THE BELLE EXPERIMENT INVESTIGATION OF CP VIOLATION AT THE KEK B-FACTORY*

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on behalf of the BELLE collaboration

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The BELLE collaboration (about 330 physicists and students from 50 laboratories representing ten countries) prepares a dedicated CP violation experiment at the KEK B-factory, now under commisioning. The BELLE detector was completed in December 1998 and should start data taking in April 1999.

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1. Introduction

A study of CP violation represents one of the most interesting topics in high energy physics. This study allows a very thorough check of the Standard Model. The report sketches the main physics goals and describes one of two detectors[1], which should soon yield high quality data.

2. CKM matrix and unitarity triangle

A very convenient parametrization [1] of the Cabibbo–Kobayashi –Maskawa matrix is as follows:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)\,,$$

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[1] another is the Babar at the PEP-II B-factory at SLAC

where $\lambda = 0.2196 \pm 0.0023$ and $A = 0.819 \pm 0.035$ are very well known. Our knowledge of ρ and η parameters (the latter being responsible for CP violation) is much worse. There have been many estimates of these parameters based on $B^0 \leftrightarrow \overline{B^0}$ mixing, V_{ub}, the strength ε_K of CP violation in K decays and (sometimes) the limit on $B_s^0 \leftrightarrow \overline{B_s^0}$ mixing. *E.g.* Mele [2] has recently given the following 2σ limits:

$$-0.025 < \rho < 0.358 \,,$$
$$0.274 < \eta < 0.531 \,.$$

It should be stressed that *all* such estimates involve theoretical uncertainties connected *e.g.* with the box factor B_K or the B decay constant f_B.

From unitarity of CKM matrix one obtains:

$$V_{ub}^* + V_{cd}V_{cb}^* + V_{td} \approx 0$$

which can be plotted as the unitarity triangle (see Fig. 1).

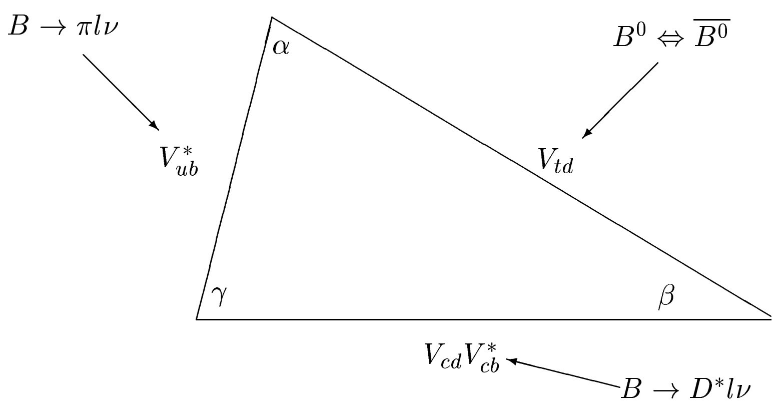

Fig. 1. The unitarity triangle

Note that all the sides of the triangle can be very precisely measured at the B-factory using *e.g.* the processes shown in Fig. 1. In principle all the angles can be determined from CP violation measurements (see next section). Together with the very precise determination of the sides this will yield an overdetermined system allowing a very demanding test of the Standard Model.

Dividing all sides of the triangle by $|V_{cd}V_{cb}^*| = \lambda|V_{cb}|$ one obtains the normalized triangle, the upper vertex located in the $(\rho,\, \eta)$ point (see Fig. 2 showing also some candidate processes for the measurement of angles).

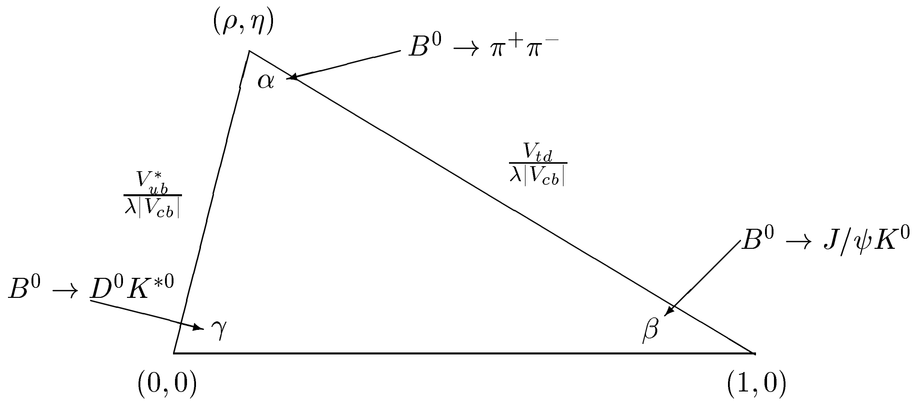

Fig. 2. The (rescaled) unitarity triangle

3. Measurement of the angles of the unitarity triangle

The best method is the measurement of a CP violation due to interference between mixing and decay of B^0 into CP eigenstate f. The state f can be produced in two ways, namely $B^0 \to f$ or $B^0 \to \overline{B^0} \to f$. One should measure a time-dependent CP violating asymmetry

$$a_f(t) = \frac{\Gamma(B^0 \to f) - \Gamma(\overline{B^0} \to f)}{\text{sum}}$$

which is expected to be large (tens of percents) for some decays. It can be shown that

$$a_f(t) = (CP)_f \sin 2\phi \sin(t\Delta M)\,,$$

where
ϕ is an angle of unitarity triangle;
$\Delta M = M(B_H^0) - M(B_L^0) \approx 0.46$ ps^{-1};
$t = t_f - t_{\rm tag}$;
t_f — decay time of "our" B into f;
$t_{\rm tag}$ — decay time of "other" B into any tagging mode.

Note that (very conveniently!) ΔM, is of the order of the B lifetime. It is the tagging B which tells us whether "our" B was originally B^0 or $\overline{B^0}$. For this purpose a full reconstruction of tagging B decay is not necessary; a sign of lepton, K or D^* is sufficient.

Two things are essential here:

- This determination of angles is free from theoretical uncertainties;
- $\int a_f(t)dt \equiv 0$ thus *both* decay vertices must be seen to study the time-dependent CP violating asymmetry. Therefore *asymmetric* B-factory is needed to provide a boost of the CM system.

A "gold-plated" decay for the determination of the angle β is $B^0 \to J/\psi K^0$ which has a reasonable branching fraction [3] *i.e.* $\mathrm{BF}(B^0 \to J/\psi K^0) = (8.9 \pm 1.2) \times 10^{-4}$. The decay products are easily identified since $J/\psi \to l^+l^-$, $K_S^0 \to \pi^+\pi^-$ and K_L^0 is seen in special detector. We expect $\Delta \sin 2\beta \approx 0.06$. This angle can be also measured in other decays like $B^0 \to J/\psi K^{*0}$, $B^0 \to D^+D^-$, $B^0 \to D^{*+}D^{*-}$.

A more difficult is the measurement of the angle α. The seemingly best candidate $B^0 \to \pi^+\pi^-$ has two disadvantages. One is a very small branching fraction [3] *i.e.* $\mathrm{BF}(B^0 \to \pi^+\pi^-) < 1.5 \times 10^{-5}$. The second is a possible contribution from a penguin graph. To solve the latter problem one should *also* measure $B^0 \to \pi^0\pi^0$ and make an isospin analysis. This will not be an easy task (the branching fraction [3] is $\mathrm{BF}(B^0 \to \pi^0\pi^0) < 9.3 \times 10^{-6}$). Other decays *e.g.* $B^0 \to \rho^+\pi^-$ may eventually appear to be better.

Measurement of the γ angle is probably even more difficult. One should either study a B decay with *direct* CP violation *e.g.* $B^0 \to D^0 K^{*0}$ or move to energy high enough to produce a $B_s^0\overline{B_s^0}$ pair and measure *e.g.* the $B_s^0 \to D^0\phi$ decay.

4. The collider

The KEK-B accelerator constructed on the TRISTAN site in Tsukuba, Japan will collide 8 GeV e^- with 3.5 GeV e^+. The design luminosity is $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponding to $\int Ldt = 100\mathrm{fb}^{-1}$ *i.e.* $\approx 10^8$ $B\overline{B}$ pairs per year. The main differences with respect to the PEP-II B-factory are larger number of bunches and 22 mrad crossing angle as compared to head-on collisions. The commisioning of the collider should be finished in March 1999 [2].

5. General features of the detector

The CP violation asymmetry will be measured for many B meson decays. The decays in question are rare ($\mathrm{BF} \approx 10^{-5} \div 10^{-4}$), mainly exclusive and often involve neutral decay products (π^0's and K^0's). Charged particles and photons should be well measured down to low momenta. The particle

[2] First collisions were observed on January 27th.

identification is essential both for good selection of a decay channel and for flavor tagging. The crucial investigation of time-dependent CP asymmetry relies on good measurement of secondary vertices. This puts special demands on the detector design. Thus we need:

wide angular acceptance and good hermeticity — BELLE detector (see Fig. 3) covers full azimuthal angle ϕ and the polar angle θ in the range of $6.2^\circ < \theta < 171.5^\circ$ (the direction of the z-axis and $\theta = 0$ correspond to that of the e^- beam),

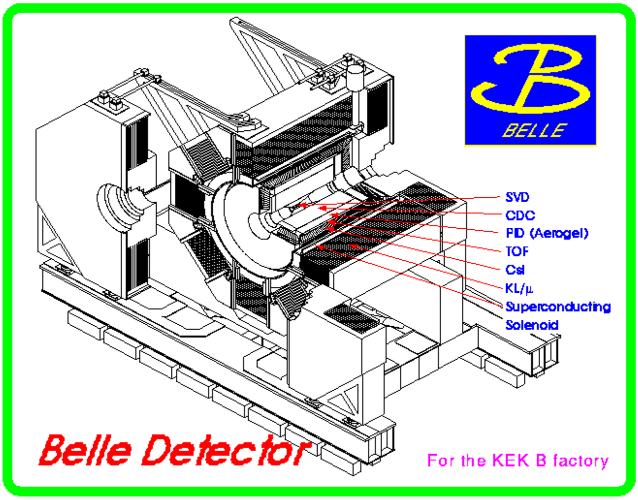

Fig. 3. The BELLE detector

vertex separation measured with high accuracy — Silicon Vertex Detector (SVD) very close to the beam pipe,

charged particle tracking — Central Drift Chamber (CDC) in $1.5T$ magnetic field will be also used for dE/dx measurement and $K_s^0 \to \pi^+\pi^-$ detection,

charged particle identification — Aerogel Cerenkov Counter (ACC) and Time of Flight (TOF) counters,

identification and energy measurement of photons and electrons — homogeneous CsI(Tl) calorimeter (called EMC-ElectroMagnetic Calorimeter) augmented by the BGO one (called EFC-Extreme Forward Calorimeter),

K_L^0 *detection and muon identification (KLM)* — return yoke instrumented with Resistive Plate Counters, *capability to run at high event rate* — fast readout, good trigger and reasonable radiation hardness.

6. Silicon Vertex Detector

The SVD design has been completely changed in mid-1997 with respect to the Technical Design Report [4]. It was then decided to construct a detector which would be simpler but ready in time. The actual detector covers $17^\circ < \theta < 139^\circ$ only. It consists of three cylindrical layers with the radius of 30 mm, 45 mm and 60 mm. They have 8, 10 and 14 ladders, each consisting of 2, 3 and 4 Hamamatsu DSSD (Double Sided Silicon Detector) wafers. In each case the n sides measure the z coordinate and the p sides measure the $r\phi$. There is a certain overlap between adjacent ladders to help in detector alig

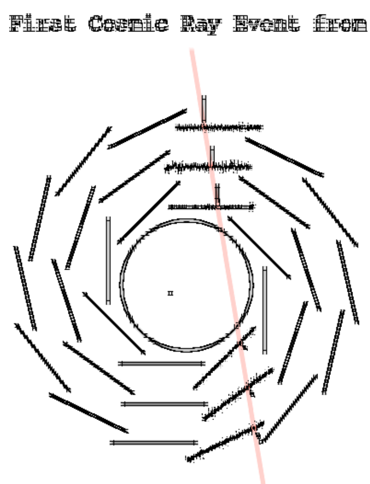

Fig. 4. Silicon Vertex Detector

An upgrade of the SVD to improve the θ range and the radiation hardness is envisaged for next year.

7. Central Drift Chamber

The main tracking detector of complicated geometry consists of 50 cylindrical layers of drift cells arranged in 11 superlayers. In addition there are three cathode layers for the z measurement. Some of wires are strictly axial for $r\phi$ measurement and some form a small-angle stereo for an additional z measurement.

A full scale prototype equipped with 41 layers and filled with He/C_2H_6 gas was extensively tested in 3.5 GeV/c pion beam. The spatial resolution of 130μm for anodes and 530μm for cathodes was obtained. This spatial resolution should give a design momentum accuracy of $\Delta p_t/p_t = 0.5\%\sqrt{p_t^2+1}$.

For 3.5 GeV/c pions the dE/dx was measured in the prototype chamber with the accuracy of 5.3%. This indicates that a 2σ K/π separation at 2 GeV/c can be achieved. At 0.8 GeV/c the e/π separation is about 4σ. This will provide a powerful handle for electron identification below 1 GeV/c where the EMC resolution is not so good.

The cosmic tests of the real CDC generally confirmed the performance of the prototype.

8. Charged particle identification

In addition to the dE/dx information from the CDC the BELLE apparatus uses Aerogel Cerenkov Counters (ACC) and the Time of Flight (TOF) system for particle identification.

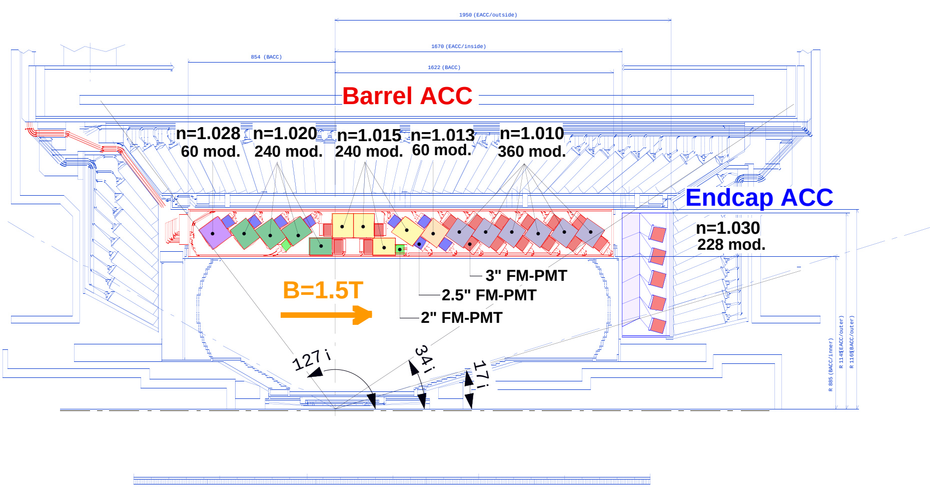

Fig. 5. Arrangement of Aerogel Cerenkov Counter, CDC (inside) and EMC (outside).

The ACC consists of 960(barrel)+228(forward endcap) modules with typical dimensions of 12×12cm × (10 ÷ 14.5)cm. The refraction index varies with θ (see Fig. 5) corresponding to momentum range expected for each θ interval. We use five tiles, each 2.4cm thick in a module which is viewed by one or two phototubes[3]. The radiation hardness was also tested; the aerogel radiators received a dose of about 10Mrad without any change of transparency or of refraction index.

Fig. 6. Installation of TOF counters

A full scale prototype of 1/30 of the barrel ACC was tested in the 1.5T magnetic field using the KEK 3.5GeV/c beam. For pions the efficiency was about 98% and only about 2% of subthreshold protons produced the signal which is consistent with the estimated number of knock-on electrons. The real ACC is now working on cosmics.

The TOF system covers the barrel region only. It consists of 128 plastic scintillation counters 4cm thick and read from both sides. They are grouped in 64 modules, each containing 2 TOF counters and one 5 mm thick Trigger Scintillation Counter(TSC). They are separated by the 2cm gap allowing most electrons and positrons from conversions in the TSC to curl up before reaching the TOF.

[3] This was the result of careful optimization since the phototubes represent the largest single component of material in front of EMC. On the other hand two phototubes provide better efficiency.

The full size TOF counters were tested in a 2 GeV/c beam and the time resolution was measured to be $(65 \div 85) ps$. A 6σ π/p separation was reached, correspondingly we expect a π/K separation at 1 GeV/c to be also on the 6σ level. An installation of TOF counters is shown in Fig. 6.

A prototype TSC counter was also tested in the beam.The light yield allows the discrimination level to be set at 0.5mips without any loss of efficiency.

Since both the ACC and TOF/TSC phomultipliers are in the magnetic field we use the Hamamatsu fine-mesh phototubes with 2000-mesh/inch dynodes. The magnetic field tests showed that with the voltage of 2800V the gain exceeds 3×10^6. The deterioration in the time resolution is about 10%.

9. Electromagnetic calorimeter

The main BELLE calorimeter (EMC) consists of 8816 CsI(Tl) crystals and covers 91% of total solid angle. The crystals have tower-like shape with front face of 5.5cm×5.5cm and the length of 30cm corresponding to $16.1\lambda_{\rm rad}$ or $0.8\lambda_{\rm int}$.

The performance of CsI was investigated using matrices of 3×3 or 5×5 crystals and the tagged photon beam with energy from $E_\gamma = 20$ MeV to $E_\gamma = 5.4$GeV The results can be described by the formula:

$$\Delta E/E = (0.081/E \oplus 1.47/E^{1/4} \oplus 1.34)\%$$

the first term due to electronics noise.

The position resolution obtained from the pulse height weighting in the crystal matrix ranges from 5 mm for the edge to $10mm$ at the crystal center. Averaging over various beam positions we obtain resolution improving from 14 mm at $E_\gamma = 100$ MeV to 3 mm at $E_\gamma = 4$ GeV. Very similar results for the energy and position resolution were obtained previously for the electron beam.

Finally the pion misidentification probability was found to be about 5% at 1 GeV/c and less than 1% above 2 GeV/c, where the calorimeter is the essential tool for electron identification.

The first cosmic ray event seen in several BELLE subdetectors (including calorimeter) is shown in Fig. 7.

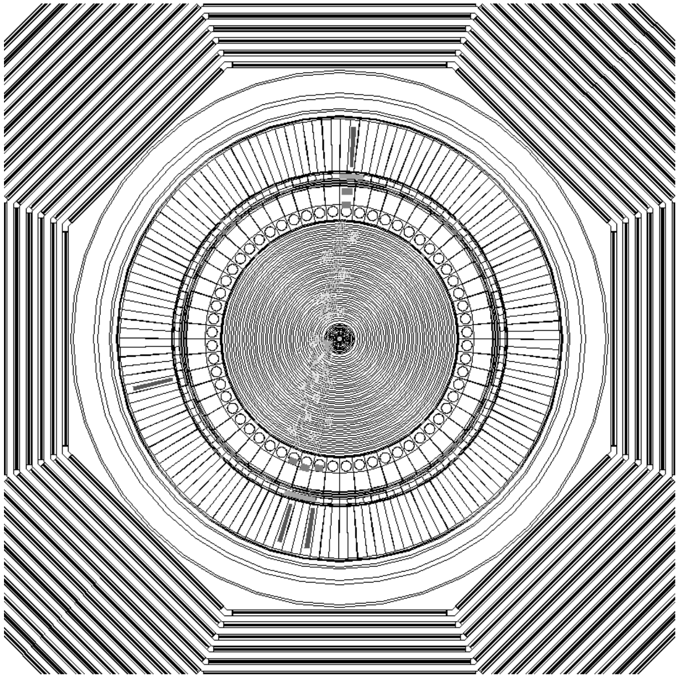

Fig. 7. Cosmic ray event in CDC, ACC, TOF and ECL detectors

10. Extreme Forward Calorimeter(EFC)

The Extreme Forward Calorimeter covers polar angle regions $(6.2 \div 11.6)^\circ$ and $(163.1 \div 171.5)^\circ$, essential for hermeticity, luminosity measurement and two-photon physics. This is the homogeneous BGO calorimeter with 5 crystals in θ and 32 in ϕ on each side. The size of crystals is $2\text{cm}\times 2\text{cm} \times 12(10)\lambda_{\text{rad}}$ for the forward (backward) endcap. It was shown that the crystals survive 10 Mrad with 10% loss of light output while only 0.5 Mrad/yr are expected. Minimum ionizing particles are well seen in the crystals.

It should be noted that there is no space for such subdetector in the BaBar apparatus because of bending magnets needed to separate the beams.

11. Magnet and iron yoke structure

The 1.5T BELLE magnet has useful warm bore of $\phi 3.4$ m $\times$ 4.4 m.

The flux return iron yoke has been installed and instrumented (see Fig. 8) with KLM detector. First cosmic tracks deflected in the magnetic field have been recorded in the BELLE detector.

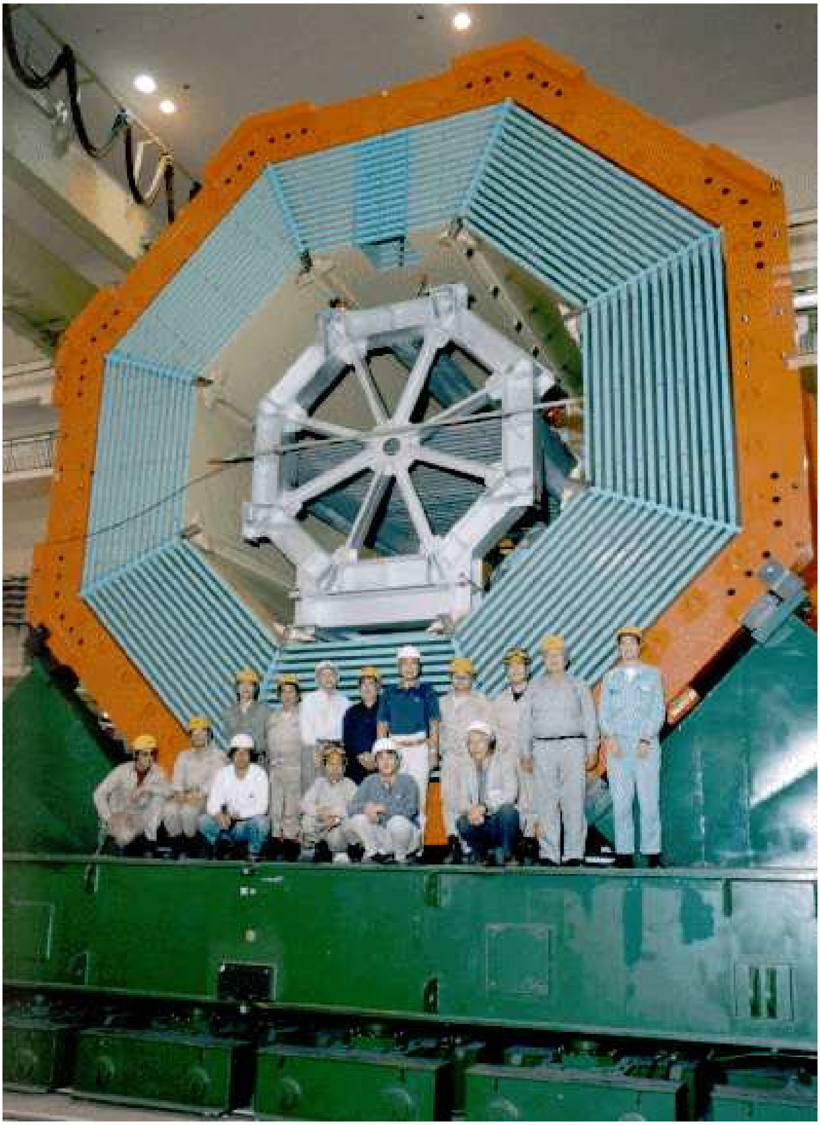

Fig. 8. BELLE magnet and instrumented iron yoke

12. KLM — K_L^0 detection and μ identification

The KLM detector is a coarse calorimeter measuring *only* the K_L^0 position and *not* the cascade energy. This is sufficient to identify K_L^0's from *e.g.* the $B \to J/\psi K^0$ decay thanks to kinematical constraints. The KLM also reduces the pion contamination in the muon sample. The muon momenta are measured in the CDC so the muon energy information is not needed. It is intended to detect K_L^0's and muons above 600 MeV/c. In addition this calorimeter increases the hermeticity of the BELLE detector. Both barrel and endcap KLM's make use of the iron yoke structure with the difference that the barrel one has an active layer at the beginning. The active layers are Resistive Plate Counters interleaved with 14 iron layers each 4.7cm thick thus amounting to about $4\lambda_{\rm int}$. It should be recalled that $\approx$ 60% of K_L^0's will interact already in the EMC.

The position accuracy was measured with cosmic rays to be about 2cm corresponding to the angular accuracy of about 10mrad. This is well within $30mrad$ needed to identify K_L^0 from the $B \to J/\psi K^0$ decay. A single RPC efficiency is $\approx$ 95% and the longevity is well in excess of 2 years for most layers. With these parameters we expect to register about 70% of K_L^0 from this decay. For muons the detection efficiency should exceed 80%. The pion contamination of the muon sample is expected to be below 2% at $p >$ 1.5 GeV/c.

A cosmic ray muon seen also in KLM is shown in Fig. 9.

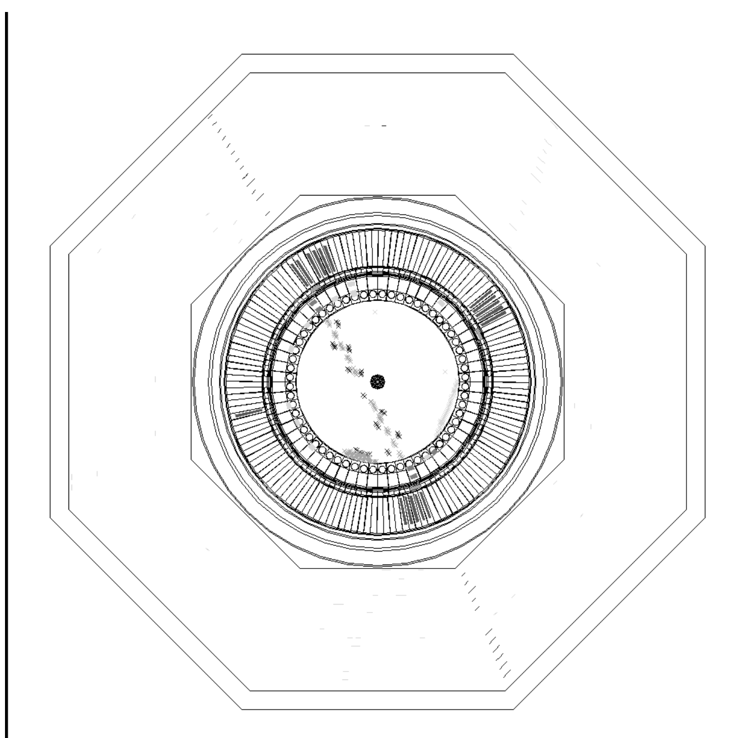

Fig. 9. Cosmic ray muon in the BELLE detector (including KLM)

13. Summary and outlook

For some subdetectors the goals set in the Technical Design Report [4] have been already surpassed but the problems encountered caused a certain delay. The detector has been completed in December 1998 while the commisioning of KEK-B started earlier. In order not to risk the vulnerable detectors (SVD and all endcap parts) a fake detector was inserted into the intersection region for the commisioning. This detector, called BEAST (BEam Exorcism for A STable experiment) consists of expendable and/or non-vulnerable subdetectors like proportional tubes, *some* silicon detectors, *some* CsI crystals, *part* of EFC, passive radiation dosimeters etc. The BEAST will be used both for background studies and for luminosity measurement till early March. We hope the complete detector to begin data taking in April 1999 and to provide us with a lot of interesting results later on.

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