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LETTER OF INTEREST

Precision CP-Violation and Rare Decay Experiments in a High Intensity Neutral Kaon Beam at the SPS

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Evidence for direct CP violation was published[1)] by the NA31 collaboration using data collected in 1986 at the SPS. The measurement of $\varepsilon'/\varepsilon = (3.3 \pm 0.7 \pm 0.8) \times 10^{-3}$ was obtained by a comparison of the relative decay rates of short- and long-lived neutral kaons into two neutral and two charged pions:

$$\varepsilon'/\varepsilon = \frac{1}{6}\left\{1 - |\eta_{00}/\eta_{+-}|^2\right\} = \frac{1}{6}\left\{1 - \frac{K_L \to 2\pi^0}{K_L \to \pi^+\pi^-}\,\frac{K_S \to \pi^+\pi^-}{K_S \to 2\pi^0}\right\}$$

This interesting result is important for understanding the origin of CP violation and it is at the level actually predicted by the Standard Model for the mixing of three quark families. Although the theoretical uncertainty is greater than the experimental error, new information such as the observation of the top quark, and better understanding of the phenomenology will require substantial improvement on this measurement. In addition, the neutral kaon system is the only practicable way of investigating CP violation and will be for many years.

At present the dominant contribution to the experimental error arises from the number of CP violating $K_L \to 2\pi^0$ decays observed. At a branching ratio of 9×10^{-4}, 109,000 such decays were used for the NA31 result. In addition, there are several sources of significant systematic uncertainty. The dominant contributions come from three sources: A possible difference in the energy scales of reconstructed $2\pi^0$ and $\pi^+\pi^-$ events, the small amount of background in the CP violating $K_L \to 2\pi^0$ and $K_L \to \pi^+\pi^-$ channels (primarily from three body decays at a level of 4% and 0.7%, respectively) and the possible effect on the detection efficiency due to accidental activity in the detector.

The NA31 experiment is currently taking data with the aim of significantly improving the precision of the original result. This new measurement, however, is still based on the techniques conceived at the time of the proposal in 1981. In principle, the systematic problems are well understood, and the aim is to improve the resulting uncertainties as much as possible. However, it is clear that substantial progress can only be achieved by a complete redesign of the experiment.

In this respect we consider it essential for a new experiment to record all four two pion decay modes concurrently in the same detector and thus remove the problem of possible changes in the detection efficiency with time and running conditions. (The NA31 experiment takes data concurrently for decays into charged and neutral pions, but alternates daily between data taking at different times in K_S and K_L beams.) We have studied two beam designs in order to achieve this. Both use two nearly collinear K^0 beams, K_S and K_L, and tagging of the K_S component by the coincidence with the proton in the primary beam. The beams would coincide at the position of the detector, and would of course be produced simultaneously. High tagging efficiency would be important, and must be monitored. This is possible for example by a small separation of the beams in the decay region and adequate vertex reconstruction. It would allow the origin of charged pion decays to be identified and similarly for the Dalitz component of the neutral pion decays. Alternatively, $K_S \rightarrow 2\pi^0$ and $K_L \rightarrow 2\pi^0$ may be distinguished by reconstruction of the K^0 direction if the two beams are separated by a sufficiently large angle (at least one degree), as in the case of the second design.

The design of the new experiment must have at least a tenfold increase in intensity. This implies a major upgrade of the apparatus. A magnetic spectrometer is needed for background rejection in the charged pion mode, and a fast photon detector with resolution as good as, or even better than, the existing NA31 liquid argon calorimeter detector. In addition, with adequate beam intensity it will also be possible to search for, and eventually measure, rare kaon decays such as $K_L \rightarrow \pi^0 e^+ e^-$ [2-3]. This decay is particularly interesting as direct CP violation could dominate, since first and second order CP conserving contributions are suppressed at the level of $\sim 10^{-12}$ in branching ratio. In the following we focus, however, on a feasibility study and conceptual design of a K_S/K_L beam and $2\pi^0/\pi^+\pi^-$ detector arrangement suitable for a precision measurement of ε'/ε as outlined above.

Two schemes are considered which allow the two decay modes from K_L and K_S beams to be recorded simultaneously:

1. Double K_L and K_S beams

In this scheme two separate beam lines converge to a common point at the detector, as shown schematically in Fig.1. A K_S beam train capable of longitudinal displacement along one of the lines is arranged so as not to interfere with the $K_L \rightarrow \pi\pi$ acceptance from the fiducial region of the adjacent K_L beam. This condition, together with the aim of distinguishing the two beam directions in the detector, requires an opening angle between the two beams of about one degree.

Two branches derived from the split of a primary proton beam are required to produce the two beams simultaneously. In one branch, protons at high intensity (~10^{12} ppp) are targeted to produce the K_L beam, while in the other, the protons are attenuated to a lower intensity (~10^8 ppp) and are transported further towards the detector onto a target mounted on the K_S beam train.

The functions of the K_S and K_L beams must be reversed from time to time to reduce the effect of any asymmetry in the detectors. Thus, both branches have to be equipped with a K_L target station and a K_S beam train in vacuum.

The principal advantage of this scheme is that, as in the NA31 experiment, K_L decays can be collected over a fiducial length of ~40 m, thereby gaining a possible factor of three in statistics compared to the second scheme discussed below. K_S decays are simultaneously observed from a region of ~2 K_S lifetimes (~10 m in length) in the adjacent beam, corresponding to the position of the train. A displacement of the train enables the K_S data to be taken over the same fiducial length as the K_L data and with suitable running conditions provides a decay vertex distribution similar to that of the K_L. However, not all the K_L decays originate from the same fiducial region as the K_S taken at the same time, and thus accidental effects and changes of detection efficiency may not exactly cancel.

2. Combined K_L and K_S beams

In this scheme the K_S and K_L beams are arranged to be as nearly collinear as possible (i.e. converging at an angle comparable to their angular acceptances). A finite separation of the K_S target with respect to the K_L beam line is required to permit different collimator apertures (radius ~2 mm and ~30 mm, respectively) for the two beams, with a minimum of shielding between them. However, the K_S and K_L beams and their resulting decay products are effectively superposed throughout the region of the detectors, thus eliminating any possible difference in the effect of accidental hits.

This is shown schematically in Fig. 2, with one primary proton beam (at an intensity of ~10^{12} ppp) targeted to produce the K_L beam at a small angle (~2.5 mrad). The remaining protons (and other charged particles) emerging from the target are deviated away from the K_L beam line by means of a sweeping magnet. A bent, single crystal is appropriately arranged[4-5] to channel and deflect a small fraction of the protons (~5 x 10^7 ppp) back towards the K_L line, whilst all other charged particles are absorbed in a beam dump/collimator assembly. The resulting beam of protons thus defined passes through a tagging counter and is then bent magnetically back onto the K_L line, where it is transported, refocussed and finally deflected by an angle of ~ 5 mrad onto the K_S target located ~60 mm below the K_L beam axis. From this target the K_S beam is defined by collimation over a length of ~6 m so as to converge towards the detector at an angle of 0.5 mrad to the K_L beam. K_L and K_S decays are observed simultaneously from the closely adjacent fiducial regions of the two beams emerging from the final collimator over an effective length of ~2 K_S lifetimes chosen such that the number of K_S is everywhere larger than the number of K_L decays in any channel. In this scheme, the K_S beam is not moved, but is located in the optimum longitudinal position with respect to the detector acceptance.

Possible parameters and counting rates for such a scheme of simultaneous, nearly collinear K_S and K_L beams are given in Table I. These beams are compatible with a new experiment to measure ε'/ε with both statistical and systematic uncertainties of ~2 x 10^{-4}.

3. K^0 beam to search for rare decays

The beam layout described above can be adapted, without major modification, to an experiment to search for rare K^0 decays such as $K_L \rightarrow \pi^0 e^+ e^-$. For this we imagine the K_L beam run on its own (i.e. without the K_S), and derived from ~10^{13} incident primary protons per pulse. Possible characteristics of such a beam are also given in Table I. The three-stage collimation adopted to protect the final collimator from a direct view of the defining collimator may be relaxed to increase the solid angle of the beam. A fiducial length for decays of ~60 m for K^0 momenta >50 GeV/c may be used. Under these conditions, and taking a detector acceptance similar to that for $\pi^0\pi^0$ decays, the experiment appears realistic with a branching ratio sensitivity of ~10^{-8} per hour, or 10^{-11} in a full year of running.

4. Detector

A high acceptance detector such as the present NA31 apparatus[6)] is required for high statistics operation. The geometrical acceptance for $K^0 \rightarrow 2\pi^0$ decays may be improved to ~30% at 100 GeV, and 20% after kinematic cuts. The lateral dimension of the detector will need to be approximately 2.5 to 3 m in diameter.

In principle the NA31 liquid argon calorimeter with energy and position resolutions of $7.5\%/\sqrt{E}$ and 0.5 mm respectively, has the required performance. It is however limited in speed and could not correctly operate in a MHz particle flux. Various ways are being considered to reduce the charge collection time by an order of magnitude. Alternatively a new type of electromagnetic calorimeter, such as barium fluoride, could be used.

A significant improvement in background rejection for $K_L \rightarrow 2\pi^0$ decays requires an elaborate anticounter system to veto $K_L \rightarrow 3\pi^0$ decays with unidentified photons. Reduced background to $K_L \rightarrow \pi^+\pi^-$ decays requires a significant improvement in mass resolution, best achieved with a magnetic spectrometer. The factor two advantage in branching ratio compared to $2\pi^0$ decays compensates for any loss in acceptance . A mass resolution of 4 MeV can be achieved with four sets of drift-chambers of 100 μm position resolution and a transverse momentum kick of 200 MeV/c by the magnet, to be compared to 20 MeV mass resolution obtained by calorimetry with the present NA31 apparatus. The layout of such a detector is sketched in Fig. 3. A solution based entirely on calorimetry, with hadron energy resolution improved by a factor of two, is a possible alternative.

A significant limitation of the NA31 experiment is its data taking capability, which leads to an undesirable trigger bias on good events in order to reduce rates. We are confident that a factor ten in rate is manageable with state of the art technology if we assume that a trigger processor to reconstruct decay vertex, momentum and mass for $\pi^+\pi^-$ decays can be designed to reject online a large fraction of the three-body background. Extrapolating from actual NA31 rates, statistics of 1 million $K_L \rightarrow 2\pi^0$ decays per year of SPS fixed target operation can be expected.

5. Location

The beams described in Sections 1 to 3 are derived from primary protons, targeted and dumped at intensities $\geq 10^{12}$ per pulse. The resulting hadron and muon fluxes are such that it becomes impractical to shield neighbouring experiments and the site perimeter sufficiently in an open experimental area, whilst providing maximum absorption and magnetic sweeping in the direction of the detector. We therefore consider a dedicated, underground area sufficiently large to house the neutral beam and detector. The only such area at the SPS is the North Area High Intensity Facility7), shown in Fig. 4, where an enlarged target and beam tunnel of length 170 m is followed by an experimental cave, 100 m long, 16 m wide and 8 m high.

At present two beam lines are installed in this area: P01 -> H10, used as a primary proton and heavy ion beam transport to experiment NA38, and the disused P02 -> E12 beam which served the photo-production experiment NA14. These two lines are designed to receive protons alternately, so that only one of the two experiments can run at a given time. The double K^0 beam scheme would, however, depend on introducing a beam split well upstream and would from there on occupy the full width of the tunnel, to the exclusion of maintaining any other experiment (NA38) in the area.

For the combined, nearly collinear beams derived from a single proton beam branch, the P02 -> E12 line appears suitable (Fig. 4). It is possible to avoid major interference with NA38, which would remain free to receive heavy-ion beams, but would be in competition for proton running time.

References

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Figure captions

Fig. 1 Schematic layout of double K_S and K_L beams (plan view).

Fig. 2 Schematic layout of combined K_S and K_L beams (vertical section).

Fig. 3 Schematic layout of detector section (side view).

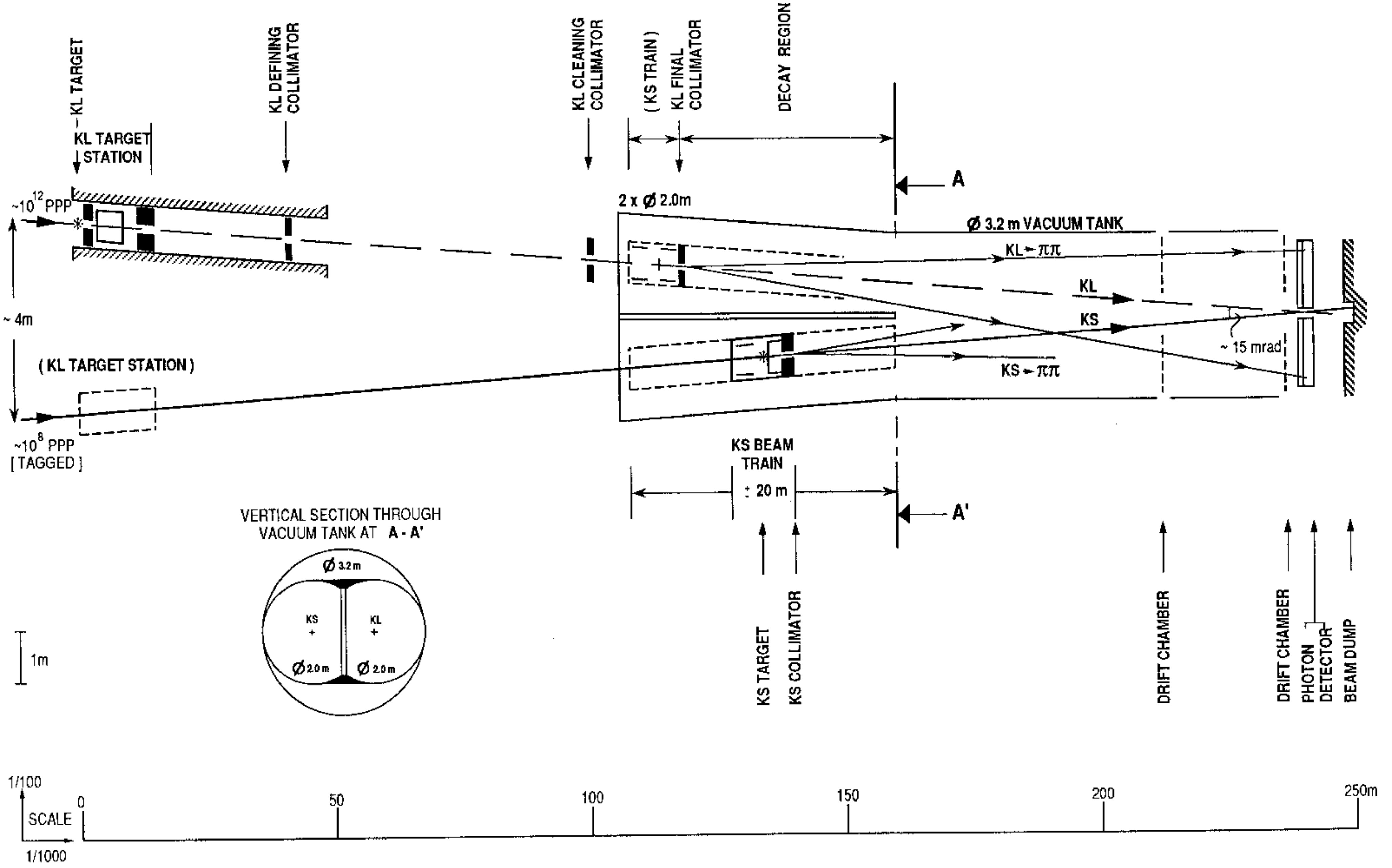
Fig. 4 Plan view of North Area High Intensity Facility indicating a possible location for a future K^0 beam and experiment.

Table 1: Characteristics of a possible combined K^0 beam

	Combined beams			High flux beam
	K_S		K_L	K_L
Protons per pulse on target	5×10^7		1×10^{12}	1×10^{13}
Spill ~2.5 s, cycle time 14.4 s				
Momentum p_0 (GeV/c)	450		450	450
Production angle (mrad)	5.0		2.5	2.5
Length of beam from target				
to last collimator (m)	6.0		126	126
to photon detector (m)	120		240	240
Angle of convergence to K_L beam (mrad)	0.5		–	–
Angular acceptance of K^0 beam (mrad)	± 0.33		± 0.17	± 0.2
Radius of beam at detector (mm)	40 ± 20		40 ± 5	48 ± 5
Radius of beam passage (mm)	84			84
K^0 momentum range accepted p (GeV/c)	$70 < p < 170$			$p > 50$
Fiducial length for decays (m)	$2\tau(K_S) \approx 10.8$			~60
at mean momentum p (GeV/c)	~100			
Total K^0 per pulse at exit last collimator	$\sim 3 \times 10^2$		$\sim 1.8 \times 10^7$	$\sim 2.4 \times 10^8$
Total K^0 per pulse of accepted p	2.2×10^2		6.4×10^6	1.6×10^8
K^0 decaying in fiducial length	1.9×10^2		2.2×10^4	3.0×10^6
$K^0 \rightarrow \pi^0\pi^0$ decays in fiducial length	60		20	
Detector acceptance for decays	0.2			0.2
Useful decays per pulse $K^0 \rightarrow \pi^0\pi^0$:	12	+	4	All: 6×10^5
" " per hour $K^0 \rightarrow \pi^0\pi^0$:	3.0×10^3	+	1.0×10^3	" 1.5×10^8
" " per year $K^0 \rightarrow \pi^0\pi^0$:	3.6×10^6	+	1.2×10^6	" 1.8×10^{11}
Counting rates (Hz):				
Incident protons on target	2×10^7 (tagged)		4×10^{11}	4×10^{12}
K^0 decays into detector	$\sim 2 \times 10^2$	+	$\sim 3 \times 10^5$	$\sim 4 \times 10^6$
μ's through detector	$\sim 1 \times 10^4$	+	$\sim 2 \times 10^5$	$\sim 2 \times 10^6$
Total rate in detector	$\sim 2 \times 10^5$	+	$\sim 1 \times 10^6$	$\sim 1 \times 10^7$

N.B. Flux estimates per pulse have been adjusted to those actually recorded by NA31 in the K4 beam under 1988 conditions. One year here corresponds to 100 days SPS operation with overall efficiency 0.5.

Fig. 1


KL TARGET
KL TARGET STATION
KL DEFINING COLLIMATOR
KL CLEANING COLLIMATOR
(KS TRAIN)
KL FINAL COLLIMATOR
DECAY REGION
A
2 x Ø 2.0m
Ø 3.2 m VACUUM TANK
~10^12 PPP
~ 4m
(KL TARGET STATION)
~10^8 PPP
[TAGGED]
KL → ππ
KL
KS
KS → ππ
~ 15 mrad
KS BEAM TRAIN
± 20 m
A'
VERTICAL SECTION THROUGH VACUUM TANK AT A - A'
Ø 3.2 m
KS
KL
Ø 2.0 m
Ø 2.0 m
1m
KS TARGET
KS COLLIMATOR
DRIFT CHAMBER
DRIFT CHAMBER
PHOTON DETECTOR
BEAM DUMP
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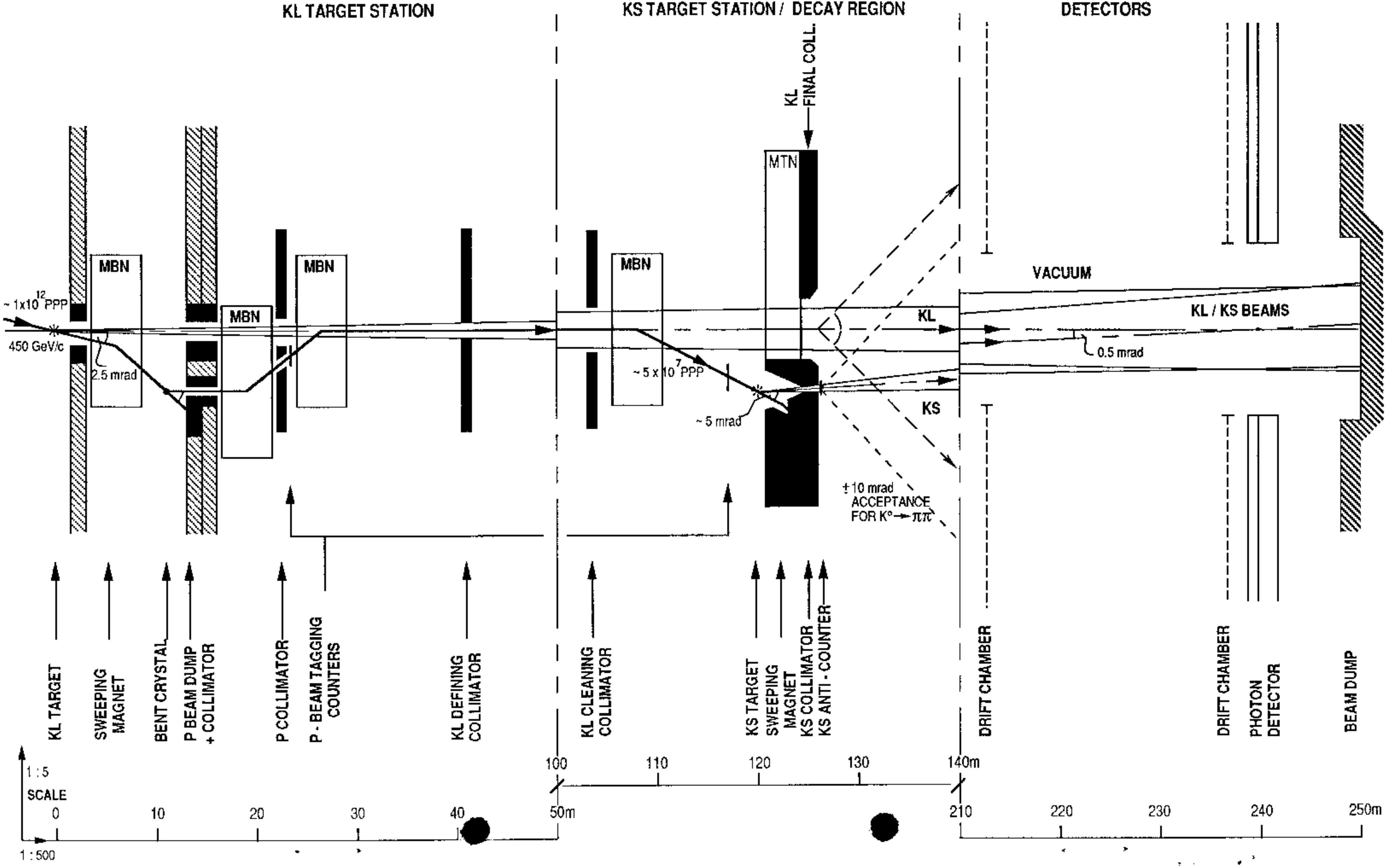
SCALE
1/1000
0
50
100
150
200
250m

Fig. 2



KL TARGET STATION
KS TARGET STATION / DECAY REGION
DETECTORS
~ 1x10^12 PPP
450 GeV/c
2.5 mrad
MBN
MBN
MBN
MBN
MTN
KL FINAL COLL.
~ 5 x 10^7 PPP
~ 5 mrad
KL
KS
±10 mrad ACCEPTANCE FOR K° → ππ
VACUUM
KL / KS BEAMS
0.5 mrad
KL TARGET
SWEEPING MAGNET
BENT CRYSTAL
P BEAM DUMP + COLLIMATOR
P COLLIMATOR
P - BEAM TAGGING COUNTERS
KL DEFINING COLLIMATOR
KL CLEANING COLLIMATOR
KS TARGET
SWEEPING MAGNET
KS COLLIMATOR
KS ANTI - COUNTER
DRIFT CHAMBER
DRIFT CHAMBER
PHOTON DETECTOR
BEAM DUMP
1 : 5
SCALE
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240
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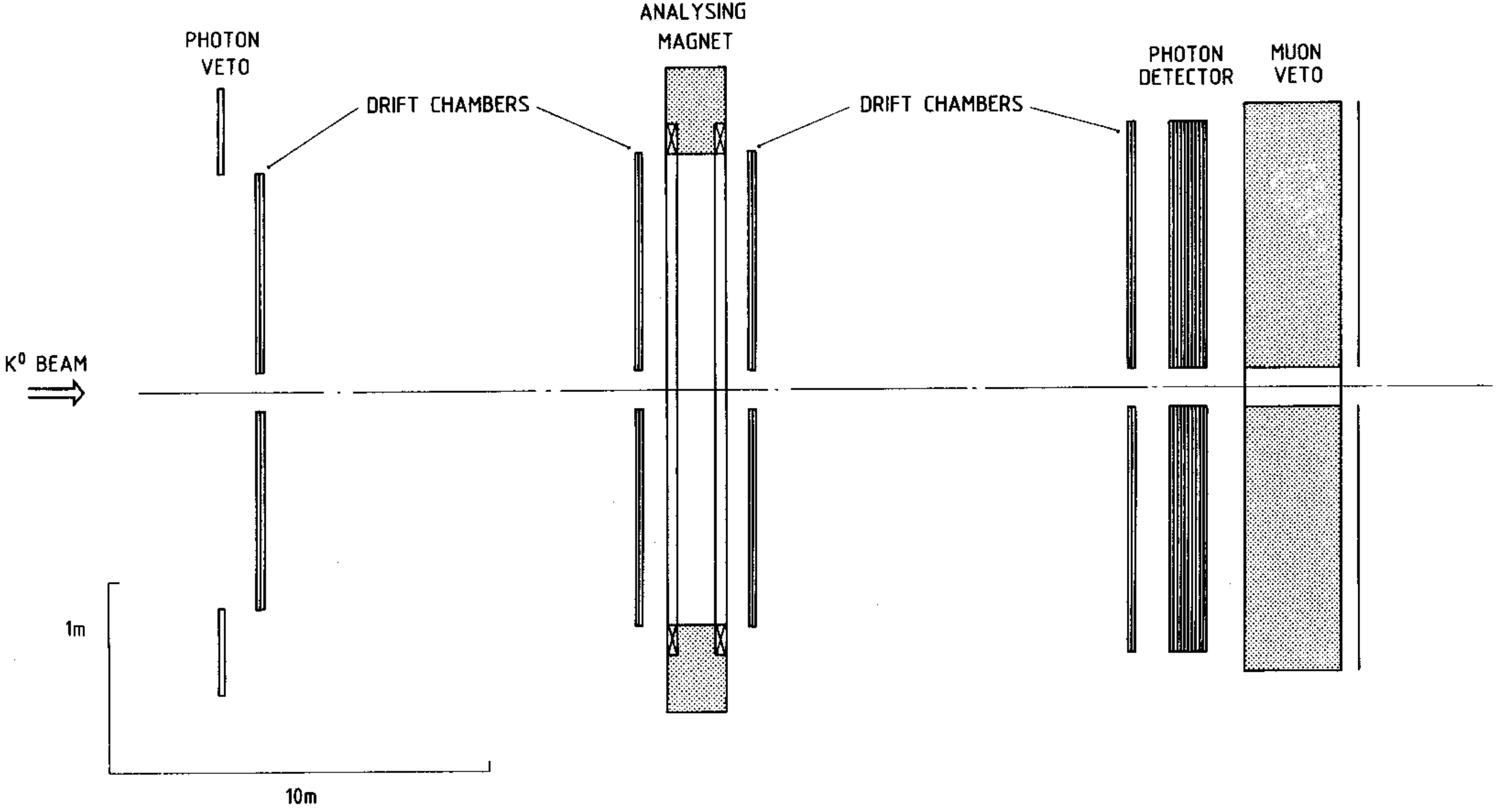
Fig. 3


PHOTON VETO
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ANALYSING MAGNET
DRIFT CHAMBERS
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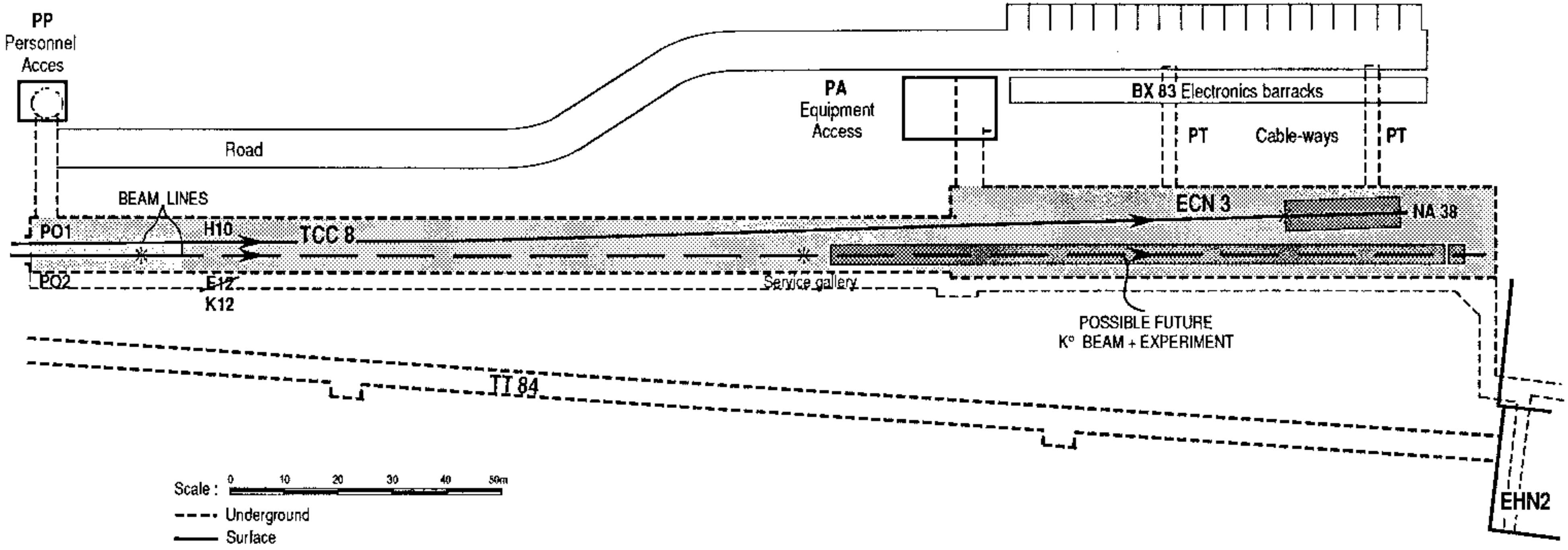
MUON VETO
K⁰ BEAM
1m
10m

Fig.4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H10
TCC 8
PO2
E12
K12
Service gallery
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K° BEAM + EXPERIMENT
TT 84
EHN2
Scale : 0 10 20 30 40 50m
Underground
Surface