Early TPC History and Recent Developments

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w/ draft of Early TPC History by
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Second “Rare-Event” TPC Workshop
Outline

• An Introduction to Time Projection Chambers
• TPC Invention & Bevatron Prototype
• PEP-TPC / “The TPC Experiment”
• PEP-4/9 TPC/Two-Gamma Experiment
• TRISTAN Topaz-TPC
• LEP ALEPH & DELPHI TPC's
• PEP-II B-Factory Commissioning - Mini-TPC
• EOS-TPC & The STAR-TPC at RHIC
• International LC-TPC R&D
A Brief Introduction to TPC's

- $e^+e^-$ Colliding Beam Configuration
- PDG “Review of Particle Properties” description
- TPC gating grid
- PEP TPC dE/dx measurements & most probable energy deposition predictions
- TPC Particle Identification
- The 2003 Time Projection Chamber Symposium
- References
TPC studies of $e^+e^-$ collisions

Fig. 2. A schematic view of the PEP-4 TPC showing the drift volume (dark blue), wire chambers (green) and pads (light blue).

From 2004 CERN Courier article by Spencer Klein, LBNL
Detectors with long drift distances perpendicular to a multi-anode proportional (wire) plane provide three-dimensional information, with one being the time projection. A (typically strong) magnetic field parallel to the drift direction suppresses transverse diffusion ($s = r^2 D t$) by a factor $D(B)/B(0) = 1/(1+w^2 t^2)$, where $D$ is the diffusion coefficient, $w = eB/mc$ is the cyclotron frequency, and $t$ is the mean time between collisions. Multiple measurements of energy deposit along the particle trajectory combined with the measurement of momentum in magnetic field allows excellent particle identification [91], as can be seen in Fig. 28.5. See next slide.

A typical gas-filled TPC consists of a long uniform drift region (1-2 m) generated by a central high-voltage membrane and precision concentric cylindrical field cages within a uniform, parallel magnetic field []. Details of construction and electron trajectories near the anode end are shown in Fig. 28.6. See following slide. Signal shaping and processing using analog storage devices or FADC's allows excellent pattern recognition, track reconstruction and particle identification within the same detector.

**Typical values:**
- Gas: $Ar + (10-20\%) \ CH_4$
- Pressure($P$) = 1-8.5 atm.
- $E/P = 100-200 \ V/cm/atm.$
- $B = 1-1.5 \ Tesla$
- $v_{drift} = 5-7 \ cm/us$
- $\omega \tau = 1-8$
- $\sigma_{x \ or \ y} = 100-200 \ um$
- $\sigma_z = 0.2 – 1 \ mm$
- $\sigma_{Edep} = 2.5-5.5 \ %$

See also [www-tpc.lbl.gov](http://www-tpc.lbl.gov), i.e. [www-tpc](http://www-tpc) server at lbl.gov
TPC Gating Grid

A TPC gating grid (GG) is used to control the backflow of positive ions generated in electron signal amplification by anode wires or Micropattern Gas Detectors (MPGD's), such as GEM's or Micromegas.

In a MWPC readout of a TPC, the gating grid is placed just before the virtual ground provided by the shielding grid and is maintained at proper average voltage, but has alternating positive and negative potential when closed.

Note: A gating grid was not included in the original PEP TPC proposal or the Bevatron prototype. The idea to include one may have originated from a comment by G.Charpak at the 1978 Vienna Wire Chamber conference. The early decision to develop the GG upgrade for the PEP-TPC was critical.

See CERN 1981 TPC seminar by M.T. Ronan.
Time Projection Chamber Symposium

Date: Friday, 17 October 2003
Location: Lawrence Berkeley National Laboratory (LBNL)
Hosts: LBNL Physics and Nuclear Science Divisions, and the U.S. Department of Energy (DOE)

Program Outline

Areas of TPC Applications

- e+e- Annihilation Studies
- Heavy Ion Physics
- Double Beta Decay Experiments
- Neutrino Physics Experiments
- Rare Event Detection

New Technical Developments / Current R&D

- Micro-Pattern Gas Detector (MPGD) Readout Technologies
- High-density, Low-mass Electronics
- Electronic Imaging Detector R&D

New Ideas Forum

- New Techniques
- New TPC Applications
# Time Projection Chamber Symposium

**Session** | **Time** | **Speaker** | **Chairman**
--- | --- | --- | ---
Registration | 8:00 AM |  |  
Opening comments | 9:00 AM | Pier Oddone, LBNL | M. Ronan
**e-e- Experiments** | 9:15-10:30 |  | H.-J. Hille
- ALEPH TPC Experience | 20 min. | Ron Selover, DESY/Munich |  
- DELPHI TPC Experience | 20 min. | Vincent Lepelletier, LAL Orsay |  
- TESLA TPC Proposal | 20 min. | Rolf-Dieter Heuer, DESY |  
Break |  |  |  
Heavy Ion Experiments | 10:45-12:00 |  | H. Wieman
- STAR TPC Experience | 30 min. | Jim Thomas, LBNL |  
- ALICE TPC Design & Construction (pdf, ppt) | 30 min. | Rudy Schmidt, GSI |  
- (also CERES Radial TPC) |  |  |  
Double Beta Decay Experiments | 12:00-12:30 |  | R. Norman
- EXO – Enriched Xenon Observatory | 20 min. | Carter Hall, SLAC |  
(Liquid Xenon TPC detector) |  |  |  
Lunch | 12:30 - 2:00 |  |  
Neutrino and Rare Event Detection Experiments | 2:00-2:45 |  | S. Freedman
- ICARUS Status | 20 min. | Elia Calligaris, Pavia |  
(Liquid Argon imaging device) |  |  |  
- Negative Ion TPCs | 20 min. | Jeff Martoff, Temple University |  
(DRIFT – Dark Matter Search) |  |  |  
New Technical Developments / TPC R&D | 2:45 – 3:45 |  | R. Heuer
- GEM’s | 20 min. | Fabio Sauli, CERN |  
(Gas Electron Multipliers) |  |  |  
- MicroMegas | 20 min. | Yannis Gionartas, Saclay |  
(Micro-MEsh GAS Multipliers) |  |  |  
- TPC Electronics | 20 min. | Luciano Musa, CERN |  
(New TPC Read-Out Developments) |  |  |  
Break |  |  |  
New Ideas / Applications | 4:00 - 6:00 |  | T. Matsuda
- New Ideas | 30 min. | Dave Nygren, LBNL |  
(Liquid TPC's, Radial TPC's, etc.) | |  |  
New Applications | 45 min. |  |  
- NA48 Beam trajectory TPC | 15 min. | Phillip Legou, Saclay |  
- LXeGRIT: A LXe TPC for MeV Astrophysics | 30 min. | Elena Aprile, Columbia |  
- YENON: A LXe TPC Dark Matter Experiment |  |  |  

M.T. Ronan, 2004 Paris TPC Workshop
This talk could have been titled as

“Gaseous TPC's for ever”

or, more specifically

“Large Gaseous TPC's for Accelerator-based Experiments”
Outline

• Invention of the Time Projection Chamber (D. Nygren, 1974)
• PEP TPC Proposal
• Prototype Bevatron TPC
• The PEP4 TPC Experiment
• The PEP4/9 TPC/Two-Gamma Experiment
• Other e+e- Applications
  – TOPAZ, ALEPH & DELPHI
  – PEP-II Commissioning Mini-TPC
• Heavy Ion Applications
• International LC TPC Detector Design Studies
A less technical TPC description


The TPC

A TPC is a barrel-shaped detector whose chamber is filled with pressurized gas and a perfectly uniform electric field. The barrel is fitted around a beamline so that the particles created in a collision fly out through its chamber. A powerful magnet surrounding the barrel curves the path of the particles passing through the chamber so that their momentum can be measured. As the particles pass through the chamber they collide with atoms of the gas, knocking out a string of electrons that respond to the electric field and drift towards the end of the chamber. At the end of the TPC chamber is a pie-shaped array of wire and sophisticated electronics that can detect and sift through thousands of particles simultaneously and can cleanly distinguish between similar types of particles.

A Time Projection Chamber is like a 3-D camera that captures images of the flight of subatomic particles. The TPC is at the heart of the STAR detector, now at RHIC in Brookhaven.

As Nygren once explained, “TPC's allow us to reconstruct any track in three dimensions by determining how long the electrons took to drift through a given distance in the gas, which of the wires on the pie-shaped array picked them up, and what point along the wire they hit and were recorded. Because of its ability to visualize tracks in three dimensions, a TPC can sort out multiple particles with ease.”

Nygren has said the idea for the TPC came to after he realized that real improvements in particle detection could not be achieved without a radical departure from the old ways. ...

see www.lbl.gov/Publications/Currents/Archive/Oct-31-2003.html
PEP4  TPC Proposal

• Physics motivation
  – “... excellent pattern recognition and charged particle identification over most of 4pi steradians, even within the high particle densities expected in jet-like events.”

• TPC Detector

• TPC Chamber
  – 1 m radius, up to 1 m drift in P10 (Ar-CH$_4$) @ 10 atm.

• Superconducting coil

• Electromagnetic Calorimeter
  – Gaseous sampling digital ECAl of Lead and Ethyl-bromide.

• Muon Detector
PROPOSAL FOR A PEP FACILITY

BASED ON THE TIME PROJECTION CHAMBER


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Time Projection Chamber

Fig. IIIA.2
TPC Endcap Wire Array

Wires With Segmented Cathode (12/Wedge)

dE/dx Wires (192/Wedge)

20 cm

Beam Pipe

100 cm

Inner Chambers

$\Theta$ $\vec{E}$

$\Theta$ $\vec{E}_{\text{Drift}}$

Fig. IIIA.8
TPC Wire Geometry Details

DETAIL OF WIRE GEOMETRY

Grid
Anode
Cathode

1.2 cm

8 cm

Field Wire
~ Grid Sense Wire
~ Cathode

Spatial Wire

To Remote Amplifiers

Preamps

Segmented Cathode Readout

Fig. IIIA.9

XBL 7612-11407
Electron Attachment in Methane

Electron Energy Distribution

Three-Body Attachment

Virtual Ion Resonances

Resonance Dissociative Attachment

Arbitrary Units

Energy (eV)

Fig. A7.1
Most Probable Energy Loss (dE_{mp}/dx)

Most Probable Energy Loss (E_{mp}) for e, \mu, \pi, K, p in 1cm of Argon at 10 Atm.

![Graph showing Most Probable Energy Loss for different particles (e, \mu, \pi, K, p) in Argon at 10 Atm.](image)

Fig. IIIA.4
$\frac{dE}{dx}$ Resolution vs. Pressure

Resolution vs. Pressure $\pi$ at 1GeV/c
Truncated Mean Energy Loss

Fig. A2.6
TPC Two Track Separation

Fraction of Tracks with Another Track within $z$

- $r = 20\,\text{cm}$
- $r = 40\,\text{cm}$
- $r = 60\,\text{cm}$
- $r = 80\,\text{cm}$

Fig. A4.5
TPC Endcap Region
Proposed TPC Detector

Dec. 30, 1976

Superconducting coil
B = 1.2T

Digital Pb-Gas ECcal

TPC P10 @ 10atm
r=1m, max. drift =1m

Fig. IIIH.1
Bevatron Prototype TPC

Principle of Operation

Fig. A5.2
Bevatron test results

- Excellent position resolution
- Clean particle identification

⇒ no show stoppers!
TPC Technical Design Reports (1977-1978)

  - Electrical Characteristics of the TPC
  - Endcap Wire and Cathode pad array

- **TPC Electronics**  (D.Landis, N.Madden, B.Jackson, D.Jared, K.Lee, ...)
  - Front end preamplifiers
  - Shaper/Amplifiers
  - CCD's
  - Digitizers

- **TPC Trigger Electronics**  (Jackson/Jared/Ronan **EET-1471**, Oct. 31, 1977)
  - IDC Two-photon rejection ($p_T$ timing cut)
  - TPC “Ripple trigger”
TPC Readout

TPC Endcap

END VIEW OF TPC FROM "I" END OF CHAMBER

Figure 1
XBL 781-6727

M.T. Ronan, 2004 Paris TPC Workshop
TPC Triggering

IDC-ODC pretrigger

Figure 1. Geometry for IDC and ODC angular coincidence.

IDC-TPC pretrigger

Figure 3. Illustration of the Supersector and Inner Drift Chamber alignment.

PTC Trigger

Figure 4. Diagram of collector strips in one endcap calorimeter. The other endcap is labeled $A_{31}$, $A_{41}$, etc.

TPC Endcap pretrigger & TPC trigger

Figure 2. Simplified logic diagram for TPCF and TPCS.
The PEP4 TPC Experiment

- Spokesmen: D. Nygren, P. Oddone, B. Shen (UCR), W. Hoffman
- Final Design, Production and Response Characterization
- PEP4-TPC Assembly '80-'81
- Commissioning '81-'82
- Upgrades '83
  - TPC Gating Grids & lower-mass IFC with resistive coating
  - Superconducting coil
- Data Taking '84-'86
  - Total int. lum. = 100 pb⁻¹
- Physics
  - Jets, jets & more jets ($\pi$, K, p, ... production and correlations)
Production
Response Characterization

![Image of detector setup](image)

(a) Wire 87

Fe$^{55}$ signal peak position (arbitrary units)

Source rod angle (degrees)

(b) XBL 8310-585

Fig. 10

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Commissioning

EVENT 5

EVENT 9

EVENT 10
Performance

MEASURED SPECTRUM - 4 mm SAMPLES

PIONS - 1.8 GeV/c
0.8 A - 0.2 CH4 - 10 ATM.

REJECT 30 PERCENT OF SAMPLES

NUMBER OF SAMPLES

ENERGY LOSS

MOST PROBABLE ENERGY LOSS IN 80% A + 20% CH4 AT 10 ATM.

θ
μ
π
K
ρ

MOST PROBABLE ENERGY LOSS (ARBITRARY UNITS)

0.1 1.0 10.0 100.0
PARTICLE MOMENTUM (GeV/c)

M.T. Ronan, 2004 Paris TPC Workshop
Ar CH4 (P20) at 8.5 bar

small relativistic rise

min. I.

M.T. Ronan, 2004 Paris TPC Workshop
PEP4-TPC Electronics

- Discrete front-end preamp's
  - First time Nuclear Instrumentation (NI) was used on a HEP experiment.
  - Very low noise, ~500 electrons

- Shaper / Amplifier circuits
  - xx

- Charge Coupled Devices (CCD) boards
  - Fairchild xxx CCD's

- Digitizers
  - Common non-linear ramp digitizers*

- Trigger Electronics
  - Self triggered using a “TPC Ripple Trigger”

* Patent by Mitch Nakamura, LBL
Figure 3.5: Schematic view of the TPC signal processing chain.
TPC Self-triggering

Fig. 1 Side view of one sector at one end of the TPC.

Fig. 2 End view of the TPC illustrating supersector definition.

Fig. 3 Test pattern - five tracks with background.

Fig. 4 Basic dE/dx structure.

Fig. 5 Timing diagram for \( M_{i,j,n} \) generation.

M.T. Ronan, 2004 Paris TPC Workshop
Fig. 8 TPC Majority trigger (one sector shown).

Fig. 9 dE/dx wire input recording for simulated event.

Fig. 10 Majority logic signal recording for simulated event.

Fig. 11 Ripple trigger recording for simulated event.

Fig. 12 TPC Majority trigger recording for simulated event.

Fig. 13 dE/dx wire input recording for cosmic ray event.
TPC Upgrades

- SECTORS
- 2 m
- P = 8.5 atm
  80% Ar
  20% CH₄
- V = -55 kV
- B = 13.25 kG
- E
Performance

E.C.1, Sector 0

Typical pickup
Min. Ionizing is
\(\sim 50\) counts
10 buckets = lusec

Channel 140 bucket vs p.h.
File: E1S0T3O 14-NOV-84 16:03:10

(a) Grid Open
(b) Grid Closed
Monte Carlo simulation
TPC Jet Physics

(a) \( q \), g

(b) q

(c) q

\( \phi \) (degrees)

(a) Jet 1, Jet 2, Jet 3, Jet 1

(b) LUND, IF, WEBBER

(c)
PEP4-TPC Publications

**Figure 1**

An approximate schedule for publications for 1984

- Jan (J)
- Feb (F)
- Mar (M)
- Apr (A)
- May (M)
- Jun (J)
- Jul (J)
- Aug (A)
- Sep (S)
- Oct (O)
- Nov (N)
- Dec (D)

- J F M A M J J A S O N D

- 83

- 1984

- 85

- 2π large mass

- Study of A2

- Study of Ξ

- 2γ production of Ψ

- τ lepton branching rate

- Strings vs. Indep. Frag. (3-jets)

- Properties of b c tagged jets

- 2γ τ, 2k τ, g2 dependence

- 2π 4π final state

- 2π 6π, g2 dependence

- WE ARE HERE

- 2π correlations

- K0 and Ψ production

- Direct μ production

- A production and polarization

- F* Ψ

- Strangeness correlations

- Proton production

- Σ0 Λ production

- Φ production (submitted)

- Search for 2/3e 1/3e quarks (submitted)

- Direct electrons (submitted)

- Particle fractions π K Λ (published)

- Search for 4/3e quarks (published)

Pier Oddone
Apr. 1984
The PEP4/PEP9 TPC/2γ Experiment

- Spokesmen: Elliott Bloom, SLAC & Mike Ronan, LBL
- Upgrades '86-'87
  - Straw Tube Vertex Chamber
  - ... 
  - Injection from SLC Damping Rings (DR's)
  - PEP “High Lum.”: Insertion quads: mini-β
- Data Taking '89-'90 \( \text{Int. lum./day} = 1 \text{ pb}^{-1} \)
  - Switching between PEP I injection & SLC/SLD running.
  - \( \text{Int. lum.} = 10 \text{ pb}^{-1} \)
- Planned Physics
  - B-quark jets
  - Tau
  - Two-photon
TPC Detector and IR2 Upgrade

1982-86

1988
TPC / 2-GAMMA

COME SEE YOUR WORK IN ACTION!!

TPC / 2-GAMMA will treat you to lunch* and a tour of the facility in Interaction Region 2 at PEP.

WEDNESDAY
FEBRUARY 27
12 NOON - 2 P.M.
IR-2 at PEP (SLAC)

Please let us know if you are coming (call Julia Davenport at 486-7164 or Robin Shaver 486-7374). Also let us know if you need a ride (we are planning to have a bus between SLAC and LBL).

* Menu: Steak + garlic bread + salad + beans + beer
Inside Currents:
Horizon program, page 3
LBL bowling results, page 4

PEP, TPC are up and running at SLAC

By Judith Cockbourn

The PEP accelerator and the Time Projection Chamber (TPC), that have been running for more than two years, are now back in action at the Stanford Linear Accelerator Center.

Both PEP and the TPC were upgraded while the new Stanford Linear Collider (SLC) was being built and tested.

LBL scientists are now collaborating in this effort. PEP is a high-energy storage ring — designed and built in the seventies by a SLAC/LBL collaboration — in which beams of electrons and their antiparticles (positrons) are injected, stored, focused, and then collided. Many new forms of matter, including heavy quarks and their antiquarks, are created in the resulting electron-positron annihilation.

The Time Projection Chamber, the major experimental facility at PEP, was designed and built at LBL, and members of the Physics Division continue to play an important role in the 94-member international collaboration that operates it. TPCs detect and identify particles by translating position (the position of particle tracks in space) into time (the time it takes the signal to drift through a gas), and by measuring the ionization deposition.

The TPC is expected to run for several years at PEP, gathering data on B mesons — particles made out of the B or "bottom" quark (the heaviest and most recently discovered of the quarks) combined with other, lighter quarks. So far, only a few hundred B mesons have been found — 2600 from the MARK II detector (another LBL-SLAC collaboration), the CLEO detector at Cornell, and the ARGUS detector at DESY in Germany, among others. Many mesons are needed if their lifetimes and other characteristics are to be measured accurately.

The physicists are hoping that the upgraded PEP will be a "better" detector, providing about 10 times more data than is currently available. With that many particles to look at, they expect to be able to measure the lifetime of the B very accurately, and also to distinguish between the various types — negative, positive, and "strange" (that is, those made out of a B, a B, or an S, or "strangeness" quarks).

The real prize in this area of research would be the discovery of CP violation (a breakdown in left-right-hand asymmetry) in the decay of B mesons. Theory predicts that this kind of symmetry breaking should occur, just as it does in the decay of K mesons, which are made up of lighter quarks. Teams planning experiments at the world's next generation of high-energy accelerators (including CERN's Large Electron-Positron collider and Stanford's SLC) hope to be the first to make this discovery. Though PEP is not expected to have a high enough luminosity (collision frequency) to observe CP violation, the accurate lifetime measurements it provides...

Life Sciences Retreat

The focus was on formal presentations by researchers describing new techniques and the scientific challenges ahead, but there was also time for informal discussions when more than 180 participants, representing seven LBL divisions, got together last week for the third annual Life Sciences Retreat. A primary goal of the retreat, held in Taos, New Mexico, 21-26, was to engage in discussions and interaction among researchers in different areas.

The multidisciplinary nature of the Human Genome Project, for example, requires the talents not only of biologists, but also of computer scientists and engineers — to develop analytical tools, database systems, instrumentation for automation, and so forth.

A principal speaker at the retreat was Charles Cantor, director of LBL's Human Genome Center, who described the approaches to be used and the difficulties that are necessarily encountered in undertaking the analysis of the human genome, in order to see the information within biological and medical disciplines.

A speaker was LBL Division Head David Shurtleff, who observed the Laboratory's continued support for the life sciences, noting that the Human Genome Center should be viewed as one of the cornerstones of other major new initiatives in the life sciences.

Bill Jagust (left), Peter Yalk, and Ron Hageman of the Research Nanofabrication and Radiation Biophysics Division talk with Amy Koenig of Cell and Molecular Biology.

Charles Cantor (left), director of the Human Genome Center, discusses a point with Max Koenig of CMB and Tom Jukes, professor of biophysics emeritus at UC Berkeley.

Computer scientists Carl Queng and Ed Thull, electronics engineer Joseph Jablonske, and CMB researcher Mike Esposito, chairman of the organizing committee, engage in a relaxed discussion.

Ler Raya, a member of the organizing committee for the retreat, chats with Jacob Fabianek of RMR based in China (right), also of RMRRA, samples the refreshments.
**VC Pretriggering**

**TPC Triggering**

A pretrigger decision within 500ns is used to gate on the TPC gating grid and to enable the TPC Ripple trigger logic.

**VC Trigger**

To selectively trigger on interesting γγ interactions in the expected high luminosity environment at PEP...

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We use a coincidence between azimuthally aligned straws in the outer quadruplet to select high $p_T$ tracks. Due to the non-saturated drift velocity, we had to develop variable coincidence width circuits.

The remaining left-right ambiguity is resolved using an inner doublet to restrict the sagitta of the track.
SLAC Program Committee

Steady progress

- **1986 - 1987 Upgrades**
  - Detector: new Straw VC
  - PEP mini-β
  - SLC injection
- **1988 Injection testing**
  - High efficiency injection
  - Switching between SLC & PEP
- **1989 Pilot run**
  - Sep. '89 Int. lum. 1 pb⁻¹/day
  - **Oct. 1989 Earthquake**
  - PEP knocked out of alignment
  - Damaged IR2 beam pipe
- **1990 Production**
  - Int. lum. ~ 10 pb⁻¹
B Physics

One event from PEP4/9 commissioning run in 1989.
PEP-TPC/2γ Experiment

PEP-4 TPC

'78-'81 Design and construction of Time Projection Chamber apparatus.

'82-'84 First results: π,K,p fractions - up to modest x
Inclusive φ,γ,π0,... production.
Upgrades: Gating grid, thinner field cage with coating
Superconducting magnet (1.3 Tesla).

PEP-4 / PEP-9 TPC/2γ Collaboration

'84-'86 Jet Fragmentation / Two-Photon Physics:
π,K,p fractions - large x;
γγ spectroscopy (spin-1), γ structure function.

High-Luminosity Collaboration

'86-'87 Vertex chamber / PEP Mini-β and Injection upgrades

'88-'90 Demonstrated high (6x10^{31}) luminosity and switching
between SLC operation and PEP filling with
< 25% impact.

Recent

'91-'92 Complete event reconstruction and Monte Carlo
development.

'92-'93 Analysis and publication of final topics.
First observation of the $\tau \rightarrow K_1 \nu$, strange axial-vector, decay mode.

Ref. M. Ronan, 1993 Tau Lepton Workshop & PR D ...
Other $e^+e^-$ Physics Applications

- TOPAZ-TPC
- ALEPH-TPC
- DELPHI-TPC
- PEP-II B-Factory Commissioning Mini-TPC
The TOPAZ Detector at Tristan, KEK
Presented by Ron Settles,
TPC Symposium, Oct. 2003
see http://www-tpc.lbl.gov/symposium2003
Presented by Vincent Lepeltier,
TPC Symposium, Oct. 2003
see http://www-tpc.lbl.gov/symposium2003
The “PTA” Collaboration

An informal collaboration of present and former PEP-TPC fellows working on a common analysis of data from the PEP / Topaz / Aleph TPC's

Mainly,
M.R. PEP
M. Yamauchi Topaz
R. Itoh
G. Cowan ALEPH

\[ \alpha_s \]

\[ \alpha_s \left( E_{cm}^2 \right) \text{from } y_3, R \text{- matching, Lund PS hadr. corr.} \]

\[ \Lambda = 300 \text{ MeV} \]

error key:
- statistical
- experimental sys.
- hadronization

matching and scale errors not included

\[ E_{cm} \text{ (GeV)} \]
Conception of the B Factory

How can we do time-dependence measurements in the clean $e^+e^-$ environment?

Pier Oddone has won the 2005 Panofsky Prize “For his insightful proposal to use an asymmetric B-Factory to carry out precision measurements of CP violation in B-meson decays, and for his energetic leadership of the first conceptual design studies that demonstrated the feasibility of this approach.”
PEP-II Commissioning Mini-TPC

Berkeley, Cincinnati, Orsay Collaboration

• Designed to commission the PEP-II interaction region (IR).
• Tested up to $10^6$ particles/cm$^2$ in CERN test beam.
• Obtained complete Gating Grid (GG) opacity.
• Used to understand IR backgrounds in 1997 High-Energy Ring (HER) Commissioning by taking “snap-shots” of tracks in the Mini-TPC without distortions.
• Used to develop and test improved simulations of Asymmetric B-Factory backgrounds in $e^-$ HER / $e^+$ LER colliding beam commissioning.
• Measured first Asymmetric $e^+e^-$ annihilation event in 1998.
• Also used to commission the STAR IR at RHIC in 2000.
PEP-II Mini-TPC

Figure 1: Some views of the mini-TPC: electrostatic cage, transverse view of the wire region and pad arrangement.

Figure 2: Single pad efficiency for the sector traversed by the beam, as a function of the radial position of the pad (row number increasing towards the outside): (a) gate open; (b) gate pulsed.

Figure 3: Display of a mini-TPC event recorded with 200 mA e⁻ beam; z is parallel to the beam direction, y is also in the horizontal plane, while z (the TPC symmetry axis) points upwards.

Figure 4: Variation with beam intensity of some TPC measurements: (a) with gate pulsed; (b) with gate closed.
PEP-II HER Commissioning Beam Line

Drawings

Simulation

Mini-TPC
PEP-II HER Beam line simulation

Event #1

Event #2

⇒ Found that copper mask was hollow leading to a beam line hot spot near Mini-TPC location!
First Asymmetric e+e- annihilation event

Figure 24: Track rate in the mini-TPC as a function of beam current. Data are compared to Monte Carlo using either the pressure profiles of table 3, or a TDR-like model where zone 4 is neglected and values of 0.5 nT and 0.5 nT/A bar and dynamic pressure are used for zones 1, 2 and 3.

Figure 25: Spatial distributions for tracks in the mini-TPC: intercept to the beam in the horizontal plane (left) and angle θ in the vertical plane (right). Data from the 100 mA run of January 91 are compared to Monte Carlo. The component of expected backgrounds coming from the “hot spot” of the beam pipe (see figure 20) is also indicated.

Figure 26: Origin or point of last scattering of charged particles eventually traversing the mini-TPC or producing showers reaching it. in BaBar coordinates. The plot represents a view from above in the horizontal plane containing the beam line (see figure 6). The box indicates a “hot spot” of the beam pipe where an important component of mini-TPC backgrounds are produced in the showers of primary lost particles.
Heavy Ion Physics Applications

- **EOS-TPC**
  - Fixed target experiment with “pads partout.”
  - Heavy element dE/dx identification.

- **NA49-TPC**
  - Many innovations: low mass field cage, front-end ASIC's.

- **STAR-TPC**
  - Spectacular success: 4 m diameter “pads partout”, 2 m drifts and tremendous signal event track occupancies.
  - Excellent particle identification and exciting physics.

- **ALICE-TPC**
  - Many new developments: e.g. ALTRO chip (see Luciano Musa's talk at TPC Symposium, [http://www-tpc.lbl.gov/symposium03](http://www-tpc.lbl.gov/symposium03)).
The EOS TPC

E910 – fixed target in a magnetic field

- Anode & field wires, w/Gating Grid
- 15,360 channels
- 12 mm x 8 mm pads
- Multiplicity goal ~200 tracks

- Cubic meter scale
- Inherits technology from PEP4
- Contemporary of NA35

Presented by Jim Thomas,
TPC Symposium, Oct. 2003
see http://www-tpc.lbl.gov/symposium2003
EOS at the Bevelac

HISS - a heavy ion spectrometer

- Beautiful dE/dx spectra and good dynamic range
- Space point resolution 300 m
- Unique features of EOS
  - Pad Readout
    - Avoids projective problem at high Mult
    - Accept pad response function broadening. Two track resolution ~ 2.5 cm
  - Electronics
    - IC pre-amp with discrete shaper. SCA as analog memory. External ADC.
    - Optical fiber output & highly multiplexed
    - Factor of 30 reduction per channel of outboard rack space
Another Great Heavy-Ion TPC

- 4 TPCs, Main & Vertex
- 3.9 meter height in Main TPCs
- 1.1 m drift in the Main TPCs
- Vertex TPCs in the field, Main TPCs not in the magnetic field
- 182,000 channels (all TPCs)

Presented by Jim Thomas,
TPC Symposium, Oct. 2003
see http://www-tpc.lbl.gov/symposium2003
The Birthplace of Many Great Ideas

- Main TPC Pad readout is at the top (to avoid dust)
- Asymmetric gap between GG, anodes, and pads.
  - Narrow pad response function.
- Pre-Amp & shaper on one chip.
- SCA and ADC on one chip.
- Electronics uses direct connection to pad plane.
- Super simple field cage
  - Al coated Mylar strips
  - Stretched over posts
  - Simplicity makes “BIG” possible
- Low Diffusion & Fast Gas
  [Ar/CH<sub>4</sub>/CO<sub>2</sub>, 90/5/5]

Presented by Jim Thomas, TPC Symposium, Oct. 2003
A TPC lies at the heart of STAR

Not Shown:
- pVPDs, ZDCs, PMD, and FPDs

Presented by Jim Thomas,
TPC Symposium, Oct. 2003
see http://www-tpc.lbl.gov/symposium2003
TPC Gas Volume & Electrostatic Field Cage

- Gas: \( \text{P10 (Ar-CH}_4\text{ 90\%-10\%) @ 1 atm} \)
- Voltage: -28 kV at the central membrane
  135 V/cm over 210 cm drift path

Self supporting Inner Field Cage:
  Al on Kapton using Nomex honeycomb; 0.5% rad length
Cathode Pad Plane: Outer and Inner Sectors

- 24 sectors (12 on a side)
- Large pads good dE/dx resolution in the Outer sector
- Small pads for good two track resolution in the inner sector

Outer Pads
6.2 mm x 19.5 mm
Total of 3,940 Pads
6.7 x 20mm Centers

Inner Pads
2.85 mm x 11.5 mm
Total of 1,750 Pads

Outer sector
6.2 x 19.5 mm pads
3940 pads

Inner sector
2.85 x 11.5 mm pads
1750 pads
Readout of a Pad Plane Sector

A cosmic ray + delta electron

3 sigma threshold
STAR-TPC Installation
A side view of tracks from 200 GeV per nucleon for a gold-on-gold collision at RHIC, as reconstructed in the TPC of the STAR experiment

From 2004 CERN Courier article by Spencer Klein, LBNL
STAR Jet Physics ...

It's easier to find jets in $e^+e^-$

Jet event in $e^+e^-$ collision

STAR-TPC Au+Au collision
STAR-TPC Particle Identification by dE/dx

\[ \frac{dE}{dx} \] PID range:

\[ \sim 0.7 \text{ GeV/c} \] for \( K/\pi \)

\[ \sim 1.0 \text{ GeV/c} \] for \( K/p \)

600,000 Au+Au events at \( \sqrt{s_{NN}} = 130 \text{ GeV} \)

Anti-\( ^3\text{He} \)
International LC-TPC R&D

- TESLA CDR Detector / NLC ZDR Detector '96
- American Large (TPC) Detector '98-'99
- TESLA TDR Detector '01
- ILC Large Gaseous Detector Design Study '05 - ...
  - Medium TPC Detector (European/American group)
  - Large TPC Detector
  - Huge (“Truly Large”) TPC Detector (Asian/American group)
- Micro-Pattern Gas Detector (MPGD) Studies '01 - ...
  - GEM-TPC R&D
  - Micromegas-TPC R&D
TESLA TPC Proposal
or
A TPC for a Linear Collider Detector

R.-D. Heuer
Hamburg University

TPC Symposium
Berkeley, Oct.2003
ILC Gaseous TPC Detector Model

It might look somethink like
Multijet Higgsstrahlung events

e.g. \( e^+e^- \rightarrow Z \ + \ \text{Higgs} \ \rightarrow 2-4 \ \text{jets} \)
TPC Tracker Design and R&D

Current TPC design and R&D focus is on gas choice and readout technology. Hope to begin studying front-end electronics (FEE) designs soon.

Gas options:
- Ar CH4
- Ar CO2 CH4
- Ar CF4
...

Readout pad plane
- Gating device ??
- MPGD
- GEM
- Micromegas
- Pads partout

Electronics
- Very low noise
- Full integration ?
Recent TPC developments

New Gas Amplification Systems

Replace conventional MWPC system (wires) by Micro Pattern Gas Detectors (MPGD):

Most promising examples:

- **Gas Electron Multiplier (GEM)** (F. Sauli, 1997)

- **Micromegas** (Y. Giomataris et. al., 1996)
GEM: Gas Electron Multiplier

Thin metal-coated polymer foil pierced by a high density of holes (50-100/mm²)
Typical geometry: 5 µm Cu on 50 µm Kapton, 70 µm holes at 140 mm pitch


Presented by Fabio Sauli, TPC Symposium, Oct. 2003
see http://www-tpc.lbl.gov/symposium2003
GEM holes

Standard Double-Conical

Technology developed at CERN-EST
(Fields computed by S. Kappler)

Low field to high field:

200 V/cm

High field to high field:

2.5 kV/cm

S. Bachmann et al, Charge amplification and transfer processes in the gas electron multiplier
Nucl. Instr. and Meth. A438(1999)376
Micromegas: Micro-mesh Gas Structure

MICROMEGAS

Y.Giombataris, Ph. Rebourseau, J.P. Robert, and G. Charpak

NIM A375 (1996) 29

Presented by Yannis Giomataris,
TPC Symposium, Oct. 2003
see http://www-tpc.lbl.gov/symposium2003
Large dynamic range with gain stability

Optimum gap: 30 - 100 microns
- Stable gain and relative immunity to flatness defects or pressure variation
- Good energy resolution

Ref: A. Delbart et al, NIM A461, p84 (2001)
International Linear Collider (ILC)
Large-Area Micromegas TPC R&D

P. Colas, Y. Giomataris, V. Lepeltier & M. Ronan
Berkeley – Orsay – Saclay
Micromegas TPC R&D Collaboration

As presented at
Orsay, Saclay, Rome & Frascati, Oct. 2004
and
Purdue, Fermilab & Carleton, 15-19 Nov. 2004
Chamber design and pad layout

Chamber
diameter 50 cm
length 50 cm

Readout anode pad plane
1024 pads
2x10 mm² pads
1x10 mm² pads

Copper Mesh
50 µm pitch
50 µm gap
1. Industrially mass produced MICROMEGAS using 3M’s FLEX circuit technology
2. Conical pillars (1 mm pitch) to create a 50 mm gap.

The flat area that has contact with the anode board

Pillar cross section profile

70-80 micron (anode side)  50 micron height  300 micron wide (mesh side)

Presented at ALCPG SLAC Jan. ’04
1st Mass Production of Micromegas

First results
Ar:DME 9:1

feb4_04gaincurve, Ar:DME=9:1, Drift=-500 V

Radiation harness under study

25 % energy resolution

Presented at ALCPG Victoria July '04
Gas Property Measurements

- **Drift velocity**

  We measure the drift velocity of different gases using the data itself. The longest drift time tracks observed are from tracks passing through the far end of the chamber, 50 cm from the readout plane.

- **Electron attachment**

  Using the variation in the average energy deposition, measured by the truncated mean, with drift distance allows us to determine the electron attachment coefficient.

- **Transverse diffusion**

  Measured through maximim likelihood fits to the distribution of signals on pads collecting ionization electrons from individual tracks. Relevant pads with no signals provide information as well.

- **Magnetic field suppression**

  We measure the variation in the transverse diffusion as a function of the magnetic field to determine the suppression factor defined as \((D_T[B]/D_T[0])^{-1/2} \sim \omega \tau\).

From 2004 Rome IEEE Nuclear Science Symposium, Mike Ronan, LBNL
see http://www-ilc.lbl.gov/detector/talks
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**Measured Gas Properties**

### Drift velocity

We measure the drift velocities for the 3 gases being studied using the time distribution of cosmic ray tracks in our Micromegas TPC. We find at $B = 1T$

- Ar-CF4: 3% \( v_{\text{drift}} = 8.8 \pm 0.2 \text{ (stat.) cm/\mu sec.} \)
- Ar-CH4: 10% \( v_{\text{drift}} = 5.7 \pm 0.1 \text{ (stat.) cm/\mu sec.} \)
- Ar-Isobutane: 5% \( v_{\text{drift}} = 4.4 \pm 0.1 \text{ (stat.) cm/\mu sec.} \)

#### Electron attachment

We measure electron attachment by drift distance variation in the truncated mean.

- Ar-CF4: 3% \( \lambda_{\text{attachment}} > 4.4 \text{ m} \) @ 90% confidence

### Transverse diffusion

We measure the diffusion from maximum fits to the track ionization spread on pads in each row. We find at $B = 1T$

- Ar-CF4: 3% \( D_T = 75 \pm 2 \text{ (stat.)} \pm 7 \text{ (sys.) \mu m/\sqrt{cm}} \)
- Ar-CH4: 10% \( D_T = 100 \pm 1.4 \text{ (stat.)} \pm 10 \text{ (sys.) \mu m/\sqrt{cm}} \)
- Ar-Isobutane: 5% \( D_T = 160 \pm 1.0 \text{ (stat.)} \pm 16 \text{ (sys.) \mu m/\sqrt{cm}} \)

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Micromegas TPC Performance

- Gas gain
  We obtained high gains (~5000) at modest mesh voltages, 300-350 V, except for ArCH4:10% (P10).

- Electronic noise
  We operated the STAR front end electronics at very low noise levels (~1000 e's), typically 1-2 ADC counts.

- Point resolution measurement
  We determine the point resolution by comparing the position measurements of the two center 1mm pad rows, correcting for track angles and for track fitting errors. The resolution measurements are binned in drift distance and fit with a linear dependence. We take the zero drift intercept as the intrinsic Micromegas position resolution.

Note: We measure intrinsic (“zero-drift”) Micromegas resolutions of 60-100 microns, even with ArCH4 (P10) operating at low gain (~1000) as shown above.
Transverse position resolution measurements

For near vertical tracks at small angles, we measure Micromegas intrinsic (“zero drift”) resolutions of roughly 60, 80 and 100 microns for Ar-CF4, Ar-CH4 and Ar-Isobutane gas mixtures, respectively.

We measure a large (X2) angular dependence of the resolution due to our elongated 1X10 mm² anode pads.

We obtain position resolutions as small as 60 - 80 microns for near vertical tracks using our 1X10 mm² pads.
Summary

• An exciting 25 years of fun and profit
  – New inventions: Time Projection Chamber, Asymmetric B Factory
  – State of the art detectors, electronics and software.
  – Operated TPC experiment for 10 years under challenging conditions.
  – Built significant machine components (e.g. Injection Timing & Controls)
  – Many very talented friends, colleagues, engineers and students.
  – However, no major discovery at PEP-I!

• And an exciting future lies ahead
  – Many new Micro-Pattern Gas Detector (MPGD) based TPC's.
  – ILC Large TPC detector design, R&D and construction.
  – Precision measurements of the Higgs boson in an accelerator-based laboratory environment.
Concluding Remarks

• Dave Nygren

• Pier Oddone     Fermilab Today, 18-19 Nov. 2004
   see http://www.fnal.gov/pub/today

• Mike Ronan

• A View of the ILC for the Next 10 Years or so

• 2nd Time Projection Chamber Symposium
   see http://www-tpc.lbl.gov/symposium05
Dave Nygren

1985 E.O. Lawrence &
1998 Panofsky prizes

Dave at the LBL (Berkeley) TPC Symposium
17 Oct. 2003

Dave Nygren (left) and Fred Catania during TPC detector assembly in PEP IR2 at SLAC, circa 1980.

Dave Nygren in M.R.'s office
3 Nov. 2004

M.T. Ronan, 2004 Paris TPC Workshop
Fermilab Today 18-19 Nov. 2004

Pier Oddone
2005 Panofsky prize

Message to the Fermilab Community

Pier Oddone

I am deeply honored to have been chosen as your next director. Fermilab is a great laboratory with a proud tradition of innovation and discovery. At the same time both Fermilab and the field of particle physics are confronting major challenges in securing the resources to carry out our most important projects. So feeling honored has quickly given way to feeling humbled. Nevertheless, while I may be humbled personally, I am not humble about Fermilab and Fermilab’s capabilities to achieve a brilliant future.

Under Mike Witherell’s leadership, Fermilab has come through challenging times to emerge in a very strong position. The Teratron is performing better than ever, and for the next few years, Fermilab will lead the

Press Release
November 19, 2004
Pier Oddone of Berkeley Lab Named Fermilab Director

Batavia, Ill.-Officials of Universities Research Association, the consortium of universities that operates the Department of Energy’s Fermi National Accelerator Laboratory, today (November 19) announced the appointment of Piermaria Oddone as Fermilab’s fifth director. Acting on the recommendation of its Board of Overseers and with the approval of Secretary of Energy Spencer Abraham, URA’s Board of Trustees appointed Oddone to succeed Fermilab’s current director, Michael Witherell, on July 1, 2005. Witherell announced in October 2003 that he would serve as Fermilab director through June 2005.

Calendar

Thursday, November 18
11:00 a.m. Research Techniques Seminar - Cita II
Speaker: M. Ronan, Lawrence Berkeley National Laboratory
Title: Micromegas TPC R&D for the ILC
2:30 p.m. Theoretical Physics Seminar - Cita II
Speaker: S. Riemann, DESY Zeuthen
Title: Z’ Signatures in Precision Measurements
3:30 p.m. DIRECTOR’S COFFEE BREAK - 2nd Flr X-Over
THERE WILL BE NO ACCELERATOR PHYSICS AND TECHNOLOGY SEMINAR TODAY

Friday, November 19
1:30 p.m. All-Hands Meeting to Introduce New Fermilab Director - Ramsey Auditorium
A live broadcast of the meeting will be shown in One West and in the cafeteria area of the Atrium. The meeting will also be available on streaming video and on Fermilab closed circuit channel 9. Employees and users will be able to watch the All-Hands meeting by turning to channel 9 from any Fermilab channel 13 receiver.

Wilson Hall Cafe
Friday, November 19
Beef Pepper Pot $4.75
Buffalo Chicken Wings $4.75
Cajun Breaded Catfish $3.75
Spaghetti with Meat Sauce $3.75
Honey Mustard Ham & Swiss Panini $4.75
Double Stuffed Pizza $3.25
Cavend Turkey $4.75

Wilson Hall Cafe Menu
Chez Leon

Weather

Rain 54/54°
Michael T. Ronan

1971-1976
1. Fermilab E365 Thesis: “J/Psi(3100) Production by Pion and Protons”
   Joined LBL Group A (old Alvarez group).
   Student of Luis Alvarez

1976-1986
2. SPEAR Lead Glass Wall Experiment
   Spokes. L.Galtieri & M.Perl
   * Discovery of “Decay Mode J/ψ(3100) → γg” with T.Trippe, LBL
   Ref. 1979 Fermilab Lepton Photon Symposium, pg. 610.
3. PEP-4 TPC Experiment
   Spokes. D.Nygren, P.Oddone
   * Design of TPC “Ripple” trigger
   * Ran experiment 1983-1991

1987-1994
4. PEP-4/9 TPC/2γ Experiment
   * Co-Spokesman with Elliott Bloom, SLAC
   * Spokesman from 1991-1994
   * Expert on Tau and Two-photon physics with many Jet physis publications

1995-present
5. PEP-II BaBar Experiment
   * Conceptual and Engineering Design of PEP II Injection Timing and Control System
   w/ R.Settles, T.Matsuda et al.

1992-2004
6. American Next Linear Collider Physics & TPC Detector Studies
   * World expert of Java programming for HEP.

2004-
7. Co-Leader of International LC (ILC) Large Gaseous (TPC) Detector Design
The Next 10 years or so (2005-2017)

2004-2005
  ILC Technology choice for Superconducting RF, Aug. '04
  Paris TPC workshop, 20-21 Dec. '04
  Berkeley Generic TPC R&D meeting, 23-24 Apr. '05
  2nd Time Projection Chamber Symposium, Oct. '05 ??

  ...

2006-2007

2008-2009
  LHC & Detectors Fully Operational

2010-2011

2012-2013

2014-2015
  ILC & Large TPC Detector, ... Operational

2016-2017
  First comparisons of LHC and ILC results
Second Time Projection Chamber Symposium

Date: October 2005 ??
Location: Lawrence Berkeley National Laboratory (LBNL)
Hosts: LBNL Physics and Nuclear Science divisions, and the U.S. Department of Energy (DOE)

Program Outline

Areas of TPC Applications

- e+e Annihilation Studies
- Heavy Ion Physics
- Double Beta Decay Experiments
- Neutrino Physics Experiments
- Rare Event Detection

New Technical Developments / Current R&D

- Micro-Pattern Gas Detector (MPGD) Readout Technologies
- Pixel TPC Readout Systems
- High-density, Low-mass Electronics
- Electronic Imaging Detector R&D

New Ideas Forum

- New Techniques
- New TPC Applications