

# India-based Neutrino Observatory

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**India has a rich history in neutrino physics. The first ever atmospheric neutrino interaction was observed in the deep underground laboratory at the Kolar Gold Fields (KGF) Karnataka in 1965. This laboratory later also looked for nucleon decay and placed limits on the proton lifetime. The KGF underground laboratory ceased its operation in 1992 due to the closure of the mine. The India-based Neutrino Observatory (INO) project is a recent initiative to develop a new underground laboratory to conduct experiments in the area of neutrino physics and dark matter searches under a mountain with at least 1000 m rock cover. It is expected that over the years, INO will become a full-fledged underground science laboratory hosting experiments that can exploit its special low background environment and infrastructure.**

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## Introduction

INDIA has a rich history in underground science. Starting from 1951, many experiments were conducted at various depths in the Kolar Gold Fields (KGF), Karnataka to study cosmic muons and neutrinos, and to investigate the stability of protons. These experiments were pioneering in nature and put India on the world map of underground science. The very first detection of neutrinos produced by cosmic rays was made at KGF by a group of scientists from Tata Institute of Fundamental Research (TIFR), Mumbai; Durham University, UK and Osaka City University, Japan in early 1965 (ref. 1). This paved the way for future atmospheric neutrino experiments around the world. In addition, during the early 80s scientists from TIFR in collaboration with Osaka City University, set up two massive 100 tonne and 400 tonne particle detectors at 2.3 and 2 km depths respectively, to study the stability of the proton. Apart from exciting physics, these experiments also led to large-scale detector and instrument development activities in the field of high-energy physics and astro-particle physics in the country. Unfortunately during the late 80s, the Bharat Gold Mines Limited (BGML), the public sector unit responsible for running the KGF mines decided to close it down as it became

financially unviable. Several attempts, however, were made by physicists to save the underground laboratory at KGF. At the initiative of Prof. M. G. K. Menon, a study was conducted to find out the financial implication of running this facility for scientific research alone. However, the estimated cost turned out to be prohibitively high and BGML went ahead with the closure of the KGF mines in 1992. With this a glorious chapter of high-energy physics and astro-particle physics research using deep underground facilities in the country came to an end.

The current India-based Neutrino Observatory (INO) project<sup>2</sup>, discussions about which first took place in the Workshop on High Energy Physics Phenomenology (WHEPP-VI) in Chennai<sup>3</sup>, is an ambitious proposal to recapture this pioneering spirit and do experiments in neutrino physics at the cutting edge. The immediate goal of the INO project is the creation of an underground laboratory which will house a large magnetized Iron CALorimeter (ICAL) detector to study the properties of cosmic-ray-produced neutrinos in the earth's atmosphere. Apart from experiments involving neutrinos, in the long term, it is envisaged to develop into a full-fledged underground laboratory for studies in physics, biology and geology.

The main goals of the project include:

(a) Construction of an underground laboratory and associated surface facilities at Pottipuram village in Bodi West hills of Theni District, Tamil Nadu (TN) in South India. The underground facility is being designed keeping in mind the present experimental goals and also future possibilities. The site is selected and finalized based on the physics requirement, geotechnical studies for stability and ecological assessment. The underground laboratory, consisting of a large cavern and several smaller caverns, will be accessed by a 1900 m long and 7.5 m wide tunnel.

(b) Setting up a 50 kt magnetized ICAL detector at the INO underground laboratory. In addition, discussions regarding several additional proposals for setting up experiments to study neutrinoless double beta decay (NDBD) and to detect dark matter are at an advanced stage. Furthermore, preliminary discussions for setting up a low-energy particle accelerator to measure very low energy cross-sections of importance to astrophysics have also started. The underground laboratory should also be available to the international community for setting up collaborative experiments.

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## ASTRONOMY: SOME LARGE PROJECTS

(c) Setting up an Inter-Institutional Centre for High Energy Physics (IICHEP) in Madurai, TN, located 115 km from the underground site to coordinate all INO-related activities. IICHEP will act as the centre for the operation and maintenance of the underground laboratory, human resource development and detector R&D along with its applications. It will also be the nodal centre for bringing together members of the collaboration from universities, IITs and research institutions.

The detector R&D, electronics and control, magnet design as well as physics studies and numerical simulations are ongoing at various participating institutions. Components of ICAL will be fabricated within various institutions and industries, and installed at Pottipuram by combined efforts of the collaborating groups. IICHEP will be responsible for the operation of the facilities and will be set up with induction of scientists and engineers in a phased manner, achieving full strength by the end of the project. On a smaller scale, the development of human resources has already started in the form of the INO Graduate Training Programme (GTP) under the umbrella of Homi Bhabha National Institute (HBNI), a deemed-to-be university within the Department of Atomic Energy, Government of India, and at various universities and IITs which are members of the INO collaboration.

### INO underground laboratory

The primary requirements of a suitable site for locating an underground laboratory apart from the physics requirements, are the safety and long-term stability of the lab. Hence the search for a suitable site for INO was mainly guided by the rock quality, availability of water and power for the project, low rainfall, ease of access and minimal environmental impact, and its management. In addition, issues such as availability of infrastructure and length of access tunnel impact, both the physics (time taken for executing the project and hence maintaining the competing edge) and the construction. Given these criteria, several sites were considered as possible locations for INO. The study included information from geologists, engineers, ecologists and physicists. It was based on available surveys, study of topographic sheets, several site visits by different groups and Google Earth images. It should be noted that peninsular India, south of  $13^{\circ}\text{N}$  lat, offers the best possible rock medium for safe and stable cavern construction. Since the laboratory cavern needs to be more than 1000 m underground, the choice of the site is primarily dictated by the rock quality, in order to obtain a stable and safe environment for such a long-term activity. Geologically, the mountains in the southern part of India have the most compact and dense rock (mostly gneiss), while the Himalaya is mostly metamorphic sedimentary rock with pockets of gneiss. A considerable part

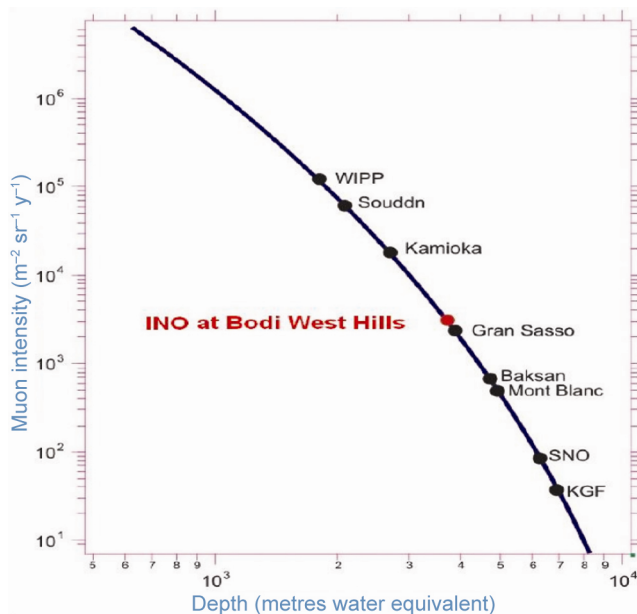
of peninsular India, the Indian shield, consists of Archean gneisses and schists which are the oldest rocks found in India and perhaps in the world.

Initially, a site on the northern slopes of the Nilgiri Mountains, TN, was chosen as the preferred one after a detailed survey of the Western Ghats in South India. While the site was found suitable with all the infrastructure facilities in place, it was located close to a wildlife sanctuary which was later declared as a tiger reserve. Hence forest clearance was not given and the environmental clearance given initially was also withdrawn.

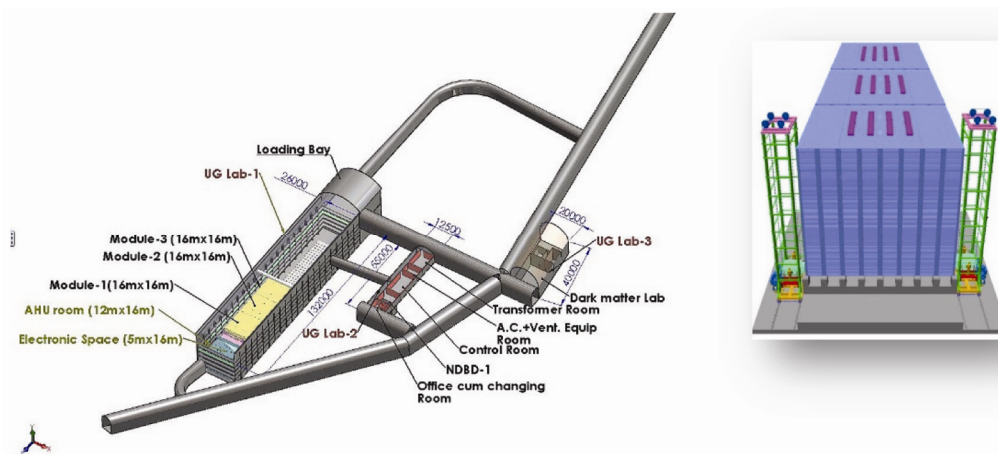
Following this a site close to Pottipuram village has been selected as the new location for the INO project. The site is located on the eastern fringe of the linear



**Figure 1.** Proposed location of the India-based Neutrino Observatory site. Credit: M. V. N. Murthy.



**Figure 2.** Atmospheric muon background as a function of depth.



**Figure 3.** Conceptual design of the INO underground complex (left) and the ICAL neutrino detector (right). Cavern dimensions are given in millimetre.

Western Ghats hills and is close to the Kerala–TN interstate boundary (Figure 1). The laboratory coordinators are  $9^{\circ}57'47.65''$  (N) and  $77^{\circ}16'22.55''$  (E). Figure 2 gives the expected muon background at the proposed INO laboratory and at other underground laboratories around the world. The site is 115 km west of Madurai, the second largest city in TN. The road between Madurai and the proposed INO site is good, except for the last several kilometres, which will soon be widened to take care of the traffic during INO construction. Madurai is well connected to the rest of India by air as well as by rail.

The underground laboratory complex will consist of four caverns accessed by a nearly horizontal tunnel of length 1900 m. The main cavern, i.e. cavern-1 will have dimensions of 132 m (L)  $\times$  26 m (W)  $\times$  32.5 m (H). This cavern is designed to house two units of ICAL, although at present only one 50 kt module will be installed. The floor level of this cavern is at 280 m amsl and is exactly under a mountain peak of 1560 m amsl providing a vertical rock cover of 1280 m. Cavern-2 will be of size 55 m  $\times$  12.5 m  $\times$  8.6 m (H). Part of cavern-2 will be used for a proposed NDBD experiment, and the rest as the control room for ICAL detector and also to install air-conditioning and ventilation system. Cavern-3 of size 40 m  $\times$  20 m  $\times$  10 m will be provided along the access tunnel. Part of this cavern will be used for setting up a dark matter search experiment. In addition, a fourth cavern will be located at a distance of 1000 m from the portal location along the access tunnel. This will be mainly used for material preparation for NDBD as well as dark matter experiments. Figure 3 shows a sketch of the various caverns. The design of caverns, adits and tunnels is done keeping in view possible extensions into deeper reaches at a future date as also space for new proposals.

A site-related detailed project report (DPR) has been prepared in association with the Geological Survey of India and the Engineering Projects Wing of the Tamil Nadu State Electricity Board. The ecological impact and

management report was prepared by experts from the Salim Ali Centre for Ornithology and Natural History (SACON), Coimbatore, TN. Environmental and forest clearances for this site have already been obtained and it is now ready for construction.

All the surface facilities associated with the underground laboratory will be located just outside the tunnel entrance on a 26 ha site. The facilities that will be created on the surface include: (i) administrative-cum-workshop building, (ii) detector assembly building, (iii) guesthouse-cum-hostel for visitors and students and (iv) residential quarters for maintenance and office staff posted at the site.

### ICAL at INO

The primary focus of INO, to begin with, is physics with atmospheric muon neutrinos. For this it has been proposed to construct a ICAL similar in concept to the Monolith detector<sup>4</sup>. The proposed detector (Figure 3) will have a modular structure of total lateral size 48 m  $\times$  16 m and will consist of a stack of 150 horizontal layers of  $\sim 5.6$  cm thick magnetized iron plates interleaved with 4 cm gaps to house the active detector layers, making it 14.4 m high. The active detector elements are gas-based resistive plate chambers (RPCs) made up of a pair of 3 mm thick glass plates of area 2 m  $\times$  2 m, separated by 2 mm spacers. The detector will be subdivided into three modules of size 16 m  $\times$  16 m. The iron structure for this detector will be self-supporting, with the layer above resting on the layer immediately below using iron spacers located every 2 m along the  $X$ -direction. This will create 2 m wide roads along the  $Y$ -direction for the insertion of RPCs. The iron plates will be magnetized with a field strength of  $\sim 1.5$  T to determine the charge of the muon produced by neutrino interactions inside the detector, so that the  $\nu_{\mu}$  and anti- $\nu_{\mu}$ -induced events can be identified

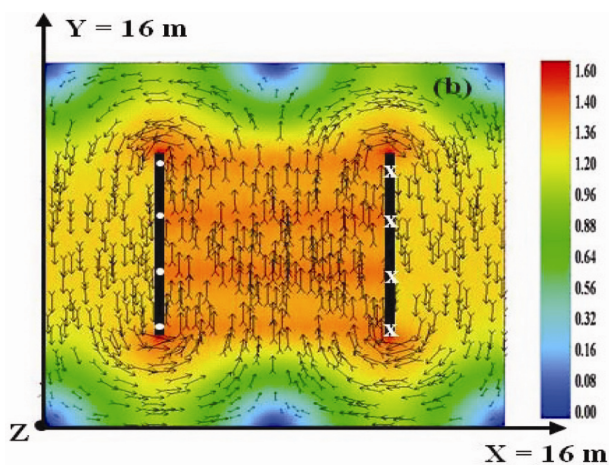
and studied separately. The magnetic field will also help measure the momentum of the final state particles, especially the muons produced in the neutrino interactions inside the ICAL detector.

The magnetic field was simulated using a commercial finite-element 3D code, Magnet 6.26. Various tiling configurations, inter-tile gap sizes, coil configurations and two low-carbon steels were evaluated for field uniformity and average field strength for various coil currents. The choice of the present configuration is supported by these simulation results. The 3D  $B$ -field maps for the ICAL magnet for the present design were used in all the physics simulations. Figure 4 shows a typical field plot inside the iron plates.

The RPCs will be operated at a high voltage of about 10 kV in the avalanche mode. A high-energy charged particle, passing through the RPC, creates an ionization trail in the gas which is amplified due to the high electric field resulting in a fast electrical signal. A typical efficiency for a minimum ionizing particle such as a 1 GeV muon is ~90%–95%. The RPC signals appear on  $X$ - and  $Y$ -pick-up strips, each 3 cm wide and 2 m long, on the top and bottom surfaces allowing determination of the  $X$  and  $Y$  coordinates of the track in the RPC, while its vertical location provides the  $Z$  information. The RPC time-resolution of ~1 ns will enable the identification of up-going and down-going particles from the time sequence of the signals from the respective RPCs. Hence from the spatial and temporal hit pattern observed in the RPCs, the four-momenta of the charged particles produced in the neutrino interactions will be reconstructed. Figure 4 shows the overall layout of the ICAL detector.

### Physics motivation

The ICAL detector will be operational at a time when neutrino physics has moved from a discovery phase to a



**Figure 4.** Plot of  $B$ -field for 5 kA.turns in each of the four coils. The current direction in the coil is indicated as also the colour coding for the  $B$ -field strength in tesla.

precision measurement phase. The pioneering SuperK and SNO experiments have firmly established that neutrinos oscillate from one flavour to another. The oscillation data imply that neutrinos have mass and the three neutrino flavour states ( $\nu_e, \nu_\mu, \nu_\tau$ ) are mixtures of three mass eigenstates ( $m_1, m_2, m_3$ ), which are different from flavour states, at least two of which have finite mass. The three mixing angles,  $\theta_{12}, \theta_{13}, \theta_{23}$  are fairly large (unlike the small mixing angles in the quark sector) and lead to large oscillation amplitudes. This has far-reaching consequences for particle physics, astrophysics and nuclear physics.

Impelled by these discoveries and their implications for the future of particle physics and astrophysics, plans are underway worldwide for new detectors to study such open issues as the hierarchy of neutrino masses, the masses themselves, the extent of CP violation in the neutrino sector, the Majorana or Dirac nature of neutrinos, etc. This involves R&D efforts for producing intense beams of neutrinos at gigaelectronvolt energies, suitable detectors to detect them at long baseline distances and sensitive NDBD experiments. A complementary approach to these is the use of atmospheric neutrinos, whose fluxes are more uncertain than beam neutrinos, but which provide a wider range of energies, and more importantly, a wider range of baselines. The INO is one such proposal aiming to address some of the challenges in understanding the nature of neutrinos, using atmospheric neutrinos as the source. The unique feature of ICAL, the main detector in INO, will be the ability to distinguish neutrino-produced events from antineutrino-produced events, which enables a clearer distinction between the matter effects on neutrinos and antineutrinos travelling through the Earth, leading to the identification of neutrino mass hierarchy.

The main physics goals of INO–ICAL are:

- (i) Measurement of  $|\Delta m_{23}^2| \approx |\Delta m_{\text{atm}}^2|$  and  $\sin^2 \theta_{23}$  precisely, where  $\Delta m_{23}^2 = m_2^2 - m_3^2$ .
- (ii) Determination of the sign of  $\Delta m_{23}^2$  and hence the neutrino mass hierarchy using the matter effect.
- (iii) Measurement of the deviation of  $\theta_{23}$  from maximality ( $45^\circ$ ), and resolving the octant ambiguity.
- (iv) Distinguish  $\nu_\mu \leftrightarrow \nu_\tau$  from  $\nu_\mu \leftrightarrow \nu_s$ , oscillations from muon-less events.
- (v) Search for CPT violation.

The ICAL detector at the INO cavern will provide an excellent opportunity to study the atmospheric neutrinos and antineutrinos separately with high detection efficiency and good enough energy and angular resolutions in the multi-gigaelectronvolt range in the presence of the Earth's matter effect. This feature of the ICAL detector is quite unique in the sense that the detection efficiency and energy resolution of the currently running or upcoming water or ice-based atmospheric neutrino detectors are



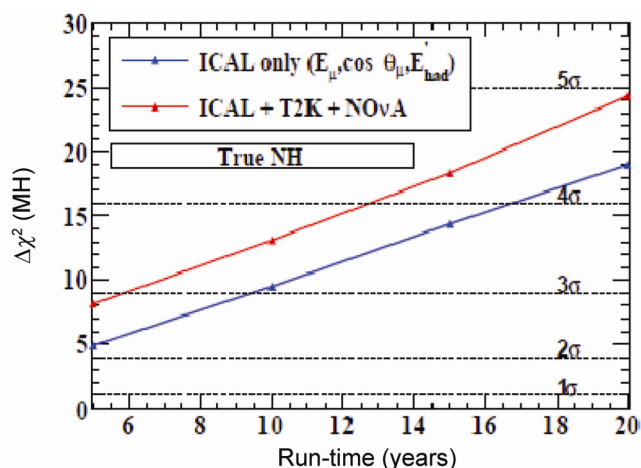
quite limited in the multi-gigaelectronvolt range where the Earth's matter effect plays an important role. There is no doubt that the rich dataset which would be available from the proposed ICAL atmospheric neutrino experiment will be extremely useful to validate the three-flavour picture of the neutrino oscillation taking into account the Earth's large matter effect in the multi-gigaelectronvolt range. The first aim of the ICAL detector would be to observe the oscillation pattern over at least one full period, in order to make a precise measurement of the atmospheric oscillation parameters. The ICAL detector performs quite well in a wide range of  $L/E$  variations compared to the water Cherenkov detectors, and can confirm the evidence of the sinusoidal flavour transition probability of neutrino oscillation already observed by the Super-Kamiokande detector by observing the dips and peaks in the event rate versus  $L/E$ , where  $L$  is the travel length and  $E$  the energy of the neutrino. Unlike in the case of Super-Kamiokande where the sub-gigaelectronvolt events have played an important role to perform this  $L/E$  analysis, in the ICAL detector, multi-gigaelectronvolt events will dominate the study, since the matter effect increases with neutrino energy. The muon neutrino events will deplete due to muon neutrinos oscillating to other flavours and get enriched by other flavours oscillating to the muon neutrinos. The relevant oscillation probabilities have a rich structure for neutrinos and antineutrinos at gigaelectronvolt energies, travelling through the Earth for a distance of several thousands of kilometres. The matter effects on these neutrinos and antineutrinos lead to significant differences between these oscillation probabilities, which may be probed by a detector like ICAL that can distinguish neutrinos from antineutrinos. This feature of ICAL would be instrumental in its ability to distinguish between the two possible mass hierarchies. The results of physics simulations show that ICAL alone can identify the normal hierarchy at a  $3\sigma$  significance in about 10 years of running. Since other experiments are already running, these experiments together with ICAL can reduce the time to about 6 years for a  $3\sigma$  result (Figure 5).

ICAL could also be used to address many new physics possibilities. For instance, the violation of CPT or Lorentz symmetry in the neutrino sector could be probed. Magnetic monopoles from the cosmos could be searched for using their characteristic signature in ICAL as straight, long tracks but with low velocity, unlike penetrating muons. The anomalous events observed in the neutrino experiment at KGF have neither been confirmed nor refuted by other experiments worldwide. They could be addressed by ICAL as the detector, and the empty space around it, will be much larger. Dark matter may accumulate in and around the core of the Sun. If so, its two-body decay or its annihilation in the neutrino channel could be looked for. The signal for such processes would point to the Sun and in its absence very useful bounds on

a possible flux of such neutrinos could be placed. A number of such physics possibilities could be investigated.

### Current status

For ICAL at INO, extensive R&D activities are being carried out at various participating institutions on detectors, electronics, magnet design, physics simulation as well as on the engineering aspect of the project. Two prototype detectors with stacks of RPCs are currently operational. One of these is working for the last seven years. It consists of a stack of 12  $1\text{ m} \times 1\text{ m}$  RPCs without any iron plates. It is being used to understand the long-term operation of RPCs using cosmic-ray muons and is a test bench for testing various electronics sub-systems. A second set-up consists of a 35 tonne magnet, using 5 cm thick soft iron plates, of a slightly different design from that of ICAL with 12  $1\text{ m} \times 1\text{ m}$  RPCs. It has been used to study the effect and usefulness of the magnetic field in determining the momentum of muons. It was also useful for comparing the simulation and measurements of the magnetic field. In addition, the effect of electromagnetic interference on the front-end electronics and ways of reducing it have been studied. A third set-up, at Madurai, has 12  $2\text{ m} \times 2\text{ m}$  RPCs manufactured in local industry and has been working for about two years. Also,  $2\text{ m} \times 2\text{ m}$  RPCs have been successfully fabricated and tested at the RPC lab at TIFR. Local industry has also fabricated  $2\text{ m} \times 2\text{ m}$  RPCs. An order has been placed for the fabrication of 400 RPCs required for the ICAL engineering module. The first version of an 8-in-1 front-end amplifier–discriminator ASIC has been developed and tested. The INO Data Acquisition (DAQ) system will be Field Programmable Gate Array (FPGA)-based. A performance



**Figure 5.** Plots of the hierarchy sensitivity if the true hierarchy is normal when only ICAL data are used and when they are combined with data from T2K (total luminosity of  $8 \times 10^{21}$  protons on target, in neutrino mode) and NOvA (three years running in neutrino mode and three years in antineutrino mode).

FPGA-based RPC–DAQ board to be used for the engineering module as well as the final ICAL detector is under design. The trigger scheme to be used for ICAL detector has been finalized and its various sub-systems have been tested.

It is necessary to emphasize the need to engage with industry if a project of this scale is to succeed. More than a 100 industries, including those which supplied various crucial raw materials such as low-carbon steel plates, oxygen-free copper coils, float glass plates, high-precision detector parts; those which built special-purpose machines for glass painting, automatic detector assembly robots, detector construction and installation tools, gas recirculation systems, and those which fabricated high-speed ASIC electronic chips and very high density signal processing boards have already contributed to the project.

It is planned to build a 600 tonne engineering prototype ICAL detector at IICHEP, Madurai. The steel and copper conductor has been procured, but construction activity at the IICHEP site cannot begin as reclassification of the land is still awaited. While some of the infrastructure work such as water supply and road construction has been completed or is in progress, construction of the INO underground laboratory and surface facilities is stalled for

lack of the Tamil Nadu Pollution Control Board clearance, which is still awaited.

In summary, a lot of progress has been made towards setting up IICHEP and INO, and the project is ready to push ahead once the necessary clearances from the Government of Tamil Nadu are obtained.

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