10 GeV electrons
- Bottom plots: signals for $\theta = \pm 30^\circ$
- Top plots: difference between the two orientations, i.e. PMTs response to the Čerenkov component

Average difference between the times the two PMTs need to reach a certain threshold level as a function of the orientation of the crystal

Data for 150 GeV muons and two different threshold values
ECAL

✦ Small electromagnetic calorimeter (ECAL) made of 19 PbWO4 crystals in front of DREAM (HCAL)

✦ 50 GeV pions - Select events that deposit at least 10 GeV in ECAL

ECAL measurements correlate quite well with HCAL

\[ \frac{Q}{S} \sim f_{em} \]
Efficient neutron detection would allow direct measurement of the “invisible energy”
Identifying Čerenkov component in BGO

- Very preliminary from 2007 test beam

Average pulse shapes
- S and Č components very well separated
- confirmed by the directionality effect

Yellow side
Pure angular independent S component

UV side
Pure angular dependent Č component
Program for 2008

- Analysis of the 2007 test beam data
- Test beam at CERN (H4)
  - New measurement with the present DREAM prototype
  - Test on an electromagnetic section based on BGO
  - Studies on how to detect separately scintillation and Čerenkov light (filters and/or time structure of the signals)
- Development of new crystals better suited for the dual readout technique
  - Gd (Gadolinium) doped PbF$_2$
  - Pr (Praseodymium) doped PbWO$_4$
- Development of the new generation of the Domino Ring Sampler to exploit the time structure of the signals
- Optimization of simulations including Čerenkov light production
Main activities of the INFN Groups

- Test beam preparation, data taking and data analysis: all
- Test beam DAQ: Cosenza, Pavia, Pisa
- BGO electromagnetic section: Cagliari, Roma I
- Domino development: Pisa
- New crystals development: Pavia
- Simulation: Cosenza, Pisa
The Domino Ring Sampler (DRS)

- Developed at PSI for the MEG collaboration (NIM A 518(2004)470) and extensively used in the MAGIC collaboration
- It implements a series of switched capacitor arrays (SCA) which allow a digitization of the signal at the GHz level
- The ~10000 cells (current DRS2 has 10 channels with 1024 cells) are readout with an external 12 bit flash ADC
The “Domino-2” chip

- The sampling signal freely propagates through an inverter chain ("domino");
- The “domino” wave runs continuously in a circular way up to 2 GHz;
- Stop at any cell by an external trigger signal;
- Storage depth larger than usual PMT signal width;
- Sampling capacitances connected to NFET transistors producing a current proportional to the voltage in the sampling cell → S/N dramatically improved;

Domino2 reconstruction of a 0.9 ns rise time input edge sampled at 0.3 ns
Advantages of this technique

1. it allows a *time history* of the signal: at trigger hold the capacitors are read back for $t$ up to 500nsec

2. its *cost and power consumption* are orders of magnitude less than the cost of commercial flash ADCs with the same performances (in terms of sampling, not of rate)

3. in Pisa there are other groups, in particular *MAGIC*, which use this chip and collaborate to develop new versions: DRC could profit of their experience and collaborate with them in developing a new board which profits of the newly developed DRS3 chip.
From DRS-2 to DRS-3

Limits of DRS-2:

- Poor linearity, careful calibration needed
- Temperature dependence of the response
- Internal bandwidth $\sim 300$ MHz $\rightarrow$ incomplete refresh of the cells, depending on the stored charge

Improvements with DRS-3:

(S.Ritt, Fast Waveform Digitization with the DRS Chip, 15° IEEE NPSS Real Time Conference 2007, Fermilab, Batavia IL, 29Apr-4May, 2007)

- non-linearity $< 0.5$ mV in the 0.1-1.1 V range;
- temperature coefficient of 50 ppm/deg.C;
- random noise 25 mV (RMS);
- bandwidth (-3 db) 450 MHz, can be improved with small design changes.
Program for 2008 (electronics)

- start tests with current VME board ("Domino-2") used by MAGIC experiment;
- develop a custom VME board, based on PSI DRS3 design (S.Ritt), with:
  - 32 channels ( = 4 DRS3 chips);
  - custom input driver board to match PMT signals with DRS (differential) inputs.
- Goal is to test the new board as PMT readout in The DREAM test beam of 2008
BGO EM Calorimeter

- Small electromagnetic calorimeter to be put in front of the DREAM fiber module to continue the studies started in 2006 with a small PbWO$_4$ calorimeter.

- As we have seen in the 2007 test beam BGO is not perfect but is much better than PbWO$_4$
  - Better time separation (longer decay time 300 vs 10 ns)
  - Better wavelength separation (480 vs 440 nm)

- Approx. 100 BGO crystals from L3 on loan

- Mechanics and readout to be implemented
Search for the optimal crystal I

- We have started to collaborate with:
  - **Anna Vedda** (Dept. of Material Science - Milano Bicocca)
  - **Martin Nikl** (Inst. of Physics - Academy of Science - Prague, at present Visiting Professor at Milano Bicocca)

- They work on scintillation in crystals and have collaborated with CMS on studies on PbWO$_4$

- Milano + Prague have all the instrumentation needed to completely characterize the optical and timing properties of scintillation in crystals

- Prague has also the possibility of growing small crystals ($\Phi \sim 1.5$ cm, $L \sim 5$ cm)

- A. Vedda will join DRC soon and M. Nikl could also join later as Prague
Search for the optimal crystal II

- After some discussions they are very pessimistic about PbF$_2$ (Gd) but they will measure and characterize some samples we got from C. Woody from BNL who reported weak evidence for scintillation (IEEE Trans. in Nucl. Sci. 1996_43(3)).

- They propose to test PbWO$_4$ (Pr) heavily doped (5 - 10%)

- This crystal should have nice properties:
  - Maintain transparency to the Čerenkov light while strongly quenching the blue scintillation light of PbWO$_4$
  - Emit scintillation light in the green-red region
  - Have a reasonable decay time (few tens of ns)

- Thanks to the generous help of S. Altieri and some other Colleagues we are ordering the Prague Institute 3 PbWO$_4$ crystals with 0.1%, 1% and 5% doping that will be hopefully produced and fully characterized by the end of the year
Future developments

✧ Possible full containment prototype
  ✧ Needed to fully test the properties of the dual readout method

✧ Readout studies
  ✧ PMTs are not the best solution. Investigations on SiPM, GEM PM?

✧ Ultimate Hadron Calorimetry
  ✧ Measure the neutron content in hadronic showers to correct for fluctuations in the invisible energy
  ✧ Add a third type of fiber (neutron sensitive) TREAM
  ✧ Use time structure of the hadronic signal
Back-up Slides
## Richieste finanziarie

### 2008

<table>
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<th>Group</th>
<th>FTEs</th>
<th>M. Interno kEuro</th>
<th>M. Estero mesi uomo</th>
<th>M. Estero kEuro</th>
<th>Consumo kEuro</th>
<th>C. Apparati kEuro</th>
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<td>37.5 Crystals</td>
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<td>10.0</td>
<td>23.5 Elettronica + PMs</td>
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</table>
Quartz fibers calorimetry

Radial shower profiles in:
- **SPACAL** (scintillating fibers)
- **QCAL** (quartz fibers)
100 GeV single pions

- **Signal distribution**
  - Asymmetric, broad, smaller signal than for $e^-$
  - Typical features of a non-compensating calorimeter
BGO setup

PMT

BEAM

20mm

30mm

PMT
Schott filters for BGO measurements

UV band pass UG11

Yellow high pass GG495
The DRS3 Chip

Design Properties:

- 12 channels at 1024 bins
- Cascadable 6x2k, ..., 1x12k bins
- Sampling speed 10 MHz – 5 GHz
- Readout speed 33 MHz
- ROI readout (3 $\mu$s for 100 bins)
- Fabricated in 0.25 $\mu$m 1P5M MMC process (UMC), 5 x 5 mm$^2$
- Radiation Hard (CMS Pixel library, R. Horisberger)
- Power consumption: 50 mW @ 2 GHz
- Packaged chip costs:
  - 35 $ / chn. (MPW run)
  - 3 $ / chn. (SPW run)
• Careful design gave linearity 0.1V ... 1.1V better ±0.5 mV, $T_c \approx 50$ ppm

• “Fixed pattern noise”: 6 mV (RMS)

• Noise after offset correction (in FPGA code during readout): 0.25 mV (RMS) $\rightarrow$ 12 bit SNR

• Bandwidth: 450 MHz, to be improved with small design change for mass production
VPC & USB boards

PSI general purpose VME board with 2 PPC cores

DRS2

USB interface board

DRS3

14-bit flash ADC AD9248

32 channels input
## Comparison with other chips

<table>
<thead>
<tr>
<th></th>
<th>V1729 (CAEN) MATAcq chip</th>
<th>LABRADOR Univ. Hawaii</th>
<th>DRS3</th>
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<td>Bandwidth (-3db)</td>
<td>300 MHz</td>
<td>&gt; 1000 MHz</td>
<td>450 MHz</td>
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<td>Sampling frequency</td>
<td>1 or 2 GHz</td>
<td>10 MHz ... 3.5 GHz</td>
<td>10 MHz ... 5 GHz</td>
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<td>Full scale range</td>
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