DAE-DST Vision Meeting of Nuclear, Particle and High Energy Physics

Homi Bhabha Centre for Science Education, Mumbai 24-25 August 2014

Preamble: The last DAE-DST Vision meeting for Drawing Roadmap for High Energy and Nuclear Physics Research was held in Mumbai during April 7-8, 2006, which produced a Roadmap with a number of recommendations. Some of these have been implemented and yielded very encouraging results. The community has expanded in this period with the recruitment of many young faculties. A proposal was made in the Programme Advisory Committee of the DST for a vision meeting with wide participation of the members of the community and after consultations with the members of the organizing committee and several members of the community the venue and date of the meeting were fixed at HBCSE, 24-25 August. Names of active members of the communities were suggested by the organizing committee members and invitations were sent to 162 scientists to attend the meeting, with approximately 44% from Mumbai (BARC, TIFR, Mumbai Univ, IITB, and SAMEER). The actual number of participants was 130, whose list is appended (Appendix A). Both the DAE and DST secretaries were invited for the meeting and the DST secretary, Dr. K. Vijayaraghavan addressed the meeting through Skype as he was travelling and the DAE secretary, Dr. R.K Sinha could not attend due to some urgent commitments. Dr. Praveer Asthana and Dr. B. Purniah made short presentations on the DST and DAE outlooks, respectively.

Format: With large number of participants, the format of the presentation was decided to be having an introductory plenary session followed by three parallel sessions for Particle and High Energy Physics including Astro-Particle Physics, Nuclear Physics and Accelerators. Second day was kept for panel meeting with the presentation from conveners of the three areas and discussion sessions with a final summary session. The agenda of the meeting is presented in Appendix B.

Introduction: The chairman welcomed the participants with a brief background of the meeting and mentioned the purpose and goals of the meeting.

- With the discovery of Higgs boson at LHC, the goals of high energy physics are being focused and redefined. Discussions are going on for starting the next major venture in accelerator in the form of a linear collider. Discussions of a Future Circular Collider (250 GeV for the e+e- option and 100 TeV or so for the pp option) are on.

- On the non-accelerator particle physics side much progress has been made world-wide. In India the INO (Indian Neutrino Observatory) project is now underway and international collaboration proposals are under consideration for neutrino physics. It's time to take a holistic and critical look at the scenario and choose the optimum path.
- In low energy Nuclear Physics, the two heavy ion facilities at TIFR and IUAC have been completed and are in regular use for experiments. The Radioactive Ion Beam facility is under construction at VECC.
- Several new large Accelerator programmes have been planned with considerable investment of resources.
- Indian researchers are already involved in several international mega projects like FAIR, High Intensity proton project at Fermilab in addition to the ongoing programmes at CERN, BNL, and KEK.
- While there has been remarkable progress in many directions, in some areas, especially in the generation of human resource, progress has been slow and needs more attention.
- In light of the results achieved so far and with the availability of new techniques and technologies, India is now in a position to take up bigger challenges by building facilities of international scale. This is needed to put the country at the forefront of technology and basic research. This will require not only matching investments of funds and human resource but also more autonomy in execution of these projects.
- A well debated set of recommendations to the funding agencies would be generated in the meeting.
- In order to bring out where we stand today and to determine how we should proceed, the speakers were requested to highlight the points like the current status, vision for next 10-15 years, capabilities & scientific and technological gap areas, human resource development, international collaboration, industry participation in their talks.

The important role played by the two funding agencies to foster research and development in these areas and the continued support of both the secretaries were acknowledged by all participants.

Executive Summary of the Meeting

After introductory plenary presentations, detailed working group discussions and later open discussion on the issues the following summary emerged.

In all the fields, Particle & High Energy Physics, Nuclear Physics, Astro-particle Physics and Accelerators, Indian scientists have made significant contributions which are internationally recognized. Multi-disciplinary, multi-institutional programmes are now a substantial part of the Indian research in all three areas of study. However, more multi-institutional involvement in the domestic programmes should be encouraged.

High Energy Physics

There are two types of mega projects that particle physics community the world over is currently involved. One is physics at the colliders, be it high intensity colliders like Super-BELLE or the high energy ones like LHC, S(upper)LHC, LHCb including the heavy ion option and the other is physics studies at the non-accelerator based HEP projects.

The Higgs discovery has convinced us that our understanding of how elementary particles can acquire mass and yet follow laws of motion which satisfy the fundamental gauge symmetries is correct. However, many aspects of the mass problem are still unsolved: the first and foremost is to understand generation of nonzero neutrino masses. Further, we have no understanding of more than 30% of the matter which makes the universe and yet does not shine, the so called ’Dark Matter’ (DM). A quantitative understanding of the matter-antimatter asymmetry observed in nature is also lacking.

Now that experiments have revealed existence of an EW scale, stable under radiative corrections, a natural question to ask is whether there a guiding principle on which the stability can be founded? As said above, the need for this stability had driven many of the BSM ideas. For cracking this EWSB puzzle more and more precise measurements of the Higgs and top properties are needed! In addition to this precision measurements in the B sector are crucial too! So precision study of Higgs at the high energy/luminosity LHC or the low energy e^+e^- colliders, precision study of physics of the K,B mesons and that of the neutrino properties, may be our hope to learn what is beyond the SM.

At present the colliders that are surely going to be available are the 13/14 TeV LHC with 300fb^{-1} (LHC300). For flavour physics LHCb and Super Belle will continue to provide more precision data. Belle II at SuperKEKB is an upgraded version of the Belle detector, designed to exploit approximately 50 times larger data samples of *B* mesons, *D* mesons and τ leptons, compared to Belle. The Belle II experiment is currently in the construction phase until late 2017, after which a five-year physics run is planned. The phenomenological community in India is surely going to be engaged in probing SM and BSM at LHC 300 and Super Belle. The Indian experimental community is going to be involved in experiments at both the colliders.

For the future after that, the European Strategy Group report as well as the American HEPAP report has been discussing the High Luminosity LHC at 14 TeV with 3000 fb^{-1}: HL LHC. CERN is committed to this. Necessary studies on machine and detectors towards this have started.

The International Linear Collider (ILC) with staged energies of 250 GeV, 500 GeV and 1TeV has been in discussion for more than two decades now. The TDR, prepared in the true international spirit by a team consisting of scientists from all over the world, has been released. Worldwide there are talks on different options of future colliders as well. The need of the time is to form a Future Colliders Forum at all India level just like the ILC-India Forum.

The India-based Neutrino Observatory (INO) Project is a multi-institutional effort aimed at building a world-class underground laboratory for construction of an underground laboratory and associated surface facilities at Pottipuram in Bodi West hills of Theni District of Tamil Nadu. This project is now fully approved by the Govt. of India. The construction of underground and surface facilities will be starting soon and will be completed in 5 years. A feasibility study to search for $0\nu\beta\beta$ in ^{124}Sn has been initiated. The TIN.TIN experiment (The India-based TIN detector) will be housed at India based Neutrino Observatory (INO). A ton-scale or multiton-scale Dark Matter search experiment at INO – called the DINO (Dark-matter@INO) experiment is proposed to be set up by about 2018-19 when the INO facilities are expected to become operational.

A neutron-antineutron oscillation experiment is proposed to be set up at the Indian Spallation neutron source at RRCAT.

The primary goal of the LBNE Science Collaboration is to perform a world-leading, long baseline neutrino oscillation experiment with unprecedented sensitivity and precision and thereby determine the neutrino mass hierarchy (i.e., the ordering of neutrino masses), CP violation in neutrino mixing, and the value of the mixing parameters. Collaboration between Indian institutions and Fermilab on both accelerator and neutrino physics would enable Indian physicists and engineers to participate in the world's leading neutrino physics and detector development program, while building infrastructure and similar accelerator and detector facilities in India.

From the discussions a strong view emerged that in all the future international collaborations, emphasis should be given more on studies, in which, the theoretical prediction followed by the full analysis is done by Indian groups.

Astro-Particle Physics

In parallel, smaller scale experiments with new precision techniques are playing an ever important and vital role in the unravelling of the structure of matter. That is certainly an interesting area of investigations where the Accelerator based HEP and Non-accelerator based HEP meet very fruitfully! These also provide synergy with cosmology and Astrophysics. Some of these possibilities are 1) Electric Dipole Moment of electron 2) N− Nbar oscillation, 3) DBD: double beta decay 4) LENS: Low Energy neutrinos from the Sun.

The detection of very high energy (VHE: $E \geq 100$ GeV) photons provides a unique probe into the non-thermal processes occurring in the Universe. The HAGAR (High Altitude GAmma-Ray) array of seven telescopes each with 7 para-axially mounted mirrors of 0.9 m diameter has been operational since 2008 at Hanle in the Ladakh region of Himalayas.

The MACE (Major Atmospheric Cherenkov Experiment) telescope which is currently being setup at Hanle will explore the gamma-ray sky at energies down to 30 GeV. In order to exploit the full physics potential of this field, the next generation instrument Cherenkov Telescope Array (CTA) which aims for an improvement in sensitivity by an order of magnitude with respect to current experiments is being constructed by the international community, in which Indian community is interested in participating.

The GRAPES-3 project has been successfully running for several years with indigenously developed scintillators and electronics. The planned upgradation with SiPM detectors would enhance its capabilities further.

Nuclear Physics

A number of facilities have been created within the country in low energy Nuclear Physics in the last one decade. The completion and successful operation of Indian National Gamma Array has been a landmark collaborative achievement on the national scene; it has now been regularly used for experiments at IUAC, TIFR and VECC. Besides INGA, many other major facilities have been constructed and made operational at IUAC, TIFR and VECC and all these are being used as national facilities.

Most importantly, these experimental facilities within the country have led to a revival of nuclear physics at home. A large pool of trained manpower has been generated in this critical area and is now available to take up new challenges.

Indian researchers have made significant contributions in the area of Quark-Gluon Plasma (QGP) and the study of phase diagram at the most fundamental level. It is strongly recommended that sufficient support be provided for experiments to study the QGP phase diagram at the three international facilities, BNL, LHC and FAIR.

The INGA array should be upgraded and expanded such that a reasonable array can exist at each of the three accelerator laboratories viz., IUAC, TIFR and VECC. Fission fragment gamma-ray spectroscopy work was also carried out in India for the first time and has yielded very important results. The NUSTAR collaboration for FAIR and other collaborations for utilization of radioactive beams at GANIL, CERN-ISOLDE, RIKEN, and MSU should be supported. Collaboration with JINR is also recommended as it can provide exciting new opportunities for both experiment and theory.

Center for Radiation detectors, Nuclear Instruments and Innovative technologies for societal needs should be set up. A dedicated centre for nuclear theory and extensive computation is essential to revive the tradition of nuclear theory in the country in order to strengthen and support the existing and planned experimental programme.

In view of the growing interest in nuclear astrophysics, it is recommended that a Center for Nuclear Astrophysics be established at a place where few scientists are actively working.

Accelerator Physics

Significant progress has been made in accelerator related activities since the last vision meeting held in August 2006.

Indus-2 synchrotron radiation source at RRCAT has been successfully commissioned at 2.5 GeV beam energy, 200 mA beam current and is operational round the clock. High power 505.8 MHz solid state amplifiers have been developed in-house as a substitute for the imported klystrons to power the RF cavities in the Indus-2 storage ring. Upgradation of Indus-2 with insertion devices is in progress. A high energy, high brilliance synchrotron radiation source is envisaged as the next source at RRCAT. The construction of this source may take 10-15 years. Compact ultrafast THz free electron laser (FEL) is under commissioning and Infrared FEL (IRFEL) is under development at RRCAT.

*K*500 Superconducting cyclotron has been commissioned at VECC with internal beam at the last orbit and beam extraction trials are in progress. Development of ultra light compact SC cyclotrons should be taken up for use in medical imaging and therapy at VECC. A low energy radioactive ion beam (RIB) facility has been set up around *K*130 cyclotron at VECC and RIBs has been produced with this facility. Construction of next generation facility named ANURIB has started and the development of high current superconducting linac required for this facility is in progress.

An active international collaboration between Indian Institutions (BARC, RRCAT, VECC and IUAC) and Fermilab, USA has been started in the area of high energy and high intensity superconducting proton accelerators.

New projects for the development of accelerator technology for high energy and high intensity superconducting CW and pulsed proton linacs for ADS and Indian spallation neutron source (ISNS) respectively, have been initiated by DAE. Infrastructure for the development of superconducting radio-frequency (SCRF) cavities etc and cryogenics required for these accelerators has been set up at RRCAT. A few single-cell 1.3 GHz and 650 MHz and multi-cell 1.3 GHz niobium cavities have been developed at RRCAT under the IIFC.

The indigenous development of niobium cavities initiated in India at IUAC, has enabled the completion of the superconducting linac booster for the Pelletron, which has been delivering a wide variety of heavy ions to users routinely. Further development of new types of cavities are being pursued at IUAC using in-house set up of superconducting cavity fabrication facility. Niobium 1.3GHz single-cell and multi-cell cavities, 350 MHz spoke resonators have been fabricated under the IIFC. There has been considerable progress in the plan to develop a high current injector (HCI) for the superconducting linac at IUAC. A radiofrequency quadrupole, one unit of drift tube linac and prototype Nb low beta cavity have been designed and fabricated. The HCI will allow heavy ion beams to overcome the Coulomb barrier up to A=120 on 120 in next 10 years. A programme to develop a Free Electron Laser based on a photocathode gun has been initiated at IUAC in the XII Plan period.

ECR based heavy ion accelerator development is in progress at BARC-TIFR Pelletron facility. The development of this accelerator is expected to be completed in next 10-15 years.

India is participating in the FAIR facility coming up in Germany in both building accelerator equipment and detectors through in-kind contributions. FAIR facility is scheduled to be operational in 2019. An Indo-FAIR Co-ordination Centre (IFCC) has been set up at Bose Institute to coordinate India’s participation in FAIR project.

Acceleration of electrons to 50 MeV in gas-jet irradiated by ultra-intense laser beam has been achieved at RRCAT using laser wakefield acceleration (LWFA).

International Linear Collider (ILC) will require a large number of SCRF cavities. Participation of India in ILC can give a big impetus to accelerator technology and the industry.

Manpower crunch is affecting the progress of accelerator activities in national laboratories. Accelerators should be set up in the universities and other teaching institutes to train new manpower for execution of accelerator projects. Industries should be roped in for production of identical accelerator components required in large numbers. Development of accelerators used for medical, food processing and industrial applications should be encouraged.

END OF EXECUTIVE SUMMARY

Section I: High Energy Physics & Astroparticle Physics

There are two types of mega projects that particle physics community the world over is currently involved. One is physics at the colliders, be it high intensity colliders like Super-BELLE or the high energy ones like LHC, S(upper)LHC, LHCb including the heavy ion option and the other is physics studies at the non-accelerator based HEP projects.

Particle theorists at present have been presented with what one may call the LHC paradox. We seem to have found the light Higgs but so far there is no evidence/indication for the different particles expected in different extensions of physics beyond the Standard Model (BSM): either in the pp option with the general purpose detectors CMS/ATLAS, in flavor physics at LHCb or in the heavy ion option. As things stand the mass and the couplings of the light Higgs boson that has been discovered might be one of the windows through which we can get a view of BSM at present! Situation may be different in a few months after LHC 13/14 TeV kicks in!

The Higgs discovery has convinced us that our understanding of how elementary particles can acquire mass and yet follow laws of motion which satisfy the fundamental gauge symmetries is correct. However, many aspects of the mass problem are still unsolved: the first and foremost is to understand generation of nonzero neutrino masses. Further, we have no understanding of more than 30% of the matter which makes the universe and yet does not shine, the so called ’Dark Matter’ (DM). A quantitative understanding of the matter-antimatter asymmetry observed in nature is also lacking. This and similar observational features have convinced the particle physics community that new particles and interactions beyond the ones in the Standard Model (SM) must exist: the so called BSM.

There exist many different theoretical ideas how to extend the SM, but theorists do not have very firm indications as to the energy scale at which it must exist. While ’fine tuning’ and ’hierarchy’ arguments have been used to ’anticipate’ the scale of BSM, there is a degree of subjectivity there. The case of BSM scale is just like the case of the Higgs mass in the SM, where logical and reasonable requirements lead to bounds but there is no prediction in the SM for the same. So the seriousness of the ’LHC-paradox’ mentioned above has to be judged with this fact in mind. Further, just like there was no precise prediction for the Higgs mass but there existed constraints on it coming from precision measurements of the SM parameters, it is anticipated that one can probe the BSM physics through a precision measurement of the mass of the Higgs, of the Higgs couplings and last but not the least through precision flavor physics. Just as much as LHC ’paradox’ is challenging the

’hierarchy’ folklore or ’fine tuning’ folklore, Dark Matter (DM) is providing its own puzzles. The direct DM detection experiments as well as astrophysical observations, both are challenging the usual DM folklores.

Now that experiments have revealed existence of an Electro-Weak scale, stable under radiative corrections, a natural question to ask is whether there a guiding principle on which the stability can be founded? As said above, the need for this stability had driven many of the BSM ideas. For cracking this Electro-Weak Symmetry Breaking puzzle, more and more precise measurements of the Higgs and top properties are needed! In addition to this precision measurements in the B sector are crucial too! In addition, observed value of M_h might be indicative of the possibility that we may be living in a Universe which sits on the fine line between stability and (in)stability, thereby indicating that perhaps some of the BSM physics may be at energy scales that colliders can never reach! So precision study of Higgs at the high energy/luminosity LHC or the low energy e+e− colliders, precision study of physics of the K,B mesons and that of the neutrino properties, may be our hope to learn what is beyond the SM. The baton at the energy frontier has passed back and forth between electron-positron colliders which make precision measurements and the proton-proton or proton-antiproton colliders which make broad sweep measurements. Both have played their part in furthering our understanding of the basic laws of nature. However, due to the unique situation (the so called LHC paradox mentioned above) we seem to be in need of both the types.

At present the colliders that are surely going to be available are the 13/14 TeV LHC with 300fb^{-1} (LHC300). For flavor physics LHCb and Super Belle are sure to be around. The phenomenological community in India is surely going to be engaged in probing SM and BSM at LHC 300 and Super Belle. The Indian experimental community is going to be involved in experiments at both the colliders.

For the future after that, the European Strategy Group report as well as the American HEPAP (http://science.energy.gov/hep/hepap) report have been discussing the High Luminosity LHC at 14 TeV with 3000 fb^{-1}: HL LHC. CERN is committed to this. Necessary studies on machine and detectors towards this have started.

The same European Strategy Group report has also mentioned that the demands of physics exploration also need an electron positron machine. The International Linear Collider (ILC) with staged energies of 250 GeV, 500 GeV and 1 TeV has been in discussion for more than three decades now. The TDR, prepared in the true International spirit by a team consisting of scientists from all over the world, has been released (https://www.linearcollider.org/ILC/Publications/Technical-Design-Report). Europe, Japan seems strongly in favor of a staged, linear e+e− collider at present with possibilities of CLIC, colliders etc. to be decided by physics discoveries of the next decades. Japanese Government has sanctioned just recently first time in its budget an ’ILC designated’ budget to evaluate feasibility of an International project. (http://newsline.linearcollider.org/2014/02/06/the-year-2014-the-real-starting-year-of-the-ilc/).

There are also discussion of the FCC : future circular colliders. One part of this is just a circular e+e− collider. This would mean increasing the radius of the collider to XXX so that energy loss from radiation remains within manageable limits. USA, China, Europe are studying the possibilities of an FCC. These circular colliders can go up to centre of mass energies of about 300 GeV. Only an electron positron collider with energy greater than or equal to 500 GeV can study the Lorentz structure of $t\bar{t}h$ coupling with precision! Such precision studies are very likely to hold key to our cracking the EWSB problem completely. This is a qualitative difference between the ILC/CLIC on one hand and the circular e+e− and seems to tip the scale in favor of an ILC as far as physics considerations are concerned.

In USA and Europe, the circular electron-positron collider is being looked at as one step towards a possible 100 TeV pp collider and a high energy ep collider (LHeC). The Chinese on the other hand are thinking seriously about just the electron positron option as it remains to be seen whether magnets to deliver 50 TeV to a proton beam are feasible.

In India, in the framework of Indian Linear Collider Working Group and the ILC-India forum, we have had a sustained activity on phenomenology front mainly by theorists with some involvement in accelerator front and during the early days some work done on the experimental front too! The need of the time is to form a Future Colliders Forum at all India level just like the ILC-India Forum.

As the above discussions show it is at present not clear which path the International community will take after the LHC 300 and HL/HE LHC. But various options are considered very seriously. Collaborations on the phenomenological front with the International Community as well as on the accelerator and detector front are where Indian community is all geared up for now.

But it is not just the Large Scale experiments that will probe fundamental physics. This is also the age of smaller scale experiments with new precision techniques. That is certainly an interesting area of investigations where the Accelerator HEP and Non-Accelerator HEP meet very fruitfully! Some of these possibilities are 1) EDM of electron 2) N− Nbar oscillation, 3) DBD: double beta decay 4) LENS: Low Energy Neutrinos from the Sun.

This synergy is a new thing for the Indian HEP community and needs to be explored carefully. Time is also ripe for theorist/experimentalist joint action. It will be worthwhile to organize small meetings to explore this further. One should/could identify some niche areas where our expertise can make a difference! These are also the days of Cosmo-particle physics: cosmology and particle physics. This is evidenced by the immense interest and number of papers that BICEP2 result had generated. Again the community feels the need of short focused meetings which could be used to focus on specific issues.

- **Participation in Belle II at KEKB:**

Belle is an intensity-frontier experiment that operated at the KEKB asymmetric-energy e^+e^- collider. While KEKB holds the current world-record for the highest luminosity ever achieved by a machine, its upgrade to SuperKEKB will take this to new heights by achieving 40 times higher luminosity. Belle II at SuperKEKB is an upgraded version of the Belle detector, designed to exploit approximately 50 times larger data samples of *B* mesons, *D* mesons and τ leptons, compared to Belle. The Belle II experiment is currently in the construction phase until late 2017, after which a five-year physics run is planned. The samples produced during this run will allow for indirect probes of new physics beyond the SM either via the observation of rare decays or precision measurements of flavour parameters, including *CP* violation and lepton flavour violation. Such measurements virtually probe energy scales up to few hundreds of TeV, much beyond the reach of the LHC. The Indian Belle-II project is well underway with key contributions to the Silicon Vertex Detector (SVD) hardware and software. Once built, the Indian group will participate in the installation, commissioning and operation of the SVD. In addition, analysis tools development for the vital task of background suppression, which is required to reveal the rare decays of most interest, is underway by the Indian groups.

In summary, Belle II already has a strong Indian flavour, which can be enhanced through the lifetime of the experiment with adequate supports from the community as a whole. The complementary nature of the Belle II physics mandate to those at the energy and cosmic frontiers will allow India to have a well-rounded and world class high-energy physics programme.

- **India-based Neutrino Observatory:**

The India-based Neutrino Observatory (INO) Project is a multi-institutional effort aimed at building a world-class underground laboratory with a rock cover of approx. 4000 meters water equivalent for non-accelerator based high energy and nuclear physics in the country. The underground laboratory, consisting of a large cavern of size 132m × 26m × 20m and several smaller caverns, will be accessed by a 1900 m long and 7.5 m wide tunnel. The project is jointly supported by DAE & DST.

The project includes (a) construction of an underground laboratory and associated surface facilities at Pottipuram in Bodi West hills of Theni District of Tamil Nadu, (b) construction of an Iron Calorimeter (ICAL) detector consisting of 50000 tons of magnetized iron plates arranged in stacks with gaps in between where Resistive Plate Chambers (RPCs) would be inserted as active detectors, the total number of 2m × 2m RPCs being around 29000, and (c) setting up of Inter Institutional Centre for High Energy Physics (IICHEP) at Madurai, initially as a wing of TIFR, for the operation and maintenance of the underground laboratory, human resource development and detector R&D along with its applications. The IICHEP will have full-fledged manpower setup to operate the laboratory.

The primary physics goal of ICAL detector is the study cosmic ray produced neutrinos in the earth's atmosphere. Determining the neutrino mass hierarchy is one of the most important open problems in physics today. The ICAL detector is designed to address this key open problem in a unique way. INO underground laboratory when fully operational will develop into a full-fledged underground science laboratory for other studies in physics, biology, geology, hydrology etc. Development of detector technology and its varied applications is an important aspect of the project.

The detector R&D, electronics and control, magnet design as well as physics studies and numerical simulations, have been done in-house at various participating institutions. The development of human resource has already started in the form of the INO Graduate Training Programme (GTP) under the umbrella of Homi Bhabha National Institute (HBNI). A conscious and consistent effort at developing local components and solutions for all the engineering aspects has been undertaken. A key feature of this project is the INO-Industry interface that has developed because of the large scale of activity involved.

INO project is now fully approved by the Govt. of India. The construction of underground and surface facilities will be starting soon and will be completed in 5 years.

- **Neutrinoless Double Beta Decay Project (TIN.TIN):**

The mass and nature of neutrinos play an important role in theories beyond the standard model. The nuclear beta decay and double beta decay (DBD) can provide the information on absolute effective mass of the neutrinos, which would represent a major advance in our understanding of particle physics. In India, a feasibility study to search for $0\nu\beta\beta$ in ^{124}Sn has been initiated. The TIN.TIN experiment (The India-based TIN detector) will be housed at India based Neutrino Observatory (INO), an underground facility with ~ 1000 m rock cover all around. It is envisaged that the prototype stage of TIN.TIN detector would consist of an array of small Sn crystals (natural/enriched of 3 x 3 x 3 cm^3) arranged in tower geometry with corresponding readout sensors. The R&D on Tin cryogenic bolometer and NTD Ge sensors has been initiated. The development of TIN.TIN prototype is a multi-disciplinary, multi-institutional project and currently TIFR, BARC, IIT-Ropar, Univ. of Lucknow, VECC and PRL are involved. A large scale project like this necessarily needs to have a HRD component. The challenging physics goal will attract young faculty members. At present, the Ph.D. students for NDBD project are selected through INO GTS, where emphasis is on training and developing experimental skills. It is envisaged that INO GTS will expand the programme to train ~10 students/year, who will participate in experimental projects at INO. In addition, these projects will actively work to engage engineering students.

- **Direct Detection of Dark Matter – DINO :**

Direct detection of DM in the form of WIMPs is one of the most challenging goals of contemporary physics, and involves interdisciplinary efforts cutting across several major areas of experimental physics including particle physics, nuclear physics, condensed matter physics, low-temperature physics, and so on. Recognizing the importance and implications of the subject for fundamental physics, a national collaboration has been formed. Most importantly, at the international level, this move found enthusiastic response and support from the Dark Matter search experiment group at the Texas A&M University (TAMU), College Station, Texas, USA, which is currently one of the leading groups in the world involved in dark matter search experiments. It is recognized that the most suitable location for setting up a DM search experiment in India would be the deep underground laboratory facilities of the upcoming India-based Neutrino Observatory (INO) to be constructed in the Bodi Hills region of Theni District of Tamil Nadu. It is envisaged to eventually set up a ton-scale or multiton-scale DM search experiment at INO – called the DINO (Dark-matter@INO) experiment – by about 2018-19 when the INO facilities are expected to become operational. This was endorsed by the erstwhile INO Programme Management Committee after a discussion meeting held at TIFR, Mumbai on 24 August 2011 in which some of the senior scientists involved in INO were present. The INO laboratory layout design now includes a separate cavern for the possible future dark matter search experiment.

However, while INO gets built over the next 5 – 6 years, it is proposed that in preparation for the large DINO experiment at a future stage, we should first try to set up a smaller experiment, hereafter called “mini-DINO”, within the next 2 years or so at an already existing suitable underground location (albeit at a shallower depth than the proposed INO) to gain expertise in the area. In this context it is suggested that we may try to utilize the already existing underground facilities and infrastructure of an existing mine cavern or that of hydroelectric power project somewhere in the mountains of India, with a bit more than 400 m rock cover to reduce the cosmic muon flux which creates a radiation background for the mini-DINO experiment. Initial negotiation and technical discussion with the concerned authorities and engineers at some of the possible sites are going on.

The proposed mini-DINO experiment will use silicon or germanium as the active detector material, and employ silicon or germanium wafer iZIP (interleaved Z-sensitive Ionization and Phonon) detectors of the kind used by the Cryogenic Dark matter search (CDMS) experiment. The detector fabrication will be done in collaboration with the TAMU group, which is one of the leading groups involved in the CDMS experiment, using the proven detector fabrication technology developed by the TAMU group.

Indian contribution to dark matter search till date: Experimental / Theoretical: From 2009-2010, a group from SINP is deeply involved in a collaborative direct dark matter detection experiment PICASSO (Project In CAnada for the Search of Supersymmetric Objects) which is stationed at SNOLAB, Sudbury, Canada.

- **High Energy gamma-ray experiments**

The very high energy (VHE: $\geq$100 GeV) part of the electromagnetic spectrum is currently being investigated by means of ground-based arrays of imaging atmospheric Cherenkov telescopes (IACTs). The detection of these photons provides a unique probe into the non-thermal processes occurring in the Universe. TACTIC (TeV Atmospheric Cherenkov Telescope with Imaging Camera) with a light collector size of ~10 m^2 and having an energy threshold of ~1 TeV has been in operational at Mount Abu for last several years. The telescope has detected gamma-ray emission from Crab nebula, Mrk 421 and Mrk 501. Recently, the telescope performance has improved in terms of sensitivity and energy threshold following upgrade of the hardware coupled with the implementation of the new analysis techniques.

Following a different approach of wave front sampling, the HAGAR (High Altitude GAmma-Ray) array of seven telescopes each with 7 para-axially mounted mirrors of 0.9 m diameter has been operational since 2008 at Hanle in the Ladakh region of Himalayas, in northern India. Operating at an energy threshold of ~200 GeV HAGAR has also detected the VHE gamma-ray emission from above mentioned sources.

The MACE (Major Atmospheric Cherenkov Experiment) telescope which is currently being setup at Hanle will explore the gamma-ray sky at energies down to 30 GeV. The 21m diameter light collector of the telescope is made up of honeycomb based spherical aluminium mirror facets (size 50cm x50cm) which have been manufactured within the country. The proof assembly of the telescope has been completed recently at ECIL, Hyderabad and the telescope is being shifted to Hanle. The telescope will be commissioned at Hanle by the end of the next year. There is plan to construct one more similar telescope for stereo observations.

In order to exploit the full physics potential of this field, the next generation instrument Cherenkov Telescope Array (CTA) which aims for an improvement in sensitivity by an order of magnitude with respect to current experiments is being constructed by the international community. The instrument will extend the accessible energy regime from some tens of GeV to the 100 TeV range and will improve angular and energy resolution compared to existing telescopes. An expression of interest to join CTA was submitted to CTA consortium last year by the Indian community.

The GRAPES-3 experiment at Ooty is a research collaboration programme of TIFR with Osaka City University, Japan. It aims to look at the origin, acceleration and propagation of UHE ($>10^{14}$ eV) particles in the galaxy and beyond, “Knee” in energy spectrum of UHE particles and their nuclear composition. It also looks for production and/or acceleration of highest energy ($\sim10^{20}$ eV) particles in cosmic rays. Other aims are astronomy of UHE gamma-rays from neutron stars and other compact objects, understanding of the Sun as a source and accelerator of energetic particles and its effects on the Earth. In-house development of fast plastic scintillators and pulse processing circuits has enabled this array to work at a high efficiency and precision level over a decade. The detection system is planned to be upgraded as also the electronics.

- **Neutron-Anti-Neutron Oscillation Experiment.**

There is a strong scientific motivation to pursue a higher-sensitivity n-nbar oscillation search experiment in the era of LHC/ILC as it would probe BSM in an area not easily accessible to other probes. In particular, there are compelling reasons to take up the neutron-antineutron oscillation experiment in India, as the experiment generates facilities that will be useful to researchers engaged in particle physics, high energy physics, and condensed matter physics and among accelerator physicist planning to develop 1 GeV proton accelerator, spallation neutron source. A neutron-antineutron oscillation experiment can be carried out by developing a cold neutron source following spallation target and an essentially background free measurement of the annihilation of antineutrons in an annihilation chamber using free neutrons would be possible. As presence of magnetic field can stop transformation of neutrons to antineutrons and a large volume free from magnetic field (~nano tesla) would be required. The experience gained from the development work in this neutron-antineutron oscillation experiment will also serve other national goals. So, we propose for development of an ultra cold neutron source (UCN) at CAT, Indore and carrying out n-nbar oscillation experiment in India. This experiment bridges the gap between the non-accelerator particle and astroparticle physics, an area in which India is planning to take a lead by developing the INO, and the intensity frontier accelerator physics, which is being strengthened in India to use the high Thorium reserve for power generation through accelerator driven sub-critical system (ADSS) by developing 1 GeV LINAC with few mA current with MW power at Indore CAT.

- **Long Baseline Neutrino Facility.**

The primary goal of the LBNE Science Collaboration is to perform a world-leading, long baseline neutrino oscillation experiment with unprecedented sensitivity and precision and thereby determine the neutrino mass hierarchy (i.e., the ordering of neutrino masses), CP violation in neutrino mixing, and the value of the mixing parameters. The experiment's capability to perform simultaneous determinations of these quantities is a unique feature among not just the long-baseline experiments, but among all neutrino experiments worldwide. This will be accomplished by using a new high-intensity, broadband neutrino beam and a high-resolution, multi-kiloton liquid argon far detector. Searches for proton decay and the neutrino spectrum from a supernova collapse are among the long-term goals of LBNF.

The core scientific capability of LBNF will be significantly enhanced by a high-resolution near neutrino detector (ND). We propose to design and build a near detector in India that will not only add to the capabilities of the overall LBNE oscillation program, but will also independently conduct precision measurements of quantities such as neutrino-nucleon and neutrino-nuclear cross sections, electroweak parameters, sum-rules and sensitive searches for new physics, with previously unachievable precision, potentially leading to additional discoveries in neutrino physics.

The LBNE Project is currently organized into three main projects: Beam line, Near Detector Systems, Liquid Argon Far Detector. The LBNE experiment plans to take physics data starting in 2023, initially with a 708 kW beam extracted from the existing Main Injector but using a new neutrino beam line. Later, a beam power of roughly 1.2 MW, upgradable to 2.3 MW would be possible with PIP-II. India is already an integral part of PIP-II at Fermilab. Collaboration between Indian institutions and Fermilab on both accelerator and neutrino physics would enable Indian physicists and engineers to participate in the world's leading neutrino physics and detector development program, while building infrastructure and similar accelerator and detector facilities in India.

The recommendations are:

- Indian HEP community is already involved at LHC 300 and Super Belle. Full support for experiments at both the colliders should continue to be provided.
- The need of the time is to form a Future Colliders Forum at all India level just like the ILC-India Forum. Collaborations on the phenomenological front with the International Community as well as on the accelerator and detector front are where Indian community is all geared up for now.
- Full support should be given to the INO project and the additional projects that would be housed in the same facility, viz., the Double beta decay experiment, Dark Matter Search experiment and the low energy accelerator for nuclear astrophysics.
- High Energy Gamma ray experiments, TACTIC, MACE and GRAPES-3 should be supported and expanded further.
- An ultra cold neutron source (UCN) should be developed at the proposed Indian Spallation Neutron Source at RRCAT, Indore for carrying out n-nbar oscillation experiment in India.

- The collaboration in LBNE would be very useful for Indian researchers and students, especially, in the context of the national INO project. These two projects should be run in synergy with each other.

Section II: Nuclear Physics

Indian researchers have made significant contributions in the area of Quark-Gluon Plasma (QGP) and the study of phase diagram at the most fundamental level. This has led to a growth of this field in the country, although all the experimental facilities in this area are located abroad.

A number of facilities have been created within the country in low energy Nuclear Physics in the last one decade. The two heavy ion accelerator facilities at TIFR, Mumbai, and IUAC, New Delhi, have been working very successfully; they have also been upgraded by adding SC Linac modules to deliver higher beam energies and heavier ion beams. The VECC cyclotron at Kolkata has also been refurbished and is in operation.

The completion and successful operation of Indian National Gamma Array has been a landmark collaborative achievement on the national scene; it has now been regularly used for experiments at IUAC, TIFR and VECC. It's utilization at the three accelerator centers has led to many new findings and phenomena in high spin physics; these new phenomena have been internationally recognized and cover a wide area in nuclear structure and reactions.

Besides INGA, many other major facilities have been constructed and made operational at IUAC, New Delhi like the Hybrid Recoil Mass Analyzer (HYRA) which is a gas filled separator and the National Neutron Detector Array; both have been completed and tested. Digital data acquisition system was put in place for the last INGA run at TIFR, Mumbai. Fission fragment gamma-ray spectroscopy work was also carried out in India for the first time and has yielded very important results. The fission fragment spectroscopy and related works by using thermal neutrons from the research reactor Dhruva at BARC, Mumbai using a dedicated neutron beamline have also been initiated.

A Radioactive Ion Beam (RIB) facility is under development at VECC, Kolkata and may still take more time. A low energy high current accelerator is being put in place at SINP, Kolkata, which will focus on nuclear astrophysics work.

Most importantly, these experimental facilities within the country have led to a revival of nuclear physics at home. A large pool of trained manpower has been generated in this critical area and is now available to take up new challenges.

Indian researchers are also actively involved in the international mega-projects like FAIR at GSI, High Intensity proton project and LBNE at Fermilab. They are also part of other international projects like SPIRAL2 at GANIL, France and ISOLDE at CERN.

New contacts with scientists in East Europe and Russia have emerged in recent times and offer exciting opportunities for collaborative work in experiments and theory. These facilities are easier and cheaper to access. Notable among these facilities are the Joint Institute for Nuclear Research (JINR), Dubna, Russia, famous for its work in super-heavy elements (SHE). Collaboration with JINR will be very useful for Indian science.

The up-coming ELI-NP in Romania will create a new European laboratory to consistently investigate a very broad range of science domains, from new fields of fundamental physics, new nuclear physics and astrophysics and other areas. A very high intensity laser, where beams from two 10 PW lasers will be coherently added to get intensities of the order of 10^{23} - 10^{24}W/cm^{2}and electric field of 10^{15}V/m, will be established. Also, a very intense (10^{13} γ/s), brilliant γ beam, 0.1 % bandwidth, with $E_{\square}$ > 19 MeV, obtained by incoherent Compton back scattering of a laser light off a very brilliant, intense, classical electron beam (E_e > 700 MeV) produced by a warm linac, will become operational at ELI-NP, which is fully funded by European union. It offers opportunities to carry out new kind of nuclear physics experiments, not possible elsewhere. Collaboration with this facility will yield rich dividends in the future.

Based on the presentations made at the vision meeting, wider discussions and deliberations thereon, a consensus was reached on what the community wants in low energy nuclear physics for the next 10-15 years. Some of these recommendations would lead to outcomes in the immediate future of 3-5 years. Others will require about 5-10 years for maturing and giving results.

The recommendations are:

- It is strongly recommended that sufficient support be provided for experiments to study the QGP phase diagram at (a) the Relativistic Heavy Ion Collider, Brookhaven National Laboratory, New York at STAR and PHENIX, and at (b) FAIR program in

Germany at CBM. It is also recommended that continued support be given for detectors and electronics for studying QGP at LHC (CMS and ALICE).

- Also, participation in e-ion collider like BNL to study initial conditions for heavy ion (HI) collisions and hadron structure should be supported.
- It is also recommended that the NUSTAR collaboration at FAIR, GSI, Germany be continued and support for the same be provided. This collaboration aims to study nuclear structure, astrophysics and reactions by using beams of rare/radioactive nuclei.
- Support for the High Current injector facility at IUAC, New Delhi. The BARC-TIFR Pelletron facility has plans to upgrade the accelerator to high voltages and should be supported. Time frame ~ 3 years from the time of funding.
- (a) Expansion and up-gradation of the Indian National Gamma Array (INGA) so that a reasonable array can exist at each of the three accelerator laboratories viz., IUAC, TIFR and VECC. Time frame ~ 3 years from the time of funding. Cost ~ Rs. 50 crores.
- (b) Futuristic gamma-ray tracking array. The R&D of such a project must be started now and the cost is about Rs. 5 crore. Once successful, the full array may be established in the coming 5-10 years. The cost of the full array will be about Rs. 300 crores and should be taken up after the pilot study is successful.
- Up-gradation of IUAC facilities at New Delhi – Cost Rs. 40-45 crores.
- 12 CS Clover detectors at HYRA focal plane, Rs. 30 cr
- 6 LEPS HYRA target site, Rs. 6 cr
- 4 LEPS HYRA focal plane, Rs. 4 cr
- Ancillary devices (Electron spectrometer +CPDA+Multiplicity filter+electronics) Rs. 2-3 crore
- Ancillary devices (Transient field g-factor measurement, Si strip CD detector, LaBr , electronics) Rs. 3 crore
- Center for Nuclear Theory and High End Computation – This recommendation was made in the 2006 Vision meeting also. It is very important that such a center should become a reality soon in order to provide a strong theoretical support to the experimental programs. A virtual center already exists at IIT Roorkee, where a strong group of theorists in low energy nuclear physics is very active. The running cost of such a center will not be more than Rs. 50-60 lacs per year with an initial support for

high end computation of the order of Rs. 3-4 crores. No permanent staff should be employed in the center.

- Center for Radiation detectors, Nuclear Instruments and Innovative technologies for societal needs. Such a center should again be established at a place where sufficient manpower already exists so that the recurring costs are low.
- To establish a collaboration with JINR, Dubna. This will allow our scientists to work in niche areas like SHE, RIB and neutrino physics. An associate membership will cost Rs.5 crore per year and will cover the cost of Indian scientists to travel and stay at Dubna for experimental work. Theorists can also visit and collaborate with scientists in the Bogoliubov Lab at Dubna.
- To establish a fund for proposing and conducting experiments at the up-coming RIB facilities around the globe, e.g., CERN-ISOLDE, RIKEN, MSU and GANIL. About Rs. 10 crores will be required for 5 years. This kind of program can be started right away.
- To support small RIB facilities in the country by using the existing facilities like HYRA at IUAC and Solenoid based facility at TIFR-BARC.
- In view of the growing interest in nuclear astrophysics, it is recommended that a Center for Nuclear Astrophysics be established at a place where few scientists are actively working. It is also recommended that a small accelerator be put up at a university which could be used for nuclear astrophysics work. This may be combined with the proposed center and may work in tandem with the INO facility where a similar accelerator can be put up under-ground.

Section III: Accelerator Physics

Particle accelerators are used not only for research in nuclear and particle physics but, these have also emerged, consequent to the development of synchrotron radiation sources, as major tools for materials science research. Besides, accelerators are also developed and used extensively for medical and industrial applications. Truly, the technological capability of a country can be gauged by the accelerators it can build. In this meeting, 10 presentations were made bringing out the accelerator activities in the country, which should be pursued during the next 10-15 years. Important technological achievements and the status of major ongoing accelerator projects in the country were discussed to get a glimpse of the current technological strengths and challenges to be met for the development of new accelerators.

Presentations were made by the scientists who are actively involved in different R&D areas of their expertise. The topics covered in the talks were Accelerator Driven Systems, Spallation Neutron Source, Radioactive Ion Beams, High Brilliance Synchrotron Radiation Source, Superconducting Heavy Ion Accelerators, High Intensity Short Wavelength FEL, International Linear Collider, Cyclotron and their Applications, Pelletron Linac Facility at Mumbai and FAIR-India Collaboration.

Following is a summary of the presentations.

Indus-1 and Indus-2 synchrotron radiation sources at RRCAT are operated round the clock and serving as a national facility. Presently, Indus-2, the largest and highest energy accelerator built in the country is operational up to 200 mA beam current at its design energy of 2.5 GeV. Indus-1 is operational at its design energy of 450 MeV and 100 mA beam current. Various components and sub-systems of these accelerators have been developed indigenously and most of them for the first time in the country. 12 beamlines on Indus-2 and 6 beamlines on Indus-1 have been commissioned and used by an increasing number of researchers from universities, academic institutions and national laboratories. The performance of Indus-2 is going to be further enhanced by installing 5 insertion devices, which will increase the brilliance to ~ 10^{17} photons/s/mm^2/mrad^2/0.1% BW for photon energies < 1 keV.

A new technology of solid state amplifiers was indigenously developed at RRCAT as the substitute for the imported klystrons to power the RF cavities in the Indus-2 storage ring. Availability of more than 200kW RF power with these solid state amplifiers has made it possible to operate Indus-2 at 2.5 GeV beam energy and 200 mA beam current.

There is a demand from Indian user community to have a nanometer (nm) emittance, high energy synchrotron radiation source providing photons of brilliance 10^{20} photons/s/mm^2/$mrad^2$/0.1% BW or better, for energies extending to several tens of keV. Considering the know-how generated at RRCAT for the development of synchrotron radiation sources Indus-1 and Indus-2, the design and development of such an advanced light source is within indigenous capability. Preliminary design studies indicate that such a source may be based on a medium energy (for instance 4.5 GeV) synchrotron with sub-nm rad emittance (for instance ~ 250 pm.rad) and 200 mA electron beam current. Such a machine would be adequate to meet user requirement of photon energy up to ~ 100 keV. Final specifications of the source need to be evolved in consultation with the user community, keeping in view the available capabilities and cost-benefit aspect. However, a high brilliance, low emittance source poses stringent requirements on its sub-systems. Broadly speaking, the beam stability requirements for the new source will be about one order of magnitude better than Indus-2. R&D work will be carried out to address the technical gap areas during pre-project phase. Resources like technological infrastructure, land, electrical power etc. required for the new source are already available at RRCAT. The estimated time frame for building the new source is ~ 10 years with 3-4 years of pre-project activities. The present estimated cost of this project is Rs 5000 Crores.

The *K*500 superconducting cyclotron has been constructed at VECC and internal beam up to the extraction radius has been accelerated. Attempts are now being made to extract the beam out of the machine into the zero degree beam line. A novel design has been carried out of an ultra-light compact superconducting cyclotron producing 25MeV proton beam useful for producing isotopes for nuclear imaging at VECC. Cyclotrons are widely used for medical-radioisotope production and particle therapy. Development of compact cyclotrons for medical applications should be considered a priority area.

VECC has developed a low energy radioactive ion beam (RIB) facility around the *K*130 cyclotron. A number of state of the art accelerators have been developed and built for the facility such as India's first RFQ linac, heavy ion drift tube IH linac and on-line ECR source. Several RIBs and stable isotopes have been produced using this facility. The present RIB facility has been built with extensive R&D effort, supported by Indian industry and national as well as international collaborations. With this success, VECC has now started the construction of the next generation facility named ANURIB (Advanced National Facility for Unstable and Rare Ion Beams) which will employ a unique combination of ISOL and PFS methods to produce intense radioactive ion beams. ANURIB will be built in two phases at

VECC's new campus at Rajarhat. In Phase-1, neutron rich RIBs will be produced using photo-fission of actinide targets. The development of a 50MeV, 100kW superconducting electron linac to be used as the primary accelerator is being done in collaboration with TRIUMF (Canada).

India has vast reserves of thorium. To use thorium for energy generation, naturally available fertile thorium is required to be converted into fissile thorium and this can be done using an accelerator driven sub-critical system (ADS). Keeping in view the increasing energy needs of the country, DAE has envisaged utilizing thorium for energy generation and it has, accordingly, taken up a long term programme to develop an accelerator driven sub-critical system. In order to fulfill this objective, R&D work has been initiated to develop a high energy (1GeV) and high current (>20mA) CW proton linear accelerator (linac) to be based at BARC(Vizag) and a 1 GeV and 1MW superconducting pulsed linac and accumulator ring for setting up of a spallation neutron source at RRCAT(Indore).

Development of the CW linac will be done in three phases. The most challenging part of this accelerator is development of the low-energy injector, because the space charge forces are maximal at low energies. Therefore, the development of a 20 MeV, 30 mA proton accelerator (LEHIPA) has been taken up at BARC. As a first step, a 400 keV RFQ has been developed and commissioned. Development of 1 GeV CW linac may take around 15 years.
RRCAT is pursuing R&D for indigenous development of superconducting radio-frequency (SCRF) cavities, RF power amplifiers, cryogenics and associated infrastructure required for the development of the 1 MW pulsed linac for the proposed Indian Spallation Neutron Source (ISNS). An accumulator ring is also planned to compress the beam pulse length and enhance the intensity of proton beam. Physics design for the 1GeV linac and the accumulator ring is also being worked out at RRCAT. Single-cell and multi-cell 1.3 GHz and single-cell 650 MHz niobium SCRF cavities have been developed under the framework of IIFC. A vertical test stand facility has also been set up for characterization of these cavities. A new technique of welding niobium SCRF cavities by lasers offering several advantages over the conventional technique has been pioneered at RRCAT. RRCAT-IUAC collaboration has successfully developed state-of-art 1.3 GHz single and multi-cell TESLA type cavities under IIFC collaboration. After having successfully developed 500 MHz RF power amplifiers for Indus-2, R&D is now being carried out for the development of 650 MHz solid state amplifiers for the proton linac as well as for the accelerators of Fermilab programme under the frame-work of IIFC. With the capabilities generated at RRCAT, the development of a 1 GeV superconducting pulsed linac and the accumulator ring may take about 10 years.

Free electron lasers: Free electrons lasers (FELs) are fourth generation light sources, to produce photon beams with peak brilliance of several orders of magnitude higher than the present day synchrotrons. Many FELs are operational around the world and are used for a wide variety of experiments from biology to condensed matter physics. Various laboratories in India have programmes on FELs with RRCAT and IUAC being the main organizations having ongoing activities for the development of FELs. IUAC is working on the development of an infrared FEL using a superconducting photocathode gun and linac. RRCAT has developed a compact THz FEL using an indigenously built electron linac and undulator, which is currently going through commissioning trials. The first signature of build-up of coherence has been observed in this laser operating at 1.5 THz. Work is underway to set up an FEL in the infrared region and construct beamlines for materials research. This R&D experience should pave way for a project on the development of an FEL providing photons of shorter wavelengths (VUV/X-rays).

Heavy ion accelerators: IUAC and BARC-TIFR Pelletron accelerator laboratories are pursuing R&D in this area. The development of Nb Superconducting cavities was pioneered in India at IUAC where the first indigenous cavity fabrication facility was established. Nb quarter wave resonators, 1.3 GHz single cell cavities, 350 MHz spoke resonators have been fabricated using this facility. The Pelletron –Booster Linac combination has been delivering heavy ion beams of a wide variety for user experiments in Nuclear Physics, Materials Science, Atomic Physics and Radiation Biology on a regular basis. There has been considerable progress in the plan to develop a high current injector (HCI) for the superconducting linac at IUAC. A radiofrequency quadrupole, one unit of drift tube linac and prototype Nb low beta cavity have been designed and fabricated. The HCI will allow heavy ion beams to overcome the Coulomb barrier up to A=120 on 120 in next 10 years.

An ECR based heavy ion accelerator development is in progress at BARC-TIFR Pelletron facility. The development of this accelerator is expected to be completed in next 10-15 years.

Participation in FAIR project: FAIR is the largest basic science facility coming up in Germany and will provide high intensity heavy ion beams, radioactive ion beams and antiproton beams. Indian experimentalists have shown interest in using this facility for research in nuclear physics, hadron physics, atomic physics and high energy physics. India is participating in both building accelerator components and detectors for FAIR experiments. As a part of India's in-kind contributions, a number of equipments have been identified which include a power converter, a beam stopper, vacuum chambers and superconducting magnets.

All these are under various stages of development and will be installed in the FAIR facility, which is scheduled to start in 2019. In addition, Indian scientists are also involved in building advanced detectors, electronics and data analysis. All activities in India related to the FAIR project are carried out under project funded equally by DST and DAE through the Indo-FAIR Co-ordination Centre (IFCC) at Bose Institute, Kolkata. The vision for this project can be divided into two parts, namely short term vision and long term vision. Short term vision is to deliver all the equipments to FAIR in coordination with industry and laboratories. Additional funds may be required to fulfill this commitment. In the long term, this centre will have two major functions (1) to coordinate all experimental activities including training of researchers and engineers (2) to work with Indian industry to promote its participation in building FAIR related equipment and India's future accelerator projects

Accelerators for societal applications: RRCAT, BARC and VECC are working on the development of accelerators for societal applications. VECC is setting up a cyclotron facility which will be used for production of medical isotopes and sterilization of medical products. At RRCAT, a 7-10 MeV, 3 kW electron linac is being used for irradiation of food, agricultural and medical products. BARC has also developed electron accelerators for industrial applications. VECC has the expertise to develop ultra-light cyclotrons useful for medical imaging applications.

Laser based acceleration schemes: These schemes can offer very high accelerating gradients and thus the size and cost of high energy accelerators can be drastically reduced. Laser wakefield acceleration (LWFA) is an extremely promising new technique of acceleration. Using this technique, acceleration to 2 GeV has been demonstrated and efforts are being focused on getting good quality beams. RRCAT has also initiated R&D in this area using its 150 TW Ti-Sapphire laser and has accelerated electrons to 50 MeV. Research in this area need to be strengthened.

ILC : International Linear Collider (ILC) is the proposed 31 km long 0.5-1 TeV electron positron linear collider. The Technical Design Report (TDR) of this collider has been published in 2013. Future of ILC depends on the results yet to be obtained from the LHC upgrade. If this project is taken up, India can supply SCRF cavities, a large number of which is required for this project and Indian industry can greatly benefit from this involvement. Technology of superconducting cavities will be well matured in India in coming few years.

Manpower crunch is likely to become a hindrance to future expansion of accelerator activities in national laboratories. Accelerators should be set up in universities to train manpower, which is available for execution of accelerator projects. It may be useful to follow the INO model and start a PhD programme on training students in accelerator beam science and technology and employ them in accelerator projects. This may be shaped on the model of UGC Faculty Recharge Programme.

Participation of Indian industry: A number of national mega science projects such as Accelerator Driven Subcritical Systems, ANURIB, Indian Spallation Neutron Source and High Brilliance Synchrotron Source are being envisaged, the participation of Indian industries in these projects will be very useful. These projects will require a large number of identical components such as magnets, RF cavities, RF amplifiers, vacuum pumps etc. Indian industries have a golden opportunity to improve their technical capabilities by participating in these projects. This will also help optimizing the requirement of R & D manpower in the research laboratories.

The recommendations are:

- **Support for existing accelerator facilities:** Synchrotron radiation source Indus-2 is operational in round the clock mode at 2.5 GeV, 200 mA beam current and is being upgraded with insertion devices. This source is extensively used by researchers from universities, academic institutes and national laboratories. *K*500 cyclotron is commissioned with internal beam and is likely to be available soon for users' experiments. The radioactive ion beam facility setup around the *K*130 cyclotron is the only RIB facility in the country and is a very useful facility. The two pelletron-linac heavy ion accelerators at IUAC and BARC-TIFR continue to be in great demand for a wide variety of experiments. In order to keep these facilities available to the users, a financial outlay of Rs 500 crores is required.
- **High Brilliance Synchrotron Radiation Source:** Synchrotron Radiation (SR) sources have emerged as a powerful tool for research in materials science, chemistry, physics, biology etc. The 2.5 GeV synchrotron radiation source Indus-2, operational round the clock, with undulators will provide the radiation with brilliance ~ 10^{17} photons/s/mm^2/mrad^2/0.1% BW for photon energies < 1 keV. There is a demand from Indian user community to have a nm emittance, high energy synchrotron source providing photons of brilliance 10^{20} photons/s/mm^2/mrad^2/0.1% BW or better, for energies extending to several tens of keV. A 4.5 GeV energy, sub-nm rad. emittance, 200 mA machine could be a viable option satisfying user requirement of photon

energy up to ~ 100 keV. Scientists, engineers and technical staff experienced in various areas of accelerator R&D are available in DAE institutions for design and development of such a new source. Resources like technological infrastructure, land, electrical power etc. required for the new source are also available at RRCAT. The estimated time frame for building new source is ~ 10 years with 3-4 years of pre-project activities. Total outlay for this project is around Rs 5000 crores.

- **High intensity, high energy proton accelerator for ADS:** Three stage nuclear energy programme of DAE, in its third stage, envisages utilizing thorium available in a large quantity in India for energy generation. ADS is considered to be a safe and viable option to produce the fissile thorium required for energy generation. It is a challenging task to develop a reliable high energy high current (typically 1 GeV, 20mA) proton accelerator required for this system. R &D efforts are being made all over the world to develop such an accelerator. DAE has initiated R&D in this area and expertise and infrastructure being developed at BARC and RRCAT will be useful for the development of this system. DAE's programme for the development of ADS, which is a frontline area of R&D in the world, needs to be fully supported in view of its vital importance to its nuclear energy programme. The estimated time frame for the development of such a system is 15 years and would require approximately Rs 10,000 crores.
- **Indian Spallation Neutron Source:** Indian Spallation Neutron Source (ISNS) will be a materials science research tool complementing the synchrotron radiation sources at RRCAT and neutron facilities at BARC. This source will also be used for studying the behavior of the materials to be used in ADS under intense neutron irradiation. The technology required for building superconducting cavities, cryo-systems, RF systems, vacuum system etc will be similar to that required for ADS. The technological infrastructure developed at RRCAT will be useful in the development of ISNS. This ISNS facility will also help in training manpower. The design of the accelerator including the accumulator along with a conceptual design report will be ready in 5 years and subsequently about 8-10 years period will be required to complete the accelerator and beam transport to the target. The total outlay required for realization of the ISNS will be around Rs 8000 crores.
- **Radioactive ion beam facility ANURIB:** The need for a national radioactive ion facility was expressed in the last vision meeting. VECC has subsequently

developed a low energy RIB facility around *K*130 cyclotron. With this experience, the development of a next generation facility named Advanced National Facility for Unstable and Rare Ion Beams (ANURIB) has been taken up at VECC in XII Plan. The facility will use a unique combination of ISOL and PFS methods to produce intense RIBs. In phase-1, neutron rich RIBs will be produced using photo-fission of actinide targets. This facility will be built in phases at VECC's new campus at Rajarhat and may cost around 1000 crores.

- **Participation in FAIR facility:** The participation in this project should be continued. The vision for this project can be divided into two parts namely short term vision and long term vision. Short term vision is to deliver all the equipment to FAIR in coordination with industry and laboratories. Additional funds may be required to fulfill this commitment. Long Term vision envisages establishing a centre to coordinate India's participation in FAIR experiments. Overall outlay for this project will be Rs 500 crores.
- **FEL for shorter wavelengths**: The long term aim of FEL R&D in the country should be the development of a fourth generation light source. An intermediate aim could be the development of UV free electron laser test facility to develop required expertise. While expertise in some areas is presently available, there are technological gap areas like bunch compression, generation and manipulation of high brightness beams, single bunch and short pulse electron beams, seeding schemes etc., which should be developed in the coming 5-10 years. A budget for this activity will be around Rs 200 crores.
- **R&D in laser based acceleration schemes**: Laser wakefield acceleration is a very promising field with potential of making table top accelerators at much lower cost which could be useful for several applications. In long term future, many physical investigations where gigantic conventional accelerators may not be possible to build, will be conducted by the laser plasma accelerators. Comprehensive R&D activities should be carried out in this area with a funding to the tune of Rs 300 crores.
- **Accelerators for societal and other applications**: Compact cyclotrons and linacs should be built for production of radio-isotopes for medical diagnostics and therapy and industrial applications. Application of accelerators in Earth Sciences and Archaeology is an area of great importance and demand and should be supported.

Appendix A

S. No.	Name	Institution
1	M. Sajjad Athar	AMU, Aligarh
2	Satyaki Bhattacharya	SINP, Kolkata
3	Brajesh Choudhary	DU,Delhi
4	Debajyoti Choudhury	DU
5	Md. Naimuddin	DU
6	Biswarup Mukhopadhyay	HRI, Allahabad
7	Rohini Godbole	IISc, Bengaluru
8	Vipin Bhatnagar	PU, Chandigarh
9	Poulose Poulose	IIT Gauhati
10	D. Indumathi	IMSc, Chennai
11	Prafulla Behera	IIT, Chennai
12	Sanjib Aggrawal	IOP, Bhubaneswar
13	Manas Maity	ViswaBharati, Santiniketan
14	P. Mal	NISER, Bhubaneswar
15	Sunanda Banerjee	SINP
16	Satyajit Saha	SINP
17	Ritesh Singh	IISER, Kolkata
18	Amlan Ray	VECC, Kolkata
19	Parnika Das	VECC
20	Ananthanarayan B.	IISc
21	Saurabh Rindani	PRL, Ahmedabad
22	Rahul Sinha	IMSc
23	J.B. Singh	PU
24	Bipul Bhuyan	IIT, Gauhati
25	Ravindran V.	IMSc
26	Kirti Ranjan	DU
27	Gautam Bhattacharyya	SINP
28	Raj Gandhi	HRI
29	D.K. Ghosh	IACS, Kolkata
30	Utpal Sarkar	PRL
31	P.C. Vinod Kumar	Vallabh Vidyanagar, Anand
32	Bedangadas Mohanty	NISER
33	Prince Ganai	NIT, Srinagar
34	Jane Alam	VECC
35	P. Arumugam	IIT-R, Roorkee
36	R. Chatterjee	IIT-R
37	Manoj Kumar Sharma	Thapar Univ, Patiala
38	Subinit Roy	SINP
39	A.M. Vinod Kumar	Calicut Univ
40	Gopal Mukherjee	VECC
41	G. Gangopadhyaya	Calcutta Univ
42	S. Mandal	Delhi Univ
43	A.K. Singh	IIT Kharagpur
44	R.P. Singh	IUAC, New Delhi
45	N. Madhavan	IUAC
46	Ashok Jain	IIT-R

47	B. Behera	Panjab Univ
48	A. Goswami	SINP
49	Tapan Nayak	VECC
50	Jhilam Sadhukahan	VECC
51	D.K. Srivastava	VECC
52	Sandeep Ghugre	UGC-DAE CSR, Mumbai
53	Maitreyee Saha Sarka	SINP
54	S. Muralithar	IUAC
55	Sukalyan Chattopadhyay____	SINP
56	Ushasi Datta Pramanik	SINP
57	P.D. Gupta	RRCAT, indore
58	Gurnam Singh	RRCAT
59	P:.R. Hannurkar	RRCAT
60	S.B.Roy	RRCAT
61	S.C. Joshi	RRCAT
62	G.S. Lodha	RRCAT
63	A.C.Thakurta	RRCAT
64	P.K.Kush	RRCAT
65	Tushar Puntambekar	RRCAT
66	K.K. Pant	RRCAT
67	Vinit Kumar	RRCAT
68	D. Kanjilal	IUAC
69	S. Chopra	IUAC
70	Alok Chakrabarti	VECC
71	Vaishali Naik	VECC
72	Malay K. Dey	VECC
73	Amit Roy	VECC
74	Arup Bandyopadhyay	VECC
75	S. Chattopadhyay	VECC
76	Puneet Jain	IIT-R
77	A.K.Mohanty	BARC, Mumbai
78	Alok Saxena	BARC
79	Arunodoy Mitra	BARC
80	Bidyut Roy	BARC
81	Bency V. John	BARC
82	Basanta K. Nayak	BARC
83	Dipak C. Biswas	BARC
84	Dipanwita Dutta	BARC
85	K. Ramachandran	BARC
86	Prashant Shukla	BARC
87	Sudhir R. Jain	BARC
88	Suresh Kumar	BARC
89	Satyaranjan Santra	BARC
90	S.V. Suryanarayana	BARC
91	Vivek M. Datar	BARC
92	Lalit M. Pant	BARC
93	Kripa Mahata	BARC
94	Rahul Tripathi	BARC

95	S. Kailas	UM-DAE-CBS
96	V Jha	BARC
97	Ajay Kumar	BARC
98	H Kumawat	BARC
99	A Bhattacharya	BARC
100	J A Gore	BARC
101	A Bhagwat	BARC
102	Sujit Tandel	UM-DAE-CBS
103	Hemlata	UM-DAE-CBS
104	Sushil Kumar	Chitkara Univ, Solan
105	Paresh Joshi	HBCSE, Mumbai
106	Basanta Nandi	IITB, Mumbai
107	Pragya Das	IITB
108	Raghava Varma	IITB
109	S. Uma Sankar	IITB
110	Pradip sarin	IITB
111	Anuradha Misra	Mumbai Univ
112	Manoranjan Guchait	TIFR, Mumbai
113	Gagan Mohanty	TIFR
114	Atul Gurtu	TIFR
115	Amol Dighe	TIFR
116	B. Satyanarayana	TIFR
117	B. S. Acharya	TIFR
118	Gobinda Majumder	TIFR
119	Kajari Mazumdar	TIFR
120	Naba K. Mondal	TIFR
121	Rudrajyoti Palit	TIFR
122	R. S. Bhalerao	TIFR
123	R.G. Pillay	TIFR
124	Rajiv Gavai	TIFR
125	Shashi R. Dugad	TIFR
126	Sudeshna Banerjee	TIFR
127	Sunil K. Gupta	TIFR
128	Tariq Aziz	TIFR
129	Vandana Nanal	TIFR
130	Abhay P. Deshpande	SAMEER, Mumbai

Organizing Committee:

Amit Roy (Convener), Atul Gurtu, Rohini Godbole, Ajit Mohanty (Local Convener), L. M. Pant (Local organisation), P.D. Gupta, Alok Chakraborty, Naba K. Mondal, Vivek M. Datar, Ashok K. Jain, Praveer Asthana (DST), B. Purniah (DAE)

Appendix B
Agenda for Vision Meeting of Nuclear, Particle and High Energy Physics
HBCSE, Mankhurd, Mumbai, 24-25 August 2014

Day 1: Sunday, 24th August 2014

9.30 - 10.45 Session I **Introductory session (VGK Auditorium, HBCSE)**

- **a.** Welcome - **Vivek Datar**
- **b.** Introduction to the meeting - **Amit Roy**
- **c.** Overview of Particle & High Energy Physics - **Atul Gurtu**
- **d.** Inaugural Remarks -**Prof. K.Vijay Raghavan, Secretary, DST (via SKYPE)**
- **e.** DAE Perspective - **Dr. B.Purniah**

10.45 – 11.15 High Tea

11:15 - 13:00 Session II **Parallel Sessions (individual presentations)**

a. Accelerator Physics - **VGK Auditorium, HBCSE** (capacity 150 persons)
- Conveners : P. D. Gupta & A. Chakrabarti

Accelerator Driven System, ***S.V.L.S. Rao***
Spallation Neutron Source, ***S.C. Joshi***
Radioactive Ion Beams, ***Vaishali Naik***

b. Nuclear Physics (including QGP) - **Conference Room G1, HBCSE** (capacity 60 persons)
- Conveners : **A. K. Jain & V. M. Datar**

Reaction mechanisms and theoretical understanding vis a vis structure, ***K. Mahata***
Nucl. Str. at high spin, isospin, deformation, temp, application toNDBD, ***R.Palit***
Clustering, Heavy Cluster, Spon. fission decays & search for Super Heavy Elements, ***P. Arumugam***
Nuclear Astrophysics, cross sections at Gamow energies, ***Subinit Roy***

c. Particle & High Energy Physics - **Conference Room G2, HBCSE** (capacity 60 persons)
- Conveners : **Rohini Godbole & Naba Mondal**

Theor. Motivation for Future accel. based Phy project, ***Debajyoti Choudhury***
Theor.Motivation for future non accel. based Phy projects, ***Amol Dighe***
Indian Participation at LHC pp physics: Status and future, ***Satyaki Bhattacharya***
India-based Neutrino Observatory- Status & Future, ***Gobinda Majumder***
Double beta decay initiative, ***Vandana Nanal***
Dark matter search initiative, ***Satyajit Saha***

13:00 – 14:00 Lunch

14:00 – 16:00 Session III (VGK Auditorium, G1 & G2, HBCSE) Parallel sessions continued

α. Accelerator Physics - **VGK Auditorium, HBCSE** (capacity 150 persons)
- Conveners : **P. D. Gupta & A. Chakrabarti**

High Brilliance Synchrotron Radiation Source, ***T. Puntambekar***

Superconducting Heavy Ions Accelerator, ***D. Kanjilal***
High Intensity Short Wavelength Free Electron Laser, ***K.K. Pant***
International Linear Collider, ***S. Krishnagopal***

β. Nuclear Physics (including QGP) **- Conference Room G1, HBCSE** (capacity 60 persons)
- Conveners : **A. K. Jain & V. M. Datar**
Hadron Str.& their interactions, embedding mesons, strange hadrons in nuclei, ***Nilmani Mathur***
Electroweak interactions in nuclei, probing fundamental symmetries and low energy neutrino physics ***M. Sajjad Athar***
Quark Matter in the lab and in stars, ***Jane Alam***
QGP Experiments,Present & Future ***Bedangdas Mohanty***
Applications of nuclear physics, ***B.K. Nayak***

χ. Particle & High Energy Physics **- Conference Room G2, HBCSE** (capacity 60 persons)
- Conveners : **Rohini Godbole & Naba Mondal**
Indian participation in Super KEKB: Status & Future, ***Gagan Mohanty***
ILC initiative: Indian views, ***Poulose Poulose***
LBNF : Indian views, ***Vipin Bhatnagar***
High Energy Gamma ray experiments, ***K.K.Yadav***
N – Nbar Oscillations, ***Parnika Das***
GRAPES update, ***Sunil K Gupta***

16:00 – 16:30 Tea

16.30 – 18.45 Session IV (VGK Auditorium, G1 & G2, HBCSE)
Parallel discussions on 3 topics leading to agreement on the vision and defining the thrust areas within each topic
(α) Accelerator Physics
Part A *Cyclotrons and their Applications,* ***M.K. Dey***
Pelletron- Linac Facility at Mumbai, ***Anit Gupta***
FAIR-Indian contributions, ***S. Chattopadhyay***
Part B Discussions

Day 2: Monday, 25th August 2014

09:00 – 10:30 Session V (Plenary) (VGK Auditorium, HBCSE)

Talks by 3 conveners (one from each area) on what they agreed upon in their respective topics. (30 mins each)

10:30 – 11:00 General discussion on these topics

11.00 – 11.30 Tea

11:30 – 12:30 Session VI (Plenary) (VGK Auditorium, HBCSE)
Discussions on miscellaneous points that anyone may want to raise..HRD, difficulties/problems faced by people

12:30 – 13:30 Session VII (Parallel Session) (VGK Auditorium, G1 & G2, HBCSE)
Each topic to summarize the thrust areas, etc.

13:30 – 14:30 Lunch

14:30 – 16:00 Session VIII (Plenary) (VGK Auditorium, HBCSE)
Summary presentations on the three topics by conveners(3x30 mins).

16:00 – 16:15 Conclusion

END OF MEETING