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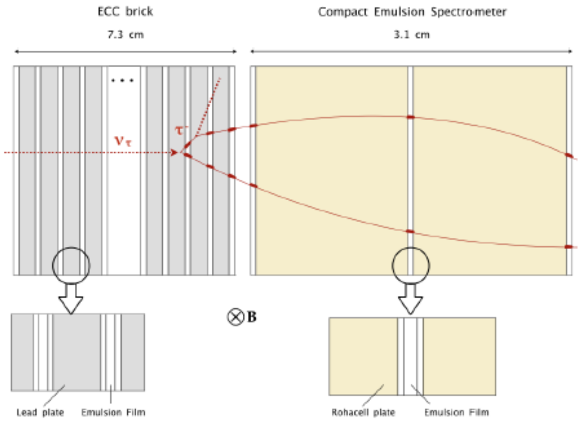


Compact Emulsion Spectrometer

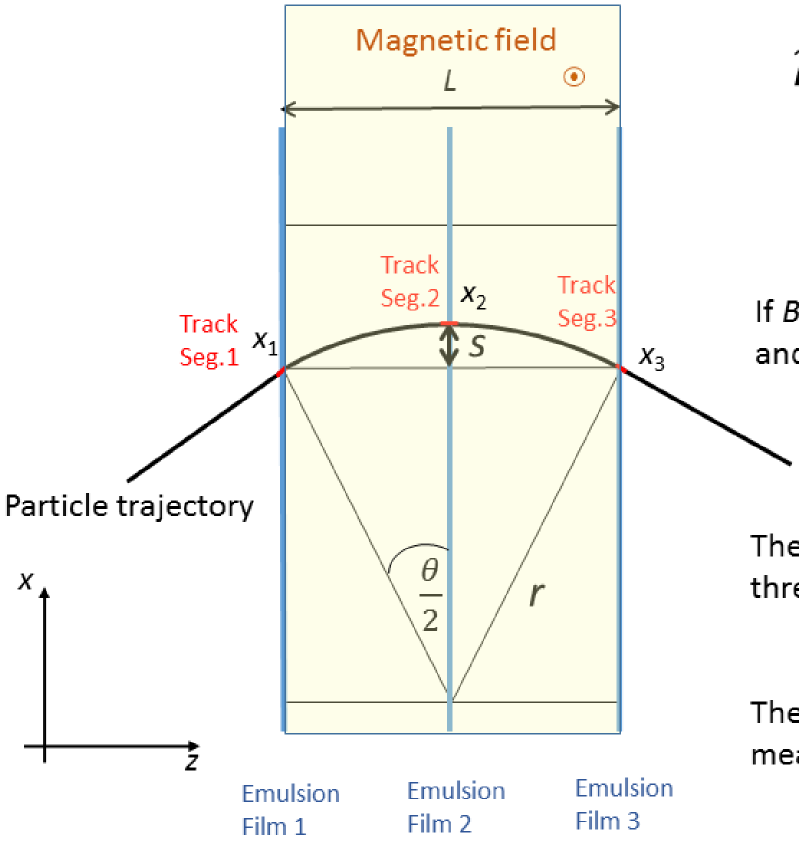
The Compact Emulsion Spectrometer (CES), placed in a magnetic field, is composed of emulsion films interleaved with low-density material plates,

or with a stable structure producing an empty space between two consecutive films. Our CES was originally designed to identify tau neutrino by measuring the sign of the electric charge of tau decay products.

Conceptual design
Detrimental effect of MS
Beam test of CES at KEK
Results of the beam test
Practical problems
Summary

October 3, 2016
H. Shibuya for Toho University Group

Conceptual design



Trajectory of a charged particle in a magnet

$$p = e\,B\,r = e\,B\cdot\frac{L}{\theta} \qquad \theta \ll 1$$

$$s = r\,(1-\cos\frac{\theta}{2}) = 2\,r\,\sin^2\frac{\theta}{4}$$

$$= \frac{r\,\theta^2}{8} = \frac{r}{8}\cdot\left(\frac{eBL}{p}\right)^2 = \frac{eBL^2}{8p} \qquad \theta \ll 1$$

If *B* is measured in Tesla, *L* in meters and *p* in GeV/*c*, the sagitta is given by

$$\boxed{s = \frac{0.3\,B\,L^2}{8p}}$$

The determination of sagitta requires at least three position measurements, x_1, x_2 and x_3.

$$s = x_2 - \frac{x_1+x_3}{2}$$

Therefore, the momentum resolution from track measurement errors is given by

$$\left.\frac{\sigma(p)}{p}\right|_{\mathrm{TR}} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\,\sigma(x)\cdot 8p}{0.3BL^2}$$

Track measurement error

If the track positions are precisely measured, momentum can be determined precisely.

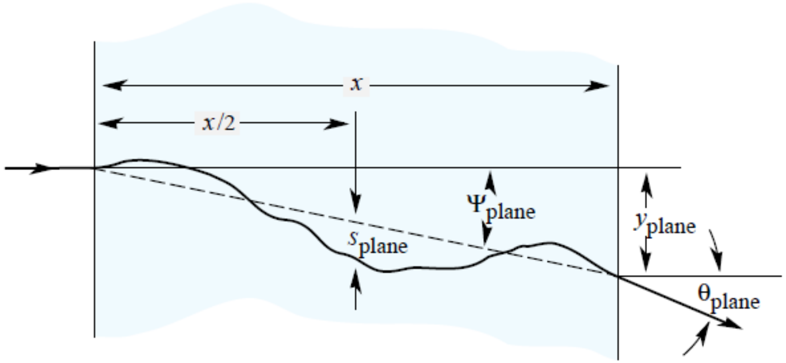
assuming that the track measurement errors $\sigma(x)$ are the same for all films.

Therefore if emulsion films are used as position detectors, an excellent magnetic spectrometer can be made.

The Lorentz force causes charged particles to follow circular or helical trajectory around the direction of the magnetic field.

Detrimental effect of Multiple Scattering

A charged particle traversing a medium is deflected by many small angle scatters.



$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\theta_{\text{space}}^{\text{rms}}$$

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]$$

$$s_{\text{plane}}^{\text{rms}} = \frac{1}{4\sqrt{3}}\, x\, \theta_{\text{plane}}^{\text{rms}} = \frac{1}{4\sqrt{3}}\, x\, \theta_0$$

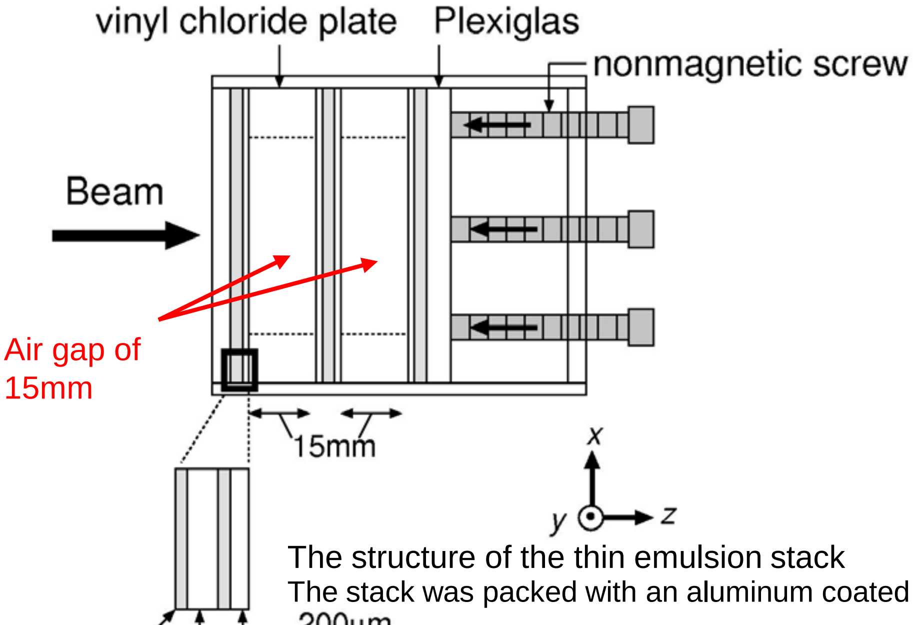
K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38** 09001 (2014) and 2015 updates.

$$\frac{\sigma(p)}{p}_{\text{MS}} = \frac{\sigma(s)}{s}_{\text{MS}} = \frac{\sigma(s)\cdot 8p}{0.3BL^2} = \frac{1}{4\sqrt{3}} L \frac{0.0136}{\beta c p}\sqrt{\frac{L}{X_0}}\frac{8p}{0.3BL^2} = \frac{2}{\sqrt{3}}\frac{0.0136}{\beta c}\frac{1}{0.3BL}\sqrt{\frac{L}{X_0}}$$

The momentum resolution limited by the effect of multiple scattering does not depend on the momentum of the particle.

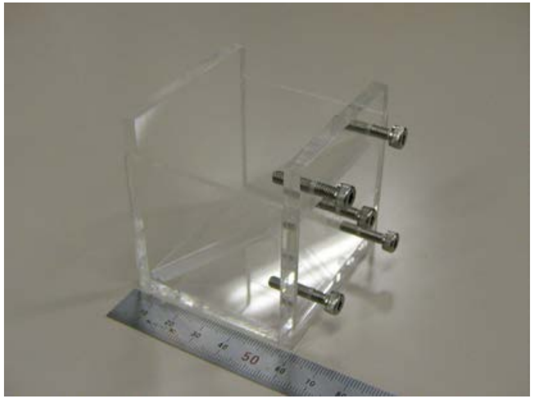
The less material the detector has, the better the resolution is.

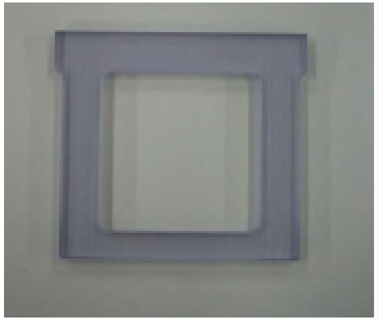
A prototype for a test beam experiment



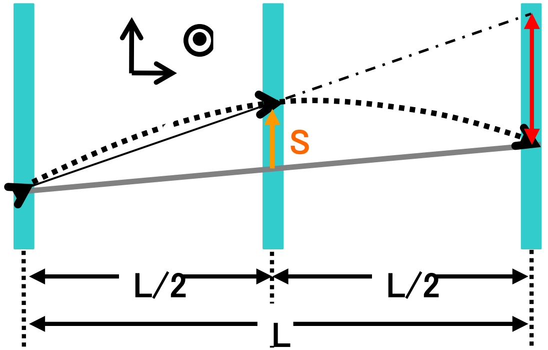
The structure of the thin emulsion stack

The stack was packed with an aluminum coated film by thermal welding.





The spacer is a vinyl chloride plate which has a hole of 40mm x 40mm at the center.



Momentum [GeV/c]	Sagitta [μm]	Spread [μm]
0.5	79.6	10.6
1.0	39.8	5.2
2.0	19.9	2.7

Expected performance of the CES placed in a magnetic field of 1.06 T.

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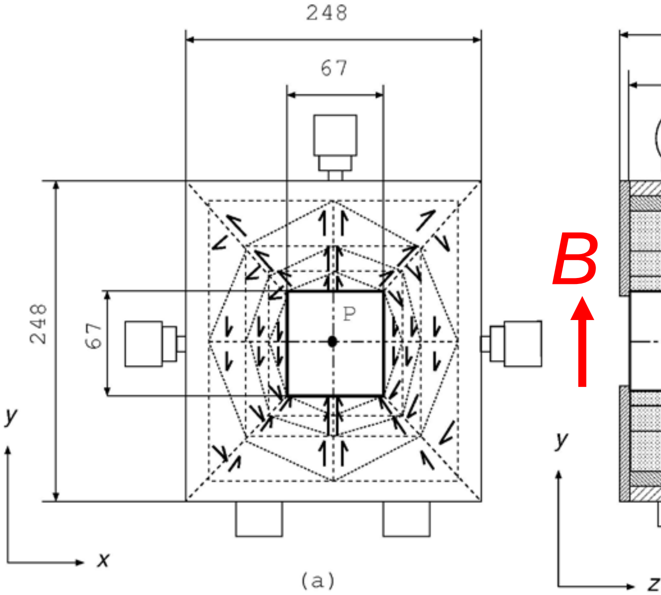
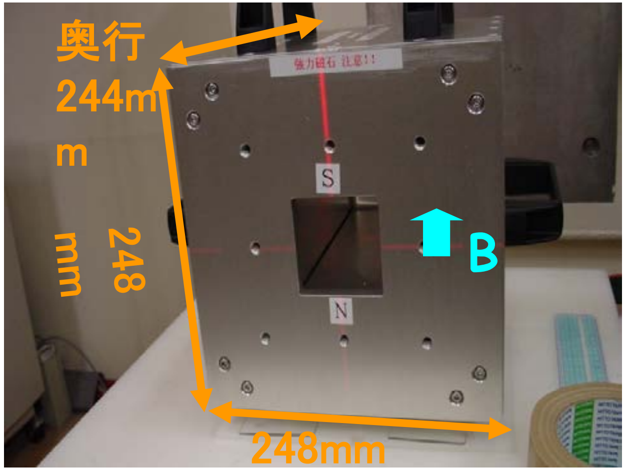
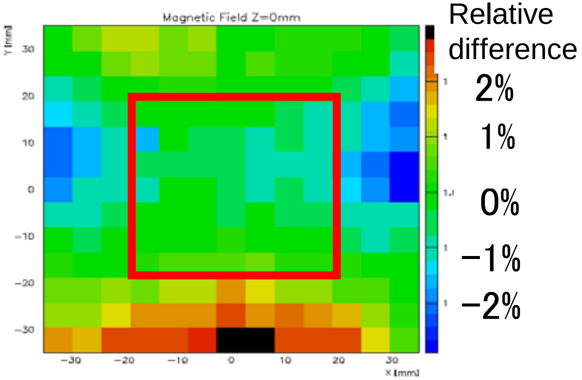
A compact permanent magnet used in the test experiment



Halbach-type magnetic circuit

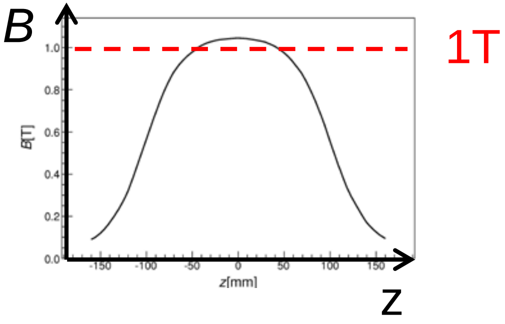


The inner gap size is 67 mm x 67 mm x 200 mm.



Magnetic field distribution (z=0)

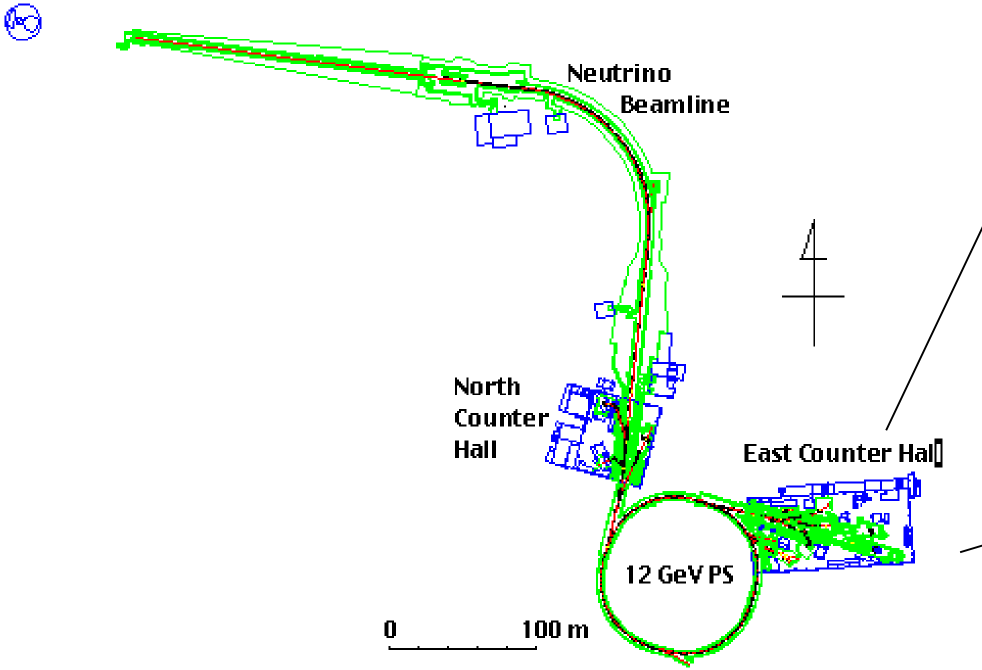
We adopted the three-layer configuration as the structure, and Nd–Fe–B sintered magnet (NEOMAX) with a residual field strength Br of 1.3 T as magnet material. It produces a dipole magnetic field of 1.06 T at the center.

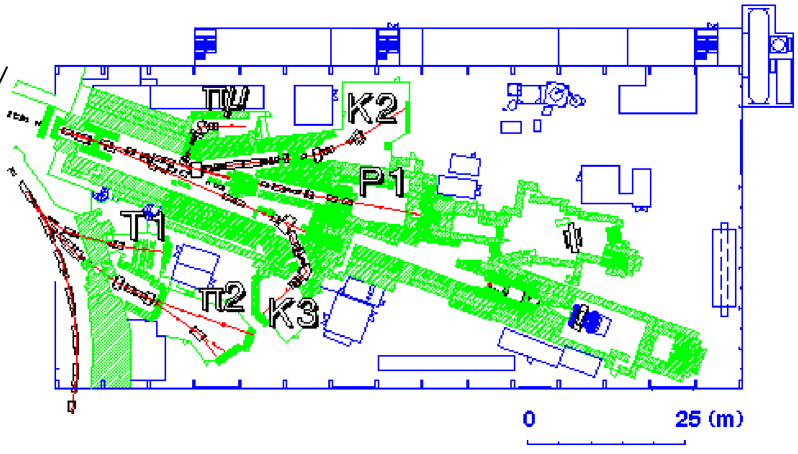


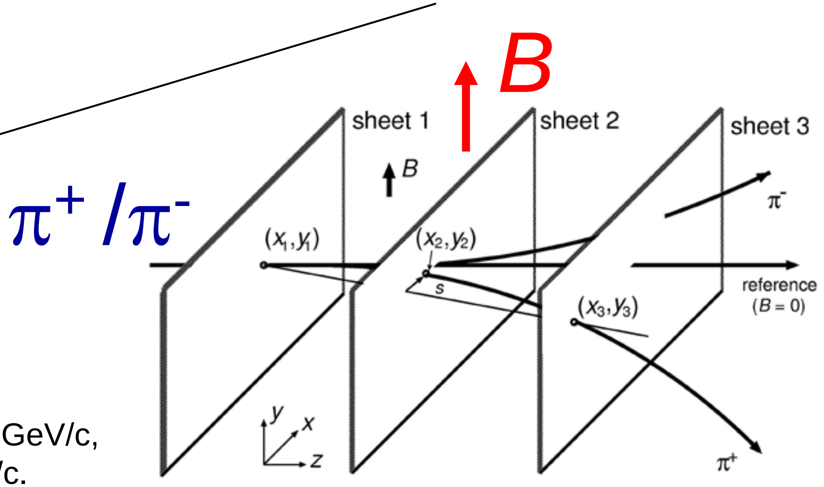
The deviations of the field strength were found to be less than 1%.

A beam test for CES was performed

The beam momentum was set for 0.5, 1.0 and 2.0 GeV/c
with the relative spread, $\Delta p/p$ of 5%.







Test Beam Experiment at KEKPS T1 beam

One stack was exposed to positive and negative beams of 0.5 and 2.0 GeV/c,
the other one was exposed to positive and negative beams of 1.0 GeV/c.
In addition, for the purpose of relative film alignment, each emulsion
stack was exposed to the 2.0 GeV/c positive beam without the permanent magnet.

Data Analysis

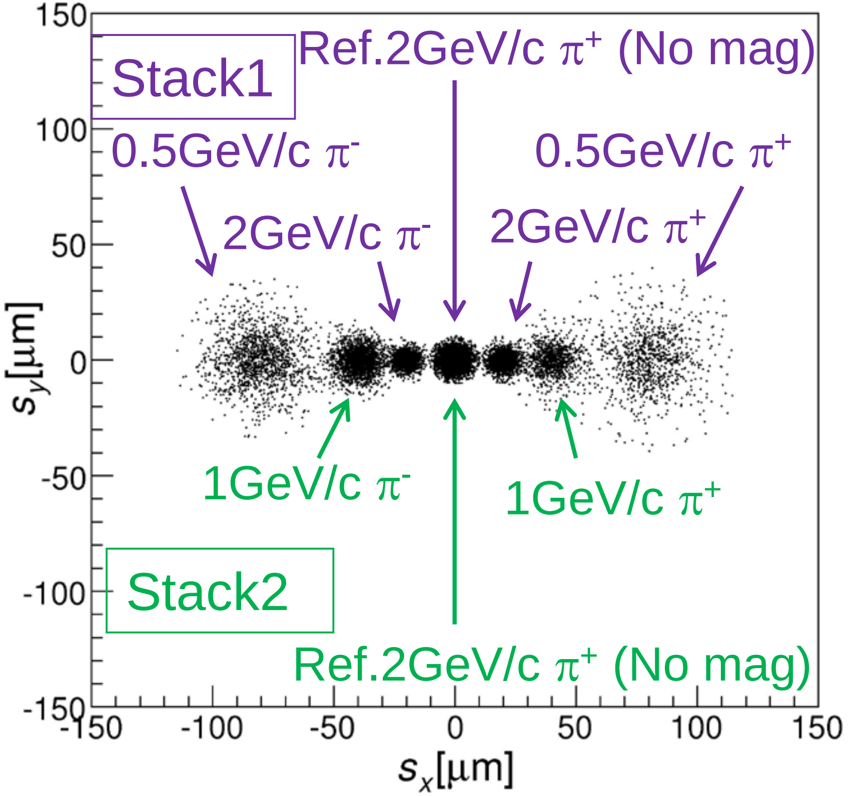
1. **A central area of 4 cm^2 was scanned** on both emulsion layers of each film.
2. **First the reference beam tracks were connected** from additional emulsion film to the upstream film and extrapolated to the second film. A connection was established if a base track was found within a wide tolerance of 3.5 σ from the predicted position. The same procedure was repeated from the second to the third film. **After the measurement of about 6000 reference beam tracks the three emulsion films were aligned with a precision of submicron over the scanned area.**

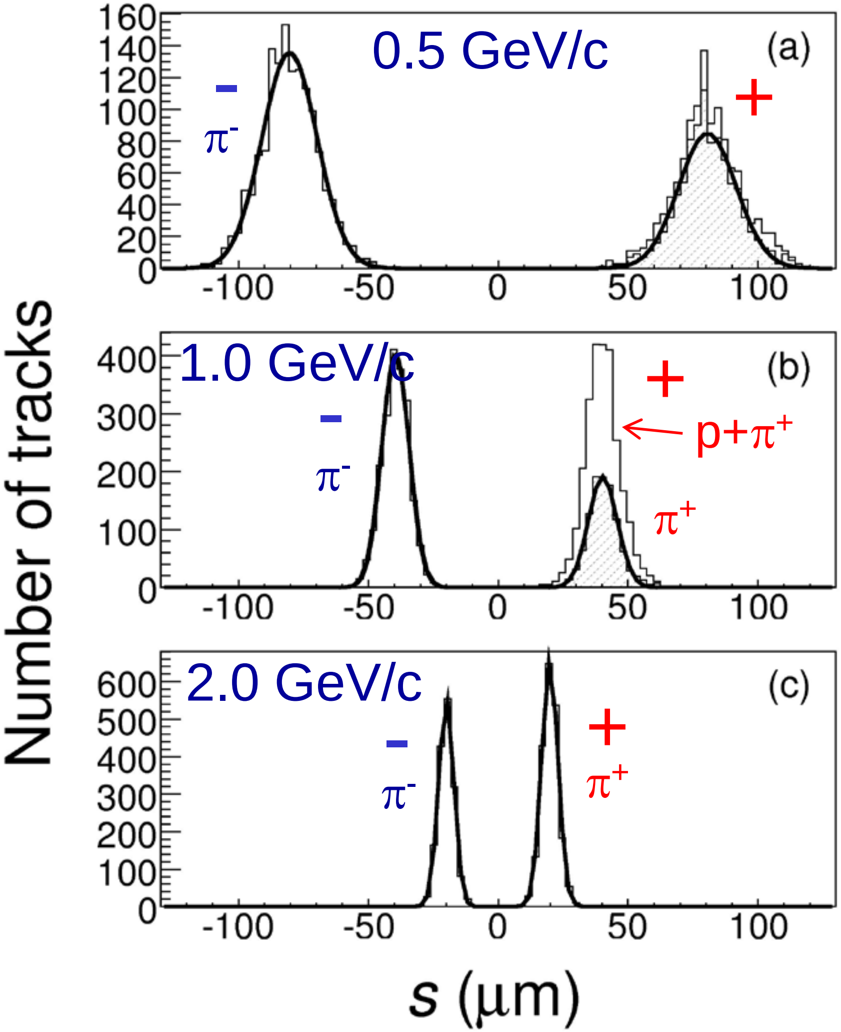
3. **Second**, **beam tracks exposed in the magnetic field were connected.** The connection was searched by successively shifting the x positions of base tracks in the second film with possible values of magnetic deflections. The same procedure was iterated between the second and third films. **A total of 10757 tracks were reconstructed along the whole stack and associated to well defined exposure.**

4. **The last step was to calculate the sagitta *s* of each reconstructed track in the second film.** **Then momentum of each track can be calculated.**

Results from the test beam experiment

2D sagitta values of 0.5, 1.0 and 2.0 GeV/c charged particles



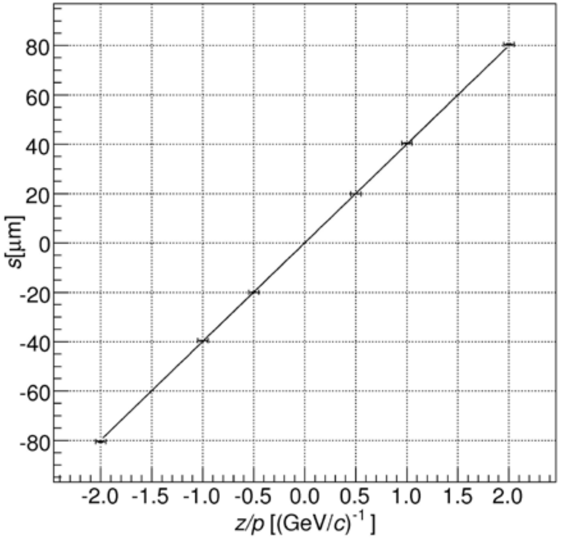


Results from the test beam experiment

Test Beam Experiment at KEK PS

p(GeV/c)	0.5		1.0		2.0	
particle	π^+	π^-	π^+	π^-	π^+	π^-
entries	912	1374	1044	2020	2016	1591
s[μm]	80.4	-80.4	40.2	-39.6	19.9	-20.1
σ_s[μm]	10.8	10.6	5.3	5.1	3.0	2.8
σ_s/s[%]	13.4	13.2	13.2	12.9	15.1	13.9
expected s[μm]	79.6	-79.6	39.8	-39.8	19.9	-19.9
RMS[μm]	10.6	10.6	5.2	5.2	2.7	2.7

Sagitta vs. momentum^{-1}



Beam momentum $^{-1}$

Results of Gaussian fit, mean and sigma values of sagitta distributions are summarized in the table. They agree well with the expected values.

C. Fukushima et al., Nucl. Instr. and Meth. A 592 (2008) 56-62.

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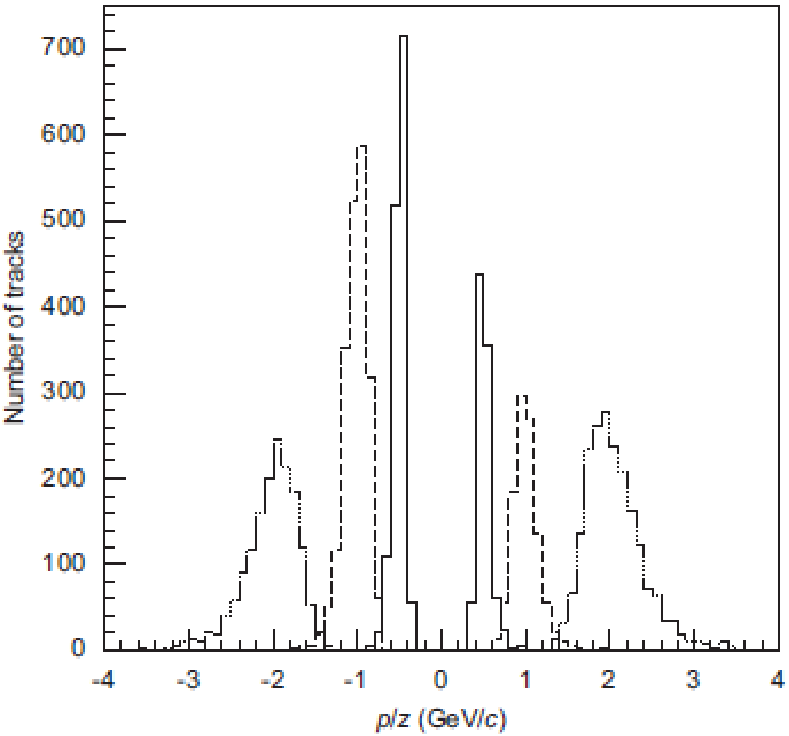
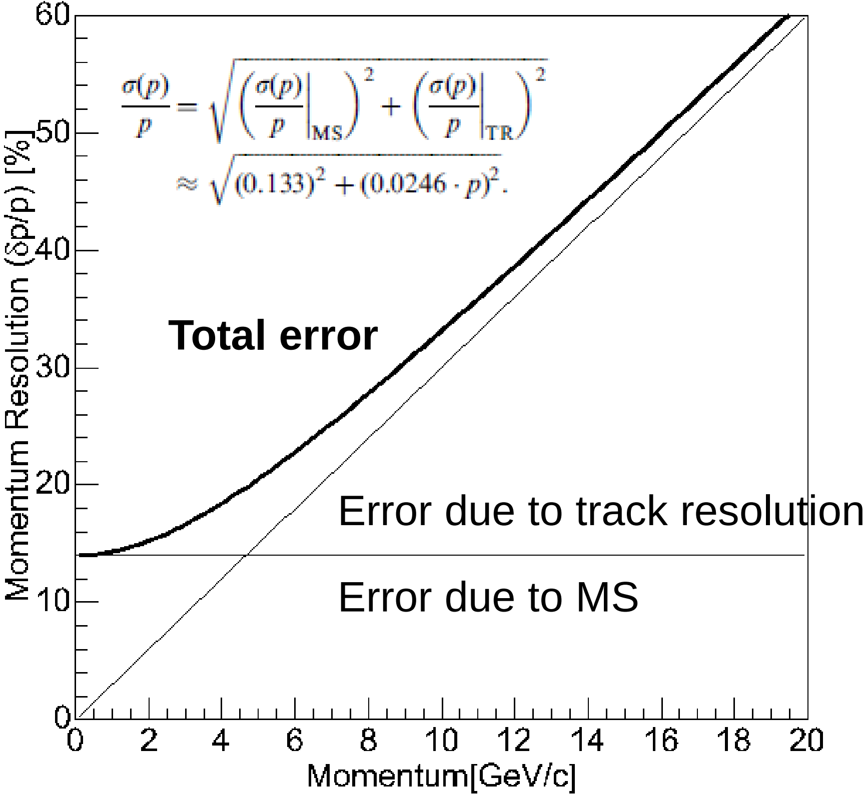
Results from the test beam experiment

Measured *p/z* distributions



Momentum resolution



$$\frac{\sigma(p)}{p} = \sqrt{\left(\left.\frac{\sigma(p)}{p}\right|_{\mathrm{MS}}\right)^2 + \left(\left.\frac{\sigma(p)}{p}\right|_{\mathrm{TR}}\right)^2} \approx \sqrt{(0.133)^2 + (0.0246 \cdot p)^2}.$$

The momentum resolution of the emulsion spectrometer depends on the errors due to multiple Coulomb scattering and due to the track resolution.

C. Fukushima et al., Nucl. Instr. and Meth. A 592 (2008) 56-62.

At low momenta multiple scattering dominates the error and at high momenta it is limited by the track measurement error.

Summary of the results and future prospects

This test beam experiment and its simulation clearly demonstrated that the CES has excellent intrinsic performance, where the accuracy of track position measurement is about 1 μm.

Advantage:
CES is a thin detector, which ensures wide acceptance for downstream detectors.
More precise measurement will be possible if it has a multi-layer structure.
Disadvantage:
Long scanning time after the beam exposure, which has been overcome by HTS (Nagoya)
Therefore, CES can be widely used in a variety of experiments.

However there are some practical problems which may deteriorate its intrinsic performance in each case.

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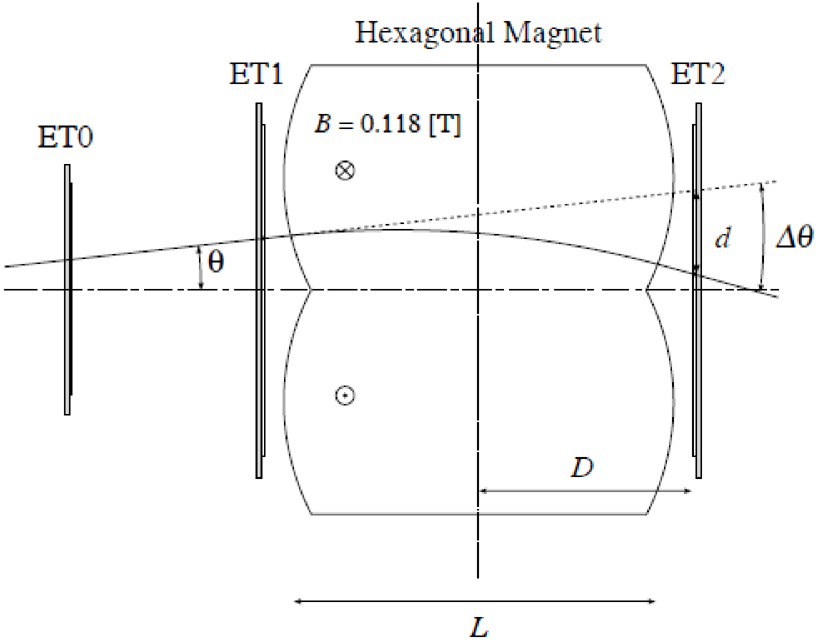
Practical problems

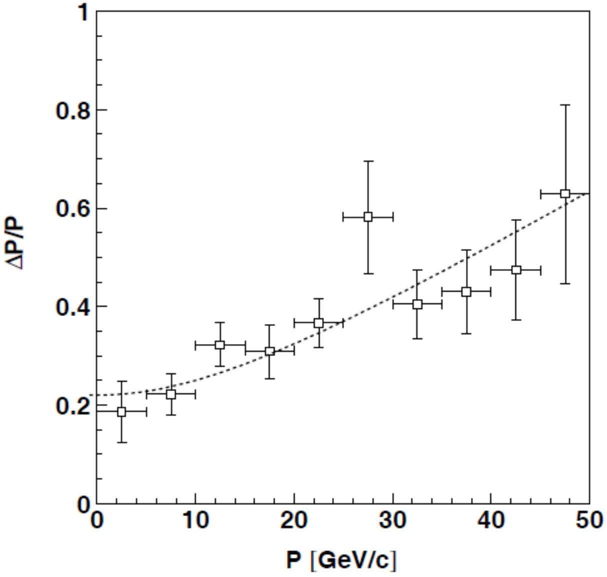
1) Construction of the CES

- Structure of the CES to ensure the flatness of emulsion films
- Choice of low density material, Rohacell, Airex,... Or air gap?
- an Emulsion-Tracker type package in CHORUS?

Each emulsion film is packed in vacuum and attached by vacuum to the thick honeycomb board.

(S. Aoki et al., NIM A 488 (2002) 144.)





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Practical problems

2) Deformations in emulsion films

- Temperature effect

  keep the CES films at a stable temperature!
- Distortion

  good development

  usage of a photomask to correct the deformation?

(M. Kimura et al., NIM A 711 (2013) 1.)

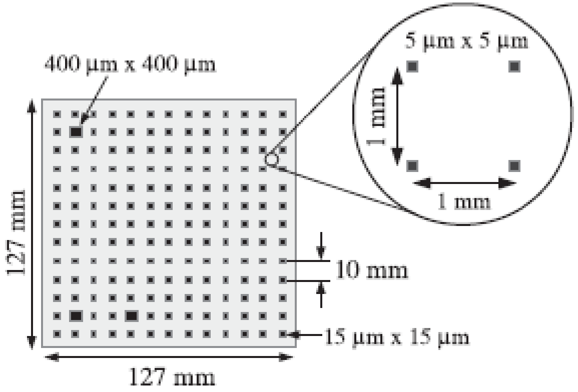

Fig. 1. Design pattern of grid mark on photomask. Grid marks of 5 µm square shape are located with spacing of 1 mm. These marks are for the correction of track position. 15 and 400 µm marks are guides to move the microscopic view center to 5 µm marks.

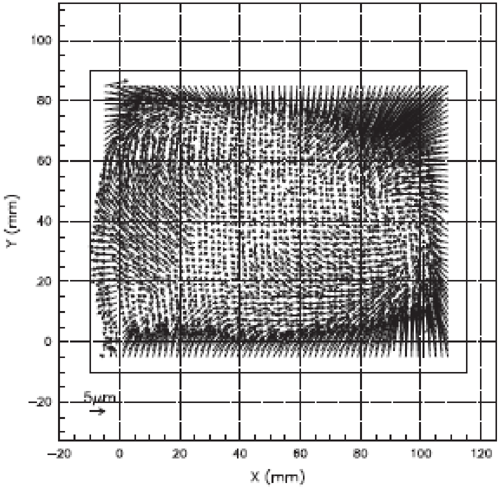

Fig. 5. OPERA film deformation reproduced from the grid mark measurements. Each vector shows the position displacement from the original coordinates of the grid mark. Maximum vector size is about 20 µm.

Practical problems

3) Good alignment between the emulsion films

- by using high energy beam tracks (muons?)
- how many beam tracks needed?

Practical problems

4) Connection and matching of the track among emulsion films

- low background tracks
- changeable CES?

Summary

- **The principle of the CES was clearly confirmed by a test beam experiment and also by simulations.**
- **Therefore, CES will be widely applicable in a variety of experiments.**
- **However there are some practical problems which may deteriorate its intrinsic performance.**
- 1) Construction of the CES
- 2) Deformation of emulsion films
-     - Temperature effect
-     - Distortion during the development
- 3) Good alignment between the emulsion films
- 4) Connection and matching of the track among background tracks
- **R&D and MC study are needed for each actual experiment.**

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