

CALIBRATION OF SUPER-KAMIOKANDE USING AN ELECTRON LINAC

The Super-Kamiokande Collaboration

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Abstract

In order to calibrate the Super-Kamiokande experiment for solar neutrino measurements, a linear accelerator (LINAC) for electrons was installed at the detector. LINAC data were taken at various positions in the detector volume, tracking the detector response in the variables relevant to solar neutrino analysis. In particular, the absolute energy scale is now known with less than 1% uncertainty.

Key words: Solar neutrinos, linear accelerator, calibration, Super-Kamiokande
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1 Introduction

Past solar neutrino experiments[1–4] have established the solar neutrino problem. The data collected by these experiments suggest an energy dependent suppression of the solar neutrino flux measured on Earth. Some physical interpretations of the data make specific predictions for spectral distortions of the measured solar neutrino spectrum[5]. Thus a new generation of solar neutrino experiments set out to perform high precision measurements of the solar neutrino spectrum. On April 1, 1996, Super-Kamiokande (SK) was the first of these experiments to start taking data[6].

SK uses the elastic scattering of electrons in water to observe the high energy ^8B neutrinos from the sun. As a water Cherenkov counter it provides real time directional and energy information on the recoil electron from the neutrino interaction. Since the energy of solar neutrinos is less than 20 MeV and angular

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resolution is limited by multiple Coulomb scattering, a kinematic reconstruction of the incident neutrino's energy is precluded. The recoil electron energy measured in the detector only gives a lower limit for the energy of the incident neutrino, so the features of the incident solar neutrino spectrum have to be inferred from the resulting recoil electron spectrum measured in the detector. This increases the sensitivity of spectral analysis and ^8B solar neutrino flux estimation to the calibration of energy scale and resolution in the detector. A linear accelerator (LINAC) was installed at SK to provide precise detector calibration with single electrons of known energy and direction at various positions in the detector volume.

2 Super-Kamiokande and Solar Neutrinos

SK is a water Cherenkov detector located in the Kamioka Mine in Japan. It is divided into an inner and an outer detector (ID and OD), which are concentric cylindrical water volumes separated by an optical barrier. All photomultiplier tubes (PMTs) collecting Cherenkov light are mounted on this optical barrier, with 20 inch ID PMTs looking inward and 8 inch OD PMTs looking outward. The OD has a uniform thickness of 2.5 m surrounding the ID, and in the solar neutrino analysis it is used as a veto counter. It also passively shields the ID from gamma activity from the surrounding rock. Cherenkov light emitted by electrons recoiling from neutrino scattering in the ID is collected by 11,146 ID PMTs. These PMTs are uniformly distributed on a 0.707 m square grid, enclosing 32,000 metric tons of water in a volume of 36.2 m height and 33.8 m diameter. The fiducial volume for solar neutrino analysis starts 2 m inside the physical confines of the ID, and contains 22,500 metric tons of water. The timing range of the time-to-digital converters used with the ID PMTs is $1.2 \mu\text{s}$, while the time needed for light to travel the diagonal of the ID is about 230 ns.

Solar neutrinos measured in SK have energies from 5 to 18 MeV. Their recoil electrons have ranges of a few centimeters, allowing use of a point fitter for vertex reconstruction. Knowing the vertex position, the characteristic directionality of Cherenkov radiation allows reconstruction of the recoil electron direction from the distribution of light around this vertex. The total amount of light emitted in an event is used in the energy determination. With a yield of about 6 hit PMTs per MeV of electron energy, even for the highest energy solar neutrino events less than 1% of all PMTs have signals. The number of hit PMTs is related to the electron energy. This number must be corrected for absorption and scattering as well as for geometrical acceptance, depending on event location and direction in the detector.

SK's predecessor, Kamiokande, used gamma-rays from the $\text{Ni}(n,\gamma)\text{Ni}$ reaction for the calibration of its absolute energy scale[7]. Uncertainties in branching

ratios and the neutron absorption cross sections for different nickel isotopes limit the accuracy of such an energy calibration to 1–2%. Nickel calibration also provides no information on the angular resolution of the detector and only limited information on energy resolution. The angular resolution as a function of energy is used to fit the distribution of event directions with respect to the direction to the Sun. This fit is fundamental to the solar neutrino analysis in SK.

The LINAC offers the means to study the detector response to electrons, its position dependence and angular resolution *in situ*. It allows the injection of single electrons of well-controlled energy at various positions in the ID. The LINAC covers the energy range of solar neutrino events and provides an excellent calibration of the absolute energy scale.

The following sections will describe the LINAC and its beam transport system, its calibration, and the results obtained from the first scan of the ID with this new and powerful calibration tool.

3 The Electron LINAC

The LINAC employed at SK is a Mitsubishi ML-15MIII produced for medical purposes in 1978. It was used at the hospital of Miyazaki Medical University until its installation at the SK detector in 1996. Certain modifications were necessary to adapt the LINAC to its new purpose. It is now mounted on a solid support structure in a tunnel to the side and slightly above the top of the steel tank containing the water Cherenkov detector (Fig. 1). For SK calibration, single electrons are needed in the detector. A special electron gun reduces the number of electrons entering the acceleration tube to appropriate levels. Its output current is adjustable, allowing control of the beam intensity.

Microwave pulses of $\sim 2\mu\text{s}$ width are generated in a Mitsubishi PV2012M klystron with an adjustable pulse rate between 10 and 66 Hz. Electrons from the electron gun are accelerated as they travel with the microwave in the accelerating tube. Manipulating the input power and frequency of the microwave changes the average beam momentum. The electron energy can be varied in a range from 5 to 16 MeV, well matched to recoil electron energies from solar neutrinos. Features of the LINAC are summarized in Tab. 1.

After the accelerating tube, the electron beam is rather divergent and spans a modest momentum range. Mono-energetic electrons are selected from this spectrum by an arrangement of collimators surrounding D1, the first 15 degree bending magnet (Fig. 2). After the C3 collimator (Fig. 3), the beam momentum spread is reduced to 0.5% at FWHM. Constraining beam momentum

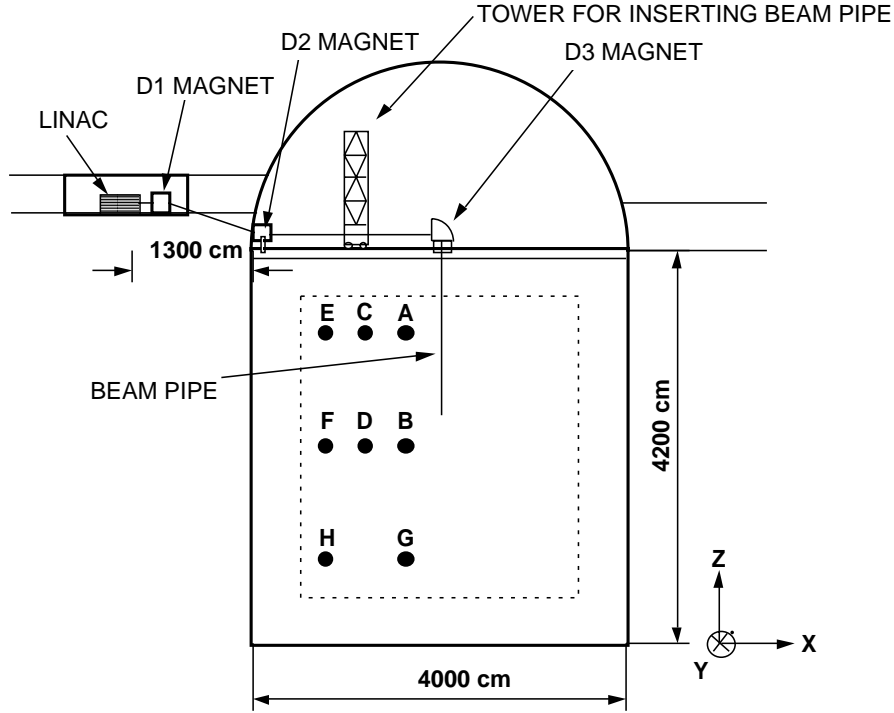


Fig. 1. The LINAC and its beam line at the SK detector. The fiducial volume for the solar neutrino measurement is indicated by a dashed line. Black dots indicate where in the fiducial volume calibration data were taken with the LINAC (see also Tab. 4).

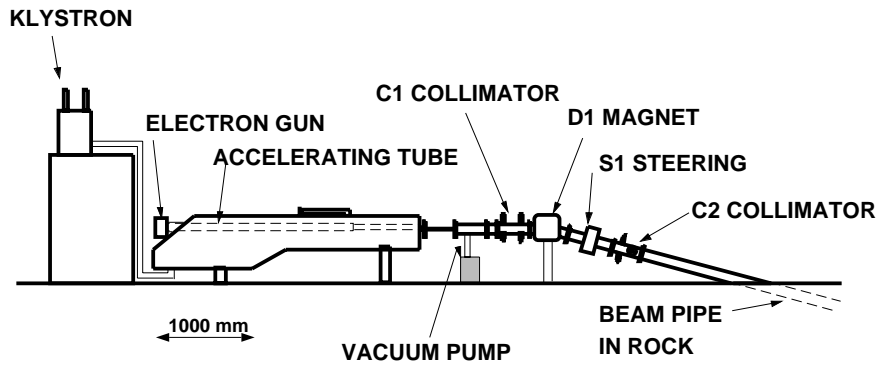


Fig. 2. Beamline detail: First bending magnet (D1) and associated collimators. Here the beam momentum is defined.

and divergence reduces the beam intensity from $\sim 10^6$ to a few electrons per microwave pulse. Thus almost the entire beam intensity is either dumped into collimators or deflected out of the beamline by the magnet. If any gammas generated in this process were to reach the ID, additional light from their Compton electrons would produce correlated background, altering the energy calibration.

Type	Mitsubishi ML-15MIII
Accelerating tube	1.69 m length 26 mm inner diameter
Acceleration type	traveling-wave
Microwave frequency	2.856 GHz
Klystron	Mitsubishi PV2012M
Electron gun	0.125 mm diameter tungsten filament
Electron gun intensity	200 μ A maximum
Vacuum in accelerating tube	10^{-7} torr
Maximum beam intensity	$\sim 10^6$ electrons/pulse at the accelerator tube end
Beam momentum	5 - 16 MeV/c
Pulse width	1 - 2 microsecond
Repetition rate	10 - 66 pulses / second
Beam size	~ 6 mm
Beam angular spread	~ 3 mrad
Power consumption	30 KVA

Table 1

Technical data on the electron LINAC.

To shield the detector from this radiation, the beam pipe passes through 9 m of rock after the 15 degree downward bend in D1 before it emerges on top of the SK detector. There it is bent back to horizontal by D2, also a 15 degree bending magnet (Fig. 3). Gammas travelling towards SK in the inclined section of the beampipe before D2 are absorbed in a lead shield.

After D2, the electrons travel in a horizontal beam pipe along the top of SK. Calibration holes reaching through the OD into the ID at regular intervals allow insertion of a vertical beam pipe of variable length. A 90 degree bending magnet, D3, bends the horizontal beam into this vertical beam pipe. Before and after D3, sets of quadrupole-magnets (Q-magnets) focus the beam onto the endcap of the vertical beam pipe in the tank (Fig. 4).

The endcap of the beam pipe is closed by a 100 μ m thick titanium window of 3 cm diameter (Fig. 5). In addition to separating the inside vacuum from outside water pressure of up to 4 atm, it must transmit electrons of energies down to 5 MeV with as little energy loss and multiple scattering as possible. The pointed shape that is approximated by cylinders of decreasing diameter towards the titanium exit window reduces shadowing by the beam pipe in the electrons' backward direction. A 1 mm thick, 24 mm diameter plastic scintillator (the "trigger counter"), is mounted 17 mm above the titanium window and supplies a trigger signal. LINAC triggers are issued if a trigger

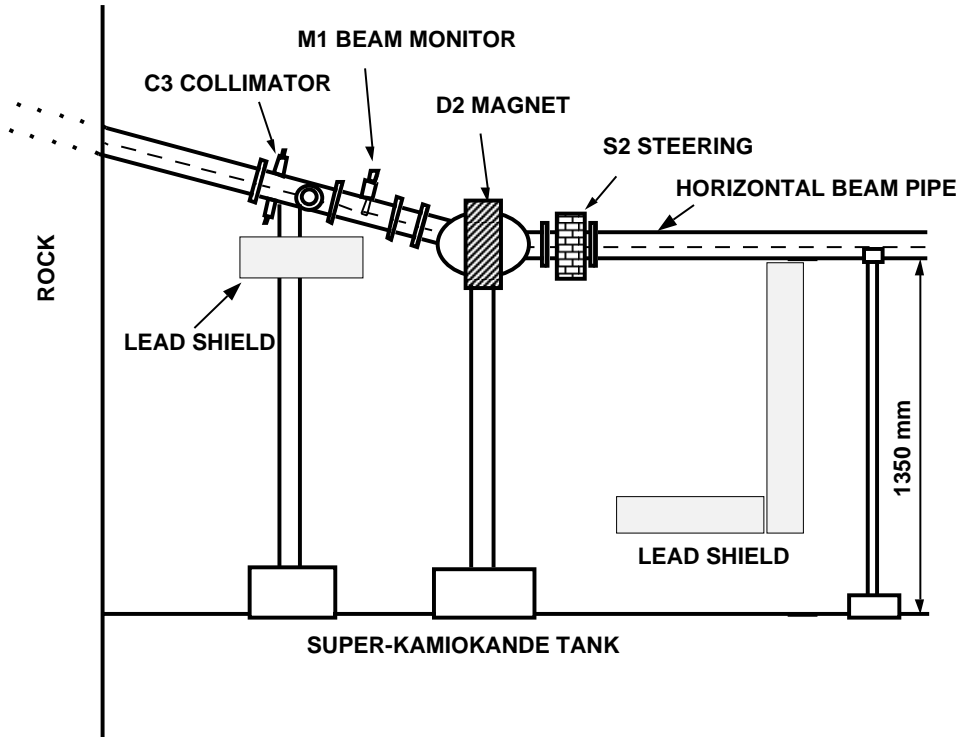


Fig. 3. Beamline detail: Returning the beam to horizontal after momentum selection.

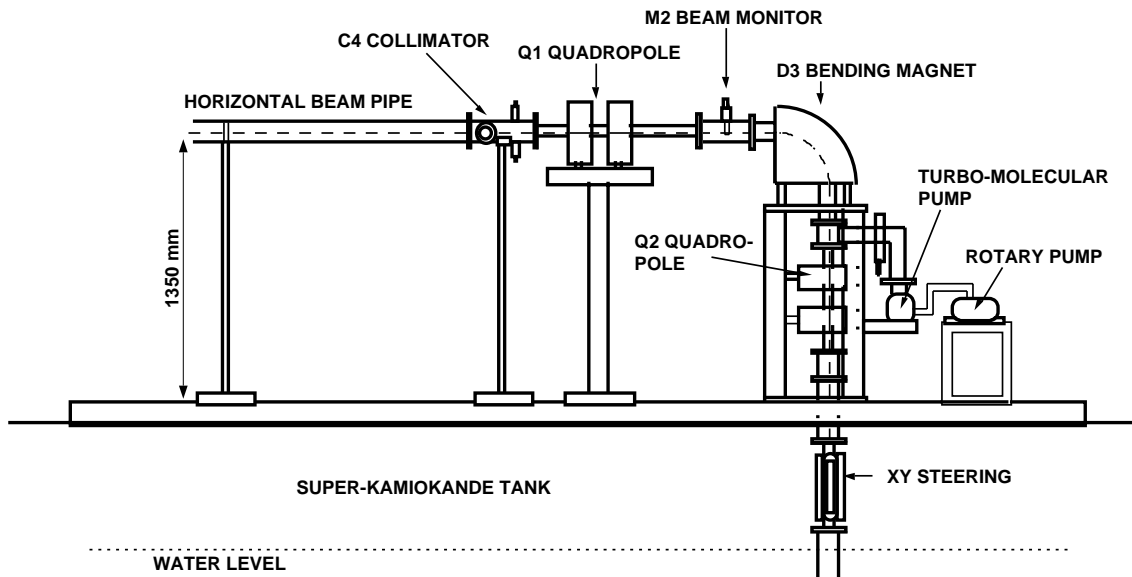


Fig. 4. Beamline detail: 90 degree bending and focussing of the beam.

counter hit coincides with a LINAC microwave pulse. Four scintillators of 1 cm thickness surround the beam 80 cm above the trigger counter. They are used when steering the beam onto the trigger counter.

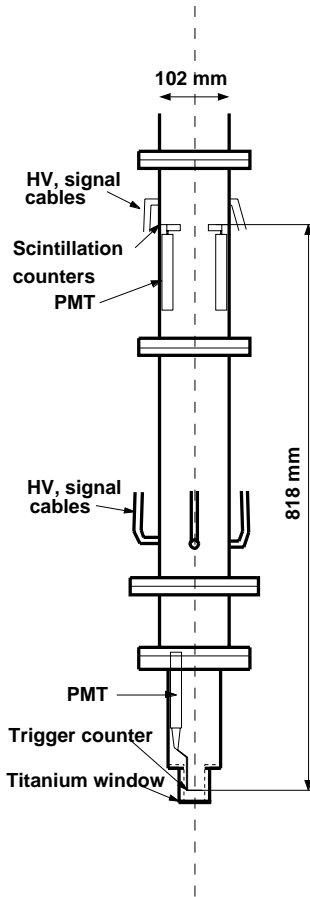


Fig. 5. Beamline detail: Endcap

Steering magnets S1 and S2, installed after D1 and D2 respectively, are adjusted to keep the beam on the pipe axis. Since D1 and D2 take care of bending the beam out of and into the horizontal plane, the steering magnets need only be effective in the orthogonal direction. After D3, another set of magnets (XY-steering) installed right above the water level in the tank steers the beam in two orthogonal directions, independent of D3. These magnets are also used to scan the beam profile at the trigger counter. Measured beam profiles are of order 2 cm wide or less, well contained within the trigger counter.

While fixed settings of D1 are used to control the beam momentum, all other magnet settings are tuned for minimal beam loss. Beam monitors before D2 and D3 can be inserted into the beam without breaking the vacuum in the beam pipe. Only the Q-magnet settings rely on a simulation of the beam optics. The validity of the Q-magnet settings is borne out by measurements with the scintillation counters in the endcap. The beam intensity is controlled by the electron gun. To ensure single electrons in detector, the beam intensity is reduced to ~ 0.1 electrons per microwave pulse. Specifications of the magnets in the beam line are shown in Tab. 2.

Name	Purpose	pole gap	Length	Magnetic field (for 16.3 MeV/c)
D1	15 degrees bending	2.5 cm	7.5 cm	1.3 KG
D2	15 degrees bending	2.5 cm	7.5 cm	1.3 KG
D3	90 degrees bending	2.5 cm	39.3 cm	2.0 KG
S1	horizontal steering	3.8 cm	4.0 cm	18G/A (typically 1.0 A)
S2	horizontal steering	3.8 cm	4.0 cm	18G/A (typically 1.0 A)
Q1	doublet quadropole	4 cm	2×10cm	48G/cm/A (1.54A and 3.81A)
Q2	doublet quadropole	4 cm	2×10cm	48G/cm/A (2.70A and 2.86A)
XY	steering in SK tank	5.2 cm	30 cm	12.6G/A (typically 0.2 A)

Table 2
Beamline magnet specifications.

A mu-metal shield inside the horizontal and vertical pipes protects the beam from external magnetic fields. Unfortunately this mu-metal shield is missing in the vicinity of elements like magnets, monitors and collimators in the beam pipe. Especially around the D3 magnet, there are many such elements, leaving the beam exposed. The net effect is a loss in beam intensity between the monitor M2 and the trigger counter. This loss gets worse for low beam momentum (up to 80% for a 5 MeV beam), and has the potential of producing gamma-rays in the surrounding material. At the same time, the relative impact of gammas accompanying LINAC electrons in the tank would be largest at low momenta.

The impact of such systematics can be evaluated from a comparison of different types of “empty” triggers. Since the timing of the momentum selected electrons is constrained within a few hundred nanoseconds relative to the 2 μ s LINAC microwave pulse, a trigger can be set up independent of the trigger scintillator in the endcap. Ninety percent of the time this trigger will record “empty” events, where no electron is seen in the trigger counter. Taken in a separate run, this data set constitutes the so-called “microwave triggers.” Empty events for which detector readout is triggered by an external 100 Hz clock, independent of the LINAC, are taken in yet another run. Comparison of background rates in these two empty trigger runs, which are routinely taken after each LINAC run, no significant effect can be seen in the data. Differences between the respective background rates fluctuate around zero, and a conservative estimate for the systematic error of the absolute energy scale from beam correlated background is obtained by averaging the absolute values of these fluctuations, yielding 0.16%.

Positions in the detector that are accessible to the LINAC are restricted by the arrangement of calibration holes, which are situated with 2.12 m spacing (three PMT gridpoints along the top of the detector) along the radius that in

SK coordinates is referred to as the x-axis. The vertical axis of the detector is the z-axis (see Fig. 1). The origin is placed at the center of the ID. For structural reasons the calibration holes are offset from the radial x-axis by one PMT spacing (0.707 m). Only three of these holes were used in the current SK calibration. The z-coordinate of the endcap, where the electrons are delivered into the detector, is determined by the length of the vertical beam pipe. The necessity to reconfigure the beam pipe every time the LINAC position in the detector is changed automatically organizes LINAC data taking by position. For each position data are taken at seven different beam momenta between 5.08 and 16.31 MeV/c. Currently all LINAC electrons exit the endcap in the -z direction.

4 Beam Energy Calibration

The absolute energy of the beam is measured with a germanium detector. After data are taken at a certain position, the D3 magnet is removed and the vertical beam pipe pulled out of the tank. To calibrate beam energy, the last section of the vertical beam pipe (containing the trigger counter) is connected directly to the horizontal beam pipe, so that it lies horizontally rather than hangs vertically as in the tank. The germanium detector is placed right after the titanium window, and D1 is set to the same value as for the measurement in SK. Ge calibration relates D1 magnet settings to beam energies.

The germanium detector used in the calibration is a Seiko EG&G Ortec GMX-35210-P, which has a germanium crystal of 57.5 mm diameter and 66.4 mm length. The resolution of this germanium detector is 1.92 keV for the 1.33 MeV gamma-rays of ^{60}Co . The germanium detector is connected to a Seiko EG&G Multi-Channel-Analyzer 7700.

The germanium calibration system (crystal, electronics and multi-channel-analyzer (MCA)) is calibrated each time it is used. A variety of gamma-line sources, spanning an energy range from 0.662 MeV for a ^{137}Cs source to 9.000 MeV from the $\text{Ni}(n,\gamma)\text{Ni}$ reaction, establishes the relationship between energy and MCA channel. The linearity of this system calibration is found to be better than 1.5 keV over the whole energy range, corresponding to an error of less than 0.03% in the momentum of a 5 MeV/c electron beam. The stability of the system is also excellent: without recalibration, the systematic error would still be less than 0.1%.

However, Ge detectors respond slightly differently to electrons and gamma-rays. Incident electrons lose energy in the crystal's beryllium entrance window and in a passive layer at the crystal surface before they reach the active volume, while gamma-ray conversions mostly take place inside the active volume.

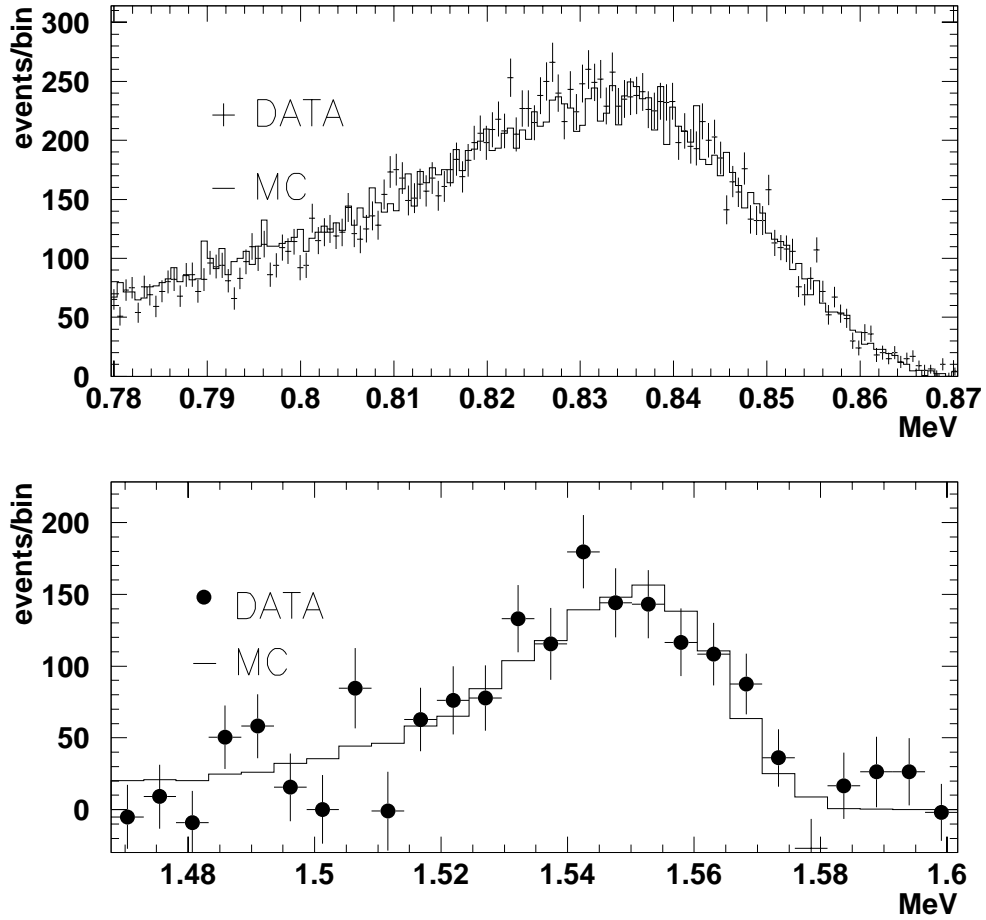


Fig. 6. Data and MC for ^{207}Bi internal conversion electrons. Both data and MC include energy loss in a $500\ \mu\text{m}$ Be window and a $41\ \mu\text{m}$ passive layer in the Ge crystal. The top figure is for 975.7 keV electrons, and the bottom for 1682.2 keV.

To measure this initial energy loss, the Ge detector was taken to an air-core beta spectrometer at the Tanashi-branch of KEK. At the spectrometer, internal conversion electrons of 975.7 and 1682.2 keV from a ^{207}Bi source were injected into the crystal. The average energy loss measured for these lines was 143.5 and 132.3 keV, respectively. Fig. 6 shows the background subtracted spectrometer data, which are matched by Monte Carlo (MC) simulation under the assumption of a $41\ \mu\text{m}$ passive layer behind the $500\ \mu\text{m}$ beryllium entrance window to the crystal. A scan across the entrance window did not reveal any inhomogeneities.

A MC simulation is used to evaluate the impact of energy loss and multiple scattering in the trigger counter, the titanium window, the beryllium window and the passive layer of the Ge crystal. The vacuum in the beam pipe is

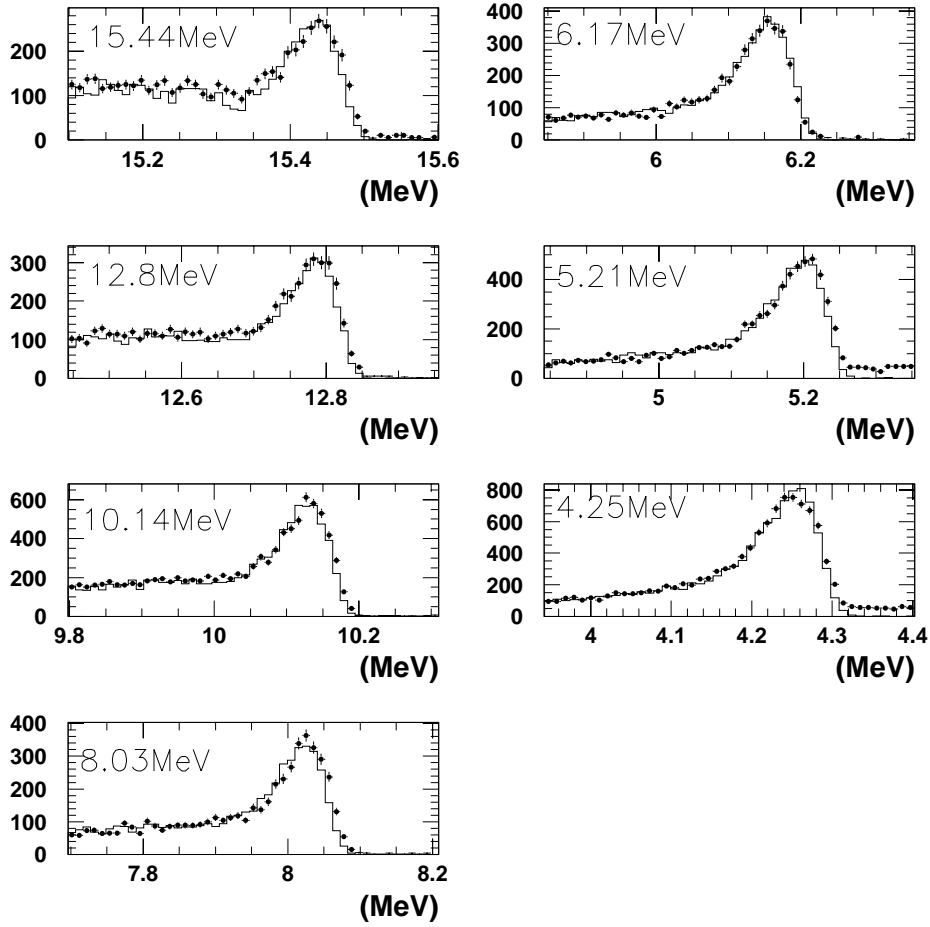


Fig. 7. Ge calibration data (points) and MC simulation (histogram) for LINAC beams of various energies (see Tab. 3). One bin corresponds to 10 keV.

better than 10^{-4} Torr, so energy loss in the rest gas can be neglected. In Fig. 7, spectra recorded in the MCA are displayed for various beam momenta, as selected by the setting of the D1 magnet. Tails towards lower energies are due to electrons that are not contained in the Ge crystal. The simulation reproduces the width of the spectra to better than 10 keV. The results of the beam momentum calibration are summarized in Tab. 3. Five Ge calibrations were done during the time the LINAC data for SK calibration were collected. Like the SK calibration data, Ge data were taken at three different x-positions. The reproducibility of the relationship between D1 magnet setting and beam energy is better than 20 keV.

D1 current (A)	beam momentum (MeV/c)	Ge energy (MeV)	in-tank energy (MeV)
1.8	5.08	4.25	4.89
2.15	6.03	5.21	5.84
2.5	7.00	6.17	6.79
3.2	8.86	8.03	8.67
4.0	10.99	10.14	10.78
5.0	13.65	12.80	13.44
6.0	16.31	15.44	16.09

Table 3

D1 setting and associated beam momentum. The third column gives the energy measured in the Ge calibration system. The last column lists the total energy of the electrons after leaving the beampipe.

Position	X (m)	Y (m)	Z (m)
A	-3.88	-0.71	12.28
B	-3.88	-0.71	0.27
C	-8.13	-0.71	12.28
D	-8.13	-0.71	0.27
E	-12.37	-0.71	12.28
F	-12.37	-0.71	0.27
G	-3.88	-0.71	-11.73
H	-12.37	-0.71	-11.73

Table 4

List of positions where LINAC data were taken

5 Super-Kamiokande Calibration

After installation of the LINAC in 1996, testing and commissioning of the various components proceeded through the summer of 1997. Systematic LINAC data taking in SK started in September 1997. High quality data sets were obtained for eight different positions in the ID (Tab. 4 and Fig. 1). With a maximal repetition rate of 66 Hz and only 10% of pulses actually delivering an electron, it takes about two hours to collect the necessary statistics for one energy setting.

LINAC data are reconstructed using the standard solar neutrino analysis chain (see Ref.[6]). A resulting typical two-dimensional projection of the vertex dis-

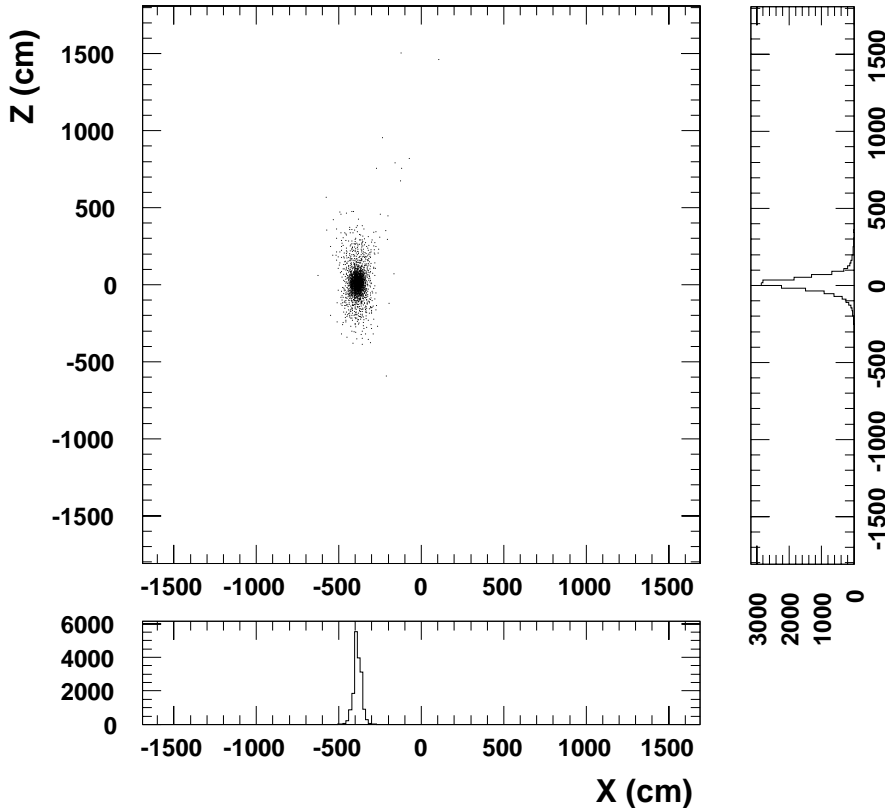


Fig. 8. Vertex position distribution of LINAC data taken at $(x,z)=(-4m,0m)$, beam momentum 16.31 MeV/c. Projections of the scatter plot are shown to the right and underneath. Scatter plot limits correspond to the limits of the ID.

tribution onto the x,z -plane (SK coordinates) for LINAC trigger events is shown in Fig. 8. Also shown are the corresponding projections onto the x and z axes.

To select the calibration data from this data set, one additional cut is applied to these LINAC trigger data to reject events with multiple electrons. If the timing information for the event is corrected for the time of flight (TOF) from the end of the beampipe, electrons that left the beampipe at times different by only a few tens of nanoseconds can be clearly separated. Examples for such TOF subtracted timing distributions are shown in Fig. 9. Events are rejected if multiple peaks of more than 30% of the expected signal are found more than 30 ns apart in a single event. About 5% of the LINAC trigger events are rejected by this cut.

The resulting set of LINAC calibration data for the various positions and energies is used in two ways. First, it is used to tune parameters in the detector simulation; second, it is used to evaluate systematic errors from the remaining discrepancies. While the LINAC provides samples of data for limited sets of positions and energies and (until now) only one fixed direction, a single MC

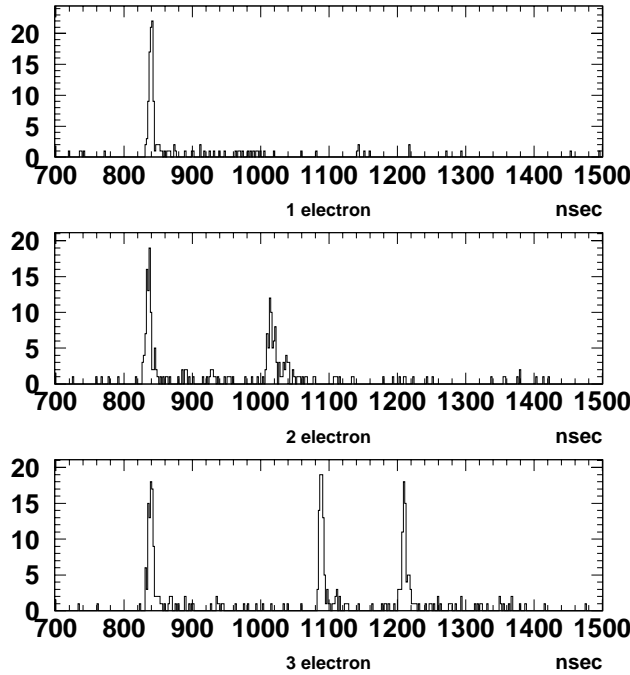


Fig. 9. Examples for TOF subtracted timing information for LINAC events containing one, two and three electrons.

description covers the whole range of solar neutrino events. LINAC calibration data and MC simulation output will hereafter be referred to as LINAC and MC. MC simulation is based on GEANT version 3.21[8]. Calibration equipment is included in this simulation. All MC shown in the figures uses the current best set of tuned parameters. New insights in details of the detector response may change this MC description and the derived parameters.

The PMT timing resolution for single photo-electrons in the MC is tuned to reproduce the vertex resolution throughout the detector. The value of 2.4 ns derived here is in agreement with independent measurements on the SK PMTs reported in a previous NIM paper[9]. An example of MC and LINAC vertex distributions in terms of distance from the beampipe end position to the reconstructed vertex is shown in Fig. 10. Fig. 11 shows the vertex resolution for all positions as a function of energy and the relative differences between MC and LINAC. Vertex resolution is defined as the radius of the sphere around the beampipe end position that contains 68% of the reconstructed vertices. Errors in the position averaged diagram reflect the spread (RMS) of values deduced for the individual LINAC positions.

Many MC parameters have influence on the energy scale. Its position dependence is mostly affected by Cherenkov light attenuation, while the overall scale is adjusted by the PMT collection efficiency. At short wavelengths, the

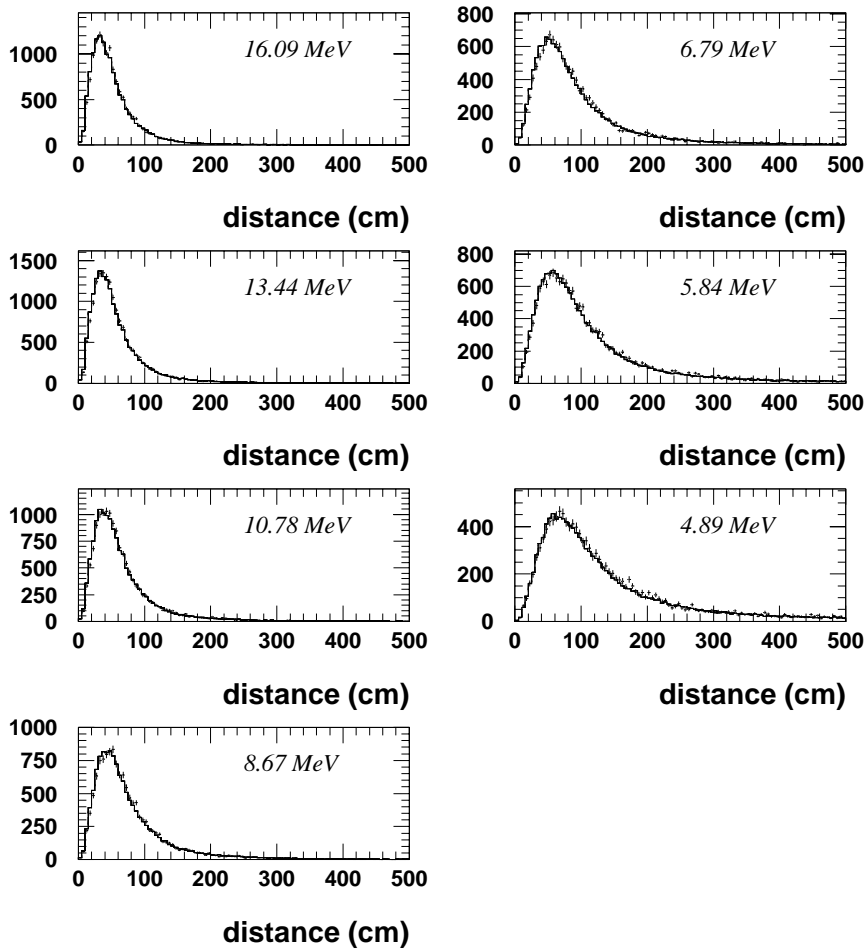


Fig. 10. Vertex distributions for $(x,z)=(-12m,+12m)$. Histogram is MC, points LINAC.

attenuation length is limited by scattering. MC tuning fixes it at $\bar{5}9.4$ m for 380 nm. The same result is obtained from a direct measurement in the SK tank, yielding $\bar{5}9.4 \pm 1.6$ m at this wavelength⁹. PMT quantum efficiency and the reflectivities of various detector materials are put into the simulation from direct measurements. MC and LINAC reconstructed energy distributions overlaid for one position in the tank are shown in Fig. 12.

Fig. 13 compares absolute energy scales as a function of both energy and position. For this comparison, MC and LINAC distributions, like the ones shown in Fig. 12, are reduced to peak value and width by a Gaussian fit around the center. In Fig. 13b the systematic error of the position averaged scale shift

⁹ For wavelengths longer than 400 nm, the attenuation length becomes longer than 75 m, until absorption starts beyond ~ 430 nm. Most of the Cherenkov light is detected near 380 nm.

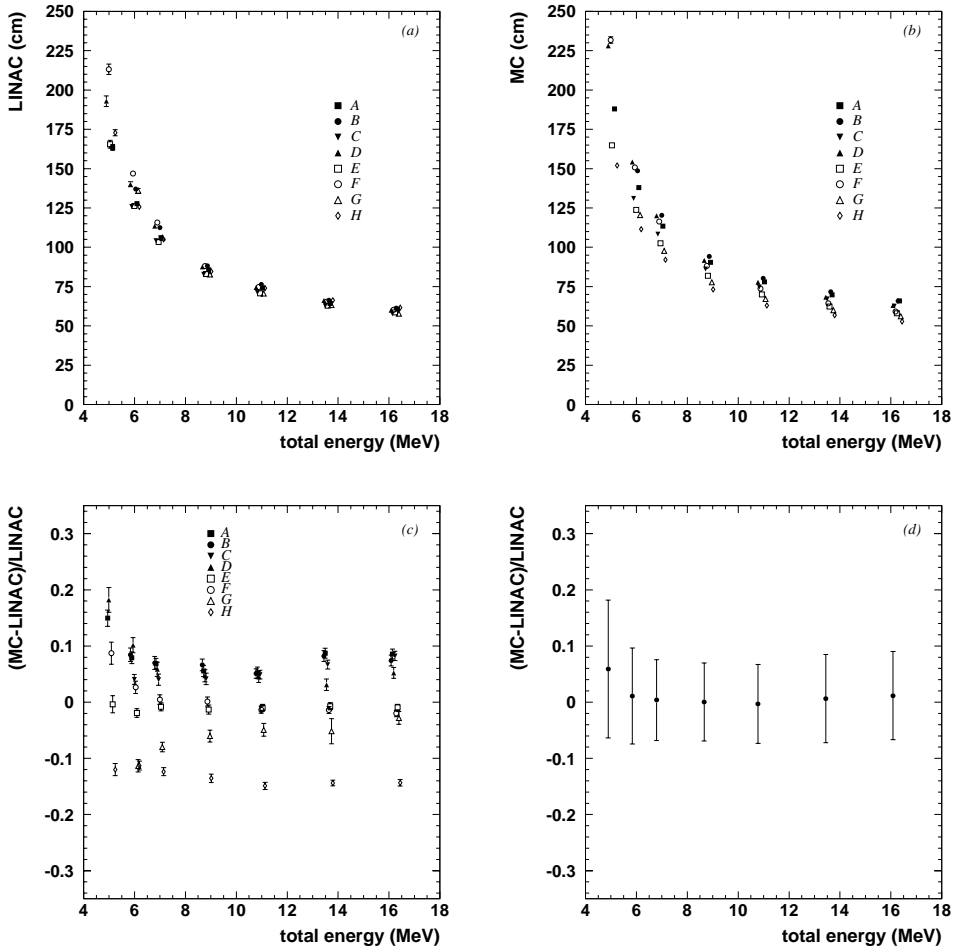


Fig. 11. Vertex position resolutions of (a) LINAC and (b) MC. A–H are defined in Tab. 4. (c) shows relative differences for all positions over momentum, (d) averages over position. Errors in (a)–(c) are statistical, while in (d) it is the RMS of the spread over positions in (c).

increases toward lower energies, but the central value always stays within $\pm 0.5\%$. This increase in error is due to uncertainties in the reflectivity of the beampipe endcap’s materials (see below). The statistical errors in this figure represent the spread (RMS) of the central values for the different positions.

Energy dependence of the energy resolution for MC and LINAC is compared in Fig. 14. The energy resolution is not tuned directly. It is defined as the width of the Gaussian fit divided by its peak value. The current MC reproduces the experimental distributions to within 2%.

Estimates for the systematic error of the absolute energy scale are given in Tab. 5. With uncertainties of the energy loss in the beam pipe endcap estimated to be 2 keV, and 1.5 keV from the calibration of the germanium detector, the reproducibility of the momentum selection in D1 with 20 keV

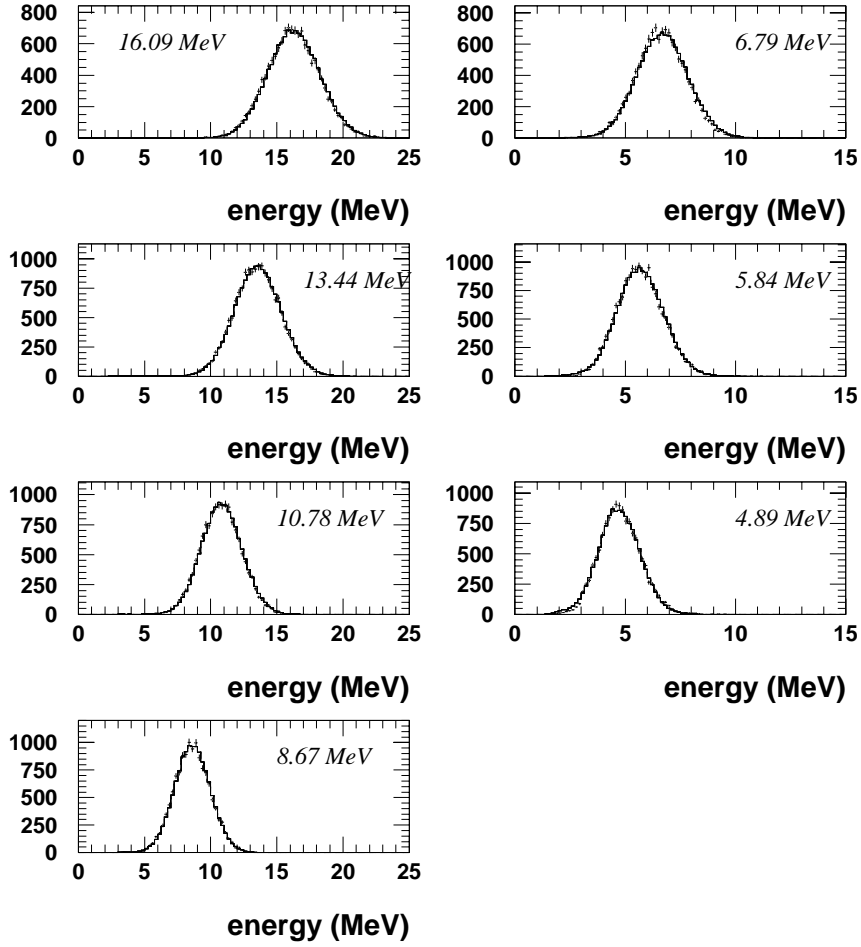


Fig. 12. LINAC (crosses) and MC (histogram) energy distributions for $(x,z)=(-12m,+12m)$.

dominates the uncertainty in the LINAC beam momentum. Beam correlated background may contribute up to 0.16% (see section 3).

The most serious difficulty is the reflectivity of the endcap. At 5 MeV, about 5% of the Cherenkov photons emitted by an electron leaving the beampipe will hit the endcap (see column 2 of Tab. 5). Recent tests revealed that there is some danger for a bubble of air to be trapped within the rim closing the seal of the titanium window. Thus, although the reflectivity of the steel beampipe and the titanium window were measured, the presence of a bubble of air of unknown size in front of it would change the situation significantly. MC estimates for the extreme cases of no air and maximum bubble size are currently used to obtain a conservative estimate of this uncertainty. The numbers are given in column 3 of Tab. 5.

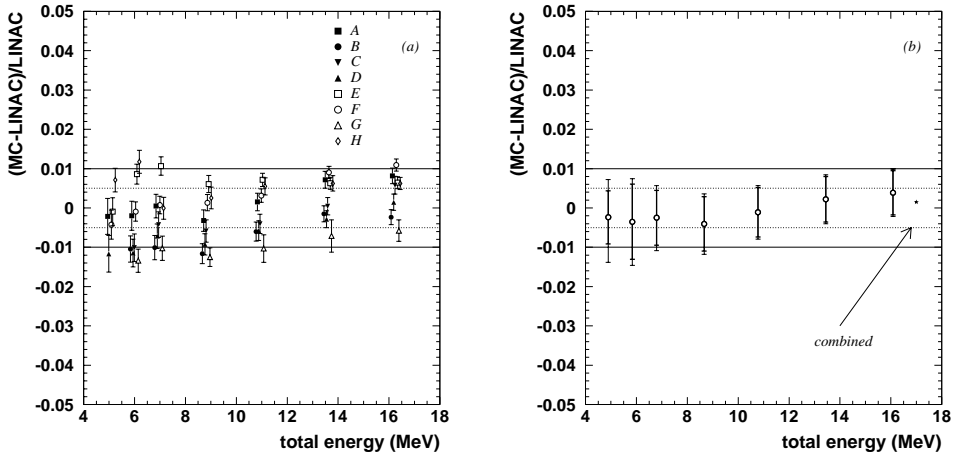


Fig. 13. Comparison of absolute energy scales for LINAC and MC. A–H are defined in Tab. 4. (a) has only statistical errors. For the position averages shown in (b), the inner error is the RMS of the spread over position while the outer one is the systematic error. Dotted and solid lines show ± 0.005 and ± 0.01 in $(MC-LINAC)/LINAC$. The last point in (b) represents the total average over all positions and beam energies.

beam momentum (MeV/c)	fraction hitting beam pipe	error due to reflectivity	total systematic error
5.08	4.7%	$\pm 0.68\%$	$\pm 0.81\%$
6.03	3.3%	$\pm 0.40\%$	$\pm 0.55\%$
7.00	2.2%	$\pm 0.28\%$	$\pm 0.44\%$
8.86	1.3%	$\pm 0.18\%$	$\pm 0.33\%$
10.99	0.88%	$\pm 0.11\%$	$\pm 0.27\%$
13.65	0.67%	$\pm 0.08\%$	$\pm 0.24\%$
16.31	0.51%	$\pm 0.06\%$	$\pm 0.21\%$

Table 5

Systematic errors at the various LINAC momenta. The first column shows beam momentum, the second the fraction of Cherenkov photons hitting the beam pipe, the third the systematic error due to uncertainty of the reflectivity of the endcap, and the last the resulting total systematic error in the derived absolute energy scale.

A cross-check validating the absolute energy scale established in the LINAC calibration comes from ^{16}N decays. ^{16}N is produced throughout the detector by stopping cosmic ray muons, providing a data sample free of the mechanical constraints of the LINAC. This data sample also is well reproduced by the MC simulation.

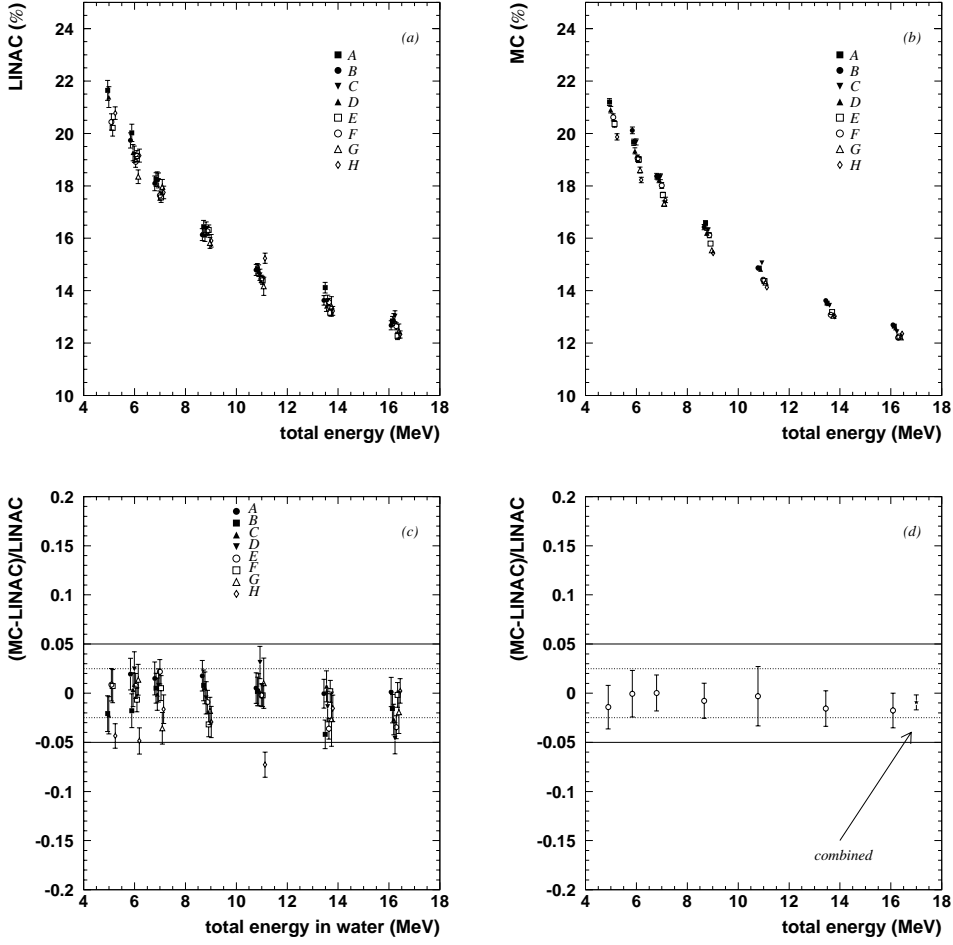


Fig. 14. Energy dependence of energy resolution of (a) LINAC and (b) MC, (c) relative difference between (a) and (b). (d) shows the position averages, and its last point the total average. Errors as in Fig. 11. A–H are defined in Tab. 4. Solid and dotted lines are ± 0.05 and ± 0.025 in $(MC-LINAC)/LINAC$.

Angular resolution is another quantity that is not tuned directly. Fig. 15 shows the opening angle between the reconstructed particle direction and the direction of beam injection for MC and LINAC at a chosen position. In Fig. 16(a) and (b), the angular resolution of LINAC and MC are displayed as functions of energy and position. Angular resolution is defined as the opening angle of a cone around the beam direction which contains 68% of the reconstructed directions. Fig. 16(c) shows the normalized offset between LINAC and MC resolution for all positions in the tank, Fig. 16(d) the same quantity averaged over position. The relative difference between LINAC and MC becomes smaller for a slightly different choice of MC tuning parameters. The current choice of these parameters optimizes the uniformity of the energy scale throughout the detector volume.

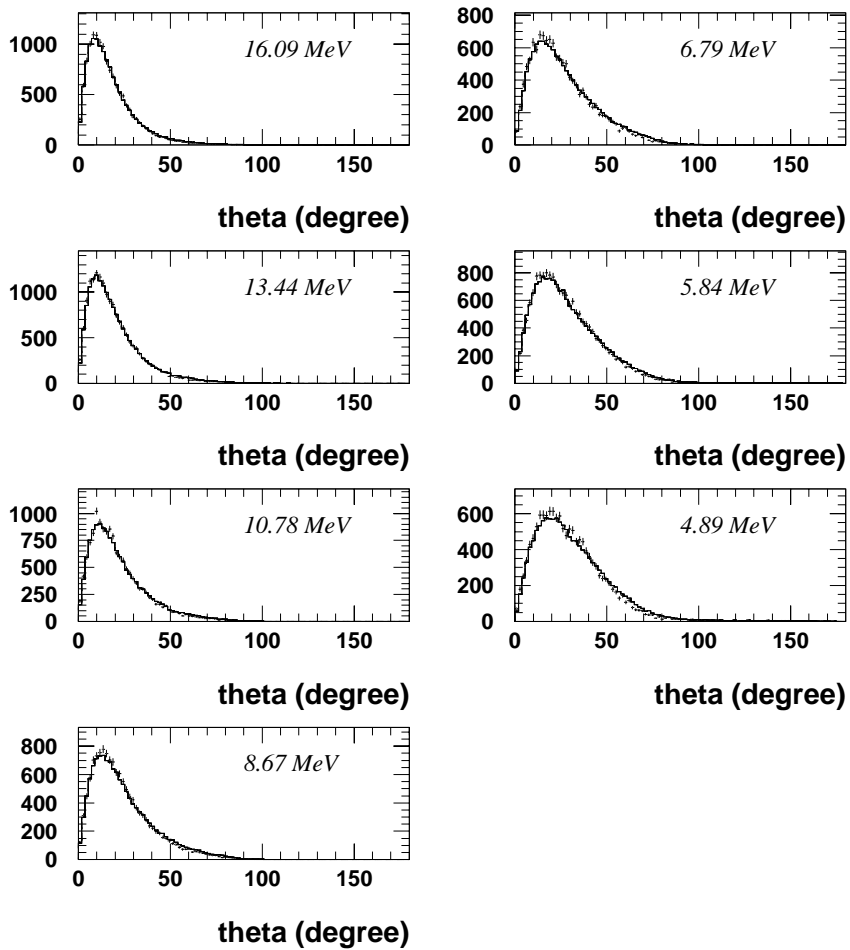


Fig. 15. Angular distributions for $(x,z)=(-12m,+12m)$. Histogram is MC, points LINAC.

Tab.6 summarizes experimental resolutions of the Super-Kamiokande detector as observed on single electron LINAC events. Numbers for individual positions are extracted from experimental distributions like the ones shown in the figures 10, 12, and 15 as described above. Entries in the table are averages over all LINAC positions. The spread observed between the various LINAC positions is reflected in the quoted errors (RMS).

6 Conclusions

The Super-Kamiokande detector is calibrated with an electron LINAC for the energy range from 5 MeV to 16 MeV. By this means the absolute energy scale for the solar neutrino analysis is known with an accuracy better than 1%.

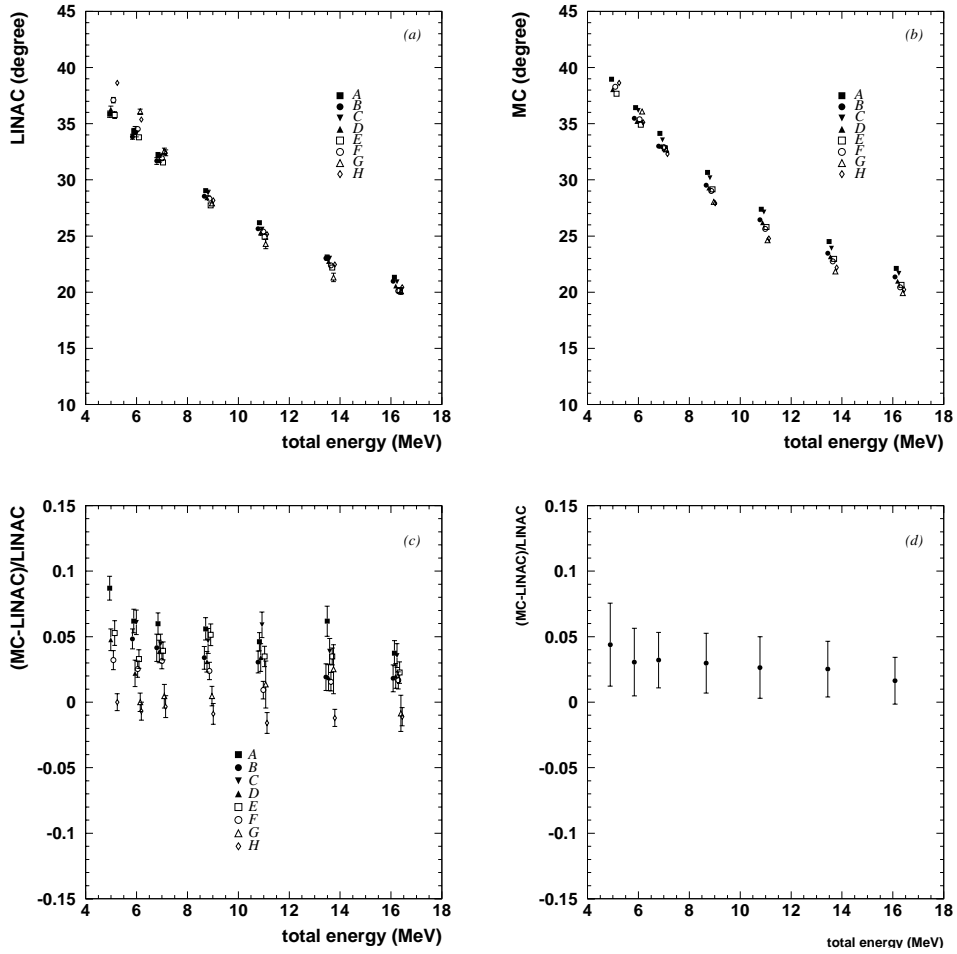


Fig. 16. Energy dependence of angular resolution of (a) LINAC and (b) MC. (c) is the difference between (a) and (b), (d) is averaged over positions. Errors as in Fig. 11. A–H are defined in Tab. 4.

MC simulation reproduces the energy resolution of the Super-Kamiokande detector to within 2% and its angular resolution to better than 1.5 degrees for 10 MeV electrons. MC vertex resolution is well tuned to match the LINAC data.

Various improvements of the current setup are in development and will soon be implemented. A permanent magnet for installation at the end of the beam pipe is currently being designed, which will allow bending of the LINAC electrons out of the -z direction.

total energy (MeV)	energy resolution (%)	angular resolution (degree)	vertex resolution (cm)
4.89	20.9±0.6	36.7±0.2	182±21
5.84	19.2±0.5	34.6±0.2	133±8
6.79	18.0±0.3	32.0±0.1	108±5
8.67	16.2±0.2	28.4±0.2	85±2
10.78	14.7±0.3	25.3±0.2	73±2
13.44	13.5±0.3	22.5±0.1	65±2
16.09	12.6±0.3	20.6±0.1	50±2

Table 6

Experimental detector resolutions for Super-Kamiokande as derived from LINAC data

7 Acknowledgement

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