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Performance of the OPAL Jet Chamber

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Abstract

The jet chamber of the OPAL experiment at the LEP e^+e^- collider is designed to measure the direction and the momentum of charged particles as well as the specific energy loss in the chamber gas. The jet chamber has been operated at LEP since August 1989 and has recorded 500 000 hadronic decays of the Z^0 , resulting in a good understanding of the stability and systematics of the chamber. Resolutions obtained in the measurement of particle direction, momentum, and specific energy loss are presented, as well as the corrections and calibration procedures necessary to attain original design goals. A momentum resolution of 6.8% for particles with a momentum of 45 GeV/c and an energy loss resolution of (3-4)% over all momenta have been achieved.

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1 Introduction

The OPAL jet chamber, a large pictorial drift chamber, performs the main tracking of charged particles in the OPAL detector [1] by measuring three-dimensional coordinates¹ from wire position (R), drift time (ϕ), and charge division (z). The jet chamber operates in a solenoidal magnetic field of 0.435 T and measures the direction and momentum of charged particles over almost the entire solid angle. Multiple sampling by measuring the total charge collected at each wire is used to calculate the specific energy loss, dE/dx , for the purpose of particle identification. The jet chamber is designed to be used in conjunction with a high resolution vertex chamber [2] and a silicon microvertex detector [3] close to the interaction point, and with z -chambers [4] that precisely measure the z -coordinate of charged particles as they exit the jet chamber. All these elements comprise the OPAL central detector as shown in fig. 1.

The design and construction of the OPAL jet chamber has previously been described in detail [5, 6] as have preliminary results from a full scale prototype [7] and for cosmic rays and laser tracks in the jet chamber [6]. In the meantime, much experience has been gained during the operation of the jet chamber at the LEP e^+e^- collider since August 1989 and the recording of 500 000 decays of the Z^0 , with a typical recorded decay shown in fig. 2. After a brief description of the jet chamber and the calibration and correction procedures necessary to achieve design goals, this report presents measured point resolutions and the performance of the jet chamber. In some cases, the performance of the jet chamber combined with the other elements of the OPAL central detector will be shown. The description, calibration procedures, and performance of the dE/dx system have been given in detail elsewhere [8] and only a short summary of these results is presented.

2 Description and Operation

The sensitive volume of the jet chamber is a cylinder with a length of about 4 m with conical end plates and is divided in ϕ into 24 identical sectors, each containing a sense wire plane with 159 anode wires and two cathode wire planes which form the boundaries between adjacent sectors. The anode wires are located between radii of 255 mm and 1835 mm, equally spaced by 10 mm and alternating with potential wires. The maximum drift distance varies between 3 cm and 25 cm. To resolve left-right ambiguities, the anode wires are staggered by $\pm 100 \mu\text{m}$ alternately to the left and right side of the plane defined by the potential wires. A schematic drawing of a section of a jet chamber sector is shown in fig. 3. Gravitational sag of the anode wires reaches a maximum of $192 \mu\text{m}$ at $z = 0$. A solid angle of 73% of 4π is covered with 159 points on a track, and 98% of 4π with at least 8 points.

The anode wires are at ground potential, and the potential wires are maintained at -2.38 kV , determining the chamber gas gain. The outer cathode wires are held at -25 kV graded to -2.5 kV at the inner cathode wires, leading to an electric drift field of 890 V/cm . Electrostatic deflection of the anode wires reaches a maximum of $57 \mu\text{m}$ at $z = 0$. More details of the high voltage system are described in refs. [6, 8].

The chamber is operated with a gas mixture of 88.2% argon, 9.8% methane, and 2.0% isobutane at a pressure of 4 bar. The gas pressure chosen optimizes [9] particle separation using dE/dx , and is also a compromise between high pressure to minimize diffusion effects that degrade spatial resolution at long drift distances, and low pressure to minimize multiple scattering for good momentum resolution.

¹In the OPAL coordinate system, positive z is along the e^- beam direction, ϕ is the azimuthal angle, and θ is the polar angle.

A track travelling perpendicularly to the anode wires encounters 4.9% of a radiation length of material due to the chamber gas. The gas is recirculated and purified in a closed system and the oxygen content is kept below 2 ppm to minimize electron attachment over long drift distances. The water content of the gas is maintained at (500 ± 50) ppm to alleviate wire aging and to reduce field distortions at the field degraders at the outer radius of the jet chamber.

In the jet chamber tracking volume, the magnetic field of 0.435 T is measured to be uniform to within $\pm 0.5\%$. The Lorentz angle by which drift paths are tilted due to the magnetic field is $\alpha_L \approx 20^\circ$. The given high voltage configuration results in a gas gain of 10^4 and a drift velocity that is approximately saturated at $v_D \approx 53 \mu\text{m/ns}$.

100 MHz flash analogue-to-digital converters (DL300 FADCs [10]) digitize the waveforms of amplified signals from each end of every anode wire, and 256 (or 1024) samples are stored in fast memories. The FADCs have a 6-bit resolution, which is effectively extended to 8 bits by a nonlinear response function. By reading out data in special pulser runs, pedestals in the FADCs are determined to better than 0.1 counts and show a stability of better than 0.03 counts for any channel over a period of one week. Zero suppression, linearization, and pedestal subtraction are performed, and then drift times, charges and z -values are calculated online by a microprocessor system. Hits are recognized using a "difference of samples" (DOS) algorithm [11], and the charge of a pulse is obtained by integrating each pulse over 200 ns with respect to the start of the pulse. After the readout and processing, the event size of an average hadronic decay of the Z^0 is 45 kbytes.

3 Calibration

The desired spatial, angular, and momentum resolution puts high demands on the stability of the coordinate measurements and therefore on the stability and precise knowledge of several detector parameters such as drift velocity v_D and Lorentz angle α_L . This section outlines how coordinates are calculated and describes the calibration procedures used to determine the various parameters needed for coordinate reconstruction.

3.1 Coordinate Reconstruction

In the $R - \phi$ plane, space points x and y are calculated in a sector reference frame with the x axis along the anode wire plane according to :

$$\begin{aligned} x &= x_w - v_D \cdot \sin \alpha_L \cdot t + \text{corrections}; \\ y &= v_D \cdot \cos \alpha_L \cdot t + \text{corrections}, \end{aligned} \quad (1)$$

where x_w is the x coordinate of the anode wire, and t the measured drift time. The jet chamber has a homogeneous drift field, and a constant drift velocity is assumed over the whole sector except near the anode wires. The various corrections of equation 1 are described below.

The third coordinate is measured using charge division. From the charges Q_L and Q_R of the two pulses arriving at the two amplifiers at the end of each wire, the z coordinate is given by:

$$z = \frac{l_{\text{eff}}}{2} \frac{gQ Q_L - Q_R}{gQ Q_L + Q_R}. \quad (2)$$

Here l_{eff} is the effective wire length including both the anode wire resistance ($175 \Omega/\text{m}$) and the input impedance of the amplifiers, and g_Q is the relative gain given by the ratio of the amplification of the amplifiers on each side.

3.2 Laser Calibration

In the centre of each of the 48 half-sectors, parallel ultraviolet laser beams with a spacing of 10 mm in the $R - \phi$ plane can be injected by a Nd:YAG laser situated outside the detector. Sectors are selected using moveable mirrors outside the detector. The beams originate from both positive and negative z coordinates. Complete laser scans are performed during LEP shutdowns, and laser events are also read out at a rate of 0.04 Hz interleaved with physics events during normal physics runs. The entire laser system is described in more detail in ref. [12].

Relative differences in arrival times, t_{0i} , of chamber signals due to differences in cable lengths and delays of electronic modules are measured by executing laser runs on each side of the anode wire planes. The effective staggering (mechanical and electrostatic) of the wires at the position of the laser beams is also measured. Drift velocity and Lorentz angle are monitored by measuring the difference in arrival time of the signals produced by the two parallel laser beams with known spacing. The systematic uncertainty on v_D is about 0.1% and the absolute knowledge of α_L is currently not better than 1.5%. Residuals of hits on laser tracks at the inner and outer wires from straight line fits aid the parametrization and correction of remaining drift field distortions. The two laser measurements at different, precisely known, z positions allow the determination of the effective wire length l_{eff} and relative gain g_Q for each wire. Typical values of constants and their errors are summarized in table 1.

3.3 Boundary Crossing Tracks

Another calibration procedure [13] uses tracks from physics runs: in this case, tracks from hadronic Z^0 decay events. In case of miscalibration, many effects result in track displacements at chamber boundaries. A special sample of tracks crossing one or more anode or cathode wire planes is selected online using the online pattern recognition [14]. Each track is fit separately on either side of the wire plane, and the gap or displacement of the track pieces at the plane is minimized by simultaneously adjusting the appropriate calibration constants. A sample of a few thousand hadronic Z^0 events is necessary to determine the required calibration constants with sufficient precision. Typical values of constants and their errors are again summarized in table 1.

From tracks crossing anode planes, the time difference between the FADC trigger signal and the time of beam crossing (global constant T_0) can be determined to about 0.6 ns for individual sectors. A linear dependence of wire t_0 s on the radius of the wire position, not detectable by the laser calibration, is measured. Referring to fig. 3, the “aberration radius” is the radius inside which the drift path is approximately radial to the anode wire, whereas outside this radius, the drift path is parallel to the drift region boundaries. The aberration radius can also be determined, averaging over all sectors, using tracks crossing anode planes.

From tracks crossing cathode planes, drift velocity and Lorentz angle can be determined with a statistical error of 0.01% and 0.1%, respectively in each sector. Systematic uncertainties are respectively less than 0.05% and 0.5% for v_D and α_L . It should be noted that it is essentially only a $\cos \alpha_L$ term that enters in the determination of the particle momenta; hence v_D and α_L are determined to comparable precision in this respect. The measured drift velocity as a function of time is shown

in fig. 4. Variations of the order of 0.4% are observed, mostly due to varying water content in the chamber gas [12], stressing the necessity of maintaining a constant water content and continuously monitoring v_D to ensure reliable performance of the jet chamber over the entire running period.

4 Efficiencies and Coordinate Resolutions

4.1 Efficiencies

It has not been necessary to replace any of the 3816 anode wires due to breakage. The number of bad channels that cannot be considered for track pattern recognition [15] due to failures in the electronic read out chain is typically kept as low as 0.3%. Excluding these bad channels, a single hit efficiency of 99.2% is measured by examining the distribution of the number of hits on tracks in $Z^0 \rightarrow \mu^+\mu^-$ events. On average, only 10 noise hits per event are observed due to synchrotron radiation from LEP. The ability of the DOS algorithm to resolve closely spaced hits is shown in fig. 5 where 80% of hits greater than 2.5 mm apart are resolved. The difference between the dashed histogram for all hits and the solid histogram for both hits associated to tracks is due to a low level of imperfect hit assignment by the pattern recognition algorithms. The tracking efficiency has been studied using a Monte Carlo simulation of hadronic Z^0 decays. For tracks above a momentum of 0.1 GeV/c and within an angular range of $|\cos\theta| < 0.95$ the single track finding efficiency was determined to be 97.9% inside jets. A slight loss in efficiency is observed for very high momentum tracks parallel to, and within 3 mm of anode wire planes.

4.2 Coordinate Resolutions

Fig. 6a shows the $R - \phi$ plane intrinsic coordinate resolution, $\sigma_{R\phi}$, determined using triplets of adjacent measured coordinates as a function of drift distance for isolated coordinates in $Z^0 \rightarrow \mu^+\mu^-$ events. The dependence of $\sigma_{R\phi}$ on the drift distance is due to electron diffusion at long drift distances and the production statistics of the primary electrons at short drift distances. Averaging over all drift distances, an overall resolution of $\sigma_{R\phi} = 135 \mu\text{m}$ is found. Fig. 6b shows $\sigma_{R\phi}$ as a function of local ϕ angle of a track in a sector with respect to the anode wire plane for tracks in hadronic Z^0 decay events. A minimum is observed when the track is perpendicular to the drift path direction where effects of drift paths of different lengths for primary electrons and transverse diffusion are minimized. A degradation of $\sigma_{R\phi}$ by a factor of 1.5 due to overlapping pulses is observed only for hit separations of below 3 mm.

In the $R - z$ plane, an intrinsic coordinate resolution of $\sigma_z = 4.5 \text{ cm}$ is measured for tracks in $Z^0 \rightarrow \mu^+\mu^-$ events and $\sigma_z = 6.0 \text{ cm}$ in Z^0 hadronic decay events. These values correspond to roughly (1-2)% of the wire lengths, typical for resolutions obtained using charge division. The resolution σ_z is observed to depend on the total charge and z position of the hit considered, with better than average resolution obtained for hits with large total charge close to the ends of the wires.

The dependence of the coordinate resolutions on relevant hit and track variables have been parametrized and are used in the track fit as coordinate errors.

5 Performance

Even after careful calibration and coordinate resolutions corresponding to design specifications, remaining systematic effects in the jet chamber need to be considered and corrected. These corrections are described below along with resulting track parameter resolutions.

5.1 $R - \phi$ Plane

Systematic Effects

Corrections of systematic effects in the $R - \phi$ plane have resulted in an improvement of the jet chamber momentum resolution, σ_p/p , by a factor of 2.5 since OPAL began recording Z^0 decays in 1989. By examining track residuals from laser tracks and high momentum tracks in the data, individual wire offsets were adjusted to compensate for sometimes intermittent measured t_0 displacements due to hardware problems in some FADC electronic crates. Similarly, corrections due to non-homogeneous drift fields in each sector were carefully adjusted. These corrections are particularly important for the electrostatic boundary regions of the innermost 4 wires and the outermost 16 wires in each sector, reaching values of up to 800 μm for the outermost wires used in track fits. Close to anode wires, the electric field and v_D are no longer constant, and near-anode corrections were determined from tracks crossing anode wire planes. These corrections are important within 3 mm of each anode wire and range up to 20 ns in magnitude very close to the anode. Small time corrections quadratic in wire number due to electronic systematic sagitta effects were found by examining the structure of $1/p$ distributions for muon tracks in $Z^0 \rightarrow \mu^+\mu^-$ events. A correction for a torsion of 50 μrad between the jet chamber conical endplates, measured in stand alone laser runs and confirmed by studying $Z^0 \rightarrow \mu^+\mu^-$ events, is applied. Finally, v_D and α_L as found by the calibration method of boundary crossing tracks are averages over all radii in a sector. Small variations in these calibration constants as a function of jet chamber radius were measured, parametrized, and applied as a correction.

Performance

Fig. 7 shows the resulting $1/p$ distribution for μ^+ and μ^- tracks in $Z^0 \rightarrow \mu^+\mu^-$ events measured using only the jet chamber. After suitable cuts, the momentum of each track should equal E_{beam} , where $E_{\text{beam}} \approx 45.6$ GeV is the beam energy. A momentum resolution of $\sigma_p/p^2 = 1.5 \times 10^{-3} (\text{GeV}/c)^{-1}$ (6.8% at $p = 45$ GeV/ c) is measured, to be compared with its design specification [1, 5] of between 1.6 and 2.0×10^{-3} . Including a term due to multiple scattering, the momentum resolution for all momenta is given by

$$\sigma_{p_t}/p_t = \sqrt{(0.02)^2 + (0.0015 \cdot p_t)^2},$$

where p_t in GeV/ c is the momentum component transverse to the beam axis. By comparing the measured with the expected sagitta [16] from $R - \phi$ coordinate resolution, the apparent sagitta due to remaining systematic errors is less than 45 μm .

The impact parameter resolution of the jet chamber is determined by studying the “miss distance” between muon tracks extrapolated to the beam axis in the $R - \phi$ plane in $Z^0 \rightarrow \mu^+\mu^-$ events. For the jet chamber alone, this distribution is centred at zero with a width of 160 μm , corresponding to an impact parameter resolution of 113 μm for high momentum tracks. In general, the impact parameter resolution of the OPAL central detector is not determined by the jet chamber, but mainly by the vertex drift chamber and the silicon microvertex detector. Including vertex drift chamber measurement points, the impact resolution improves to 40 μm , and adding measurements from the silicon microvertex detector, a further improvement down to 22 μm is obtained using the most recent alignment constants.

5.2 $R - z$ Plane

Systematic Effects

The method of charge division is expected to be very sensitive to systematic effects influencing the charges Q_i measured on either side of the jet chamber. Before correction of systematic effects, the theta angle resolution, σ_θ , using the jet chamber only is observed to be much worse than the $\sigma_\theta \approx 10$ mrad expected [16] from the z coordinate resolution alone. Many of the systematic effects are believed to arise due to long-range crosstalk that affects Q_L and Q_R differently. This asymmetric crosstalk induces signals on wires in a range of 20 wires on either side of a hit. Resistor networks at the output of the preamplifiers provide hardware crosstalk compensation [5] for first and second neighbouring wires, and only compensate for the component that affects Q_L and Q_R identically. The possible origin of the asymmetric component is unbalanced charging of capacitors in the potential wire termination networks followed by balancing currents in the anode wires. In addition, residual noise in the jet chamber causing asymmetric event-by-event pedestal fluctuations that affect the z measurement have been observed.

The other OPAL subdetectors are used to investigate systematic effects in the jet chamber in the $R - z$ plane. The z coordinate resolutions of vertex chamber stereo hits and hits in the z -chambers are $700\ \mu\text{m}$ and $300\ \mu\text{m}$, respectively; therefore, the position in $R - z$ of a track with associated hits in these chambers is almost independent of the lower precision jet chamber z measurements. Alternatively, track extrapolations in the $R - z$ plane are compared to measurement points in the OPAL barrel electromagnetic presampler [1] at a radius of 2.4 m that provides z coordinates with a resolution of 2–6 mm. Using these tracks, a correction Δz is determined empirically as a function of track $|z|$, Q , local ϕ angle in a sector, and the number of tracks in the event. These Δz corrections are as large as 20 cm for some combinations of values of the above parameters. A more sophisticated approach that considers the jet chamber geometry, wire termination networks, pulse amplitudes and shapes, and the capacitance and inductance between wires to calculate crosstalk coefficients is in progress. To compensate for asymmetric pedestal fluctuations during 1991 runs that tended to globally rotate jet chamber hits in θ , hits were corrected in the $R - z$ plane by considering the track to be constrained to the interaction vertex position in z as determined by the vertex chamber. The z coordinate can also be reconstructed from the time difference measured at both ends of each wire, but with a much poorer resolution of $\sigma_z = 36$ cm. The reconstructed z is formed as a weighted average of the z determined by charge division and by time difference; the two methods are sensitive to different systematic effects, and the tails on track residual distributions are reduced. By using the information of the last wire with a hit, the end point of a track inside the jet chamber can be determined. This allows to constrain the track fit to that point, with a subsequent reduction of systematic effects for tracks with $|\cos \theta| > 0.73$.

Performance

After all corrections, fig. 8a shows the distribution of z_0 , the z coordinate of the track at the point of closest approach of the track to the origin in the $R - \phi$ plane. A resolution of $\sigma_{z_0} = 6.2$ cm is achieved in hadronic Z^0 decay events and 2.5 cm for $Z^0 \rightarrow \mu^+ \mu^-$ events. Including information from the vertex and z -chambers this resolution improves to $\sigma_{z_0} = 1.0$ cm, which is dominated by the width of the beam. The angular resolution σ_θ is estimated by comparing the difference in θ between the jet chamber track and the θ of the cluster of the electromagnetic barrel presampler. Using the jet chamber only, σ_θ ranges from 40–60 mrad in hadronic Z^0 events, and $\sigma_\theta = 25$ mrad in $Z^0 \rightarrow \mu^+ \mu^-$ events. Including measurement points from the z -chambers improves σ_θ to 2.4 mrad, and constraining tracks to the reconstructed interaction vertex in z results in a further improvement to $\sigma_\theta = 0.25$ mrad. Fig. 8b shows the difference between the θ of jet chamber tracks including end point information and the θ given by muon endcap chambers [1], indicating $\sigma_\theta \approx 2.7$ mrad for muon tracks in $Z^0 \rightarrow \mu^+ \mu^-$ events. This last value is better than anticipated in the technical proposal [1] where only charge

division was assumed. The overall performance of the tracking system is illustrated in the invariant mass distribution for $\pi^+\pi^-$ pairs shown in fig. 9 exhibiting an invariant mass resolution for the K^0 mass peak of $\sigma_M = 6.5 \text{ MeV}/c^2$.

5.3 Energy Loss, dE/dx

A complete description of the measurement of the energy loss dE/dx and the necessary calibration and correction procedures are given in ref. [8]. When at least 130 charge samples are demanded on a track, resolutions of $\sigma(dE/dx)/(dE/dx) = 3.1\%$ for muons in $Z^0 \rightarrow \mu^+\mu^-$ events and 3.8% for minimum ionizing pions in jets are achieved. These numbers can be compared with the expectation of (3–4)% [1, 9]. The power to separate or identify particles of different species is the difference between their expected dE/dx values divided by the error on dE/dx . In the region of relativistic rise, this separation power is shown in fig. 10 for tracks in hadronic Z^0 events with at least 40 charge samples. A separation with a probability of at least 2σ is possible up to 13 GeV/ c between electrons and pions, and up to 20 GeV/ c between pions and kaons or pions and protons.

6 Summary and Outlook

The OPAL jet chamber has operated stably and reliably since it started recording Z^0 decays in 1989, and has played an essential role in most OPAL physics analysis. After careful calibration and correction of systematic effects, design goals have been achieved or surpassed. A more sophisticated treatment of long-range crosstalk and an upgrade of the read out system that will allow the calculation of high precision FADC pedestals event-by-event hold promise for further improvement of the performance of the jet chamber.

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Tables

Calibration Quantity	Laser Calibration	Boundary Crossing Tracks	Typical Value	Typical Error
Effective wire length	•	—	460–560 cm	0.5%
Relative gain	•	—	0.998	0.4%
Individual wire time offsets	•	—	–12 to 12 ns	0.8 ns
Effective wire staggering	•	—	115 μm	10 μm
Drift velocity	o	•	52.9 $\mu\text{m}/\text{ns}$	< 0.05%
Lorentz angle	o	•	20.0°	< 0.5%
Global time offset	—	•	300 ns	< 0.6 ns
Linear dependence of time offsets	—	•	0–0.1 ns/cm	0.007 ns/cm
Aberration radius	—	•	4.435 mm	0.05 mm

Table 1: Calibration quantities and their typical values and errors. A ‘•’ indicates that the calibration quantity using that method is used in coordinate reconstruction; a ‘o’ indicates that the quantity is used for monitoring only. The effective wire staggering is the sum of the mechanical and electrostatic staggering at the z position of the laser beams ($z = \pm 1.20$ m).

Figure Captions

- Fig. 1: Schematic view of the OPAL central detector.
- Fig. 2: A hadronic Z^0 decay event tracked in the jet chamber. The lower jet contains an inclusive electron visible as high momentum track pointing at a high energy deposit in the electromagnetic calorimeter. The track fulfils the dE/dx requirement for electrons.
- Fig. 3: Schematic view of part of one of the 24 jet chamber sectors. Anode wires are depicted with 'x' symbols, and potential wires with '•' symbols.
- Fig. 4: Measured drift velocity using boundary crossing tracks versus time in 1991. The spread of points at each time sample shows v_D measured for each of the 24 sectors. The jump around day 170 shows the immediate response when the water absorber was switched on at the end of a running period.
- Fig. 5: Efficiency for separating two hits as a function of their distance apart for all hits (dashed histogram) and both hits associated to tracks (solid histogram).
- Fig. 6: Intrinsic coordinate resolution $\sigma_{R\phi}$ as a function of (a) drift distance, and (b) local ϕ angle of the track with respect to the anode wire plane.
- Fig. 7: Distribution of $1/p$ for μ^+ and μ^- tracks in $Z^0 \rightarrow \mu^+\mu^-$ events measured using only the jet chamber.
- Fig. 8: (a) z coordinate of tracks at their distance of closest approach to the origin in hadronic Z^0 events measured using only the jet chamber (inset: including information from the vertex chamber and z -chambers). (b) Difference in θ angle between jet chamber track and muon endcap track segment when jet chamber end point information is used in $Z^0 \rightarrow \mu^+\mu^-$ events.
- Fig. 9: $\pi^+\pi^-$ invariant mass distribution showing a peak due to $K^0 \rightarrow \pi^+\pi^-$.
- Fig. 10: Particle separation power in units of $\sigma_{dE/dx}$ as a function of the particle momentum. The plot is for tracks in hadronic Z^0 events with at least 40 hits useable for the calculation of dE/dx .

Figure 1: Schematic view of the OPAL central detector.

Figure 2: Typical hadronic Z^0 decay event tracked in the jet chamber.

Figure 3: Schematic view of part of one of the 24 jet chamber sectors. Anode wires are depicted with 'x' symbols, and potential wires with '•' symbols.

Figure 4: Measured drift velocity using boundary crossing tracks versus time in 1991. The spread of points at each time sample shows v_D measured for each of the 24 sectors.

Figure 5: Efficiency for separating two hits as a function of their distance apart for all hits (dashed histogram) and both hits associated to tracks (solid histogram).

Figure 6: Intrinsic coordinate resolution $\sigma_{R\phi}$ as a function of (a) drift distance, and (b) local ϕ angle of the track with respect to the anode wire plane.

Figure 7: Distribution of $1/p$ for μ^+ and μ^- tracks in $Z^0 \rightarrow \mu^+\mu^-$ events measured using only the jet chamber.

Figure 8: (a) z coordinate of tracks at their distance of closest approach to the origin in hadronic Z^0 events measured using only the jet chamber. (inset: including information from the vertex chamber and z -chambers). (b) Difference in θ angle between jet chamber track and muon endcap track segment when jet chamber end point information is used in $Z^0 \rightarrow \mu^+\mu^-$ events.

Figure 9: $\pi^+\pi^-$ invariant mass distribution showing a peak due to $K^0 \rightarrow \pi^+\pi^-$.

Figure 10: Particle separation power in units of $\sigma_{dE/dx}$ as a function of the particle momentum. The plot is for tracks in hadronic Z^0 events with at least 40 hits useable for the calculation of dE/dx .

Fig. 1

Status
Det Tr

CV	3	0
CZ	3	3
CB	2	3
TC	3	3
PB	3	3
PR	3	3
FF	3	3
HT	3	1
HS	3	3
HP	3	3
MB	3	3
ME	2	3
FD	3	3
SI	0	0

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8a

Fig. 8b

Fig. 9

Fig. 10