Mega Science Programme in India – evolution and prospects†

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Mega Science Projects (MSPs), because of their special characteristics, require a different paradigm for planning, funding and management. The evolution of India's engagement with such projects, the national gains that have accrued because of this engagement and the structures for planning, funding and management of MSPs in the country are briefly described in this article. A reasoned response to some of the concerns raised against such projects has been provided. Finally, the article looks at the future prospect of MSPs from the Indian perspective.

Keywords: Evolution and prospects, international collaborations, management challenges, mega science projects.

MEGA Science Programme – or 'Mega Science' as it is often colloquially referred to – deals with Mega Science Projects (MSPs). In this article, we shall attempt to trace the history, growth and special features of the 'Mega Science' enterprise, especially with reference to India. We shall adopt an *ab initio* approach and start by agreeing on a definition of MSPs first.

In order to arrive at a definition of MSPs, it will be useful to first discuss what a 'mega project' is. As the name suggests, this is a 'big' project – most likely large in physical size, expensive and technologically complex to build, consisting of a large number of sub-systems, requiring participation from a large number of people, needing considerable time to build, and so on. In this sense, building a highway, a power plant, an oil refinery, etc. are all mega projects. In these familiar examples, the size and expense may pose newer challenges and complexity, but the underlying science and technologies are largely known. One can think of these as 'Mega Engineering Projects (MEPs)'. In contrast, the 'Mega Technology Projects (MTPs)' have the usual attributes of mega projects, but they set out to develop and demonstrate hitherto unknown technologies (either for the entire world, or for a nation in case of restricted-use or classified technologies). In the Indian context, for example, the development of nuclear reactors, combat aircrafts, nuclear submarines, missiles, space propulsion systems, etc. are all examples of MTPs. From this point of view, the International Thermonuclear Experimental Reactor (ITER) Project should also be classified as an MTP. Once completed, it will establish the feasibility of harnessing nuclear fusion for electrical power by humankind.

Next come the MSPs, which undertake to (a) build complex (usually also large) 'scientific instruments' and/or (b) carry out large-scale complex scientific investigations to look at frontline scientific issues in certain areas of science. Large Hadron Collider (LHC), Facility for Antiproton and Ion Research (FAIR), Thirty Metre Telescope (TMT), Giant Magellan Telescope (GMT), Extremely Large Telescope (ELT), International Linear Collider (ILC), etc. all fall under this category. If we keep the relatively recent, and currently operating, example of LHC in mind, the distinction becomes immediately obvious. After its completion, it discovered the last missing piece in the Standard Model (SM) of Particle Physics, viz. the Higgs particle. It discovered over 50 new hadrons and put important bounds on several new concepts like supersymmetry, extra dimensions, etc. These are all cutting-edge scientific issues in current Particle Physics, and LHC has served as a 'scientific instrument' to settle many of these questions experimentally.

It is needless to say that MEPs, MTPs and MSPs all involve a complex mix of science, technology and engineering. None is superior to the other. The difference is in the ultimate use of these mega projects once they are built. When comparing the relative investments made for different projects, it becomes important to distinguish between MEPs, MTPs and MSPs. Similarly, the parameters for evaluating returns from these projects will depend on the class to which they belong. Also, the public expectations from MEPs, MTPs and MSPs will be markedly different. So, proper classification of any mega project in these three categories is important.

Let us now return to the topic of our discussion, viz. MSPs. In the Indian context, MSPs were identified as a distinct scientific enterprise in the 11th Plan Period (2007–12). A Working Group on MSPs was constituted

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under the chairmanship of Anil Kakodkar (the then Chairman, Atomic Energy Commission), by the Office of the Principal Scientific Advisor (PSA) to the Government of India (GoI), to look at such projects as a distinct scientific activity for the first time. Its Report was duly considered by the 11th Plan Steering Committee on Science and Technology (S&T), chaired by R. Chidambaram (PSA to GoI) and co-chaired by V. L. Chopra (Member, Planning Commission, GoI)[1]. Chapter 7 of the Steering Committee Report was devoted to MSPs, and it defined MSPs[2] as follows:

> 'Mega-Science projects should appeal to the scientific curiosity of the researchers in search of answers to some of the important questions facing the world of science, and should be of interest to a large scientific community from various research groups within the country and outside.
>
> Mega-Science projects would be very large in terms of outlays or the complexity involved. Thus, a user group, institution or individual countries would need to join hands with other similarly interested groups. Implementation of such projects would involve multi-institutional teams, including possible international collaboration.'

The discussion on, and definition of, MSPs above tell us that they will have the following special characteristics:

- They are usually of large size.
- They require large capital, financial and human resources.
- They involve high degree of technical complexity.
- They involve technologies that are not available off-the-shelf; they push the very frontiers of technology; consequently, they involve considerable upfront R&D.
- They are manifestly collaborative, involving large number of scientists, engineers, technicians, technical managers, institutions, industries, funding agencies, etc.
- They are, very often, international ventures.

Among all these characteristics, 'technical complexity' and 'manifestly collaborative nature' remain the two most common features of all MSPs.

India's engagement with Mega Science Projects – the evolution

India's growing engagement with MSPs has taken place in a specific scientific and socio-economic context.

Scientifically, it was the field of High Energy Physics or Particle Physics that first experienced the need for MSPs. This field of basic science aims to look at the most elementary constituents of matter and their interactions. Therefore, one needs to probe deeper and deeper into the matter, utilizing projectiles (particle beams) of higher and higher energies. In some sense, these are all modern and sophisticated variants of the Rutherford Experiment. In order to accelerate particle beams to higher and higher energies, bigger and bigger, and ever more powerful, particle accelerators got built over time.

Experiments at such large accelerator facilities, even if they were built by individual nations, were mostly large international collaborative ventures. In some sense, experimental high energy physics was the first to experience the globalization of scientific enterprise. Indian scientists and/or institutions became part of these large international collaborations. In particular, Indian scientist-to-scientist collaboration with CERN (European Organization for Nuclear Research), Switzerland, dates back to the 1960s. Our scientists/institutions collaborated with Fermilab, USA; Dubna, Russia and other such accelerator facilities across the world. It was possible to do this in those days at the scientist-to-scientist or institution-to-institution level because the data were gathered in the form of bubble chamber/cloud chamber images or exposed emulsion plates. Our scientists participated in experiments abroad and brought back those images on films/emulsions and analysed them in their laboratories under microscopes.

Slowly, particle physics experiments moved to the on-line category, where data were obtained electronically using large detectors. Not only was the accelerator huge, but so were the detectors and the volume of data was also enormous. Indian scientists/institutions became part of building the detector systems, doing on-line experiments and analysing the data obtained electronically. TIFR (Tata Institute of Fundamental Research), Mumbai, contributed some hardware for the L3 experiment at the Large Electron Positron (LEP) Collider at CERN in the 1980s. Delhi University (DU), Panjab University (PU), Chandigarh, and TIFR also built muon detectors for the D0 experiment at Fermilab in the 1990s.

However, the signing of the Agreement of Cooperation between CERN and GoI in 1991, and the CERN–India Protocol in 1996, became the turning points in India's engagement with MSPs. India agreed to contribute accelerator and detector components for the LHC and became part of accelerator and detector building in an international high energy physics project in a major way for the first time.

As a result of our LHC involvement, and also the building of some world-class facilities like the Giant Metrewave Radio Telescope (GMRT) in the country, India's scientific, technological, engineering and industrial capabilities to supply sophisticated hardware with international specifications, quality benchmarks and timelines got noticed across the world. The Indian particle and accelerator physicists also got together to form well-structured collaborations like their international counterparts.

S&T, like other fields of human activity, derive sustenance from, and thrive in, the extant socio-economic context. From, 1990s onwards, India started witnessing momentous changes on the socio-economic front. The

Indian economy opened up with globalization and liberalization. Our technological drive and innovative acumen started getting noticed in the information technology/software sector. India also started recording increasingly good economic growth and had relatively better resources available. All these factors had a positive impact on our S&T sector too. Fortunately, this period also coincided with our mega science engagement.

Globally, the concept of big scientific collaborations also moved to other areas; for example, the Human Genome Project, synchrotron radiation sources, etc.

It was against these emerging global and national realities that the Planning Commission, GoI, in the 11th Plan Period, decided to consider MSPs as a separate class of scientific activity, and devoted a full chapter to them in the Report of the Steering Committee on S&T mentioned earlier in this article.

Mega Science Projects ─ India's involvement and gains

Some of the major MSPs in which India is currently involved are:

> LHC, CERN, Switzerland; FAIR, Germany; TMT, USA; Pottipuram Research Centre (India-based Neutrino Observatory, INO), India; Laser Interferometer Gravitational-wave Observatory, India (LIGO-India), India; Square Kilometre Array (SKA), Australia and South Africa; ASTROSAT, India's Astronomy Satellite; Major Atmospheric Cherenkov Experiment (MACE), India; International Thermonuclear Experimental Reactor (ITER), France; High-Intensity Superconducting Proton Accelerator (HISPA), USA and India.

In principle, the last two (ITER and HISPA) can also be classified as MTPs.

The Indian scientific community is either building, or desirous of building, some of the following MSPs in the country:

- National Large Solar Telescope (NLST);
- Radioactive Ion Beam (RIB) Facility;
- National Large Optical Telescope (NLOT);
- High Brilliance Synchrotron Radiation Source (HBSRS);
- Spallation Neutron Source (SNS).

These lists may not be complete, but are certainly indicative of the kind of MSPs in which India is participating and those (of appropriate size and scale) that our scientists are planning to build on Indian soil. The purpose of giving this snapshot is to pick a few of these MSPs as examples and illustrate the nature of gains that have accrued to India because of such engagements. We shall focus on the following five classes of gains for India.

The science gains

Let us take the example of LHC which is operating since 2010. Indian scientists and engineers participated in building the LHC (i.e. the accelerator itself) and two detectors (the CMS (Compact Muon Solenoid) and ALICE (A Large Ion Collider Experiment) detectors). The 'science' aims of the LHC programme are: (i) to establish or rule out the existence of the Higgs particle, the lynchpin of SM, which imparts mass to all the other particles; (ii) to search for and discover physics beyond the SM for which many theories exist, e.g. supersymmetry, extra dimensions, dark matter, technicolour, etc.; (iii) to study quark confinement and the nature of the Quark Gluon Plasma; etc. These are being done by studying proton–proton collisions up to 13 TeV and relativistic heavy ion collisions up to 5 ATeV energies (soon to go up further). These are some of the most outstanding scientific questions in Particle Physics (in fact, in the whole of science) and Indian scientists have made significant contributions towards discoveries of the Higgs particle and Quark Gluon Plasma. Higgs discovery also resulted in a Nobel Prize for the theorists who had propounded the idea. LHC experiments have put important bounds on other scientific ideas. Over 50 new hadrons have also been discovered. And the story has not ended yet. LHC is expected to give data till 2035 and who knows what is in store for all of us to discover. From about 10 institutional groups to start with, about 30 are participating from India in the LHC programme now. Ph.D. students from the India-LHC programme have gone to some of the finest institutions in the world for their postdoctoral work and many of them have returned to serve some of the leading institutions in the country as faculty members. Few students have also found placement in industry. India's gains from its CERN/LHC engagement have been its marked presence in one of the most outstanding global scientific ventures of recent times, enhanced scientific knowledge and capabilities of its particle physics community and enhanced 'science standing' in the comity of nations. Let us take one more example to illustrate our point. The discovery of gravitational waves by LIGO-USA announced in 2016 (ref. 3), a hundred years after Einstein's General Theory of Relativity, is another momentous discovery of our times, resulting in another Nobel Prize to three scientists. Though the LIGO-India project is yet to come up at Aundha, Hingoli, Maharashtra, as the third node of LIGO-detectors, our scientists have been participating in the LIGO-USA project for quite some time and have made significant contributions there. In fact, the 'discovery paper' on gravitational waves has 37 Indian authors from nine Indian institutions, confirming their active involvement in this grand discovery. They also shared the Special Breakthrough Prize in Physics in 2016. India, once again, has gained in its scientific capabilities and standing globally. This discovery opens an entirely new window to astronomy, viz. gravitational wave astronomy. With the third LIGO detector in India, the country is poised to have a pre-eminent place in gravitational wave astronomy in the world as part of the LIGO consortium. With the other radio, optical and gamma ray astronomy facilities in the country, multi-messenger astronomy is expected to get a significant boost in India. With these two examples, we hope we have been able to highlight the nature and level of scientific gains that have accrued to India as a result of its participation in MSPs.

The technology gains

With the help of a few examples, let us now illustrate the nature of technology gains that have accrued to India by virtue of its participation in MSPs. India contributed PMPS (precision magnet positioning system) jacks, variety of magnets, cryogenic and electronic components, etc. as in-kind items for the construction of LHC[4]. These items were designed in our R&D laboratories and mass-produced in the industry, thereby building precious capacity in laboratories and industry to produce components according to international design specifications, quality benchmarks and strict timelines. These capacities have come in handy in subsequent projects like FAIR and other national accelerator projects like the superconducting cyclotron. To highlight the crucial nature of our contributions by a simple example, it may be mentioned that the entire LHC sits on Indian PMPS jacks. A few technologies have got transferred from CERN to the Indian industry. Some technology and equipment transfers from CERN are also helping our national SNS programme. In FAIR, India will be supplying a large number of power converters of several kinds with unprecedented stability. Once again, designed jointly with our R&D laboratories, these are being produced by the Electronics Corporation of India Limited (ECIL), a Public Sector Undertaking. Vacuum Chambers of extremely challenging design are being produced by a private industry. India will also supply beam stoppers to FAIR and the entire design has been successfully completed by CSIR-CMERI (Council of Scientific and Industrial Research-Central Mechanical Engineering Research Institute) at Durgapur, West Bengal. As part of India-Fermilab HISPA Collaboration, crucial accelerator technologies are being co-developed with Fermilab. This capacity and technology know-how will help us build our SNS and push our Accelerator-driven Subcritical Systems (ADS) programme with important ramifications for our energy security. All these accelerator technologies make us confident to go ahead with building our next-generation High Brilliance Synchrotron Radiation Source. Coming to detectors, India built Photon Multiplicity Detectors (PMDs) for WA-93 and WA-98 experiments at CERN, for the STAR Experiment at Brookhaven National Laboratory (BNL), USA, and finally for the ALICE experiment at CERN. The idea to have such a detector came from sustained theoretical work by Indian physicists. The initial version had plastic scintillators, but the bigger STAR and ALICE versions had gas-based detectors innovated by the Indian groups. For ALICE, an ASIC (Application-Specific Integrated Circuit) called MANAS (Multiplexed Analogue Signal Processor) was designed and produced in India. Based on its performance, it was used in large part of ALICE. Technologically challenging Si-strip detectors were designed by Indian R&D institutions and produced by BEL (Bharat Electronics Limited). This helped BEL foray into semiconductor detector technology. Indian groups also contributed Resistive Plate Chamber (RPC) detectors for the CMS experiment. With subsequent innovations, this will be the detector element in the INO detector. The experience of supplying GEM (Gas Electron Multiplier) detectors to the CMS experiment at CERN will also help India contribute GEM detectors to FAIR. It is also a detector which has immense applied potential for imaging. Our contributions to the ITER project have helped build invaluable capacity in vacuum systems, cryogenics, controls and diagnostics. This is already helping us in other international as well as national projects. Talking of astronomy projects, we shall be learning a whole suite of segmented mirror technologies because of our participation in the TMT project. India will be supplying 88 of the 492 primary mirror segments with unprecedented surface finish. This mirror polishing technology is being transferred to the country and will be of great use in other domestic projects. Sensors, actuators and segment support assemblies for the mirror segments that will help align them and make them behave as a single mirror are all being developed in India and will be produced by the Indian industry. This is top-of-the-line mechanical engineering and will help build capacity in India. Telescope and Observatory Control Systems, not only for TMT but also for SKA (though quite different), are being produced in India with the help of our software industry. This will considerably value-add to the high-tech capabilities of our software industry. It may be recalled that earlier also, our scientists and engineers played an important role in setting up the WLCG (Worldwide LHC Computing Grid). The LIGO-India project will give us experience in building one of the largest Ultra High Vacuum (UHV) envelopes by volume in the world, in high-stability lasers, ultra-flat optics, vibration isolation by mind-boggling 14 orders of magnitude, etc. These are top-of-the-line technologies with great relevance for many national programmes as well. The list can go on and on but with these typical examples, one hopes to have shown that participation in MSPs has built precious national capacity, both in R&D institutions as well as industry, in a variety of underlying generic technologies of ever-increasing sophistication and complexity. Thus built, this capacity has found applications in successive MSPs, both internationally as well as nationally.

Site-specific gains

In some areas of science, for example, in Astronomy and Astrophysics, the location of India on the globe, or of some sites in the country, has already led to the establishment of a few unique facilities on Indian soil and there is still ample untapped potential in this regard. The Ladakh area, a dry, cold and high-altitude desert, has immense astronomical potential. India already has a functioning 2 m-class optical telescope at Hanle, Ladakh. At the same site, MACE has become a competitive gamma ray astronomy facility. It has also emerged that this site can be a good one for a 10 m-class optical-IR telescope, for which Indian astronomers have already readied a concept proposal. Merak, on the banks of Pangong Tso in Ladakh, has emerged as one of the best sites in the world for solar astronomy. The proposal to establish a 2 m solar telescope is in advanced stages of financial approval. This is expected to give a big boost to solar astronomy. With the other large (4 m) solar telescope in Hawaii, USA, this would allow for round-the-clock, high-quality observations of the Sun. Given the unique advantages of these sites, there is ample potential to develop them further as global facilities with possible international participation. A beginning has already been made with the LIGO-India project on Indian soil. By setting up the third LIGO detector in India, the LIGO Collaboration will be able to locate the gravitational wave sources better. INO has been unfortunately delayed, but a world-class neutrino observatory on Indian soil will also have the potential to play an important role in long baseline neutrino experiments.

Diplomatic gains

Most MSPs happen to be large international collaborations, if not in the construction of the facilities then certainly in their use. India started as a collaborator at CERN. In recognition of its contributions to the LHC, it became an 'Observer'. We are now an 'Associate Member', and the size of our human, scientific and technological involvement in the LHC programme is substantial. In ITER, SKA, FAIR and TMT, India is a founder-member country. India is treated as a valuable partner in all these projects irrespective of its financial share. International collaborative MSPs manifestly increase the interdependence of participating nations in high-tech ventures. The long-term nature of MSPs also ensures that they serve as a stabilizing factor in the diplomatic relations of the participating nations. These projects have enhanced India's visibility and soft power in the comity of nations.

Gains in the size of the Indian Mega Science Enterprise

Since the start of the India-CERN/LHC engagement in the 1990s with about 100 researchers and 10 institutional groups, the Indian Mega Science Enterprise has grown to include approximately 700 researchers, 150 institutional groups and 100 industries. No claim is being made here about the accuracy of these numbers, but these approximate numbers do give us a feel for the expansion in size of the community engaged in such ventures. A core group of personnel with R&D capabilities in the underlying science, technology and engineering has been built over time not only in R&D laboratories, but also in universities and other higher educational institutions. It will be important to have a continuing pipeline of MSPs (of course, of the right size and in appropriate numbers), so that this core national capacity does not get lost with time.

Mega Science Projects – the management challenges

The special characteristics of MSPs, listed above, make their management a specially challenging task. These challenges can be broadly grouped into the following generic classes.

Large size

MSPs are usually of big physical size. Land acquisition and the associated environmental clearances are non-trivial tasks compared to an individual scientist-centric laboratory-based project. Many of these projects handle large amounts of power and radiations of different kinds. So, fire-safety and radiation-safety regulations also come into play. In many ways, they are similar to large engineering projects like, say, a power plant.

Long timelines

An MSP typically goes through the following four phases:

(i) Early Consultative and Preparatory Phase: This encompasses activities like conceptual design, costing, decision on whether the project will be national or international, Intellectual Property Rights (IPR) sharing principles, cost-sharing principles, project organization and management structure, international negotiations and agreements, site decision, regulatory clearances, etc.

(ii) Design, R&D and Prototyping Phase: In this phase, component-level engineering design and prototyping are carried out to firm up the earlier conceptual design and cost.

(iii) Construction and Commissioning Phase: This is the main period of engineering activities where various components are produced in required numbers (mostly by industries, but in some cases by institutions too), put together to realize the full facility and commissioned for use by scientists for scientific studies.

(iv) Operation, Maintenance and Augmentation Phase: In this phase, the facility is operated routinely and it gives scientific data. As this scientific utilization phase is normally quite long, periodic augmentation of the facility to maximize scientific returns from the large initial investment is often resorted to.

The first two phases typically take about 10 years; the third phase also typically takes 10 years. However, the fourth phase or the utilization phase can typically run from 20 to 50 years. Because of this extremely long timeline, resource planning becomes a special challenge – whether capital, financial or human.

Large costs

Typical construction cost of an MSP may be pegged at few billion US dollars. Some like ITER (about 20 billion euros) and JWST (James Webb Space Telescope; about US$ 10 billion) may also be more expensive. The operation costs per year are typically 10% of the construction costs. Such large costs lead to long approval processes in the participating nations – in some nations needing to go to their respective Parliaments. And, since the project life cycle is long, continued stability of financial commitments on the part of the contributing nations is another significant management challenge. Fifty years is a long time in the history of any nation!

Credit sharing issues

As these projects are large-scale collaborations between scientists and engineers from many institutions in several countries, sharing intellectual property or knowledge outputs is also a non-trivial issue. There are broadly two layers of this issue. The first layer consists of sharing design IPR, etc. during design, R&D and construction. This usually is an integral part of the international agreements governing these projects. In case of bilateral projects, the existing IPR agreements (if they exist) are often invoked and respected. In multilateral projects, the IPR-sharing principles are enunciated in the Project Agreement. Broadly, it is ensured that all necessary IPR are available for successful completion of the project. The second layer consists of ownership of scientific data coming out of the project when operational. One encounters two different situations depending on the nature of the project. In the case of telescopes, synchrotron radiation sources, etc., the experimental groups are small and, in some sense, 'buy time' on these 'instruments'. They carry out the experiment and the ownership of the data and scientific results remain with the small group of scientists/engineers involved. In high energy physics experiments, like CMS or ALICE at LHC, the experimental groups are huge. It is the entire collaboration that designs and builds the detector and jointly undertakes data-taking. There are well-developed collaboration structures and principles that govern these aspects. The data emerging from experimental runs, and the scientific results based on these data, therefore, belong to the entire collaboration. That is why the scientific papers list all scientists in the collaboration as authors. It is the most natural principle to follow. However, this leads to a situation quite unlike in other areas of science. Here a scientist's name will appear on the large number of papers coming out of the collaboration. While his/her contributions in detector-building and data-taking are undisputed, his/her actual contributions towards scientific analysis of the data become a little difficult to ascertain. This created problems for these scientists in academic circles when they were compared with their colleagues from other fields. This problem has now been largely solved. Every scientist in a collaboration writes 'Collaboration Notes' on his contributions to the scientific analysis of a part of the huge volume of experimental data, which are thoroughly peer-reviewed within the collaboration. Then these analyses form part of some of the papers coming out of the collaboration. So, a scientist not only quotes all the published papers from the collaboration where his/her name appears, he/she also lists his/her (fewer) 'Collaboration Notes' showcasing his/her actual contributions towards analysis of the data. It may, thus, be appreciated that seemingly simple aspects of scientific research pose newer challenges in case of MSPs. The good news is that the community has faced the challenges squarely and found solutions transparently.

Cost and time uncertainties

MSPs, almost invariably, suffer from time and cost overruns. The reasons are broadly as follows:

(i) Inflationary uncertainties: As an MSP is constructed over a long period of time, the construction cost (which is the large upfront capex) goes through inflationary increases. Though this aspect is taken into account while arriving at the project cost by agreeing on a particular 'inflation index', the expected cost during project formulation is based on the past trends of this inflation index. However, the future trends cannot be predicted precisely, leading to uncertainties in costing. Secondly, no single inflation index captures the actual price rise in different components of the project. For example, different metal prices rise differently. Civil construction costs, being labour-intensive, rise differently depending on the site, and so on. This is another inherent inflationary uncertainty. Thirdly, if the project goes through time overrun, then cost increase due to inflation is a major secondary effect.

(ii) Technological uncertainties: When the project goes for approval, the costing is done based on a detailed but conceptual design only. The 'Cost Book' that is arrived at tries to guess the cost of each component as accurately as possible based on the material content and by extrapolating from earlier experience with similar components in other projects. The actual component-level R&D, design and prototyping get done only after the project gets approved, as these also entail substantial expenditure. As the underlying technologies are pushed beyond the existing frontiers and are not available off-the-shelf, the actual cost becomes known only after the design and prototyping phase, leading to another inherent uncertainty. This also contributes to unavoidable time overruns at times.

(iii) Regulatory uncertainties: Although an MSP is started only when all regulatory clearances are obtained, regulatory changes might occur on the site during execution. This results in redesigning of the project leading again to time and cost overruns. A recent example is the FAIR project. After the Fukushima disaster, the fire and safety regulations in Germany got considerably tightened leading to redesign of the civil structures. This has led to considerable time and cost overruns in the project. Over long periods of time, one cannot rule out such eventualities.

(iv) Other unexpected uncertainties: Sometimes, completely unexpected events take place, leading once again to time and cost overruns. LHC, after it was commissioned in 2008, suffered an unexpected leakage in its cryogenic system that delayed the start by nearly two years. The construction of TMT started at Mauna Kea, Hawaii and soon met fierce opposition from protestors objecting to the project for a variety of cultural and historical reasons. Despite court orders in its favour, it has not been possible to start the work leading to a 10-year time overrun and over US$ 2 billion cost overrun. Closer home, the INO project has got considerably delayed because of opposition by the local population on account of unrealistic fears. The scientific competitiveness of INO has been severely jeopardized. These are all examples of completely unexpected uncertainties which ultimately lead to substantial time and cost overruns.

Due to the above reasons, most MSPs undergo time and cost overruns. It is often alleged by the detractors that the proposers deliberately underprice the project proposal in the interest of getting it approved. It is unfortunate that such a motive can even be ascribed to a specific group of scientists only because they require larger resources. After all, these are some of the finest minds in the concerned areas of research and one cannot *a priori* assume that they will be less sincere compared to those in other areas of science. It must be appreciated that there are inherent uncertainties in these projects, which are also their greatest scientific, technological and management challenges. This is not to say that there is no room for improvement in 'quantifying the uncertainties'. There have been improvements over time and the concerned communities are seized of the matter. One certainly hopes that further breakthroughs in this direction will be made with time.

Managing Mega Science Projects in India

Over the past two to three decades, some basic principles and generic structures for managing MSPs in India have emerged. They are described in brief below.

Choice of MSPs

Which international MSPs should India participate in, or which MSPs should be undertaken nationally, is a decision that is taken by the concerned scientific communities in those fields. Scientist-to-scientist, institution-to-institution contacts, or at times diplomatic contacts, act as triggers for various projects, but the decision to get into, or launch a project, is a (scientific) community decision. These structured community consultations have been going on every 5–6 years since the early 1990s and have been known by different names – Thrust Area Meetings, Challenging Area Meetings, Roadmap Meetings, Vision Meetings, etc. The last Vision Meeting on MSPs took place in 2014. Given that most of these projects so far have been in the areas of Nuclear Physics, High Energy Physics and Accelerator Science and Technology, the meetings in the past were sponsored by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST), GoI. The Astronomical Society of India (ASI) has been organizing such discussions in the case of Astronomy and Astrophysics. A 'Mega Science Vision-2035 Exercise' is currently on and, this time it is being led by the Office of the PSA to GoI. Apart from Nuclear Physics, High Energy Physics, Astronomy and Astrophysics and Accelerator Science and Technology and Applications, two new areas – Climate Research and Ecology and Environmental Science – have also been included. It was felt that large-scale collaborative data-gathering and analyses had been going on in these two multidisciplinary fields too and they fitted naturally into what we call 'Mega Science'. In some sense, they have been pursuing MSPs without saying so or realizing the same. More disciplines are expected to be included in future exercises. As a result of these exercises, a prioritized list of MSPs emerges in each of the concerned fields. The community then self-organizes and submits proposals for MSPs to the funding agencies for possible funding. For the sake of completeness, it must be mentioned that this process is similar to those followed in the EU, USA, etc.

Multi-agency involvement

Most MSPs turn out to be multi-agency projects in India. This is not unexpected given the structure of the S&T establishment in the country. The project implementation skills for large projects mainly reside in the three mission agencies – DAE, Department of Space (DOS) and Defence Research and Development Organization (DRDO), GoI. However, the larger scientific community that needs to be mobilized for the project, or that is interested in the scientific/technological outcome of the project, belongs to the institutions of the Ministry of Education, University Grants Commission (UGC), other S&T agencies like DST, Department of Biotechnology (DBT), CSIR, Ministry of Earth Sciences (MoES), GoI, State Governments, etc.

Industrial issues and policies are handled by the Ministry of Heavy Industries, GoI; Department for Promotion of Industry and Internal Trade (DPIIT), GoI; Industrial Chambers, etc. International relations come under the domain of the Ministry of External Affairs (MEA), and security aspects are handled by the Ministry of Home Affairs (MHA) and Ministry of Defence, GoI. Thus multi-agency involvement is not only natural in India, but it appears that it is also desirable. First, the large funding required for such projects necessitates pooling of resources. However, if money was the only reason, it could, in principle, be channelled through one agency. What multi-agency funding does is that it ensures real partnerships, brings in greater concerted management and decision-making skills so necessary to face the inherent uncertainties in such projects, as pointed out earlier in the article. The combined management might of several agencies also instills greater confidence among the approving authorities of a project. During implementation, a concerted effort by various agencies is extremely important as the scientists, engineers and technicians belong to institutions of different agencies and there are always intra- and inter-institutional issues that need to be sorted out by way of appropriate guidelines and advisories.

Mode of Indian contributions to international MSPs

The cost of MSPs can be broadly divided into two parts: (a) the cost incurred on civil construction, personnel, centralized facilities and overhead/management expenses; and (b) the cost of hardware components that make up the facility. Obviously, in the case of a purely national project, both (a) and (b) are borne by the country building the facility. However, in the case of international collaborations, (a) is shared by all partners in cash, and (b) is largely shared in kind by various participating nations, according to an agreed fraction. This leads to technological capacity-building and enhanced high-tech manufacturing in various participating nations. Quite often, it is also a cost-saving scheme for the project as the cost of production may be lower in many participating nations. So, it is a win–win situation for all. As an agreed principle, Indian contributions to international MSPs have been largely in kind (about 70%). So, about 70% of the cost is spent in India on high-tech manufacturing. It may be appreciated that in most other areas of sciences (including in most areas of physics), 60–70% of the project cost is spent on equipment purchase and, that too, mostly in importing equipment. Instrument-building as an activity has dwindled over time.

Lead Institution/s and Lead Scientist

Normally an MSP is led by one or few Lead Institution/s. A scientist from the Lead Institution/s is identified as the Lead Scientist. He/she is known by different names, Project Director, Programme Director, Project Coordinator, and so on. In case of the India-LHC experimental programmes, the structure is a little different. All participating institutions jointly manage the projects as national collaborations with a periodically-elected scientist as their Spokesperson.

Participating institutions and principal investigators

There are a large number of other participating institutions too and those nodes are managed by Principal Investigators (PIs) and co-PIs, as in any other project.

Lead Agency

Most MSPs, as mentioned above, are funded and managed by a number of agencies. One of them handles the procedural aspects and functions as the Lead Agency.

Project management structure

Every MSP has the following oversight and management structure, starting from top: (a) apex-level inter-agency steering and oversight committee; (b) inter-agency project management board; (c) inter-agency science management board; and (d) other scientific/technical advisory committees. The exact names may vary from project to project. All committees consist of scientists, engineers and agency officials as members. The apex-level inter-agency steering and oversight committee is usually co-chaired by the heads of all major funding agencies of the project.

Approval processes

The Lead Agency spearheads these processes. A DPR is submitted in the format prescribed by the Lead Agency. All concerned funding agencies participate in joint technical evaluation of the project. Then the Lead Agency follows its processes for seeking financial approval for the project with comments and consent of all other participating agencies, especially regarding their share of the project cost. This clarity that has emerged in the country avoids duplication of evaluation and approval processes.

International Agreements

The Lead Agency, in consultation with the other participating agencies, negotiates the International Agreement in case of an international MSP, gets approval from the appropriate authority in GoI and signs it on behalf of GoI.

Fund sharing between different agencies

This varies from project to project and is agreed upon before seeking financial approval. A general principle that has been followed so far divides the capital cost equally among all the participating agencies, because the facility thus built is of equal scientific interest to all the agencies. Different agencies pick up the recurring cost of their scientists, and extramural funding agencies like DST also pick up the recurring cost of the remaining scientists from academic institutions, etc. in addition. It follows as a corollary that during the construction and commissioning phase where the capital cost is the major component, this distribution will be very close to the total cost being divided equally among all the funding agencies.

Optimum number of projects/scientist

At any given time, there are MSPs in a particular field, say high energy physics, that are being conceptualized, being designed, being constructed and those that are producing data for scientific analyses and outputs. If a scientist participates in only one project at any given time, his/her students do not receive wholesome experimental training. After considerable debate and deliberations, it has now become a practice that, generally, one scientist participates in two projects at any given time – one which is being designed/constructed and the other which is producing data for scientific outputs.

Newer scientists/groups/institutions joining an ongoing project

As the lifetime of an MSP is quite long, it is inevitable that newer scientists/groups/institutions would like to join the project on its way. Committees overseeing various projects have developed guidelines for doing this over a period of time. It essentially goes through an expert evaluation of the applicant's research record, his/her planned scientific contribution to the project and the required funding. Then the necessary financial approval for budgetary modification is obtained by the Lead Agency.

There is a reason why a rather pedantic account of the management processes for MSPs in India has been given above. All these aspects, which look trivial now, required considerable time and debate among the scientific community and the funding agencies to evolve. Our systems were not tuned to such long-duration projects with such large number of participants. It took quite a bit of effort and convincing to stabilize these principles in the governmental administrative and financial systems.

Critiques of Mega Science Projects – attempting a realistic assessment

It is a paradox that while India's engagement with MSPs enthuses young students, parliamentarians and the general public a great deal, it draws criticism (perhaps more than its fair share) from scientists in other areas of research. This stems basically from the fact that MSPs require large upfront capital investment, and lead to a perception that returns from them are not commensurate with the investment and that they impoverish other areas of scientific research. In this section, we shall attempt a realistic assessment of such critiques of MSPs.

We first need to appreciate the reason why we should engage in MSPs. First, the primary reason, something that is often overlooked, is that the underlying 'science' that one wants to research upon needs such tools to make further progress. Second, these projects look at extreme physical conditions, requiring tools/instruments of extreme technological complexity. Such tools cannot become available to an individual researcher or even a nation on its own. Third, these projects help nurture collaborations among scientists in areas where individual efforts are not enough. They spread this culture and promote multi-agency, multi-institutional and multi-national collaborations. Fourth, these projects try to answer some of the most fundamental scientific questions asked by human civilization. Being a participant in answering these profound questions is our responsibility to our future generations. If one asked whether the MSPs have advanced our understanding of the structure and functioning of the Universe, the answer would be an emphatic 'yes'.

The second question that often worries the critics is whether such large investments are worth the cause. There are several intricate layers to this debate, and let us try to uncover each, one-by-one.

(i) It is true that these projects require large upfront capital investment during construction. First, we need to realize that this is 'capex' which generates high-tech capacity in the country, high-tech employment and ultimately builds an asset in the country or a shared asset elsewhere with a typical lifetime of about 20–50 years. Second is the issue of return versus investment. In this regard, we must consider long-term returns from these projects as a whole. One must look at the per scientist per year investment over the entire life cycle of a project. If we consider the return versus investment at an arbitrary point during the life cycle of a long project, we are bound to get misleading answers.

(ii) Another point of view that is often advanced in the Indian context is that if doing science is the goal, then it might be better to participate in experiments at facilities which are operating and giving data. This will bring down the investment without compromising the scientific goals and avoid the uncertainties encountered during design, construction and commissioning of such facilities. First, it is a short-sighted view that completely overlooks the suite of technologies that become available to us while participating in the design, construction and commissioning of such facilities. Some cynics go to the extent of saying that these technologies are of no great use because they are 'one of a kind', meaning that each project is more or less unique.

Yes, LHC is different from FAIR and they are both different from HBSRS. But these seemingly different facilities require a whole range of generic technologies in RF (radio frequency) components, magnets, power converters, cables, detectors, etc. Participating in one builds capacity in the country to deliver another. This has been explained in detail in earlier sections and there is no point in repeating them. Second, because of rising costs and efforts required in building such facilities, the output data are being increasingly kept proprietary for the partners for significant periods of time so that the best scientific outputs come to the partners. Whether we should increasingly remain a fringe scientific player in these fields of research is something that we need to decide.

(iii) Regarding the original question of return on investment in MSPs for India, it has been explained in great detail earlier how these projects have enabled our scientists to be partners in top-of-the-line scientific investigations and momentous scientific discoveries. Our scientific contributions are globally well-recognized. There is yet another aspect of this debate that is often missed. While every MSP has some unique selling propositions (USPs), the instrument/facility thus built can bring a number of 'collateral scientific returns' that might not have been imagined in the first place. We have a large muon array at Ooty, Tamil Nadu, for cosmic ray research. Utilizing this array, it was discovered a few years back that solar flares lead to transient weakening of the Earth's magnetic shield[5]. This was a 'collateral scientific discovery' of great significance attracting huge world-wide attention and acclaim. Serendipity is not uncommon in scientific discoveries, but we need to have the right instruments and intellectual capacity.

(iv) About technological returns from MSPs, much has already been said about the national capacity built in high-tech areas, the role that these are playing in building important national projects, and the high-tech manufacturing and employment these have brought in industry and institutions. One aspect needs to be added here. MSPs often lead to sophisticated and previously unknown technologies. The most oft-cited example is that of the World Wide Web (WWW) which has revolutionized how we communicate and do business on the internet. A simple search on the internet reveals huge estimates of economic returns from WWW, but even the other benefits to humanity have been immense. Advances in accelerators have revolutionized medical diagnostics and cancer therapy. MSPs have led to a revolution in imaging techniques and detectors with wide-ranging use, and more are in the pipeline. A large number of instruments in other areas of science owe their origin to such projects in nuclear physics, high energy physics and astronomy and astrophysics. As an example of nationally important project, we must again mention that once the high-intensity superconducting proton accelerator technology is developed, we would have crossed the first crucial step in realizing Accelerator-driven Sub-Critical Systems so important for our national energy security. So, cynicism apart, the technological returns from MSPs have been immense and important.

(v) It may be useful to add that MSPs are increasingly rare examples where scientific instrumentation still gets done, simply because these instruments do not exist off-the-shelf. The culture of instrumentation, even in other areas of physics, is dying fast. MSPs help remind us that building instruments is an integral part of scientific research.

A fear often expressed is that the investments in MSPs would impoverish other areas of sciences in terms of R&D funding. One will have to closely examine the data in this regard. So far, in the Indian context, MSPs have been largely funded by DAE and DST. Looking at the budget figures for DST given in its Annual Reports, this fear seems misplaced, at least in the context of this Department. Even experience shows that our political system so far has been very supportive of S&T and made available the resources for any area of research once a good case has been made. What is needed is resources for all and not for one in lieu of another. Of course, all relevant questions regarding the 'appropriateness' of investment need to be asked, and the same have been asked all along.

Another remark that is often made against MSPs is that India's participation is not crucial for these projects. The projects would have been accomplished anyway. Perhaps, one is referring to the large-scale collaborative nature of these projects. Yes, this may be true, but why single out MSPs? Would the advances in research in any area of S&T wait for India's involvement? Unfortunately, the competitive world of research is too brutal to afford us this luxury. Second, this is true of all collaborations. We can only say that the global community in the concerned fields of research values India's contributions greatly and that should be a matter of national pride.

Yet another remark that is made is that participation in such projects is only a function of money, i.e. any country willing to contribute the resources can participate. This is such a cynical a remark that it may not even be worth responding to. Why is it that many natural resource-rich and per-capita-rich nations are not actively sought as partners in such projects? India has a great presence today because of its scientific traditions, strengths and increasingly promising technological and socio-economic scenario.

It is often asked why we do not build such facilities on Indian soil. Perhaps, it will give a more secure feeling that the asset is within the country. As explained in great detail earlier, choosing the best site from the point of view of technical specifications, available infrastructure and legacy expertise is an important factor while making such huge investments. We have, however, built appropriate facilities like GMRT, MACE, etc. in the country. And, there are plans to build NLST, NLOT, SNS, HBSRS, RIB, etc. in future. LIGO-India has also initiated an international project on Indian soil. The future certainly looks promising.

Prospects and conclusions

MSPs are embarked upon because further advancements in some fields of scientific research require such complex and sophisticated instrumentation. India's engagement with MSPs has come a long way since its participation, starting in the 1990s, in building the LHC and its subsequent utilization. This is not to say that there is no room for improvement in the complexion of our participation in such ventures. Some of the steps that we need to take in this direction are as follows:

(a) We need to increase the size of the scientific base involved in such projects. First, it will make the return-on-investment parameters look even more promising. Second, it will increase the likelihood of our rising further on the ladder of individual scientific eminence in these fields.
(b) MSPs, in large measure, are complex, challenging and often gigantic engineering ventures. There is an urgent need to increase the footprint of our engineering institutions like IITs and various CSIR, DRDO and ISRO (Indian Space Research Organisation) laboratories in these projects.
(c) Industry so far has been largely involved in production of components. There is a need to enhance its level of participation from just production to design and R&D. We need to handhold, nurture and strengthen the industry so that it is able to effectively compete for high-tech global tenders for MSPs or other projects, even if India is not a partner.
(d) We must consciously bring up and nurture groups to pursue translation and commercialization of spin-off technologies, e.g. in medical instrumentation, imaging, emerging computing technologies, etc. R&D activities related to this need to be funded. And, the initial funding requirements are also not expected to be huge.
(e) Both international and national MSPs are required. We need to have a properly phased national programme so that it acts as a reservoir of the underlying know-how's and technological capacity, and helps us effectively participate in, and derive maximum benefit from, international collaborations. We also need to effectively leverage the experience gained from international collaborations for the benefit of national projects/programmes.

In conclusion, therefore, the author would like to submit that given India's demography and strong tradition of doing science, it must have a strong global footprint in all areas of S&T, including those that employ MSPs for making further progress. Combined with increasing industrial capacity in high-tech areas and strong economic performance, it is natural for the Indian scientific community to be ambitious to participate in such front-ranking scientific instrumentation. MSPs are here to stay. The only questions that remain are, which ones, and at what scale?

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