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Eds. L. Maiani, G. Pancheri, N. Paver

Status of the FINUDA Experiment

M. Agnello[a], P. Amaudruz[l], G. Beer[l], L. Benussi[b], M. Bertani[b], S. Bianco[b], E. Botta[c], T. Bressani[c], L. Busso[d], D. Calvo[c], P. Camerini[e], C. Cattaneo[f], L. Celano[g], N. Colonna[g], M. Corradini[h], G. D'Erasmo[g], A. Donzella[h], F.L. Fabbri[b], A. Feliciello[c], A. Filippi[i], V. Filippini[f], E.M. Fiore[g], L. Fiore[g], P. Gianotti[b], M. Giardoni[b], D.R. Gill[l], N. Grion[e], C. Guaraldo[b], F. Iazzi[a], A. Lanaro[b], L. Lee[l], E. Lodi Rizzini[h], V. Lucherini[b], S. Marcello[c], G. Marciano[f], G.M. Marshall[l], B. Minetti[a], N. Mirfakhrai[n], P. Montagna[f], O. Morra[d], A.A. Nozdrin[l], A. Olin[l], A. Pantaleo[g], V. Paticchio[g], E. Rossetto[c], A. Rotondi[f], R. Rui[e], P. Salvini[f], S. Sarwar[b], A. Sharma[c], G. Smith[l], L. Venturelli[h], S. Yen[l] and A. Zenoni[m]

[a] *Dipartimento di Fisica del Politecnico di Torino and INFN, Sez. di Torino, I-10125 Torino, Italy*
[b] *INFN, Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*
[c] *Dipartimento di Fisica Sperimentale, Univ. di Torino and INFN, Sez. di Torino, I-10125 Torino, Italy*
[d] *Istituto di Fisica Generale, Univ. di Torino and INFN, Sez. di Torino, I-10125 Torino, Italy*
[e] *Dipartimento di Fisica, Univ. di Trieste and INFN, Sez. di Trieste, I-34127 Trieste, Italy*
[f] *Dipartimento di Fisica Nucleare e Teorica, Univ. di Pavia and INFN, Sez. di Pavia, I-27100 Pavia, Italy*
[g] *Dipartimento di Fisica, Univ. di Bari and INFN, Sez. di Bari, I-70126 Bari, Italy*
[h] *Dipartimento di Elettronica per l'Automazione, Univ. di Brescia and INFN, Sez. di Torino, I-25060 Brescia, Italy*
[i] *Dipartimento di Fisica Nucleare e Teorica, Univ. di Pavia and INFN, Sez. di Torino, I-27100 Pavia, Italy*
[l] *TRIUMF, 4004 Wesbrok Mall, Vancouver, BC, V6T 2A3, Canada*
[m] *Dipartimento di Elettronica per l'Automazione, Univ. di Brescia and INFN, Sez. di Pavia, I-25060 Brescia, Italy*
[n] *Shahid Beheshty Univ. Dept of Phys, 19834 Tehran, Iran*
[o] *INFN, Sez. di Torino - Laboratorio Tecnologico, I-10125 Torino, Italy*

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Abstract

The FINUDA experiment at the DAΦNE ϕ-factory is described with emphases on detector performances. A status report on readiness and installation is given.

1 Introduction

The DAΦNE collider proposed in 1990 [1] is now being built at the Laboratori Nazionali di Frascati of INFN. DAΦNE will run in 1997 at the center of mass energy of the ϕ meson with an initial luminosity of $\mathcal{L} = 1 \times 10^{32} cm^{-2} s^{-1}$, and a final target luminosity one order of magnitude larger.

The $\phi(1020)$ meson is produced in e^+e^- collisions with a peak cross section

$$\sigma(e^+e^- \to \phi) \sim 5\mu b$$

which translates in a production rate of

$$R_\phi = (5 \times 10^2 \to 5 \times 10^3) s^{-1}$$

from initial to target luminosity, with a 30:1 S/N ratio over the hadronic production.

The ϕ then decays [2] at rest in K^+K^- (49%), $K^0_S K^0_L$ (34%), $\rho\pi$ (13%), $\pi^+\pi^-\pi^0$ (2.5%) and $\eta\gamma$ (1.3%). Therefore a ϕ-factory is a unique source of monochromatic (110 and 127 MeV/c respectively), collinear, quantum-defined and tagged neutral and charged kaons. Detecting one K out of the two produced in the ϕ decay determines existence and direction of the other ("tagging").

An overview of the FINUDA detector is given, as well as of its physics issues, a status report, and construction schedule.

2 The FINUDA Experiment

Nuclear physics topics will be investigated by the FINUDA (standing for *FIsica NUcleare a DAΦne*) experiment[2]. A nuclear physics experiment carried out at a e^+e^- collider sounds contradictory itself, and indeed here the uniqueness of the idea stands [4]: charged kaons from ϕ decays are used as a monochromatic, slow (127 MeV/c), tagged, background-free, high-counting rate beam on a thin target surrounding the beam pipe. The possibility of stopping low-momentum monochromatic K^- with a thin (typically $0.5\, g\, cm^{-2}$ of ^{12}C) is unique of DAΦNE : K^-'s can be stopped with minimal straggling very near the target surface, so that outgoing prompt pions do not cross any significant amount of target and do not undergo any momentum degradation. This feature provides unprecedented momentum resolution as long as very transparent detectors are employed before and after the target.

The FINUDA detector is optimized to perform high-resolution studies of hypernuclei production[5] and non-mesonic decays[6] using a spectrometer with the large acceptance

[2] FINUDA is on Internet `http://www.lnf.infn.it/finuda/finuda.html`

typical of collider experiments. Furthermore, differently from fixed target experiments, the direction of the K^- is competely tagged by the detection of the K^+ and viceversa.

Negative kaons stopping inside the target produce a Y-hypernucleus ($Y = \Lambda, \Sigma, ...$) via the process

$$K^-_{stop} + \ ^AZ \rightarrow \ ^A_YZ + \pi^-$$

where the momentum of the outgoing π^- is directly related to the level of the hypernucleus formed (two body reaction). In case of Λ hypernuclei formation, the following weak interaction 'decays' are strongly favoured in medium heavy nuclei

$$\Lambda + n \rightarrow n + n$$

$$\Lambda + p \rightarrow n + p$$

with the nucleus undergoing the reactions

$$^A_\Lambda Z \rightarrow \ ^{(A-2)}Z + n + n$$

$$^A_\Lambda Z \rightarrow \ ^{(A-2)}(Z-1) + n + p$$

of interest in studying the validity of the $\Delta I = 1/2$ rule[6].

Prompt pions and decay products are all detected with the same large acceptance spectrometer featuring state-of-the-art tracking, particle identification and neutron detection, good triggering capability.

Interesting similarities there exist in expected rates between FINUDA and the proposed facility at the BNL AGS, where the (K^-, π^o) reaction, complementary to FINUDA's (K^-, π^-) , is studied with K^- at rest, both experiments with design energy resolution below 1MeV fwhm, and a comparable hypernuclei production rate. However, AGS operates with extracted beams at high rate ($2 \times 10^4 s^{-1}$ stopped K^-) and low geometrical acceptance (about 20 msr), while FINUDA's flux, at initial DAΦNE luminosity, is two orders of magnitudes lower, and the acceptance is 2 orders of magnitude larger. The AGS choice of considering neutral prompt pions is dictated by their use of thick targets, which worsens the resolution for emerging prompt charged pions in a much larger extent than for neutral pions.

Following the initial idea [4], FINUDA was formally proposed in May 1993 [7], rapidly approved and funded at the end of 1993. A technical report[8] is to appear shortly as a LNF preprint. For recent reviews, see [9],[10].

2.1 The Apparatus

FINUDA (figg.1) is a magnetic spectrometer with cylindrical geometry, optimized in order to have large solid angle, optimal momentum resolution and good triggering capabilities. Geometrical acceptance is approximately $135^0 \leq \vartheta \leq 45^0$, naturally rejecting e^+e^- background from Bhabha scattering.

FINUDA consists of (figg.2,3):

1) interaction/target region;
2) external tracker;
3) outer scintillator array;
4) superconducting solenoid.

The (K^+, K^-) pairs from ϕ decay emerge from the interaction region, whose dimensions are $\sigma_x = 2$ mm, $\sigma_y = 0.02$ mm, $\sigma_z = 3$ cm. The (K^+, K^-) pairs follow a $sin^2\vartheta$ law, ϑ being the angle relative to the z-axis.

The FINUDA spectrometer must provide a momentum resolution on the prompt π^- of the order of 0.3 % fwhm, negligible when compared to the momentum degradation due to multiple scattering. Optimization for prompt pions from Λ-hypernuclei has shown that a magnetic field higher that 1 T is needed: when applied to a 2m-long by 1m-radius detector volume, electrical power consumption considerations have suggested to adopt the superconducting option. The FINUDA magnet is a superconducting solenoid whose magnetic axis is along the beam direction, providing a highly uniform $B_{max} = 1.1$ T magnetic field (max disuniformity of 5% at the outer edges of the tracking volume). The tracking volume is generated by rotating a trapezium with ~ 20 cm, ~ 180 cm bases, and 120 cm height. The iron yoke has an octagonal shape, with two endcaps that can be open vertically to access the detector.

The cylindrical interaction/target region of FINUDA (fig.3) consists of the beam pipe, a scintillator barrel (TOFINO), an internal octagonal Si microstrip array (ISIM) and the nuclear stopping target. The above arrangement must accomplish the following tasks:

1) identify (K^+, K^-) pairs from ϕ decay for triggering, exploiting the back-to-back event topology and identification by ionization energy loss $-(dE/dx)$ (TOFINO);
2) measure the (K^+, K^-) coordinates before the nuclear target with $\sigma \sim 30{-}50\mu m$, also providing particle identification by $-(dE/dx)$ with triggering capabilities (ISIM);
3) stop the monochromatic K^- as near as possible to the external surface of the target;
4) measure the lifetime of hypernuclear states (TOFINO);
5) be radiation hard to cope with damage caused by Bhabha- and Touschek-scattered beam particles.

The thicknesses needed for the inner detectors are determined by the requirement of stopping the K^- as close as possible to the outer surface of the target, taking also into account its energy straggling and $\sin^2\vartheta$ angular distribution. Typical material thicknesses are: 400 μm Be for the beam pipe, 2.0 mm for the TOFINO, 300 μm for ISIM and finally about 1.5 mm for a C stopping target. With this setup K^- emitted from 45° to 135° stop inside the target. The length of the interaction/target region is determined by the requirement of accepting all the (K^+, K^-) pairs emitted from 45° to 135° along z coordinate from -3.5 cm to $+3.5$ cm, which corresponds to the fwhm of the (e^+, e^-) interaction region. The resulting length of the target will be 17 cm and will allow an acceptance for (K^+, K^-) of more than 90%.

The TOFINO consists of 12 strips, each 2.0 mm-thick, 14 cm-long and 2.5 cm-wide, subtending a polar angle $\Delta\varphi = 30°$. The strips are arranged following a circumference of radius 5.5 cm, and are read by Hybrid Photo Multiplier Tubes (HPMT). HPMT operate in the 1.1 T magnetic field and are very compact.

The two silicon microstrip arrays ISIM (in the interaction/target region) and OSIM (in the outer tracker) are composed of 18 modules in total. Each module is made of three $300\mu m$ thick, $52.6mm \times 65.4mm$ double-sided (ρ and φ strips) Si wafers bonded together. Pitch is $50\,\mu m$, strip width is $6\,\mu m$ for a total of 4×10^4 strips. The external tracker consists of a ten-sided outer silicon microstrip detector (OSIM), two sets of planar low-mass drift chambers (LMDC) and an array of straw tubes (ST), all immersed in a He atmosphere, with the following tasks:

1) measure the position of the prompt 270 MeV/c π^- from the hypernucleus production very close to the target, determining the position of the K^- stopping point and therefore correcting for the energy lost in the thin target, further improving in momentum resolution (OSIM);
2) measure the second and third space points of prompt π^- trajectory in the (ρ, φ) plane, with high resolution and maximal transparency;
3) measure the fourth space point with good accuracy, and independently from the incident angle of the track due to the curvature caused by the magnetic field (ST);

The LMDC are two sets of planar drift chambers using a He-based gas mixture, each one with a $(1230 \times 396)mm^2$ (inner chambers) and $(1870 \times 686)mm^2$ (outer chambers) area. Measurement of the coordinate along the wire is made by means of charge division.

The ST array is composed of 2424 0.03 mm-thick aluminized mylar straws with an inner diameter of 15 mm, and a 255 cm length. The straws are arranged in three superlayers, each superlayer made of two layers staggered by approximately half diameter. The inner superlayer is axial, the two outer superlayers are stereo oriented at $\sim \pm 13^0$.

Finally, the outer scintillator array (TOFONE) will provide a fast logic signal for the DAQ trigger (multiplicity and coincidence of the prompt π^- with the TOFINO signal) and neutron detection (with a $\sim$15% efficiency). The TOFONE is composed of 72 slabs of plastic scintillator, 255 cm-long and 10 cm-thick, read-out at both ends by 90^o deflector prisms and lightguides funnelling the light signal to photomultipliers located in a low-field region outside of the magnet.

2.2 Status of Subdetectors

2.2.1 Interaction/target Region

After tests with cosmic rays, the NE104 scintillator was selected for the internal scintillator barrel (TOFINO), providing light output in excess of 50 pe/mip for the thickness chosen (2.0mm). Two HPMT samples prototypes are under tests providing a 3.5×10^3 gain and a 50 ps time resolution. Delivery of scintillators, lightguides, HPD and preamplifier is by summer 1995, and final assembly is by November 1995.

Delivery of about 100 silicon wafers for the ISIM/OSIM detector is due from CSEM (Neuchatel, France) by April 1995. Readout hybrids prototypes (by IDEA, Oslo, Norway) are being tested, delivery of the full batch is due by fall 1995. Precision glueing of the wafers on support frames will be carried out at University of Bari, while strip microbonding will start in Fall 1995. Delivery of all readout electronics is scheduled before end 1995. Two full modules will be ready for test at CERN with m.i.p. in September 1995, and at TRIUMF with low-energy pions.

2.2.2 Outer Tracker and TOF System

A $(115 \times 57) cm^2$ prototype Low-Mass Drift Chamber has been tested at CERN with a 5 GeV/c pion beam using a $He - iC_4H_{10}$ (70%-30%) gas mixture[11]. The space resolution was measured better than $100\mu m$ along the whole drift cell, with 98% average efficiency. The coordinate along the wire is measured by charge division with a resolution of the 0.61% of the wire length. The large chambers will be assembled at TRIUMF while the small chambers will be assembled in Turin (for a total of 16 chambers plus 4 spares), from May 1995 to December 1995. All readout electronics is defined and characterized, delivery will start in October 1995.

A 8-channel Straw Tubes prototype was tested at CERN with m.i.p.'s in May 94 using DME, attaining a $40\mu m$ space resolution [12]. A 160-channel prototype with axial and stereo superlayers was tested at TRIUMF in December 1994 with a 300MeV/c pion beam to investigate the use of alternate gases $(Ar - C_2H_6, Ar - CO_2)$[13]. Test beam results show that $\sim 100\mu m$ space resolution is attained with the alternate gas mixtures studied. Assembly and quality control of about 2700 straw tubes will start at LNF in October 1995, with assembly inside the detector frame starting by March 1996.

Two scintillators (NE102A and Bicron BC408) have been tested and proved to meet both the attenuation and light output specifications of the outer TOF array (TOFONE). Geometry of the counters is defined (255 cm length, 10 cm height, 10.7 cm and 11.6 cm bases). A 80% efficiency light transmission to the photomultiplier was found by using 90^o conical deflector prisms. Extensive testing brought to characterize photomultipliers able to provide the required time resolution: Philips XP2020, XP2262B and Hamamatsu R5686 all met specifications, tender open to select the less costly option. A 700 ps time resolution was obtained with a prototype bar. Delivery is expected to be complete by November 95 for all components (scintillators, light guides, and PMT).

Table 1: Space, time and energy resolutions of the FINUDA subdetectors

	Space rms	Time fwhm	Energy fwhm
TOFINO	-	$500\,ps$	$-(dE/dx)$ 50 pe/mip
ISIM,OSIM	$50\,\mu m(x,y,z)$	-	$-(dE/dx)$ 20% for K
LMDC	$100\,\mu m(x,y)$	-	-
	1% wire length (z)		
TOFONE	$5\,cm\,(z)$	$500\,ps$	-
ST	$100\,\mu m(x,y)$	-	-
	$< 500\mu m(z)$		

2.2.3 The Superconducting Solenoid

The magnet contract was signed in December 1993 with Ansaldo, Genova, Italy. Coil and cryostat are expected to be completely assembled in December 1995, so to allow cryogenics tests, cool down and magnetic field mapping to be completed at the factory by April 1996. The magnet and endcaps will be transported assembled to LNF in June 1996, and installation in the experimental pit is scheduled to begin in mid 1996.

2.2.4 The Detector Support Frame *Clepsydra*

The interaction/target region and the outer tracker are assembled on to the Detector Support Frame, whose shape resembling a sand-clock attributed it the Clepsydra nickname. The Clepsydra provides endplates between which the straw tubes are mounted and strung to tension. The drift chambers are slid in rails made in the axial links connecting the Clepsydra radial spokes, while the interaction/target region and the beampipe with two pairs of permanent compensating quadrupoles are sustained by the two inner cylinders connecting the radial spokes on the lateral surface of the structure. The detectors will be installed in the Clepsydra independently of the magnet, connected to the readout electronics and tested with cosmic rays in an assembly laboratory. When ready in the FINUDA experimental pit, the magnet will receive the instrumented Clepsydra via the sequence shown in fig.4, and finally the beampipe section with the compensating quadrupoles.

2.3 Performances

The characterization and testing of the FINUDA subdetectors described so far show how the design momentum resolution - the most crucial feature of the detector - is met with a safety margin. To demonstrate the resolving power in hypernuclear spectroscopy, a full simulation was carried out assuming the resolutions in tab.1, all vastly met as shown by test beam results.

Production of a hypernuclear states producing a 270 MeV/c prompt π^- was simulated, the prompt pion tracked through the spectrometer, hits simulated in the detectors, tracks reconstructed by matching hits and fitting of trajectories. The reconstructed raw momentum distribution (fig.5a) shows a shoulder at low energy due to pions crossing the interaction/target region after being emitted, whose momentum is degraded by the material crossed. When selecting only the 'forward' pions (fig.5b),*i.e.*, those not crossing back the interaction/target region, the momentum resolution is of the order 0.3% fwhm. However, the momentum resolution for forward prompt pions can be further increased by exploiting the vertex measurement by the ISIM and OSIM, and correcting their momentum by the thickness of target crossed. This is shown in fig.5c, where the mean of the distribution is now set to the 270 MeV/c generated momentum, and the width of the reconstructed spectrum is reduced to 0.25%.

2.4 Triggering Strategies

The FINUDA trigger selects ϕ decays in charged kaons, against decays to $K^o_S K^o_L$, Bhabha scattering, cosmic rays. Bhabha events are naturally reduced by the geometrical acceptance covered by the TOFINO scintillator array $135^0 \leq \vartheta \leq 45^0$. The trigger requirements exploit the back-to-back topology of the $K^{\pm}$ pairs, their large $-(dE/dx)$ and the coincidence with the prompt negative pion emitted from the hypernuclear formation as detected by the TOFONE:

- TOFINO back-to-back topology with dE/dx discrimination;
- TOFONE prompt $< 10ns$ coincidence and multiplicity ≥ 1.

The prompt coincidence with TOFONE is dictated by the need of rejecting μ^+ from K^+ decay. Table 2 shows typical triggering efficiencies for hypernuclear events and residual background contaminations.

2.5 Rates and Sensitivity

Hypernuclear formation rates at the initial luminosity $10^{32} cm^{-2} s^{-1}$ are shown in tab.2, along with rates for background processes.

The rate of reconstructed hypernuclear events with resolution better than 1 MeV at $\mathcal{L} = 10^{32} cm^{-2} s^{-1}$ is given by the expression:

$$R(_{\Lambda}Z) = R_{\phi} \times BR(\phi \to K^+K^-) \times \frac{N_{\Lambda}Z}{K_{stop}} \times \epsilon_{\pi^-} \times \epsilon_{transp}$$

$$R(_{\Lambda}Z) \sim 2.5 \times 10^{-2} s^{-1} \sim 90\, events/hour$$

where $R_{\phi} = 5 \times 10^2 s^{-1}$, $BR = 0.49$, $\frac{N_{\Lambda}Z}{K_{stop}} = 10^{-3}$ is the capture rate, $\epsilon_{\pi^-} = 13\%$ is the total efficiency for forward (high-resolution) prompt pions, and $\epsilon_{transp} = 80\%$ is the chamber transparency.

The FINUDA rate and resolution capabilities are summarized in tab.3, showing beam time required (in hours) at initial luminosity $\mathcal{L} = 10^{32} cm^{-2} s^{-1}$ to produce (with 10% and 20% statistical precision) hypernuclear states with capture rates $10^{-3}/K^-_{stop}$ to $10^{-5}/K^-_{stop}$.

Table 2: Efficiency, rejection and rates for production of hypernuclear states and background processes

Efficiency for hypernuclear production events	
TOFINO BackToBack $\times$ dE/dx threshold	80%
$\times$ TOFONE 10ns prompt coincidence	46%
$\times$ TOFONE ≥ 1 multiplicity (trigger eff. ϵ_T)	39%
$\times$ π^- track has 4 hits	29%
$\times$ forward π^- (eff. ϵ_{π^-})	13%
Background rejection	
Bhabha	$< 10^{-2}$%
$\phi \to K_S K_L$	$(3 \pm 1) \times 10^{-2}$%
$\phi \to \rho\pi$	$(4 \pm 1) \times 10^{-2}$%
$\phi \to \pi^+\pi^-\pi^0$	10^{-2}%
K^- interaction without hypernucleus	7 %
Trigger rates at $10^{32} cm^{-2} s^{-1}$	[Hz]
Hypernucleus production ($10^{-3}/K^-_{stop}$ capture rate)	8×10^{-2}
Bhabha	$< 4 \times 10^{-2}$
$\phi \to K_S K_L$	5×10^{-2}
$\phi \to \rho\pi$	2×10^{-2}
$\phi \to \pi^+\pi^-\pi^0$	10^{-3}
K^- interaction without hypernucleus	15

Table 3: Beam time required (in hours) at $\mathcal{L} = 10^{32} cm^{-2} s^{-1}$ to produce with (10% and 20% statistical precision) hypernuclear states with capture rates from $10^{-3}/K^-_{stop}$ to $10^{-5}/K^-_{stop}$.

Production rate	10^{-3} 10% st.	10^{-4} 10% st.	10^{-5} 10% st.	10^{-5} 20% st.
S/B=4/1 at 10^{-3}	2.45	96	8000	2000
S/B=8/1 at 10^{-3}	1.8	56	4000	1000
S/B=12/1 at 10^{-3}	1.5	40	2300	575

3 Outlook and Conclusions

FINUDA, a large acceptance, high resolution spectrometer dedicated to nuclear physics is in construction at LNF's DAΦNE . The simulated performances based on test results of subdetector prototypes show that a 0.7 MeV fwhm resolution on 270MeV/c hypernuclear states will be achieved, with a counting rate at initial luminosity of 90 hypernuclear states reconstructed per hour. The detectors will be installed in the second half of 1996 in the DAΦNE machine, soon after the delivery of the superconducting solenoid.

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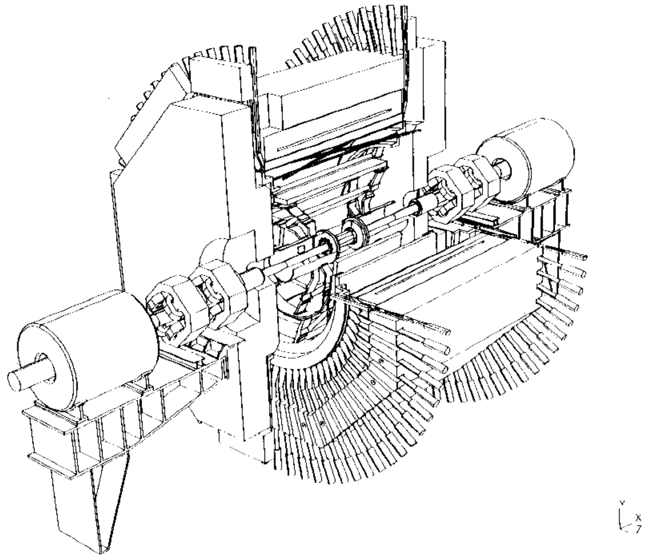

Figure 1: Cut-out view of the FINUDA spectrometer, showing also a section of the DAΦNE beam pipe and compensating quadrupoles.

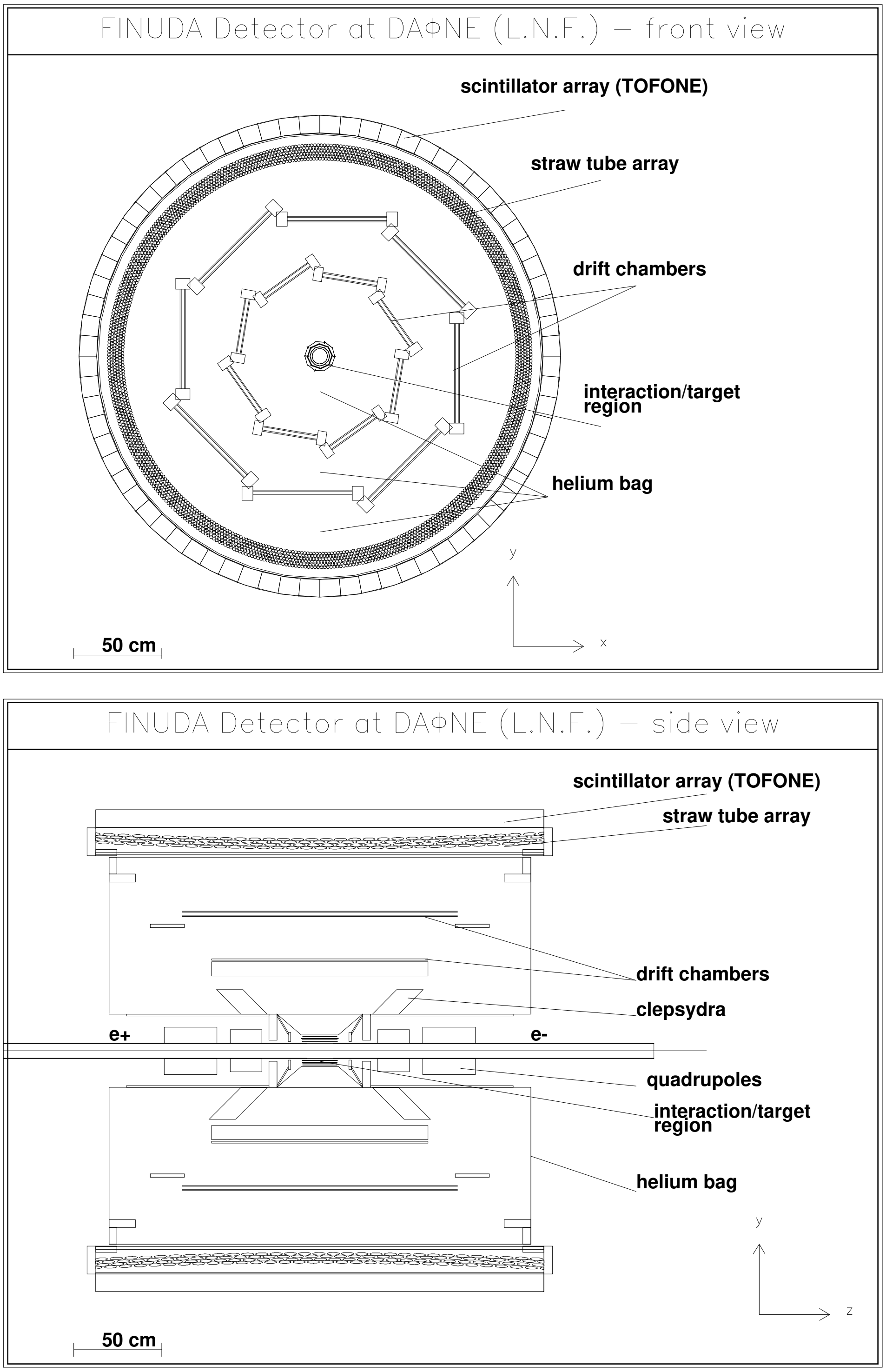

Figure 2: Sketch of the FINUDA detector beam view (top) and side view (bottom).

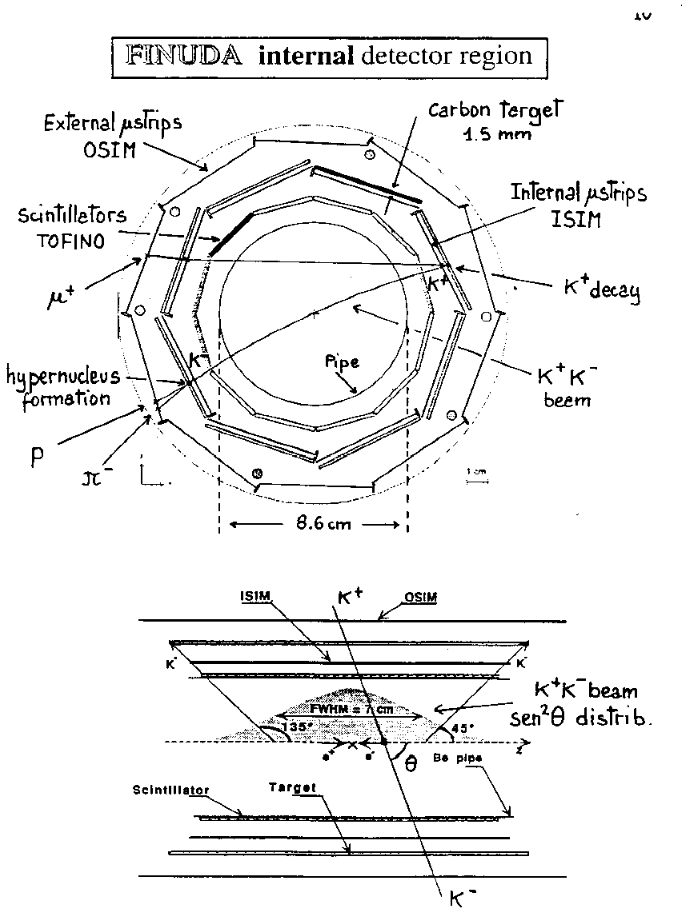

Figure 3: Sketch of the interaction/target region.

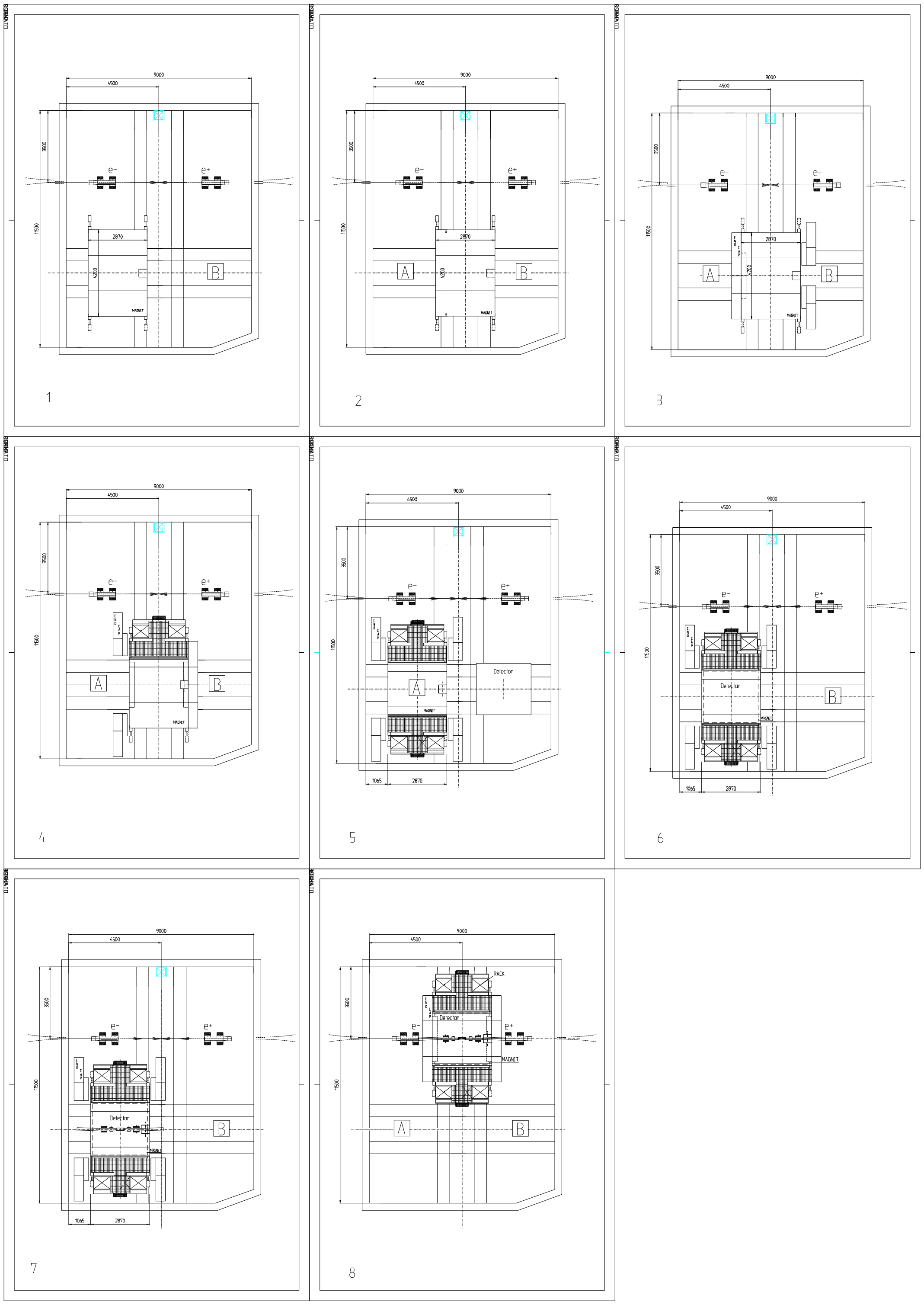

Figure 4: Sequence to slide the Clepsydra (equipped with interaction/target region and outer tracker) inside the FINUDA magnet. The beam pipe section complete with compensator quadrupoles is inserted, finally the spectrometer is moved in the DAΦNE ring.

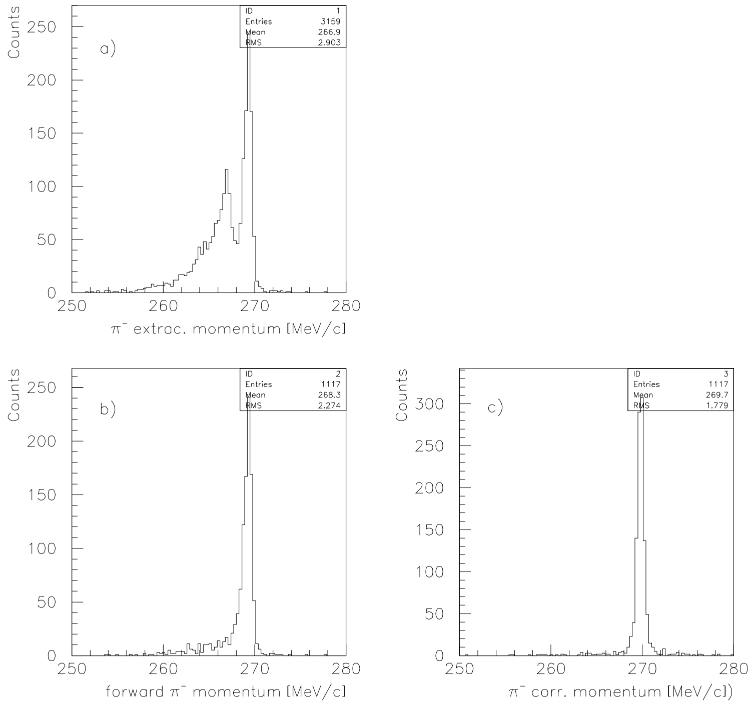

Figure 5: (a) Raw reconstructed momentum distribution of the prompt 270 MeV/c π^-; (b) only forward pions, *i.e.* not crossing back the interaction/target region; (c) only forward pions, after correction for the energy loss in the target based on the K^- stopping point as determined by ISIM and OSIM.