Astroparticle Physics

Report to the 65. PRC, Hamburg, April 2007

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1. Executive Summary

The last IceCube season was a great success. 50% of IceCube are now installed, and physics on the cubic kilometre scale is starting. Given the present dramatic boost in sensitivity and in discovery potential, the highest priority of the next years will be the physics analysis of IceCube data. DESY's hardware contributions to the IceCube detector will be completed at the end of 2008. At the same time, R&D on acoustic neutrino detection at the South Pole is continued with the aim to precisely assess the feasibility of this method in ice. Participation in Baikal will be finished in 2008 and resources directed to CTA, the Cherenkov Telescope Array. With the present participation of the Young Investigators Group in MAGIC, first steps in gamma astronomy are being done. CTA is the most consistent next step and is planned to anchor gamma astronomy as a major research line at DESY, close in physics to IceCube but complementary in the messenger particle. Section 8 of this report describes the physics potential of CTA in some detail and discusses the role which DESY could play in this large European project.

2. Introduction

A detailed report has been submitted to the last PRC in November 2007. In the present document, repetitions are not avoidable, but the focus will be on recent results and on the plans for CTA, the Cherenkov Telescope Array. We refer to the November-07 document for additional information.

The DESY astroparticle group in Zeuthen has a 20-year tradition in high-energy neutrino astronomy. With its prominent activities in Baikal and AMANDA it is a pioneer in this field. Our participation in the Baikal Experiment will finish in 2008. AMANDA is now an integral part of IceCube. In IceCube, DESY is the strongest partner after the lead institution University of Wisconsin, Madison. DESY provides backbone services (organizational, technical, financial and on the computing sector) for other German IceCube participants. Given the significant investment in IceCube and, more importantly, the dramatic boost in sensitivity and in discovery potential expected for the years 2008-2012, the highest priority of our group in the next years will be the physics analysis of IceCube data. DESY also pioneers an R&D program for acoustic detection techniques, with the aim to provide a method for future IceCube extensions towards extremely high energies.

Point source analyses and multi-messenger studies are performed within a Helmholtz-University Young Investigators Group (DESY/Humboldt University). Following the multi-messenger principle, this group also participates in the gamma telescope MAGIC. The table below sketches the present formal structure of astroparticle activities in Zeuthen.

	DESY-budget		**Third Party Funding**	
Staff members	Nahnhauer, Schlenstedt, Spiering, Walter, Wischnewski			
Lead Young Investigators Group			Bernardini	
Post-Docs	2	1		1
PhD students	5	2	2	
		Young Investigators Group NG 205		SFB 676

50% of IceCube is now installed and operating, data taking has started. IceCube installation will be completed in January 2011, DESY hardware contributions at the end of 2008. The most interesting years will likely be 2008-2013. From then on, the sensitivity for many analyses increases only with the square root of time, since it is limit by background. Given the present dramatic boost in sensitivity and in discovery potential, the highest priority of the next years will be the physics analysis of IceCube data. At the same time, the group started to think about projects that may first flank IceCube and later replace it as main activity. We propose CTA to be this project.

3. IceCube Status and Plans

IceCube includes 29 institutions from eight countries, with DESY being the second strongest in scientific manpower, after the University of Wisconsin, Madison (see Fig. 4.1 in the material submitted to the previous PRC). German participants are Humboldt University Berlin, Universities Wuppertal, Dortmund and Mainz, MPI Heidelberg (via an Emmy Noether group) and RWTH Aachen.

DESY physicists took formal responsibilities at different levels. As former spokesman, C. Spiering is ex-officio member of the Executive Committee. S. Schlenstedt is Level-3 lead for reconstruction, and chair of the Speakers Committee. E. Bernardini is chair of the point-source working group, H. Kolanoski chair of the cosmic ray working group and R. Nahnhauer chair of the acoustic working group.

In its original design, the IceCube detector was conceived to consist of 4800 Digital Optical Modules (DOMs) on 80 strings in the deep polar ice, complemented by the air shower detector IceTop on the surface. Due to an apparent cost overrun, the baseline was reduced to 70 strings in 2005, but re-adjusted to 75 strings in 2007. The remaining contingency budget will very likely allow eventual re-adjustment to 80 strings.

The recent polar season was a great success. After one string deployed in the season 2004/05, eight in 2005/06 and 13 in 2006/07, the minimum goal for the season 2007/08 was set to 14 strings. Despite initial delays due to weather and logistics, the final count was 18 strings and 26 IceTop tanks. Fig. 3.1 shows the times needed for drilling and for deployment for the first 16 of the strings. The 40 hours for drilling and 12 for deployment are now reliable standard and give hope to even exceed the 18-string benchmark in the next season (see below).

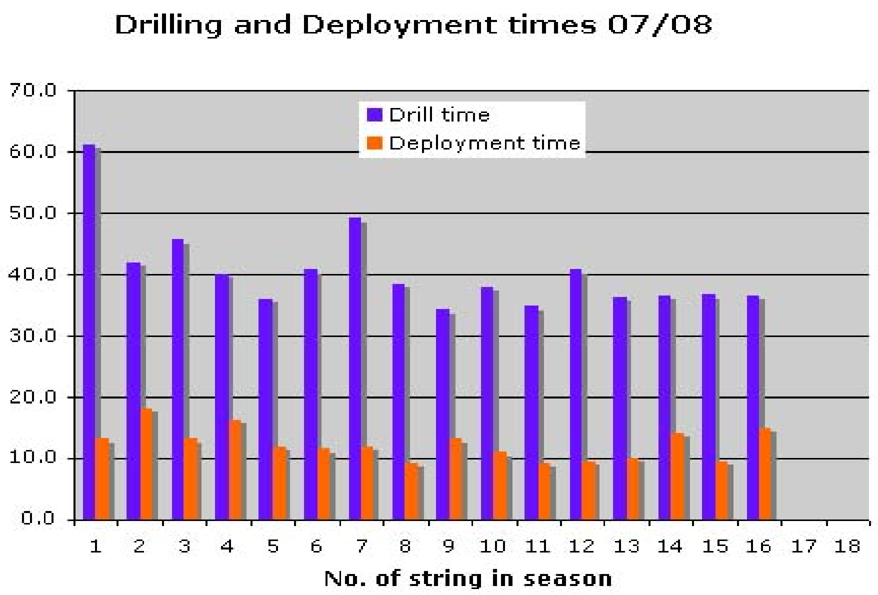

Fig. 3.1: Drilling and Deployment times in the season 2007/08

Fig. 3.2 shows the present IceCube configuration. Forty strings, e.g. 50% of IceCube, are now deployed and take data. This will allow doing physics at the cubic kilometre scale starting in a year!

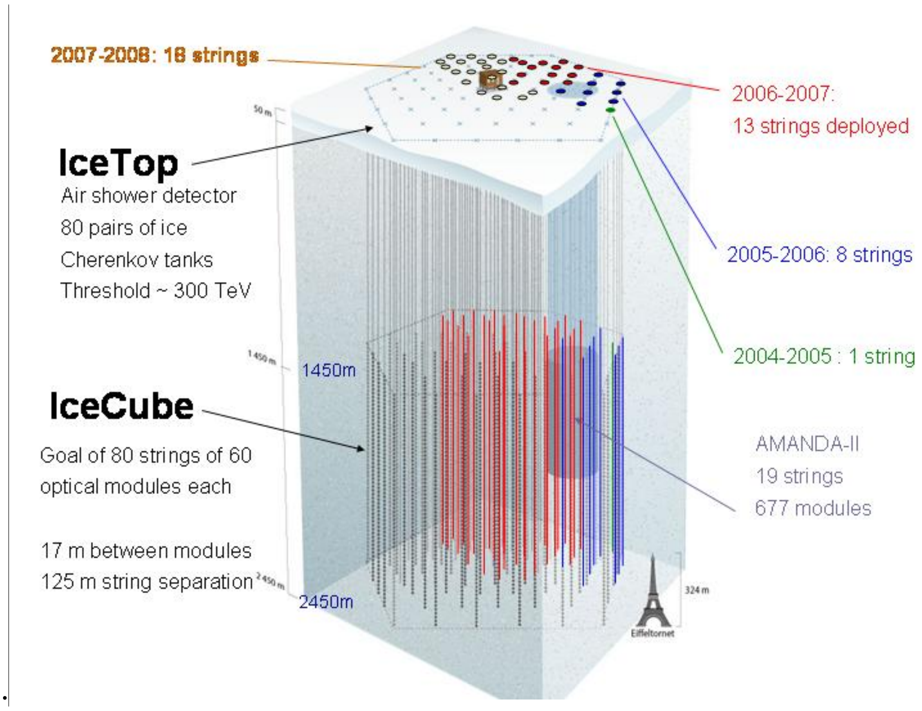

Fig. 3.2.: IceCube Observatory: construction status as of January 2008.

Fig. 3.3. sketches the deployment plans for the coming season. The goal is to deploy in 2008/09 20 strings at maximum, shown in red in Fig. 3.3 This includes one of the DeepCore strings. DeepCore is the replacement of AMANDA which will be terminated in 2010 due to the snow accumulation around the AMANDA counting house, its high power consumption and its over-proportional maintenance effort when compared to IceCube. DeepCore will consist of six additional strings which are instrumented with digital optical modules (DOM) at small spacing below the 2000 m dust layer, in the best ice. A minimum version with 40 DOMs per string, spaced by 10 meters, has recently been approved and funded (with 2.4 M US$) by the Swedish Wallenberg foundation. Additional funding for instrumentation with 60 DOMs per string and using the same type of photomultiplier but with 30% better quantum efficiency is applied for by German and Belgian universities. DeepCore will replace AMANDA as a dense core with low energy threshold. Compared to AMANDA, its performance would be significantly improved, due to the complete IceCube veto and the better ice. DeepCore would allow observation

of the Southern sky, extension of the indirect dark matter search to lower WIMP masses, slightly improved point source sensitivity for steep source spectra and, possibly, oscillation studies in a hitherto unexplored energy regime. A rearrangement of the final 8-10 outer strings on a large circle around IceCube, with 250-300 meter spacing is under discussion. This would possibly enhance the sensitivity at 100 TeV - 1 PeV by a factor 1.5-2. It would also allow testing of radio and acoustic signal transmission over more than 1 km distance – a last performance check towards a possible hybrid radio-acoustic array on the 100 km² scale. R&D on acoustic detection will be discussed in the next section.

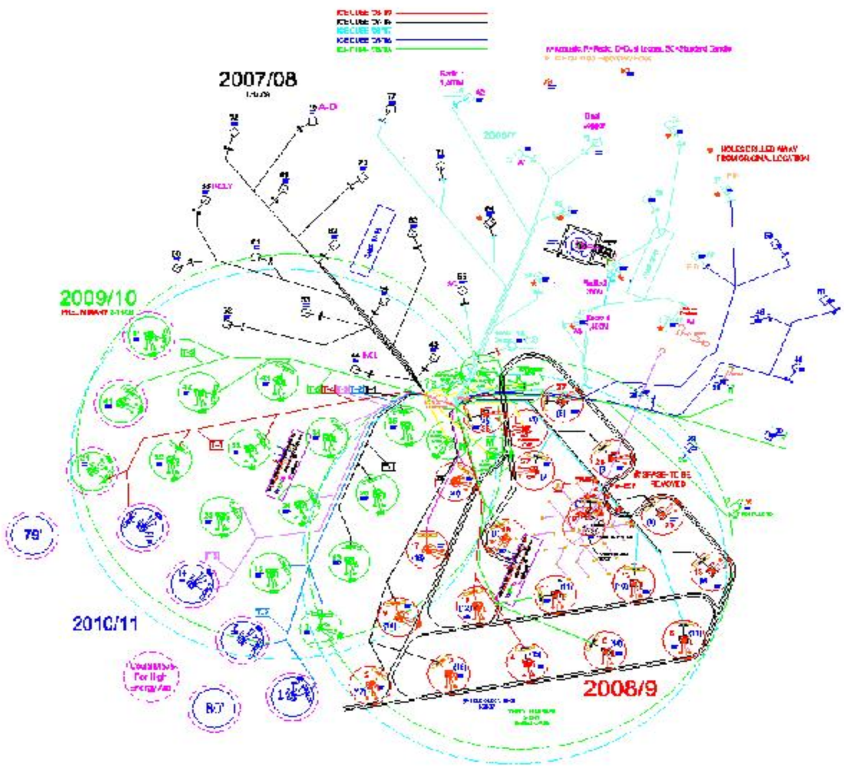

Fig. 3.3 Deployment plans for the coming seasons

DESY contributions 2007/08:

In 2007, DESY has assembled, tested and delivered 480 DOMs (after 60 in 2004, 160 in 2005 and 258 in 2006) in accordance with collaboration-wide production plans. DOM production is scheduled to be completed in 2008. With 2%, the failure rate of DOMs during freeze-in is smaller than expected. Only 2 DOMs (less than 0.2%) have failed in the months/years after freezing. DESY has developed the DOM Readout (DOR) card, is still supervising initial testing and maintenance. In 2007, 252 DOM cards have been delivered and production was completed. In the next season, a firmware upgrade allowing for doubling the transmission rate and therefore lowering the energy threshold will be installed. Moreover, DESY supplies the magnetic shielding for all DOMs of IceCube as well as all steel chains holding the DOMs. DESY is coordinating writing and implementation of the reconstruction software, including online reconstruction at Pole. It is also processing data and performs mass Monte Carlo simulation. First GRID tools have been installed. DESY is the European data centre of IceCube. At the end of 2007, 260 of 400 cores available for IceCube have been devoted to IceCube Monte Carlo simulation. DESY is also involved in IceTop calibration and monitoring, as well as in general IceCube monitoring.

4. Acoustic Neutrino Detection

Extensions of IceCube towards EeV physics using radio and acoustic methods have been discussed since long. Due to the larger attenuation length of radio and acoustic signals compared to light signals, their detection would allow larger sensor spacing and therefore a larger sensitive volume, at a less progressive cost. A 100 km^3 radio/acoustic detector has been simulated with "reasonable" assumptions on signal creation, signal transmission and ambient noise. The aim of the present R&D program is to precisely determine these parameters in situ and to assess the feasibility of a hybrid radio/acoustic detector around IceCube. A clear and qualified assessment should be ready at the time of a possible closer consideration of a large array. Hybrid detection would considerably increase the capability to discriminate signal from background. The physics of a 100 km^3 array would be that of GZK neutrinos (emerging from the interaction of charged cosmic particles with the 3K background and containing cosmologically relevant information) and of extremely energetic accelerators such as those identified by Auger. Moreover, highest energies have the potential to contribute to basic questions of particle physics.

The DESY group is spearheading efforts to detect acoustic signals from neutrino interactions since long. We have built sensitive acoustic detectors for in-ice application and tested them at accelerator beams and in the laboratory, reaching a self-noise as low as 5 mPa. For the acoustic in-situ study at the South Pole, the South Polar Acoustic Test Setup – SPATS – has been built under DESY leadership. It is aimed to evaluate the acoustic attenuation length, speed of sound and refraction behaviour as well as background noise level and transient event rates.

In January 2007, three strings were deployed in the upper 400 m of IceCube holes. They form a triangular array with inter-string distances of 125, 302 and 421 m. The upper part of the ice has a larger density gradient, therefore a larger variation of the acoustic properties is expected and the instrumentation density increases towards surface. This configuration was successfully commissioned in February 2007, followed by continuous data taking. All 21 transmitters and 53 out of 63 sensor channels were working normally.

To improve the data quality and get more information for different distances between transmitters and sensors, a fourth string was built and tested under laboratory conditions. It has been deployed in December 2007 to a maximum depth of 500 m. Besides mechanically and electronically improved SPATS sensors and transmitters, it carries two new sensors built at University of Wuppertal and a new transmitter from EPFL Lausanne. In addition, a specially prepared transmitter (pinger) has been be moved up and down in several IceCube holes, directly between drilling and deployment of optical sensors. Its acoustic signals have been registered by the SPATS sensors, provide for the first time the possibility for a relative in-situ calibration of the acoustic sensors in the ice and are the basis for detailed sound speed and attenuation length studies. Figure 3.1 shows a view of the present SPATS array configuration. In Fig. 3.2, a sketch of the location of SPATS strings and pinger holes is given. Figure 3.3 shows the pinger moving down in a bore hole.

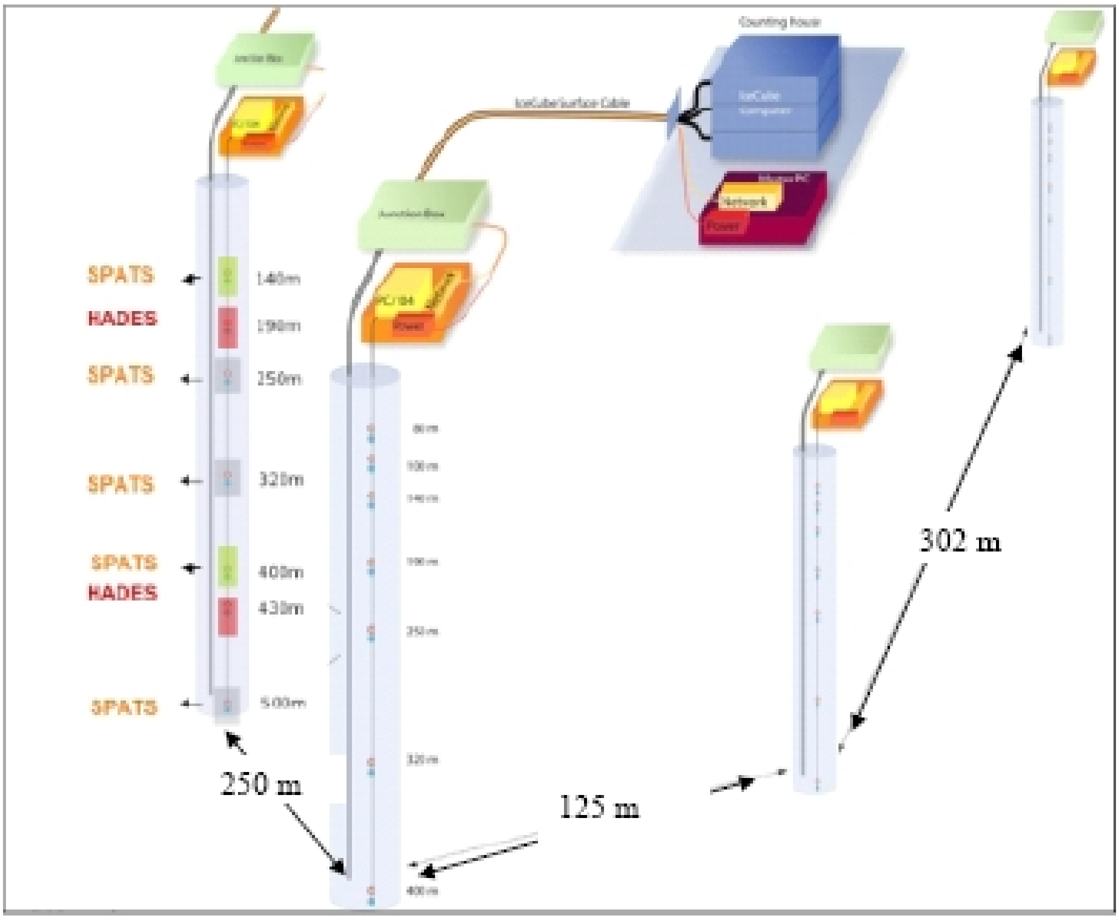

Fig. 4.1 Schematic view of the SPATS 4-string configuration

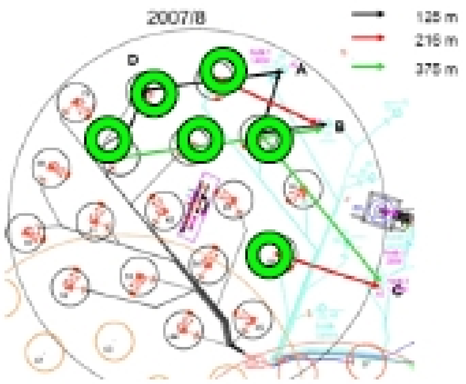

Fig. 4.2 Sketch of SPATS string locations and pinger holes

Fig. 4.3 Pinger moving down a hole

The main findings from the year 2007 and from the last deployment season are the following:

- The speed of sound has been measured with a precision of better than 1% between 80 and 500 m depth. The results above 200 m confirm previous ones, showing a large gradient to smaller values at smaller depth. This leads to a refraction pattern, bending surface sound signals back to the surface (i.e. shielding against surface noise!). Below 200 m the measurements are consistent with a constant sound speed, i.e. no refraction. This will allow easy reconstruction of sound sources.

- The frequency spectra of noise at different depths are mostly flat, with a broad maximum below 20 kHz and some sharp peaks at higher frequencies which increase with depth and are still unexplained. The precise absolute noise level is difficult to be calculated without an in-situ calibration of sensors. A preliminary rough estimate shows that the noise at 400-500 m depth is close to the SPATS sensor self-noise levels supporting the expectation that ambient noise will be below 10 mPa. Data from the new sensors built in Wuppertal (HADES) have still to be evaluated. Both a SPATS and a HADES sensor have been studied in an ice tank of the Aachen acoustic Laboratory before deployment, with the expectation that this will allow evaluating the absolute noise level with much better precision in the near future.

- During the last drilling season the SPATS sensors were able to register a noise increase originating from the water turbulences inside the bore holes during drilling, at a defined depth and up to distances of 660 m. This data may allow a completely different study of sound attenuation in comparison to the usual approach.

- The large number of transmitter/sensor combinations at different distances for SPATS transmitter as well as pinger data will allow to evaluate the quality of the surrounding ice in a three dimensional pattern. The data from the movable pinger used in six IceCube holes have been taken with the aim of a relative in-situ calibration of the SPATS sensor amplitudes, important for the attenuation length determination. First results indicate that the influence of the re-frozen bore hole ice is stronger than previously expected. Further studies are necessary to come to final conclusions.

- A more precise determination of the attenuation would profit from a longer baselines for signal propagation. Such a possibility could be offered by the possible re-configuration of the last IceCube strings and their arrangement on a ring with one kilometre radius. A decision about this high energy configuration is expected for this summer. Simulation calculations have been started which will show what additional questions can be answered if radio and acoustic sensors would be co-deployed with the DOMs. Questions like whether energy thresholds could be kept very low and whether one can hope to detect a handful of coincident radio-optical and radio-acoustic events will be answered during the next months. Also the technical performance of prototype hybrid strings, operating at kilometre-scale distances will be considered. The deployment of these test strings, if logistically feasible and positively evaluated, would happen in the season 2010/11 or 2011/12. Therefore a decision about a new hybrid test project is necessary not later than end of 2008.

5. Baikal

The Baikal Neutrino Telescope NT200 started full operation in 1998. The Zeuthen group participates in the project since 1988. Prime contributions from DESY have been the laser calibration system and large parts of the DAQ. Until recently, NT200 was the only large neutrino telescope at the Northern hemisphere. This has been changed with the installation of ANTARES. DESY considers its mission accomplished and will terminate its official Baikal membership in 2008, after 20 years of a memorable collaboration which included, among others, the pioneering operation of the first underwater telescope in 1993 and results competitive over many years with those from AMANDA, most notably limits on diffuse neutrino fluxes, on the fluxes of magnetic monopoles and on neutrinos from dark matter (WIMP) annihilation in the Earth. Publications close to submission cover the search for astrophysical point sources, the search for neutrinos from WIMP annihilations in the Sun, the search for slow monopoles and searches for coincidences with GRBs. With the publication of these results, DESY activities will be finished and the corresponding manpower directed to CTA.

6. AMANDA and IceCube physics results

For the results from 2006 and early 2007, we refer to the 2007 report to the last PRC.

Point sources:

The Young Investigator group has extended the point source search to the Southern hemisphere (upper hemisphere at the South Pole) and ultra-high energies (PeV/EeV range). Since at low energy the background from down going muons (in particular muon bundles) dominates any neutrino signal, the analysis has to be tailored to high energy, single muons. Figure 6.1. compares the sensitivities of the standard AMANDA point source search (lower hemisphere) with the high-energy search (effective also at the upper hemisphere). Here, a source with an E^{-2} spectrum is assumed. At the horizon the sensitivity curves nearly match, above the horizon only the high-energy search gives reasonable sensitivities. We note that for a source with a spectrum much harder than E^{-2}, the high-energy analysis is complementary or even superior to the standard analysis down to 30 degrees below horizon. The method is particularly exciting since it moves Centaurus A (declination -43°) into the field of view of AMANDA/IceCube. The recent Auger data show a suggestive clustering of high energy cosmic rays around Cen-A.

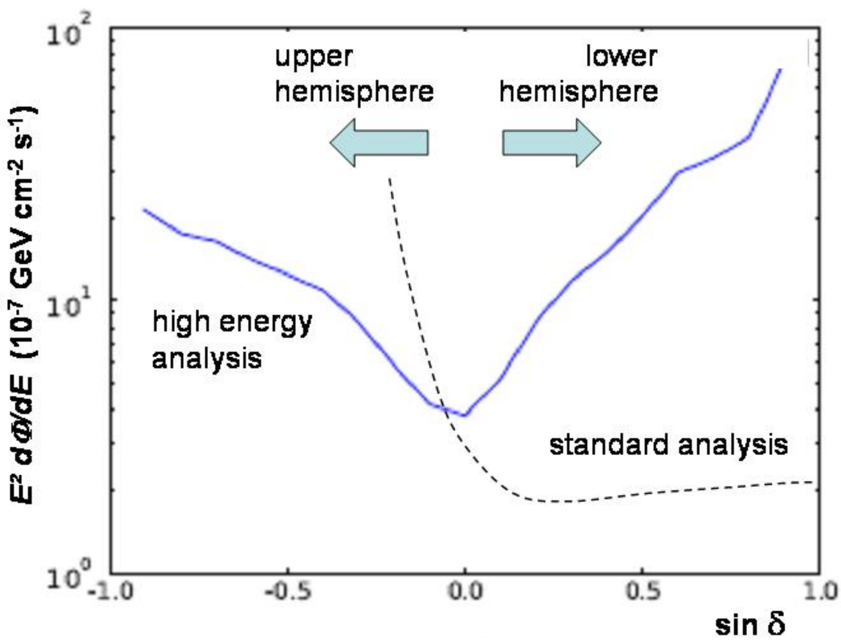

Fig. 6.1: One-year sensitivities of AMANDA to an E^{-2} source for the standard analysis and the high energy analysis vs. the sine of the declination of the source. (Note that the sensitivity of the different analyses rests on different energy bands. For the high energy analysis, northern hemisphere, most of the contribution comes from 0.1-10 PeV, for the Southern hemisphere from 1-100 PeV. The standard analysis mostly relies on the contribution from the energy band 10^{-4}-1 PeV.

Figure 6.2 shows, as a reminder, the published 5-year AMANDA sky map for the Northern hemisphere. Figure 6.3 shows a one-year "sky-map" in detector coordinates for the high-energy point source analysis (preliminary). Naturally, most events populate the Southern hemisphere. Whereas in fig. 6.2 the sample is a nearly background-free neutrino sample, most of the events in fig. 6.3 are background events from atmospheric muons: the method maximizes the sensitivity to point sources, not the neutrino-purity of the sample!

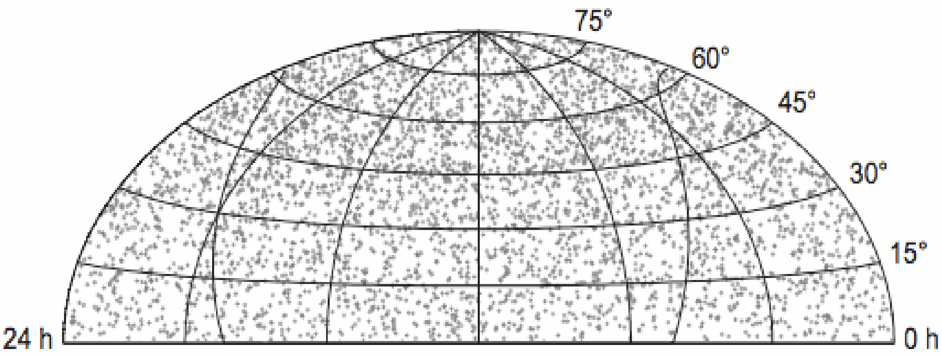

Figure 6.2: Sky map of the 4282 AMANDA neutrino events from the Northern hemisphere detected in 2000-2004 with the standard analysis

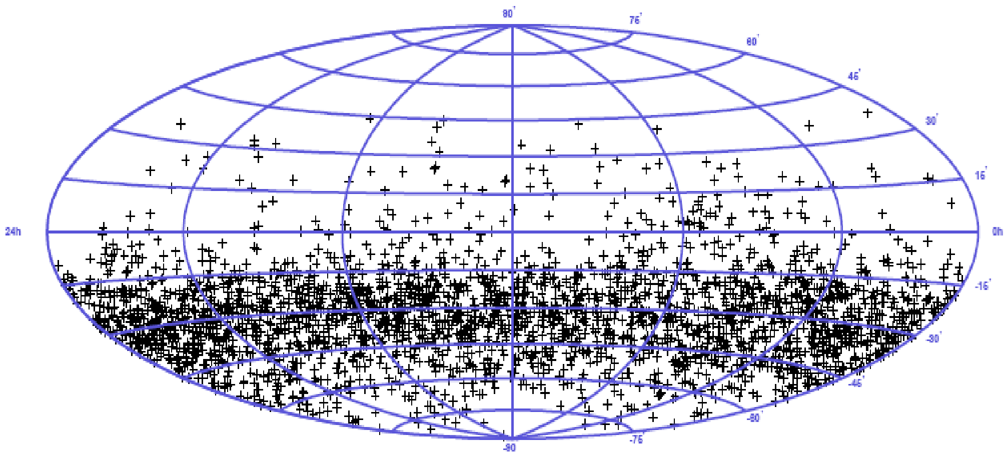

Figure 6.3: Map in detector coordinates of the AMANDA candidates for ultra-high energy neutrino events from the Southern hemisphere separated from the year 2000 data. The zenith angle corresponds to the declination in equatorial coordinates, the azimuth will be translated to rectascension only when the unblinding procedure has been finished. The focus of the ongoing analysis is the declination band between +30° and –30°.

The data shown in Fig. 6.3 will be assigned the correct sky coordinates in rectacsension values after the prescribed unblinding procedures of the IceCube collaboration have been passed. Only then, a possible point source could be identified. A similar high-energy analysis for IC-22 data (IceCube 22 strings, data taken in 2007) has started at DESY.

Standard point source analyses for IC-22 are performed at DESY and in Madison. Figure 6.4. shows the scrambled sky map for 18 days of IC-22 data of the DESY analysis. Unblinding of the full sample is foreseen to happen before the summer conferences. Note that the number of atmospheric neutrino events expected for one year is 1300-1500, i.e. not much higher than for AMANDA (850). The reason is the higher energy threshold, which cuts away more atmospheric neutrinos but appear to be no drawback in case of the harder spectra of typical astrophysical sources – see Fig. 6.5.

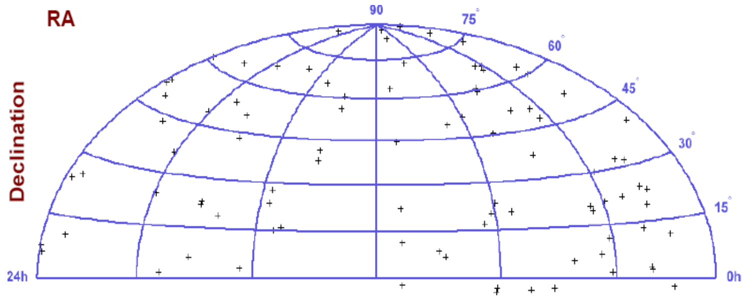

Fig. 6.4: Scrambled sky map from 18 days of IC22 data (2007), standard analysis

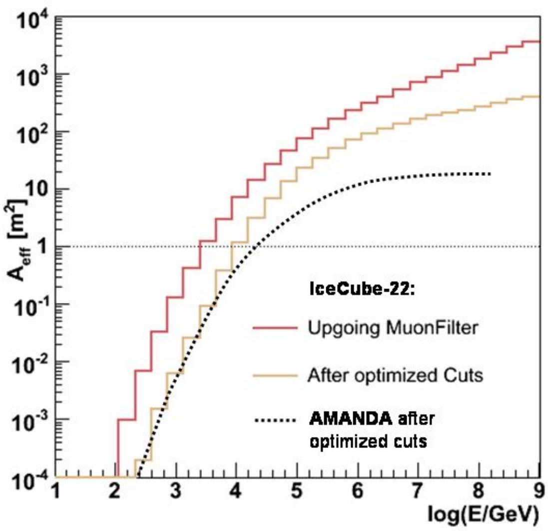

Fig.6.5: Effective area of IceCube-22 (2007) compared to AMANDA.

After the technically successful performance of a Target-of-Opportunity run together with the MAGIC collaboration at the end of 2006 (see the report to the previous PRC), the group has put much effort to improve the event reconstruction at the South Pole. Figure 6.6 sketches the main principles behind this work. The improved filtering and reconstruction methods are expected to be implemented after having passed the necessary IceCube procedures for installing new software at the South Pole.

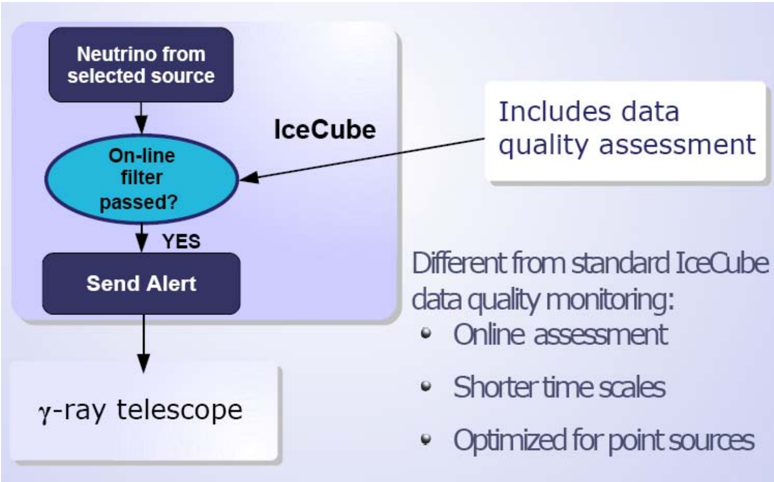

Fig. 6.6: Online filter and reconstruction improvements towards neutrino-triggered target of opportunity programs (NToO)

The results obtained so far prove a very good stability of the detector. 91% of all runs pass the filter for point sources analyses, with nearly all of the remaining 9% being due to running of light sources in calibration runs or to initial DAQ failures.

We emphasize that after the pioneering NToO run with MAGIC, various other programs with IceCube triggering Cherenkov gamma telescopes or optical telescopes have been evolved, with some of them likely being implemented in 2008.

Cascade Analyses

Interactions of electron and tau neutrinos, i.e. 2/3 of an extraterrestrial neutrino flux, lead to cascade-like events. The search for cascade events from extraterrestrial neutrinos with 5 years AMANDA data has been finished with a dissertation (DESY), and a journal publication is presently under preparation. IceCube cascade searches do not aim at point source identification but instead at the identification of the collective extraterrestrial neutrino flux of all unresolved high-energy neutrino sources. This isotropic neutrino flux (also called "diffuse flux") can be identified via an excess of events at high energies. The limit obtained from the DESY cascade analysis is shown in Fig. 6.7 as dashed curve. It is normalized to one flavour and compared to limits obtained from diffuse searches with muons. The dotted curve gives the muon result published in 2007 (years 2000-03), the three solid curves refer to preliminary muon results, which have been obtained from a second 4-year analysis to be published in 2008.

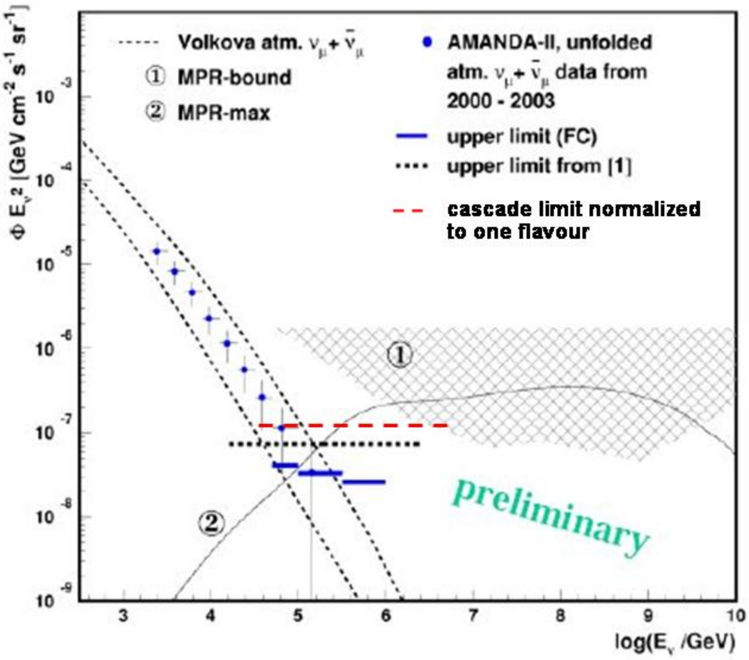

Fig. 6.7.: AMANDA limits on diffuse fluxes obtained from the analysis of 2000-2003/04 data. Dotted line: published results for muons, solid lines: preliminary results for muons based on an alternative analysis using the unfolded muon neutrino spectrum shown in the figure, dashed line: cascade limit. All limits are clearly below the upper bounds from Mannheim, Protheroe and Rachen (upper boundary of hatched area: bound for neutron-opaque source, lower boundary of hatched area: upper bound for neutron-transparent sources).

We note that the cascade limit is close to the muon limit, although the latter profits from the long muon range whereas cascade events are identified only as contained events. The containment, however, leads to a better energy determination. The larger the detector volume, the better the ratio of cascade-to-muon sensitivities. For full IceCube, both channels contribute to searches of diffuse extraterrestrial fluxes with about the same sensitivity. In close collaboration with the IceCube group at the Humboldt-University, we are preparing for the analysis of IceCube-40 data. Since cascade events typically evolve high photon intensities, the IceCube DOM technology (high dynamical range, full waveform) offers new possibilities, when compared to AMANDA. Hence our efforts are focusing on developing both new reconstruction and filtering methods to utilize this potential. A likelihood reconstruction is being developed which is using the full charge information and which allows to simultaneously fit vertex position, direction and energy. Initial results show that this method already performs similar or better then the default reconstruction methods. In addition a new first guess method for cascades has been developed which is intended to provide the seed for the Likelihood reconstruction, as well as discrimination variables to separate the cascade signal from the background of atmospheric muons.

With steadily lowered limits, the energy range for identification of extraterrestrial neutrinos naturally shifts to higher energies, since at lower energies atmospheric neutrinos dominate. With this rationale, methods are being developed to analyse showers at energies above 10 PeV, where the Landau-Pomeranchuk-Migdal (LPM) effect sets in: the decrease in electromagnetic cross sections leads to longitudinally extended showers, as shown in Fig. 6.8. In DESY, this effect has been implemented for ice. Fig. 6.9. shows the different light fields resulting from PeV and EeV showers. An analysis tailored to high-energy cascades is underway.

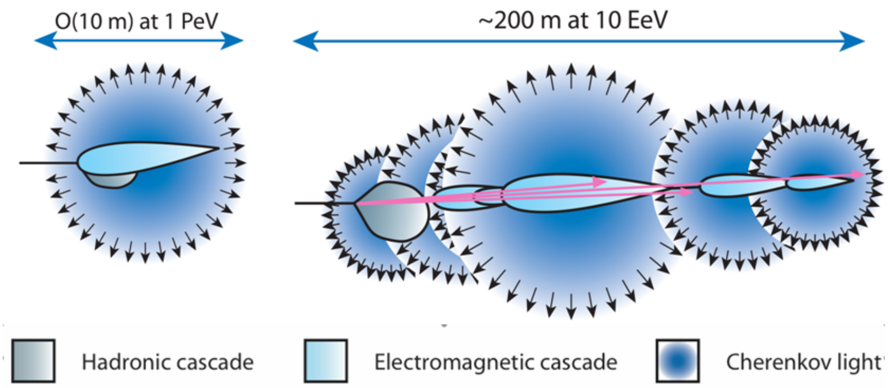

Fig. 6.8: Longitudinal extension of electromagnetic showers due to the LPM effect.

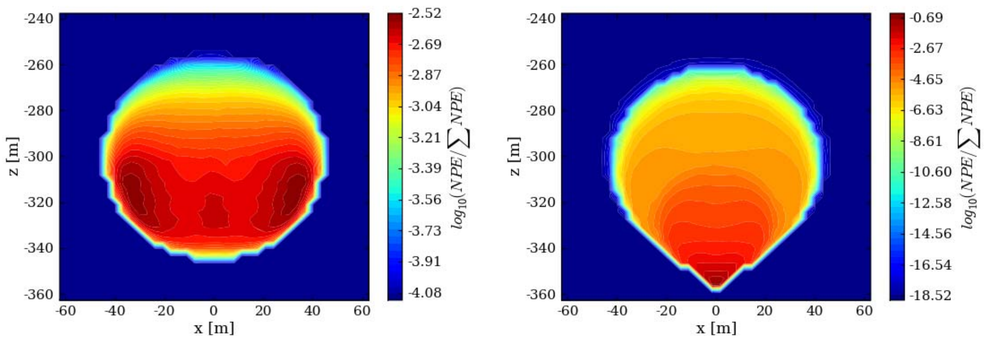

Fig. 6.9.: Left: light field 200 ns after an interaction of a 1 PeV electron neutrino moving down along the z-axis. Right: the same for a 10 EeV electron neutrino. The colour codes the intensity of the light field.

Cosmic Ray Physics with IceTop

The IceTop air shower array is located on the ice surface above the IceCube detector. It consists of 80 stations, close to the position of the strings, with a spacing of 125 m. In the year 2007, 26 stations were installed and operational (Fig.3.2). Each IceTop station consists of two ice tanks employed as Cherenkov detectors which are linked together by a local trigger coincidence.

The purpose and the physics goals of IceTop are:

- measurement of energy spectrum and the mass composition of cosmic rays around and above the knee (about 0.3 to 100 PeV);
- provision of a veto against high energy air showers for IceCube;
- employment for directional calibration of IceCube (important for the neutrino point source search, see above);
- monitoring of flux variation to study heliospheric physics and possibly transient events of other astrophysical origin.

The prime motivation is certainly the separation of contributions from different nuclei to the primary cosmic rays. For this purpose, IceTop has the unique possibility to exploit air shower measurements on the surface in coincidence with the detection of muon bundles in IceCube.

DESY/Humboldt contributions

The DESY/Humboldt subgroup working on IceTop has a leading role in the analysis of the first data. The main IceTop activity is located at the University of Delaware (USA). At present, the only other European IceTop group is from the University of Gent, but a group from Wuppertal has applied for funding for the participation in IceTop analysis.

In the framework of a Humboldt/DESY doctoral thesis, the first energy spectrum is being determined using data from the 26-station array of 2007. For the thesis only a reduced data sample, which was continuously transmitted via satellite and which is equivalent to one month of data taking, was available. For a publication of the results, which will be the first physics publication using IceTop data, the full data set, available by end of April, will be employed. A preliminary analysis using the 2006 data with 16 stations has been presented at the ICRC 2007.

With the work on the determination of the energy spectrum various analysis tools and in particular a robust reconstruction algorithm for the air shower parameters could be established. A recent major progress is the finding that the zenith angle dependence of the energy spectra is quite sensitive to the primary mass composition. This will be exploited to make a first, still model dependent, estimate of the composition as demonstrated in figure 6.10.

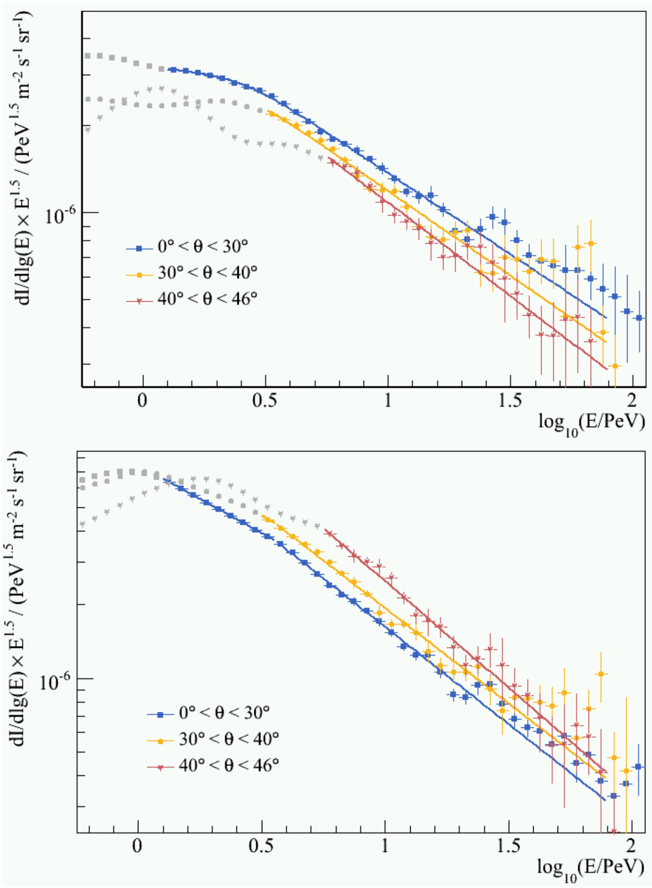

Fig. 6.10: Preliminary unfolded energy spectra for different zenith angle ranges as given in the legend. In the upper plots the spectra have been unfolded assuming protons as primary particles, in the lower plot iron nuclei are assumed. Obviously the spectra do not fall on top of each other as expected for a correct description of the unfolding kernel. The fact that the spectra are in a reverse order for the proton and iron hypothesis suggests that only a mixture of light and heavy nuclei will lead to the same spectra for all zenith angles.

The largest difficulty in the determination of the primary composition is the dependence of the analyses on air shower models. These models are based on extrapolations of measured cross sections over wide energy ranges and thus cannot be trusted *a priori*. Therefore scrutinizing the models with different complementary methods is of extreme importance. The zenith angle dependence described above is one such method. However, our principal method, unique for IceTop/IceCube, is the exploitation of coincidences with IceCube to count high-energetic muons. We have just started a corresponding analysis to keep our lead function in IceTop. As yet another measure of composition, we investigate the IceTop signal waveforms with the aim to distinguish muon and electron signals in the tanks.

Other progress

There are a large number on various analysis subjects across the IceCube collaboration. Since IC22 analyses with full data sets are being started only now, first results are not yet available for presentations outside the collaboration. Latest results from AMANDA and IceCube-9, the nine-string stage from 2006, include e.g.:

- a new limit for indirect dark matter detection via neutrinos from the Sun (AMANDA)
- the 6-year limit on neutrinos in coincidence with GRB (AMANDA)
- preliminary limit on relativistic magnetic monopoles from IceCube-9 (factor 1.5 below the previous AMANDA limit)
- preliminary limit on Extremely High Energy (EHE) diffuse neutrino fluxes from IceCube-9

Moreover, the IceCube trigger on Supernova bursts has been put into action. It would register the noise rate increase emerging from the burst of MeV neutrino interactions lasting over a few seconds. For the moment, the IceCube-trigger is not yet linked to SNEWS, the Supernova Early Warning Network. A SNEWS signal would still come from the AMANDA-Supernova trigger. After a period of stabilisation, the AMANDA trigger will be switched off and replaced by the IceCube-40 trigger which is much superior to the AMANDA trigger (due to the lower dark noise and the larger number of photomultipliers).

7. MAGIC

In the context of multi-messenger studies, the Young Investigators Group is participating with 3 of its member in MAGIC, the Cherenkov gamma telescope at La Palma. The group aims at enlarging the available statistics of gamma-ray time series. Besides combining existing data, the group is working on the analysis of new records collected with the MAGIC telescope during the AGN monitoring program of 2007. As an example we show in Figure 7.1 the light-curve recently obtained for the source Markarian 501. In this period, the source was found in a lower state. Still the MAGIC telescope could measure its flux. Besides providing essential input to understand the phenomenology of the sources (that can be studies for example investigating the variability in the emission and in the spectral properties), monitoring observation allow us to address the chance probability of random coincidences with atmospheric neutrinos. Finally, they are serving to initiate multi-wavelength Target of Opportunity (ToO) observations, which further address the problem of understanding the particle acceleration and photon emission mechanisms.

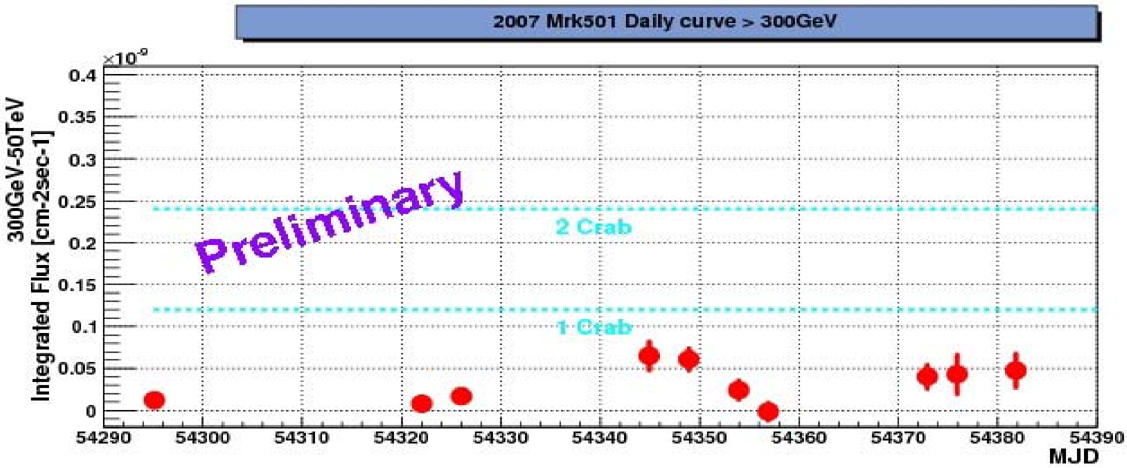

Fig. 7.1: Preliminary light-curve of the Active Galactic Nucleus Markarian 501) obtained from analysis of MAGIC 2007 monitoring observations.

To optimize the observation time, part of the monitoring observations are carried out in conditions of increased background from the light of the night sky (e.g. with Moon or twilight). This requires the development of dedicated analyses and comparison to adapted simulated data. The group has therefore started the production of dedicated Monte Carlo, but also plans to contribute to mass production of MAGIC-II Monte Carlo.
With an extra Helmholtz grant the group could support the construction of MAGIC-II and contribute advanced photo-detectors (UBAs and HPDs) which have a much improved quantum efficiency (peak efficiency larger than 50%) compared with standard photomultipliers. As a result of a large–scale field test, lowering of the energy threshold of the detector is expected, resulting in better capability to detect, among other sources, very distant AGNs. The photo-detectors will be installed in the MAGIC-II camera and tested. Preliminary results are expected in 2009.

8. The Cherenkov Telescope Array CTA

8.1. Introduction

With IceCube analysis entering the cubic kilometre scale and with the most exciting time being probably the next five years, the time has come to plan – beyond IceCube – the long-term future of astroparticle physics at DESY. As guiding rationale for a decision we have chosen our declared goal to explore the high-energy universe, plus the successful principle of a multi-messenger approach. A future project should complement IceCube and later possibly replace it in its role as main activity. We arrived at the conclusion that a next generation Imaging Atmospheric Cherenkov Telescope (IACT), namely the Cherenkov Telescope Array (CTA) is the best option with respect to the guaranteed physics potential, the complementarity to IceCube, the technical feasibility, and the timing. CTA will provide a huge amount of astronomically relevant observational results and may also contribute to fundamental physics and cosmology. Gamma-ray results will provide information essential for the interpretation of IceCube results. In the framework of our multi-messenger analyses, we use them already now. CTA also forms an ideal link to the Potsdam astronomers in the Astrophysical Institute AIP and at the University Potsdam. It would optimally correspond to the position of a theoretical astroparticle physicists affiliated at Potsdam University and DESY. Last but not least, it opens the possibility in the future to play a role adequate to Helmholtz centres: the strong, sustainable role in large infrastructure projects and a supportive function for Universities.

8.2 Arguments for a next generation Air Cherenkov Observatory

Gamma rays and neutrinos propagate on straight paths. Compared to neutrinos, gamma rays are easy to detect. Among the different techniques developed for gamma-ray detection, two have succeeded in providing catalogues with reliable source detections and spectral measurements: satellite detectors and ground based IACTs.

Cosmic particle acceleration in the energy range MeV to GeV can be studied with satellite detectors. EGRET for example has revealed more than 300 sources of radiation during its operation between 1991 and 1999. INTEGRAL was launched in 2002, the first space observatory that can simultaneously observe objects in gamma-rays, X-rays and visible light. In May of 2008 the GLAST detector with a sensitivity about 50 times that of EGRET will be launched and will provide an even richer view of the Universe at energies from 10 MeV to more than 100 GeV.

Higher energies are the domain of IACTs, covering the range above a few tens of GeV with large sensitivities. This is by virtue of the large effective light collection area, which is more than 10^4 times that of current satellite experiments. IACTs record the Cherenkov light from air showers originating from gamma-ray interactions in the atmosphere. Large mirror dishes focus the light to cameras, typically arrays of photomultipliers. From the shower image the direction, energy and character of the primary particle (hadron versus gamma-ray) can be derived.

The pioneering work of the Whipple group, later the HEGRA experiment and the recent successes of the Cangaroo, H.E.S.S., Magic and Veritas collaborations, clearly established that the IACT technique enables true ground-based gamma-ray astronomy at high energies. The measurements provide all the typical data of astronomy: images, showing spatially resolved source morphologies; light curves, showing time variations; energy spectra, extending multi-wavelength spectral energy distribution (SEDs) of known sources towards the TeV region; and surveys discovering unidentified sources and extending source catalogues.

IACTs have by now discovered more than seventy emitters of gamma rays in the energy range 70 GeV to 50 TeV, many of them in the disk of the Milky Way; many of them were shown to have a complex morphology. Most of the TeV sources correspond to known objects like binary stellar systems or supernova remnants. Others are still entirely unknown at any other wavelength and seem to emit most of their energy in the high-energy range ("dark accelerators"). Looking outside our own Galaxy, a large number of Active Galactic Nuclei have been observed and their fast variability demonstrated.

The time has come to make this exciting new astronomical window available to the wider community through the construction of a major new facility, which, unlike earlier projects, will be run as an open observatory and be made available to astronomers on the same basis as optical or X-ray observing facilities. A similar concept is being discussed in the USA, and coordination of the efforts is underway. CTA will, for the first time, combine the experience of all groups working in Europe with atmospheric Cherenkov telescopes. CTA will integrate partners from the United States and from Japan, the latter having expressed explicit interest in joining the design study. CTA is therefore expected to develop into a worldwide collaboration. Since one of the driving factors is common observation with GLAST, the construction of a major new IACT should start as early as possible. Planning has actually already started.

CTA is on the list of emerging projects compiled by the European Strategy Forum for Research Infrastructures (ESFRI) and has been proposed by the ApPEC (Astroparticle European Coordination) steering committee to be promoted to the status of a full ESFRI entry. ApPEC has given CTA a top priority, whereas the astronomers' community (ASTRONET committee) has placed it highest out of all astroparticle projects).

These are the primary goals for the proposed CTA:

- The sensitivity of the array should reach unprecedented milli-Crab fluxes, i.e. has to be a factor of ten higher than current telescopes. Extrapolating from the intensity distribution of known sources, CTA is expected to enlarge the catalogue of objects detected from currently several tens to about a thousand objects. This would allow surveying sources close to the number of objects predicted to be probed by GLAST. The sensitivity for a simulated CTA configuration is shown in the next Figure.

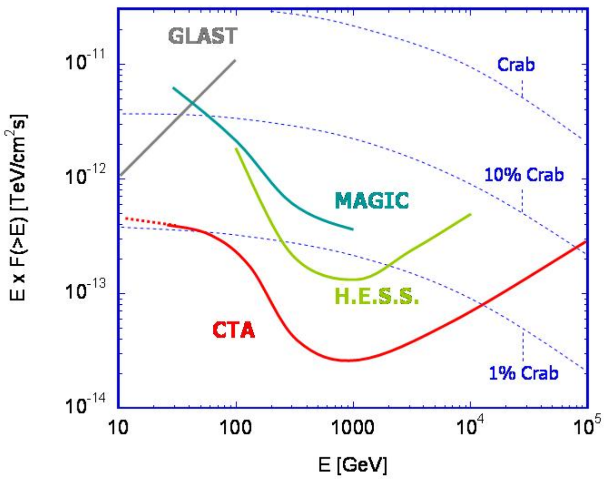

Figure 8.1 Sensitivity of the latest-generation IACTs (H.E.S.S. and MAGIC) in comparison to that of the next generation satellite experiment GLAST, and to the envisaged sensitivity of CTA. For reference, the gamma flux from the Crab nebula is shown.

- At the same time the energy range of such a telescope array should be wider than that of the current IACTs. The lower energy threshold should be 30-50 GeV, may be even lower. The extension of the coverage to higher energies shall reach the 100 TeV scale.

  The extension to higher energies would be particularly important for measuring shape and position of the cutoff in the gamma-ray spectrum, which contains information about the highest energy particles accelerated at the shock. Detection of a spectral feature of any type (a cut-off, a spectral break) would allow to strongly constrain the physical mechanism powering the gamma-ray emission. In particular it would provide important information about the character of the accelerated particles – electrons generating the observed gammas via inverse Compton scattering, or hadrons generating them via pion decay.

  Lowering the threshold will be important if a sensitivity significantly better than GLAST is achieved in the energy region of overlap between the two. It would be even more important if in the same region CTA could be better than GLAST in terms of angular resolution. In this sense, lowering the threshold can be expected to be important since the main spectral discrimination between leptonic and hadronic models in SNRs is related to the gamma ray spectrum between 1 and a few 100 GeV.

- The angular resolution should be improved, at least at the higher energies, by a factor of five to about 0.02 degree, possible according to Monte Carlo simulations.

Together with the much improved precision and lower statistical errors, measurements with CTA will enable astrophysicists to distinguish between key hypotheses such as the electronic or hadronic origin of gamma rays from supernovae. Combined with the GLAST gamma-ray observatory in orbit, the two instruments will provide an unprecedented seamless coverage of more than seven orders of magnitude in energy.

Admittedly, incontrovertible evidence for hadron acceleration can be obtained only from neutrino observations, in particular, if both, hadrons and electrons, are co-accelerated. Still, the combination of gamma data from different energy bands, particularly in the MeV-GeV region and in the 100 TeV region can accumulate increasing evidence for the one or other model. In multi-messenger analyses one will combine gamma-ray with neutrino observations and constrain the models most convincingly.

8.3. List of scientific goals

The high-energy phenomena, which can be studied with CTA, span a wide field of galactic and extragalactic astrophysics, of plasma physics, particle physics, astroparticle physics, cosmology and fundamental physics of space-time. They encode information on the birth and death of stars, on the matter circulation in the Galaxy, and on the history of the Universe. We give in the following brief examples of the physics issues, which it would be possible to address at a far more advanced level with an instrument with the capabilities of the CTA. The list is certainly not exhaustive.

Supernovae remnants, pulsar wind nebulae, and cosmic rays. A paradigm of high-energy astrophysics is that of cosmic-ray acceleration in supernova explosion shocks, and while the gamma-ray community has now clearly demonstrated particle acceleration up to energies well beyond 10^{14} eV, it is by no means proven that supernovae accelerate the bulk of cosmic rays. The large sample of supernovae which will be observable with CTA - in some scenarios several hundred objects - and in particular the increased energy coverage towards lower and higher energies will allow sensitive tests of acceleration models and determination of their parameters. Pulsar wind nebulae surrounding the pulsars created in supernova explosions are another abundant source of high-energy particles, including potentially high-energy nuclei. Energy conversion within pulsar winds and the interaction of the wind with the ambient medium and the surrounding supernova shell are challenging current ideas in plasma physics.

Pulsar physics. Pulsar magnetospheres are known to act as efficient cosmic accelerators, yet there is no accepted model for this particle acceleration, a process which involves electrodynamics with very high magnetic very fields as well as the effects of general relativity. Pulsed gamma-ray emission allows the separation of processes occurring in the magnetosphere from the emission of the surrounding nebula. Competing models predict characteristic cut-off features in the spectra of pulsed gamma rays in the low-energy range of CTA. Compared to satellite instruments, CTA with its much larger detection rate is less affected by glitches in pulsar periods, which may compromise periodicity measurements requiring very long integration times.

Microquasars and X-ray binaries. Three very high-energy gamma-ray emitters are currently known which are binary systems, consisting of a compact object - a neutron star or black hole - orbiting a massive star. Whilst many questions are open concerning gamma-ray emission from such systems - in some cases it is not even clear if a pulsar-driven nebula around a neutron star or accretion onto a black hole is the energy source - it is evident that they offer a unique chance to "experiment" with cosmic accelerators: along the eccentric orbits of the compact objects, the environment (including crucially the radiation field) changes periodically, resulting in a modulation of the gamma-ray flux, allowing the study of how particle acceleration reacts to these environmental conditions. Equally interesting, the physics of microquasars in our own Galaxy resembles the processes occurring around super-massive black holes in distant active galaxies, except for the much faster time scales, providing insights into these mechanisms.

Stellar clusters and stellar systems. While the classical paradigm emphasizes supernova explosions as the dominant source of cosmic rays, it has been speculated that cosmic rays are also accelerated in stellar winds around massive young stars before they explode as supernovae, or around star clusters. Indeed, there is growing evidence in existing gamma-ray data for a population of sources related to young stellar clusters and environments with strong stellar winds. However, lack of instrument sensitivity currently prevents the detailed study and clear identification of these sources of gamma radiation.

The Galactic Centre. The Galactic Centre hosts the nearest super-massive black hole, as well as a variety of other objects likely to generate high-energy radiation, including hypothetical dark-matter particles which may pair-annihilate and produce gamma rays. Indeed, the Galactic Centre has been detected as a source of high-energy gamma rays, and indications for high-energy particles diffusing away from the central source and illuminating the dense gas clouds in the central region have been detected. In observations with improved sensitivity and resolution, the Galactic Centre provides a rich reservoir of interesting physics from particle acceleration via the - not well known - diffusive propagation of cosmic-ray particles to exotic phenomena such as acceleration and curvature radiation of protons at the edge of a rapidly spinning black hole.

Active galaxies. The super-massive black holes at the cores of active galaxies are known to produce outflows - jets - which are strong sources of high-energy gamma rays. The fast variability of the gamma-ray flux - on minute time scales - indicates that gamma-ray production must occur near the black hole, assisted by highly relativistic motion resulting in a contraction of time scales when viewed from an observer on Earth. Details of how these jets are launched by the black hole and even the kinds of particles of which they consist are poorly understood. Multi-wavelength observations with high temporal and spectral resolution can distinguish different scenarios, but are at the edge of the capability of current instruments.

Galaxy clusters. Galaxy clusters act as storehouses of cosmic rays, since all cosmic rays produced in cluster galaxies since the beginning of the Universe will be confined to the cluster. Probing the density of cosmic rays in clusters via their gamma-ray emission thus provides a calorimetric measure of the total integrated non-thermal energy output of galaxies. Accretion/merger shocks outside cluster galaxies provide an additional source of high-energy particles. Emission from galaxy clusters is predicted at levels just below the sensitivity of current instruments.

Cosmic radiation fields and cosmology. Via their interaction with extragalactic light, high-energy gamma rays from distant galaxies allow the extraction of cosmological information on the density of light in extragalactic space and therefore about the formation history of stars in the Universe. Gamma rays experience an energy-dependent attenuation when propagating through intergalactic space, due to electron-positron pair production on the extragalactic background light. This phenomenon allows determination of extragalactic light levels, unimpeded by the overwhelming amount of foreground light from the solar system and the Galaxy, which makes direct measurements prone to very large systematic uncertainties. Pair-production halos surrounding strong active galaxies may even allow measurement of the evolution of light intensity with redshift.

Search for Dark Matter. The dominant form of matter in the Universe is a yet unknown type of dark matter, most likely in form of a new class of particles such as predicted in super-symmetric extensions to the standard model of particle physics. Dark matter particles accumulate in wells in gravitational potential, and with high enough density they are predicted to have annihilation rates resulting in detectable fluxes of high-energy gamma rays. CTA would provide a sensitive probe of this annihilation radiation, and will help to verify if such particles - which by then might be discovered at the Large Hadron Collider LHC - form the dark matter in the Universe.

Probing space-time. Due to their extremely short wavelength and long propagation distances, very high-energy gamma rays are sensitive to the microscopic structure of space-time. Small-scale perturbations of the smooth space-time continuum, as predicted in theories of quantum gravity, should manifest themselves in a (tiny) energy dependence of gamma-ray propagation speeds. Burst-like events of gamma-ray production, e.g. in active galaxies, allow this energy dependent dispersion of gamma rays to be probed and can be used to place limits on certain classes of quantum gravity scenarios, and may possibly lead to the discovery of effects associated with quantum gravity.

8.4. The CTA project

CTA is promoted by all European groups currently participating in IACTs, with a large number of additional new partners from particle physics and astrophysics. A proto-collaboration met for a first time in 2006, and the structure of the consortium was formed in 2007. A Letter of Intent will be published in the next few months. Work is going on to fix the contributions of the partner institutes in Memoranda of Understanding.

CTA will likely consist of a few very large central telescopes providing superb efficiency below 50 GeV, embedded in an array of medium sized telescopes giving high performance around a TeV, the latter being surrounded by a few-km^2 array of small dishes to catch the bright but rare showers at 100 TeV: altogether 40-70 telescopes. A sketch of an arrangement of telescopes in the CTA array is given here.

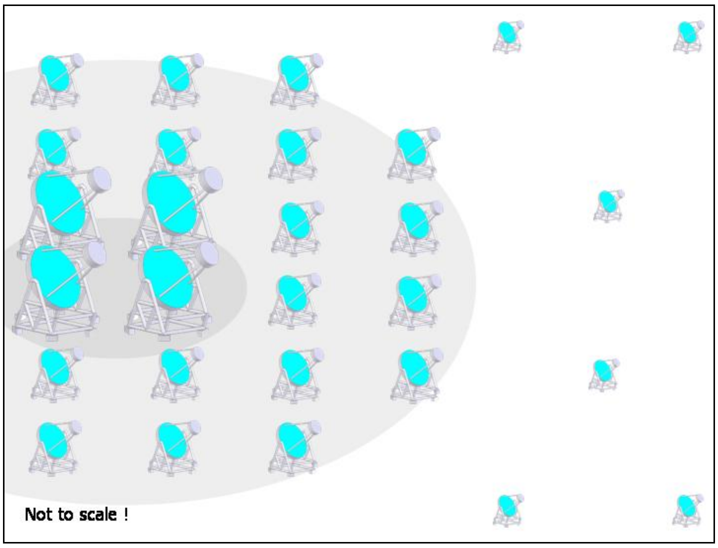

Fig. 8.2: Possible configuration of CTA (artists view).

CTA is conceived to cover both hemispheres, with one site in each. The field of view of the Southern site includes most of the Galaxy; the Northern telescopes would instead focus on extragalactic objects. At energies above a few tens of TeV and over Mega-parsec distances, gamma rays are absorbed by the cosmic infrared light fields, and above a few hundreds of TeV by the 3K background. Therefore high-energy sensitivity of the Northern ("extra-galactic") site is less important than for the Southern ("center of the galaxy") site. For the Southern site, emphasis would be put on high-energy sensitivity and excellent angular resolution in order to study the morphology of galactic objects.

While based on existing and proven techniques, the goals of CTA imply significant advances in terms of efficiency of construction and installation, in terms of the reliability of the telescopes, and in terms of data preparation and dissemination. With these characteristics, the CTA observatory is qualitatively different from experiments such as H.E.S.S. and MAGIC and the increase in capability goes well beyond anything that could be achieved through simply an expansion or upgrade of existing instruments.

The sketch below shows the currently discussed timetable for CTA. It is planned to establish the basic parameters of CTA within a design study in the next year. To reach that goal an intense simulation effort has started. In the years until 2012 an R&D phase is foreseen, building prototypes of critical components and at least one “standard” telescope. The construction of CTA is planned for the years 2012 to 2017; partial science operation can start as early as 2014.

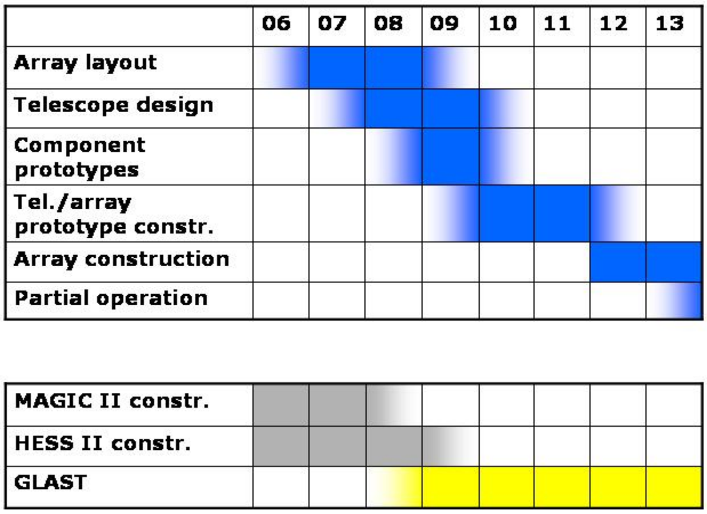

Fig. 8.3 Tentative schedule for the CTA project, indicating also the plans for the MAGIC II, H.E.S.S. II and GLAST

The goal of the recently started design study is to establish

- Knowledge of characteristics, availability of (few) good site candidates
- Array layout which optimizes physics performance for a given cost
- Detailed design and (industrial) cost estimates for telescopes and equipment
- Plan how to organize, produce, install, commission, operate the facility as observatory; estimate for operating cost
- Model and prototype how to handle and analyze the data
- Small prototype series of components such as mirrors, photo sensors and electronics, probably a few drive systems, possible a secondary mirror etc to ensure that production issues and costs are understood.

To achieve that goal CTA has set up a Work Package structure:

PHYS: Astrophysics and astroparticle physics
MC: Optimization of array layout, performance studies and analysis algorithms
SITE: Site selection and site infrastructure
MIR: Telescope optics and mirrors
TEL: Telescope structure, drive and control system
FPI: Focal plane instrumentation
ELEC: Readout electronics and trigger
ATAC: Atmospheric monitoring, associated science and instrument calibration
OBS: Observatory operation and access
DATA: Data handling, data processing, data management and access
QA: Risk assessment and quality assurance

8.5. Planned DESY contributions to CTA

We ask the PRC for support of our plans to participate in the CTA design and prototype phase, and also to embrace first steps to anchor CTA in the next phases of the general Helmholtz planning.

DESY took part from the beginning in the discussions of the CTA consortium. Within these discussions, the following plans for our participation in the design and prototype phase have been developed. They focus on three items where we can contribute with expertise gained in other projects:

a) Array optimization and exploration of physic potential

The first tasks of the CTA collaboration is to finish the simulation efforts to demonstrate how the envisaged improved sensitivity can be achieved, i.e. the optimization of basic parameters on telescope types and sizes, distances, field of view etc. within a given cost scale and taking into account the different observation modes (deep field, monitoring, sky surveys). Our group started, together with the Humboldt University in Berlin, a dedicated effort on trigger optimization. The result of those studies will determine the design of CTA.

b) Drive and Control system

One of the big tasks in CTA is to build the telescope structures; the effort is lead by the Max-Planck-Institutes in Heidelberg and Munich. They will work closely together with industrial partners. The task during the design phase is to devise telescope structures for different sizes and to deliver reliable prediction of performance parameters and costs. Technical specifications will be worked out for the mechanical stability, reliability, maintainability, safety, survival conditions and the cabling. DESY will contribute to the design and cost optimization of the drive and control system, including the safety system - one of the key systems for a robotic operation. The robotic operation of more than 40 telescopes requires a fundamentally different approach than the operation of a small number of telescopes with frequent human interactions. Part of the basic design concept will be the choice of motors, servos, gears, end switches and the emergency system (including redundancy). One needs to assemble an overview of off-the-shelf components for the structural elements and the drive/safety system. It is planned to build a prototype of a medium size telescope. The Figure below gives an impression of such a telescope structure and the critical elements of the drive system.

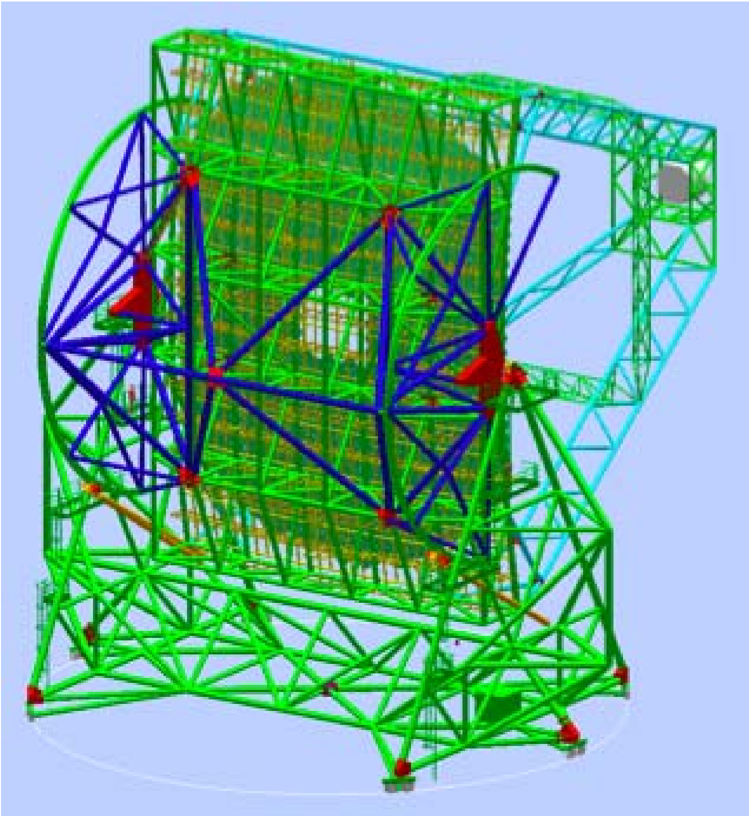

Fig. 8.4: H.E.S.S. II telescope design. Parts in red indicate bearings and motors.

c) Array Operation Centre

The installation of CTA as an open observatory poses new challenges. DESY will contribute to a prototype system for the array operation centre (AOC), an effort lead by the University of Erlangen. The task is to design a software system for CTA that allows transforming user input into an approved observing proposal, to perform the observations specified therein, and to deliver calibrated data (including further data products) to the user and to an observatory archive. This includes software to manage and administer the proposal preparation, the instrument operation and the archival use, the definition of data formats and data access protocols; local and remote data transfer, processing, storage; preparation of tools for open data dissemination and analysis; interfacing to virtual observatory; study of hardware and software infrastructure for data center; and solid cost estimates of data center installation and operation. The DESY group will start to work on the structure and requirements of an array simulator. A sketch of the AOC is given below. The AOC will be used for the prototype telescopes.

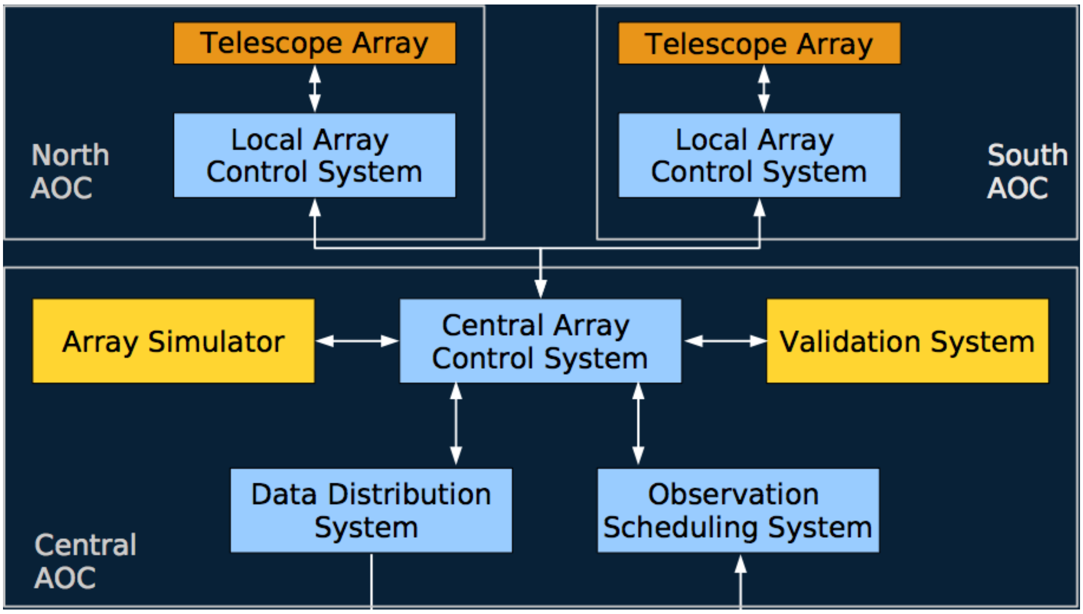

Fig. 8.5 Sketch of the Array Operation Centre (AOC)

During the design and prototype phase, the contributions of the partner institutions of CTA in the construction phase will be determined in greater detail. We want to provide contributions in the aforementioned fields of telescope construction and play a central role in the array operation centre. Both the major contributions to the prototype phase until 2012 and the possible later contributions to the construction phase in the years 2012 to 2017 will be embedded in the Helmholtz planning procedures. Eventually, we have to fill a role that corresponds to the mission of the Helmholtz association and its centres: building and running sustainable large-scale facilities and scientific infrastructures, cooperating closely with national and international partners; and supporting German Universities. DESY has proven expertise in all these fields, and all German partners expressed interest that DESY plays a strong role in CTA. This would also help to maintain Germany's leading role in this high-priority project of European astroparticle physics.