HESS - an Array of Imaging Atmospheric Cherenkov Telescopes for Stereoscopic Observations of Air Showers in the 100 GeV Energy Range

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Abstract

The HESS array of imaging atmospheric Cherenkov telescopes is proposed as a next-generation instrument in VHE γ-ray astronomy. The array will consist of initially 4, later up to 16 telescopes with 80 m^2 mirror area and 12-15 m focal length, equipped with conventional PMT cameras, and arranged on a grid with about 100 m spacing. The system provides an angular resolution of better than $0.1°$, a threshold of 100 GeV or less, and an increase in sensitivity of a factor 10 compared to the HEGRA IACT system.

1. Introduction

The HESS array of imaging atmospheric Cherenkov telescopes represents our view of a next-generation instrument for VHE γ-ray observations. HESS stands for **H**igh **E**nergy **S**tereoscopic **S**ystem; the name should also remind of V. Hess, the discoverer of cosmic rays and Nobel prize winner of 1936.

The HESS project represents a natural continuation of our present work with the HEGRA IACT system. With the HEGRA IACTs, we have demonstrated that IACT stereoscopy works as expected, and that it provides

- an angular resolution of $0.1°$
- a cosmic-ray rejection of O(100) using event shape variables, in addition the rejection of O(100) achieved using the pointing information
- a reduced threshold and a negligible rate of random coincidences, due to the multi-telescope coincidence trigger
- an energy resolution of about 20%.

The HEGRA system (Daum, 1997; Hermann, 1997) allows to detect sources at the level of 20-30 mCrab (for 100 h of observation time), and may survey a $2°$ by $2°$ field of view within an hour with a sensitivity equivalent to a fraction of the Crab flux.

The HESS instrument was conceived with the following goals

- to provide high sensitivity in the TeV regime
- to lower the minimal detectable flux by an order of magnitude compared to the HEGRA system
- to study the shape of extended sources
- to measure energy spectra and cutoff energies
- to provide sensitivity for distant extragalactic sources

The requirements of high angular resolution and good energy resolution lead us to a stereoscopic system of telescopes. The increase in sensitivity can be obtained either with many (O(100)) telescopes of the HEGRA type, or with fewer, but larger telescopes, with a somewhat reduced threshold and higher detection rates. One could also discuss cameras with higher quantum efficiency compared to conventional PMTs, but given the limited availability we consider this as an upgrade option. The wish to include sources at cosmological distances as well as practical considerations have led us to favor the option of fewer, larger telescopes. Design considerations emphasized also a low technological risk, and high reliability and ease of use. As a result, in the HESS Letter of Intent (Aharonian et al., 1997a) we propose a system of initially 4 telescopes of 80 m^2 mirror area, with a possibility to expand the system to 16 telescopes arranged in a square 4x4 grid (Fig. 1). The telescopes would be equipped with conventional PMT cameras, resulting

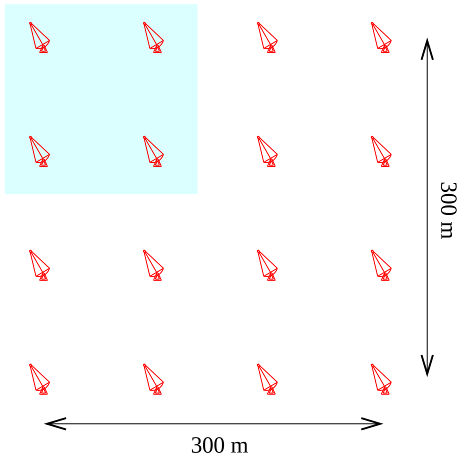

Fig. 1: Layout of the HESS IACT array; the initial installation will comprise 4 telescopes, with the option to expand to 16 telescopes.

in an energy threshold of about 100 GeV. Observation modes include in-depth observations where all telescopes point at the same source, providing a large detection area, as well as multi-source or survey modes, where the array is split up into 4 independent systems of 4 telescopes each. One might also consider a low-sensitivity mode where each telescope is used to monitor independently a given source or region of the sky.

2. HESS telescopes: the mirror

The HESS Letter of Intent discusses a number of design variants; purpose of these studies was to make sure that appropriate solutions exist and to define a cost frame. Decisions concerning details of the final design have not been taken.

Fig. 2 shows one design variant of a HESS telescope. The mirror is composed of 420 mirror tiles, and has a focal length of 12 m to 15 m. Mirror tiles are grouped into 60 clusters of 7 mirrors each; the clusters are arranged in a Davies-Cotton fashion, resulting in a point spread function of about 0.05° rms or less over the 4° field of view (for f = 15 m) (Fig. 3). Mirrors in this version are precision-machined aluminum mirrors, protected by anodization or by a quartz coating. Fig. 4 (left) shows prototype aluminum mirrors, with machined back

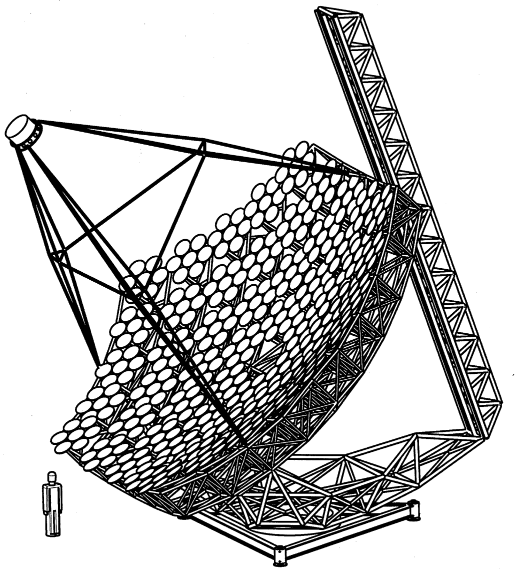

Fig. 2: Initial design of a 80 m^2 telescope with a modified alt-azimuth mount and segmented mirror.

sides for minimum weight. Their reflectivity depends somewhat on the coating (Fig. 4 (right)), and is typically better than 85% in the relevant range. The mirrors of each cluster are pre-aligned to act like a single larger mirror; the mirror clusters can be aligned using actuators under remote control. The mechanics of a mirror cluster is illustrated in Fig. 5. As alternatives to the Aluminum mirrors, aluminum-coated glass mirrors are under study, as well as larger stretched-membrane mirrors as used in solar concentrators. For these latter, a pre-tensioned steel membrane with slight underpressure on the back side provides a carrier onto which flexible reflector panels are glued. As reflector panels, either foils or very thin back-coated glass mirrors may be used. Focal length is fine-tuned by adjusting the underpressure using a feedback loop. One such mirror would have a diameter of about 1.5 m and replace a complete 7-mirror cluster. Present work concentrates on improving the image quality of these quite inexpensive mirrors; the general specification of the HESS mirror tiles is to concentrate 80% of the light within a circle of 1 mrad diameter.

3. Mount and dish

To investigate design alternatives for the mount and dish, three conceptual design studies were commissioned. In their requirements on mechanical stability and precision, IACTs range about midway between two well-studied types of dishes of comparable size: radio telescopes and communication dishes have significantly higher requirements, whereas solar concentrators have lower requirements, and emphasize minimum cost. Correspondingly, one of the designs (Vertex Antennentechnik GmbH, Duisburg) is basically a down-scoped version of a radio dish (Fig. 6), based on a commercial turning head and drives, with a modified dish structure to accept mirror clusters instead of reflector panels. The second design study (Schlaich Bergermann und

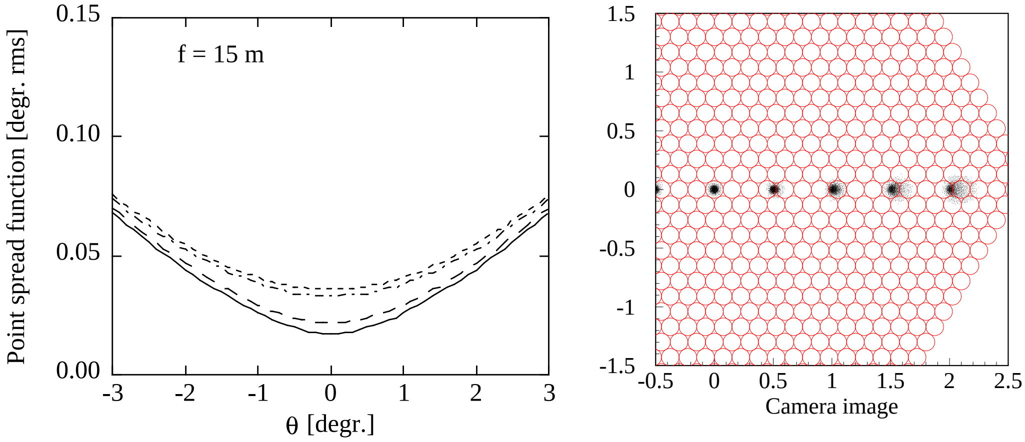

Fig. 3: (Left) Width of the point spread function as a function of the distance from the optical axis, for ideal mirror alignment. The lower two curves refer to mirrors with an intrinsic 1 mrad spot (diameter containing 80% of the light) and different mirror arrangements, the upper two curves to 2 mrad mirrors, both for $f = 15$ m. (Right) Simulated images of point light sources at infinity; superimposed are pixels of $0.15°$ *diameter.*

Partner, Stuttgart) uses the structure of a large stretched-membrane solar concentrator as a starting point (Fig. 7). The original membrane reflector is replaced by a space-frame dish, with a triangular front grid to match the cluster centers and a rectangular backing structure. Azimuthal motion is provided by a large circular rail; altitude is adjusted using a circular rack and pinion drive. Since both the azimuth and altitude drives act at large distance from the axes, forces are modest and inexpensive drive units can be employed. A third design study (Coast Steel Fabricators LTD, Port Coquitlam) follows up on the concept of the initial strawman design (Fig. 2), with a space-frame dish with triangular cells supported symmetrically in three points, two of which serve as altitude axis, with the third driven by a linear rack and pinion drive with additional fine adjustments. Unlike in the other designs, the camera masts emerge from the dish support points and minimize deformations of the dish due to the camera weights, with its large lever arm.

Specifications for the dish included a weight of each mirror cluster of 70 kg to 100 kg, and a camera weight of 150 kg at the 12 m to 15 m focal length. Deflection limits given were $0.008°$ rms for the mirror cluster, and $0.08°$ for the camera masts. The drive system must cover $10°$ to $89°$ in zenith angle, the full azimuth, provide a positioning speed of $100°$ per minute and be reproducible within $0.01°$. Wind speeds of 10 m/s were considered during operation, and worst-case winds of 55 m/s. The general experience in all designs was that the actual layout of the dish and mount is governed by the survival conditions; a dish stable enough to survive 55 m/s is well within the deformation limits when gravity loads or normal wind loads are considered. Dish structures proposed are generally welded-steel constructions, assembled on-site from pre-fabricated parts, with a total weight of the dish in the 10 t range, and similar or higher mass of the mount. Given the weight of the dish structure, the difference in static and dynamic properties was negligible when comparing 70 kg and 100 kg mirror clusters, relieving

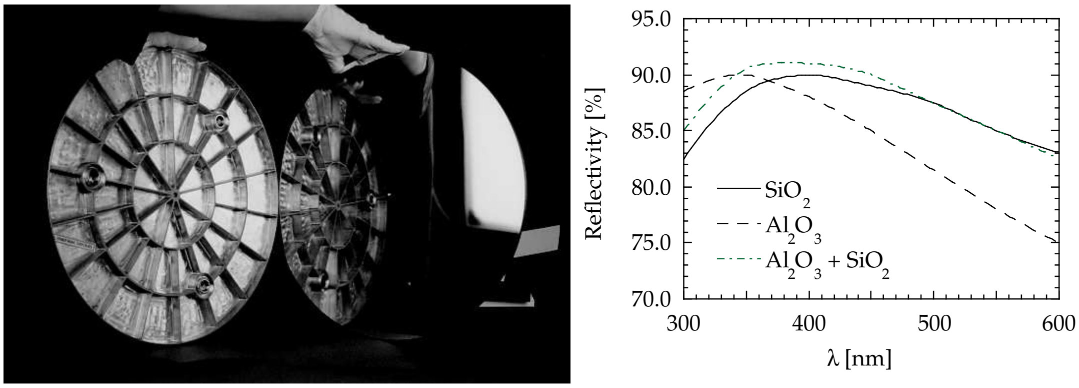

Fig. 4: (Left) Prototype aluminum mirrors, back and front side. (Right) Reflectivity of aluminum mirrors with different protective coatings.

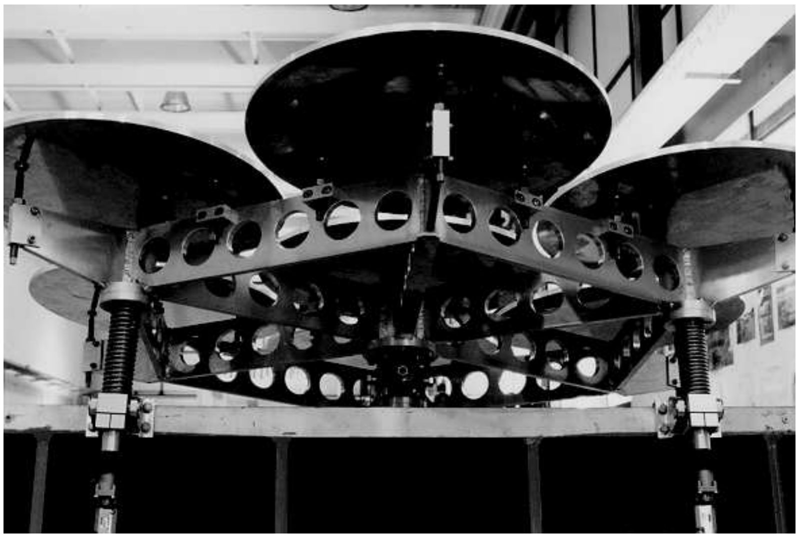

Fig. 5: Mechanical prototype of a 7-mirror cluster with actuators for precise alignment.

us from the need to use especially light-weight mirrors. Focal length is more relevant; the issue is to make the camera support stiff enough to raise the lowest eigenmodes above the critical range of a few Hz. Both with Carbon-fiber structures and with metal masts, uncritical lowest modes of 4.5 Hz could be demonstrated for $f = 15$ m.

4. Camera and readout electronics

The cameras for the telescope system will have a field of view with a diameter of about 4° in order to be able to observe moderately extended sources ($\leq 1^o$), one of the main aims of the experiment. For the same reason the pixel size will be uniform within the camera to obtain a flat acceptance for γ–showers over the field of view. The size of the pixels represents a compromise between cost and performance. We consider two options for the camera, depending

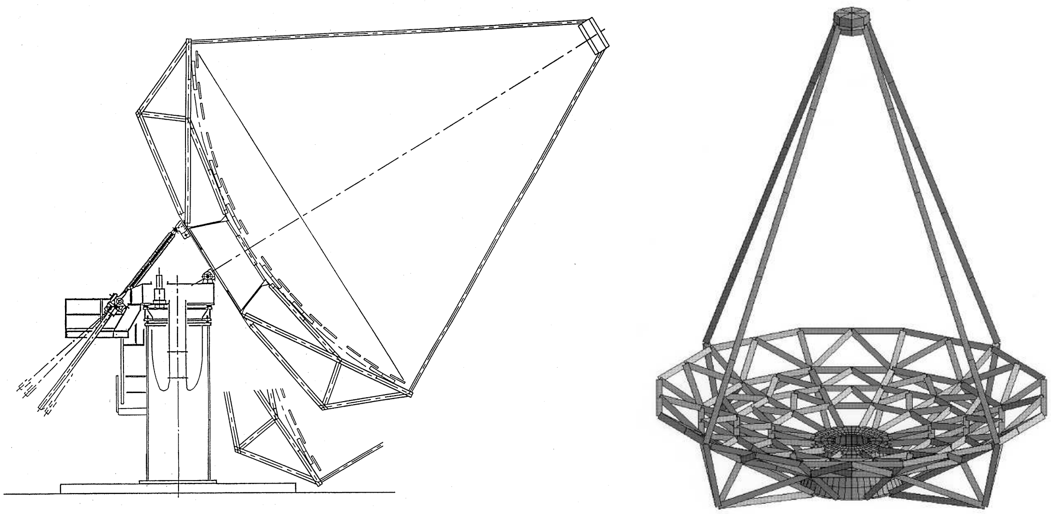

Fig. 6: Design study based on commercial communications antenna. (Left): cross section of the telescope. (Right) dish structure used in the finite-element calculations.

on the cost per channel of the readout electronics (see below): in the case of standard (Flash-ADC) readout electronics such as used in the HEGRA IACTs, a pixel size of 0.25^o would be chosen, resulting in a 271 pixel camera. If inexpensive, highly integrated custom ASICs could be realized, cameras with up to 800 pixels and a more favorable pixel diameter of 0.15° may be feasible. As photon detectors, photomultipliers (PMTs) with standard Bialkali photocathodes will be used, at least initially. The camera and the front–end electronics will be designed such that the photon detectors can be exchanged without major changes, should suitable detectors with higher quantum efficiency become available.

The readout electronics of the HESS telescopes will be based on the VME–standard, housed in a container near each telescope. A number of VME modules initially developed for the HEGRA–array can be adopted without major changes. CPUs at each telescope will be used to read out event data and to control telescope parameters. For the digitization of the camera signals, waveform recorders will be installed to fulfill the following requirements:

- Integration time: the signal from air showers is concentrated within 3 to 5 nsec. To minimize the fluctuations in the signal induced by the background light of the night sky, the charge integration time should not be much longer. We aim for an effective integration time of about 10 nsec.
- Time and pulse shape information: from the shape of the digitized pulses a reduction of night sky induced background light can be achieved. Furthermore from the arrival time of the camera signals, the relative arrival time of the shower front at the telescopes can be measured, allowing an independent determination of the shower direction. A time resolution of about 1 nsec is mandatory.
- Signal history: the telescopes will be read out only when at least two telescopes of a cell have fired. Mainly due to propagation delays of the cables, the trigger signal will be delayed by up to 2 μsec. The digitization system has to provide an appropriate signal buffer.

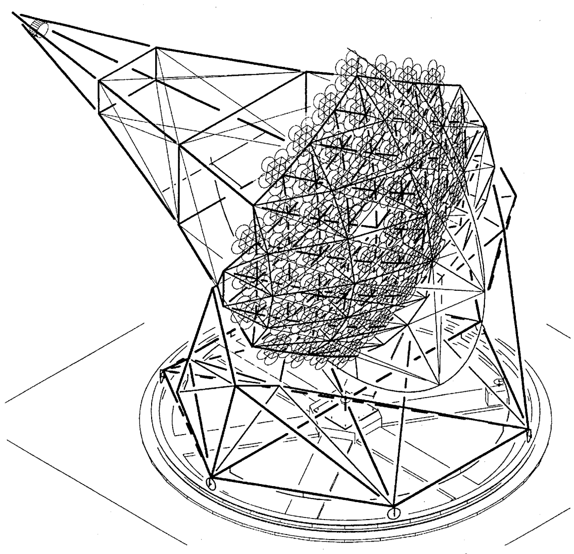

Fig. 7: Design study based on solar concentrator technology.

Two options for the digitization system are envisaged: the first option is a FADC system similar to that used in the HEGRA telescopes. Sampling frequencies from currently 120 MHz up to 200 MHz could be achieved. The FADC modules incorporate ring buffers for the digitized signals with a depth of 4k, ample to wait for the system trigger. The second option is based on switched capacitor pipeline ASICs for the storage of the analog signals (Fig. 8). Using a clocked shift register the capacitors are – one after the other – connected to a read/write line and the signal voltage is sampled at frequencies of up to 300 MHz. For the read-out, the clock is stopped and selected cells of the pipeline are switched to an external ADC at lower frequencies of 5 to 10 MHz. Several channels can be multiplexed to a 10 to 12 Bit ADC. This rather inexpensive solution would allow to build high granularity cameras with up to 800 pixels.

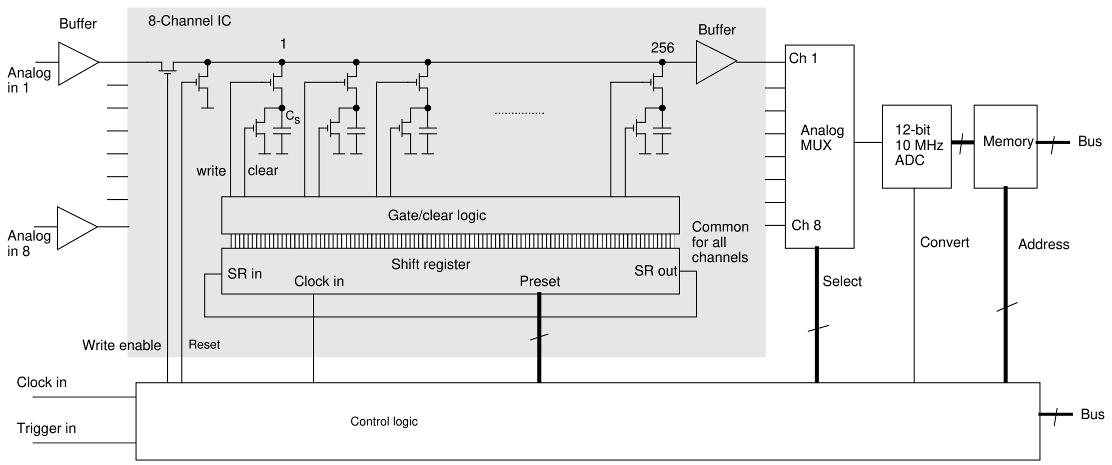

Fig. 8: Switched capacitor pipeline for sampling and storage of the input signal at frequencies between 250 and 300 MHz.

5. Trigger and data acquisition system

The trigger of the HESS array will be organized in three levels. On the first level a telescope trigger is released if the signals of a minimum number pixels exceed a preset threshold. Depending on the pixel size between 2 and 4 pixels will be required. The information on the triggered pixels is then latched to the second level topological trigger, which requires a minimum number of triggered pixels to form a compact cluster. Such a condition reduces dramatically the rate of night-sky induced noise triggers, while maintaining most of the γ–ray triggers. The signal of the second level trigger is routed to the third level, the global trigger, which fires if a minimal number of telescopes within a cell have triggered. To compensate arrival time differences of the shower front at the telescopes, depending on the inclination, the incoming trigger signals are delayed by programmable delay lines. The global trigger signal together with an event number is then sent to the telescopes of the cell and to the neighboring telescopes, and data are read out. Depending on the kind of camera and the exact trigger condition, typical trigger rates of the system will be of the order of 50–100 Hz.

The event data read out by the CPUs of the telescopes will be transmitted to a data server via a local Fast Ethernet network. For the event building, quality control and online analysis a small farm of central computers (Pentium Pro or PowerPC based PCs) will be installed.

6. Performance studies

The performance of the proposed system has been studied in detail (Aharonian et al., 1997b, 1997c). The simulations introduced the concept of an IACT 4-telescope square cell as the basic unit. The telescopes are located at the corners of the square. Only showers with their cores within the cell area are considered. Knowing the properties of a single cell, characteristics of an arbitrarily large IACT array consisting of many cells (in case of HESS, the array of 4x4 telescopes defines 3x3=9 cells) can be derived by simply multiplying the detection rate per cell by the number of cells. The resulting performance figures are conservative, since

- in a multi-cell array, telescopes in a neighboring cell may also trigger, providing additional information for improved pointing and background rejection
- in any finite array, showers beyond the outer border of a cell may trigger, adding to the detection rate. For a single isolated cell, the border region increases the rate good events by a factor three to four; even for a 3x3 cell array, the border region still contributes a 50% increase in rate.

Simulations were generally carried out for a trigger requiring 25 or more photoelectrons in two pixels of a given telescope, and a coincidence of three or four telescopes; however, pixel thresholds as low as 10 photoelectrons should be possible for a three-telescope coincidence, providing additional margin.

Fig. 9 (left) illustrates the angular resolution of about 0.1° near threshold, and significantly better at higher energy. With the nominal pixel trigger threshold (25 ph.e.), a two-pixel telescope trigger and a three-telescope coincidence, the energy threshold is about 100 GeV (Fig. 9(right)). The lower threshold and the larger detection area results in sensitivities in the mCrab range, and energy flux sensitivities at a similar level as e.g. the planned GLAST detector at lower energies (Fig. 10).

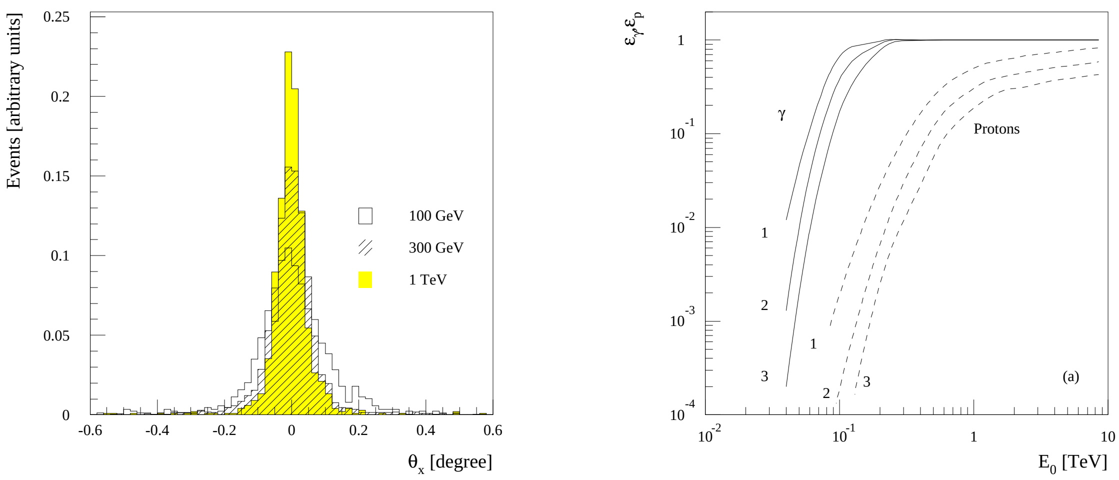

Fig. 9: (Left): Angular resolution of an IACT cell at different energies of primary γ-rays. (Right) Detection efficiencies for γ-rays and protons incident on a cell, for a two-pixel trigger with a 25-photoelectron pixel threshold and requiring a coincidence of 2 (curve 1), 3 (curve 2), or 4 (curve 3) telescopes.

7. Site

Requirements on the site for HESS include atmospheric qualities as found at good optical sites, a height ideally between 1500 m and 2500 m asl., an available and accessible area of about 400 x 400 m^2, and existing or affordable infrastructure.

As prime site candidate, we have investigated the Calar Alto/Spain in some detail. The optical observatory at the Calar Alto is operated by the Max-Planck-Society and the Institito Geografico Nacional of Spain. It provides sufficient space, and excellent infrastructure as well as a stimulating intellectual environment, and its management is open to an expansion in the scope of the laboratory, as would be provided by HESS. The main drawback is the harsh climate during winter, with snow and winds up to 250 km/h, which requires some kind of protective shelters for the telescopes; the design of such shelters is under study, but it appears that they might add significantly to the cost of the system.

Alternative potential sites might include the Canary Islands - which provided a very good site for HEGRA - and sites in the southern hemisphere, such as the Gamsberg.

8. Schedule and outlook

At this point, details of the technical implementation of HESS are under intense study, as is the site issue. We hope to be able to freeze major design features in late '97 or early '98, and, on the same scale, arrive a the decision to go ahead and implement the first cell of telescopes, which should go into operation in 2000 or early 2001. The first four telescope are - apart

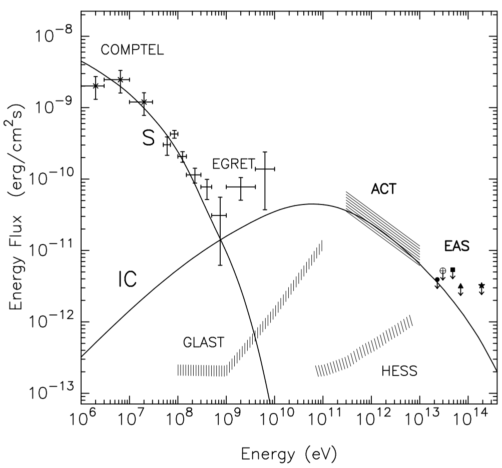

Fig. 10: Sensitivity of the IACT array in its final stage, in relation to the Crab flux as measured by the COMPTEL and EGRET instruments, by single IACTs, and by air shower arrays. The HESS flux limits refer to 100 h observation time, the included GLAST limits to the sensitivity reached in a 1-year all-sky survey.

from the infrastructure - more or less within the financial scope of the Max-Planck-Institute für Kernphysik; for a future expansion of the system, a larger collaboration will be required. A workshop on "Gamma-Ray Astronomy with Systems of Cherenkov Telescopes" at Ringberg Castle, Sept. 29 - Oct. 2, will focus on the design issues and optimization of a system such as HESS, and should lead to first organizational steps.

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