ICFA

International Committee for Future Accelerators
Sponsored by the Particles and Fields Commission of IUPAP

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The chair of the International Linear Collider Advisory Panel
Professor Shinichi Hirano
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Dear Prof Hirano:

This letter is a follow up to the short letter I sent to the ILC Advisory Panel in August, following release of the “Summary of the International Linear Collider (ILC) Advisory Panel’s Discussions to Date” (the “Interim Summary”). Before I address the report, I would like first to express my profound gratitude to the members of the panel for so carefully and seriously considering, at the request of the Japanese government, the various issues concerning the hosting of the International Linear Collider (ILC) in Japan. The “Interim Summary” provides a helpful status report for the international physics community.

I write today as chair of ICFA, the International Committee for Future Accelerators. ICFA was established in 1976 as a working group of the International Union of Pure and Applied Physics for the purpose of promoting international collaboration in the development, construction, and use of state-of-the-art accelerator facilities for elementary particle physics research. ICFA has endorsed the International Linear Collider (ILC) as particle physics’ highest priority new accelerator facility, next to the full scientific exploitation of the Large Hadron Collider (LHC) including its planned luminosity upgrade. It has set up the Linear Collider Board (LCB) to oversee the research, development and technical design of the ILC accelerator. ICFA has prepared the attached document, which is based on the discussions within the international community of elementary particle physicists, to address several issues raised in the ILC Advisory Panel’s “Interim Summary.” We hope this will prove useful in the panel’s future discussions.

Since the dawn of history, human beings have sought to discover the fundamental laws of nature, laws that govern everything from the smallest scales of matter in the materials around us to the size and shape of the universe itself. At the beginning of the last century, the Theory of Relativity advocated that time and space are inseparable, while Quantum Theory revealed that microscopic motion is indeterminable. And based on the observation of the expansion of the universe as predicted by Einstein’s Theory of Gravity, we have confirmed that the universe is not eternally unchanging, but has been constantly evolving since its birth.

For over 50 years, advanced high-energy accelerators, capable of reproducing conditions shortly after the Big Bang, have contributed significantly to answering these fundamental questions. This work culminated in the construction of the Standard Model of Particle Physics, whose experimental validation was greatly advanced by the discovery of the Higgs boson at CERN in 2012. This scientific breakthrough, together with the discovery of neutrino oscillations, both of which have recently been awarded the Nobel Prize in Physics, represent outstanding accomplishments in basic science. They give hopes and dreams to the young generation, as well as an incentive to cultivate scientists and engineers who will contribute to our world in ways that we cannot yet imagine.

The success of the Standard Model creates a platform from which we can ask new fundamental questions about the universe:

- Why there are three generations of elementary particles, as well as three types of interactions linking them? Why do the masses of the fundamental constituents vary over many orders of magnitudes, ranging from the light, sub-eV neutrinos to the heavy top quark of 175 billion eV?
- What is the identity of the invisible dark matter that pervades the universe, the amount of which is about five times that of ordinary matter?
- Despite the existence of matter and anti-matter in equal amounts immediately after the Big Bang, why did a tiny surplus of matter survive, providing the basis of our very existence?
- The Standard Model does not encompass the theory of gravity, so how can we comprehend the universe in the moments immediately after its birth?

The answers to these and other fundamental problems will require the development of a new “Standard Model” based on new theoretical and experimental insights. Recent successes suggest that particle physics is on the right track to make significant progress in understanding the microscopic world.

It is the mission of elementary particle physics not just to discover new particles, but to learn what they tell us about deeper truths. In particle physics we use well-controlled and reproducible accelerator experiments to discover the new phenomena relevant to resolving these mysteries, to achieve a deeper understanding of the universe and to approach the origin of our existence. In particular, experiments at the ILC are capable of highly precise measurements in a very well-defined environment. This guarantees that all directly generated new particles can be detected, while those too heavy to be directly produced can be discovered through their quantum effects. Major progress in particle physics does not necessarily require the discovery of new particles. For example, the recent Nobel Prizes to Japanese scientists were awarded for determining unexpected properties of neutrinos, and not for the discovery of the neutrinos themselves.

Looking back in history, progress in particle physics depends on the interplay between the highest energy hadron and the highest precision electron colliders. For both, large-scale international collaboration is indispensable – a fact that led to the formation of ICFA. Since the year 2000, in response to the strong request from the international elementary particle physics community, ICFA has made great efforts to realize a next-generation linear collider as an essential part of the strategic plans of global particle physics. The ILC Technical Design Report (TDR), completed in 2013, presented a mature technology and a cost evaluation worthy of inter-governmental discussions. The TDR was the result of eight years of research in universities and research laboratories in the Americas, Europe, and Asia. This global effort demonstrates the world consensus that attributes the highest priority to the ILC to complement and extend the discovery potential of the LHC. This strategy is fully supported by ICFA.

The development of advanced technologies and the operation of large-scale systems, such as those required for the ILC, have proven throughout history to be invaluable to the health and prosperity of humankind. For example, advanced accelerator technologies have led to the construction of synchrotron radiation facilities all over the world that make essential contributions to the development of materials, life sciences and industrial technologies. Medical accelerators capable of treating diseases such as cancer have become more powerful and affordable.

In the attached document, we try to clarify a few issues raised in the recommendations contained in the “Interim Summary” of the ILC Advisory Panel. We give examples of the potential for physics beyond the Standard Model and address some of the technical accelerator issues. As compared to other science projects of this size, we are convinced that already at this stage, the ILC is among the best prepared, with manageable technical risks.

We acknowledge that international cost sharing and the governance structure of a project like the ILC is an issue of central importance that has to be addressed and solved at a political, inter-governmental level. To help this process, ICFA has set up a working group under the LCB to discuss these issues, and has summarized the results in its Project Implementation Planning (PIP) report. We hope that this document will be useful for future discussions within the ILC Advisory Panel. In addition, I am available to meet with your panel for discussions to bring in an international viewpoint, should you find it helpful.

The ILC is a research facility that will write a new chapter in the history of humanity. Throughout the 20th century, progress in particle physics has changed our vision of the universe and paved a path for new science and technology. We are confident that the ILC will perform the same role in the 21th century.

Sincerely,

Joachim Mnich
Chair of ICFA

cc: Mr. Sdahiro Hagiwara, MEXT, shagiwa@mext.go.jp
cc: Mr. S. Yoshii, MEXT, s-yoshii@mext.go.jp

The International Linear Collider:
Comments on Scientific Significance and Technical Issues

in response to

“Summary of the ILC Advisory Panel’s Discussion to Date (June 25, 2015)”

PART A

Science Significance and Potential for Discovering New Particles

1. Particle Physics: Current Status, Issues, and Goals

The ultimate goal of particle physics is to find a unified description of the laws of nature that govern the elementary particles and the universe. Progress in particle physics has been historically made through the exploration of matter, forces, and space-time. The goal is to uncover the fundamental constituents of nature and the forces acting between them, and to unravel the history of the universe from the Big Bang to the present.

Theoretical investigations and experiments led to the establishment of a framework, called the Standard Model (SM), consisting of particles that make up matter, particles that carry forces, and the Higgs boson that gives elementary particles their mass. From the time of its proposal, it took a few decades finally experimentally completed by the discovery of the Higgs boson at the LHC in 2012. The SM can explain most observed features of particle interactions and accounts for properties of many reactions to very high accuracy. This model is seen as a triumph of particle physics. However, there are still important aspects of nature that cannot be explained by the SM. Here we give three important examples.

The first one is the existence of dark matter. Through the observation of galaxies, clusters of galaxies, and cosmic background radiation, it has been determined that there exists invisible, mysterious matter (dark matter) with an abundance of five times that of ordinary matter. There are no matter particles with the required properties in the SM.

The second example is the disappearance of antimatter. It is thought that, after the universe was created, there were equal number of particles and antiparticles (with opposite charges). However, the universe today is made only of particles. Most of the matter and antimatter particles annihilated in the early universe but a tiny excess of matter over antimatter must have been generated laying the foundation for our existence and that of our universe as we know it today. There is no explanation for this within the SM.

The third example concerns the Higgs boson. It is believed that, as the universe cooled after the Big Bang, the Higgs bosons became condensed and filled the entire space, giving mass to the elementary particles. It is, however, totally unknown what kind of mechanism caused the Higgs bosons to condense. There must be new physics, not contained in the SM, that act on the Higgs bosons.

There are several candidate models that are built to solve these and other questions. Supersymmetry is a particularly promising theory beyond the SM to provide a mechanism to cause the Higgs bosons to condense in the vacuum. It is a completely new kind of symmetry that associates with each SM particle a partner particle (supersymmetric particle). Supersymmetry contains solutions for many problems left open by the SM. For example, the lightest supersymmetric partner is a possible candidate for the particle of dark matter. It provides a raison d'être for zero spin particles and paves the way to unification of all the four forces including gravity. There is another class of models in which the Higgs boson is a composite particle consisting of more elementary particles, similar to the way that the proton is composed of quarks and gluons. In these models, there is a whole new layer of physics between our current understanding of elementary particles and the eventual unification of forces. If either of these models were correct, this would profoundly change our view of matter and even our understanding of space and time.

Evidence for these models could be obtained through the discovery of new particles or through the discovery of unexpected properties of the known elementary particles. Thus it is important that the ILC – an electron-positron collider at energies up to 500 GeV – provides both the capability to discover new particles and the capability to study known particles in unprecedented detail.

2. The Higgs Boson and the Top Quark

One way the ILC will search for new physics is through detailed measurements of the heaviest and most mysterious known particles, the Higgs boson and the top quark. The ILC measurements will dramatically improve our current knowledge of these particles, going significantly beyond the final accuracies projected for the experiments at the LHC.

All known elementary particles, with the exception of the Higgs boson, possess *spin*, a physical quantity that corresponds to, so to say, particle rotation. The Higgs boson is the only particle in the SM that has zero spin. Since the vacuum – the quantum state representing empty space – has no rotation, spin zero Higgs bosons can be condensed in the vacuum. In the SM, the interaction of particles with the Higgs bosons condensed in the vacuum creates their inertia and resistance to forces and, hence, gives them mass.

An essential prediction of the SM that has not yet been observed is the coupling of a Higgs boson to other Higgs bosons (Higgs self-coupling). Its discovery and the measurement of its value would give direct information on the mechanism of Higgs boson condensation. However, that measurement is extremely challenging for the LHC, even with the luminosity upgrade scheduled to start in the middle of the next decade. The favourable conditions at the ILC will allow observation of double Higgs events if they are produced close to the rates predicted by the SM and permit measurement of the Higgs self-coupling . In many models, it is the process of Higgs condensation in the early universe that creates the matter-antimatter asymmetry. The ILC measurement could prove or exclude this idea.

Is the Higgs boson an elementary particle? Is it a member of a larger family, as in supersymmetry? Is it composite? We now stand at an important fork in the road. At the ILC, precise measurement of Higgs boson couplings to elementary particles would settle this problem. The models of supersymmetry and Higgs composite structure predict small differences in the properties of the Higgs boson from the predictions of the SM. By uncovering differences from the predictions of the SM, and by demonstrating that these differences form a pattern, the ILC can discover the existence of new interactions and can reveal the qualitative nature of physics beyond the SM.

The fact that the top quark is much heavier than other quarks and any other fundamental constituent of matter is itself a puzzle. In the SM, the large mass of the top quark is ascribed to the large coupling between the Higgs boson and the top quark. Thus the properties of the top quark are strongly affected by the new interactions that caused the condensation of the Higgs bosons. If the Higgs boson is a composite particle, the top quark may also be a composite particle. The precision measurement of the top quark at the ILC will be able to shed light on this puzzle.

For each theory of physics beyond the SM, the deviations from the SM expectations for the Higgs boson and the top quark follow a distinct pattern. Thus, these measurements allow us not only to discover physics beyond the SM but also to recognize the nature of the new physics. These ILC measurements will guide any further exploration of physics beyond the SM, and hence will be important regardless of the results of the LHC experiments.

3. Potential for Discovering New Particles

With the increase in collision energy from 8 to 13 TeV, the LHC has a new window for discovery of new particles at higher masses. However, even if the LHC operating at 13 TeV does not find new particles, there remains significant discovery potential for new particles at the ILC. This discovery potential of the ILC program complements the search for new physics beyond the SM through precision experiments.

The LHC is a powerful accelerator whose collision energy is much higher than the ILC. However, the LHC collides protons, which are not elementary particles but rather bags containing quarks and gluons. Because of this, LHC collisions contain a lot of noise, which leads to difficulties in observing new particles. At the LHC, only new particles that are copiously produced and have sufficiently striking features can be distinguished from background events. In contrast, the ILC collides electrons and positrons, which are elementary particles and antiparticles. When an electron and a positron collide, they annihilate and turn into pure energy, from which all kinds of particles are generated. Moreover, the collision energy used to create new particles can be fully controlled. This makes it possible to perform experiments in a noise-free, clean and controlled environment. New particles that are challenging to observe at the LHC can be reliably discovered if they fall within the ILC energy range. This guarantees that all directly produced new particles can be detected, while those too heavy to be directly produced can be discovered through the detection of quantum effects.

If the LHC discovers a new particle, this will imply the presence of new laws of physics, but the nature of this new physics will not be clear. To learn about the underlying physics, we will need precision measurements of particle properties, which are in many cases challenging at the LHC and hence require the ILC. In the remainder of this section, we analyze in detail three possible scenarios associated with the discovery of new particles: 3-1) No discoveries of new particles at the LHC experiments, 3-2) LHC experiments discover relatively light new particles, and 3-3) LHC experiments discover relatively heavy new particles.

3-1) LHC experiments do not discover new particles

Even if the LHC operating at 13 TeV does not make additional discoveries, the ILC has substantial potential to discover new particles.

Supersymmetric Particles: Supersymmetric particles can be grouped into two categories: strongly interacting particles, i.e. particles which carry colour charge, and particles with only weak and electromagnetic interactions. In the following discussion, we refer to the former as “strong” supersymmetric particles and the latter as “weak” ones. The “weak” particles are no less important; for example, the particle of dark matter would be a “weak” supersymmetric particle. The main target of searches at the LHC is the “strong” supersymmetric particles, while at the ILC the main target will be the “weak” supersymmetric particles that are difficult to observe at the LHC. Our current scenario of no new discoveries at the LHC corresponds to the case that the “strong” supersymmetric particles are too heavy to be discovered. The LHC looks for “weak” supersymmetric particles as well. However, because of the large noise, discovery is only possible if these particles have sufficiently large mass differences. The ILC can discover these particles as long as they are within the ILC energy range.

Dark Matter: At the ILC, it is possible to produce dark matter from electron-positron collisions. The LHC experiments are actively searching for the kind of dark matter that can be produced in interactions of quarks, which are the constituents of protons. The ILC is sensitive to a much broader class of dark matter particles, similar to the case of “weak” supersymmetric particles above. In addition, the clean experimental environment of the ILC with its control of particle beams allows experimenters to determine the mass and many of the couplings of the dark matter particle and to see whether this particle has the correct properties to make up the observed dark matter of the universe. In this way, dark matter searches at the ILC play a complementary role to searches at other experiments.

3-2) LHC experiments discover relatively light new particles

If the LHC discovers light new particles beyond the SM, this would open the door to new and unknown laws of physics, and the ILC provides great capabilities to discover different new particles related to the LHC discovery.

Supersymmetric Particles: In this scenario, new particles accessible to the ILC are discovered either in direct production or in the decays of heavier "strong" particles. Thanks to its clean experimental environment, the ILC is not only capable of observing these particles, but also measuring physical properties such as the mass and couplings with other particles. The ILC might well discover additional “weak” particles missed at the LHC. The precise information about the particles studied at the ILC will also be used to reinterpret the data on other supersymmetric particles collected at the LHC. Combining the results from both the LHC and the ILC enables us to get a full picture of the supersymmetric theory.

Dark Matter: The same remarks from 3-1) apply concerning dark matter. In the case that the LHC finds a hint of dark matter particle, the properties of the dark matter particle can be fully studied at the ILC and the creation of dark matter in the early universe can be explained.

3-3) LHC experiments discover relatively heavy new particles

If the LHC discovers heavy new particles beyond the SM, this will imply the presence of unknown new laws of physics. The ILC offers great capabilities to uncover these new laws, by the discovery of further new particles or through new measurements qualitatively different from those at the LHC.

Supersymmetric Particles: This is the case where the supersymmetric particles discovered at the LHC are “strong” supersymmetric particles that turned out to be relatively heavy. Here again, there might be “weak” supersymmetric particles that could be seen only at the ILC. Even in the case that all supersymmetric particles are too heavy to be produced at the ILC, those particles are still expected to alter the properties of the Higgs boson. Thus the ILC program of Higgs boson measurements will be even more important. These measurements might reveal the existence of additional supersymmetric particles beyond the reach of the LHC. While performing precision studies of the Higgs boson and the top quark, we will prepare for the energy upgrade of the ILC taking advantage of energy expandability enabled by its linear shape.

Dark Matter: The same remarks from 3-1) apply concerning dark matter.

Composite Particles: If the Higgs boson or the top quark is a composite particle, there must be more fundamental unknown particles inside the Higgs boson or the top quark. These elementary particles will in turn form other composite particles that are heavier than the Higgs boson or the top quark. Discovery of these heavy composite particles may be possible at the LHC. The masses of the new composite particles are predicted to be too heavy to be produced at the ILC. However, in such cases, the properties of both the Higgs boson and the top quark will deviate from the SM prediction at a level that can be probed by precise measurements at the ILC. This will give us information about the new force that acts between the unknown constituents of the Higgs boson or the top quark. Combining this information with the discoveries from the LHC enables us to close in on a full picture of the theory of composite particles.

Particles that Mediate a New Force: The SM describes the electromagnetic force, the weak force, and the strong force. Some theories of new physics predict the existence of new particles that are associated with new forces. If such a particle is discovered at the LHC, its mass is thought to be too heavy to be produced at the ILC. However, the new force can affect the rate of production and the angular distributions of the known particles through quantum effects, which can be probed at the ILC. The precise measurements at the ILC will enable us to uncover the properties of the new force. Combining this with the information obtained at the LHC about the mass of the new force particle, we can get a full picture of this new force.

4. Summary and Prospects for Science Significance of ILC

The ILC offers several different opportunities to shed light on the puzzles that particle physics faces today. The ILC can perform clean experiments through collisions of an elementary particle and its antiparticle. Taking advantage of these features, the ILC is anticipated to open the door toward physics beyond the SM. Detailed studies of the Higgs boson and the top quark will certainly be important, regardless of the results of the LHC experiments. The ILC could also discover new particles beyond any found at the LHC. The ILC will be a big step that advances our understanding of matter, forces, space-time, and the universe.

The potential for discovering new particles at the ILC has been described here under three different scenarios:

i. LHC experiments discover no new particles,
ii. LHC experiments discover relatively light new particles, and
iii. LHC experiments discover relatively heavy new particles.

As described above, the ILC has a significant chance to discover new phenomena beyond the SM in each of the three cases. These discoveries have the potential to revolutionize the concept of space-time and matter and to bring us closer to the moment of the Big Bang.

One cannot predict today what will come after the ILC operating at 500 GeV. However, it is natural to think that the knowledge obtained there will encourage us to delve deeper into the quest to understand nature. One appealing possibility for such an endeavor, with features analogous to those described for the ILC, is an electron-positron collider with an even higher energy. Any higher energy electron-positron collider must necessarily be a linear collider, since the energy range of a circular collider of given circumference is inevitably limited by the energy loss due to synchrotron radiation. On the other hand future technology may allow an energy increase of a linear collider reusing the ILC infrastructure. A first step could be 1 TeV upgrade as described in the Technical Design Report based on improved superconducting RF technology. In the long term future new acceleration technology might become available allowing a significant further increase in energy such that the infrastructure set up for the ILC has the prospect to remain an international hub in particle physics and play an important role for many decades to come.

PART B

Comments on Technical Issues and Risk Mitigation

1. General Comments

The LCC, the international Linear Collider Collaboration created by ICFA to oversee the Linear Collider design, has already considered many of the Advisory Panel’s concerns in the document “The International Linear Collider Progress Report 2015”, which is available at:

http://ilcdoc.linearcollider.org/record/62872/files/Progress Report_151026_final_151029.pdf

The ILC accelerator and detectors have been carefully designed taking into account the technical feasibility already demonstrated during the technical design phase. The ILC cost estimate has been based on well-defined methodologies, and it is the most precise such cost estimate among all large accelerator projects ever at this stage in their design sequence.

The ILC has already integrated the “lessons learned” from major, existing accelerator projects. One of these is the construction and operational experience of the Large Hadron Collider (LHC) at CERN, which is of the same physical scale as the ILC project. Another is the European XFEL project, whose accelerator is about one tenth of the scale of the ILC main linac and uses very similar superconducting radio frequency (SRF) technology. Recent progress in the European XFEL SRF cryomodule performance, reaching 30 MV/m in accelerating gradient, shows that the ILC specification can be achieved. The XFEL experience of a substantial series production effort with one hundred cryomodules containing eight hundred SRF cavities, made by a collaboration of laboratory and industry in Europe, shows that the ILC cost risk for SRF is very low. It should also be noted that large accelerator projects have already been successfully built in Japan. KEK has built the TRISTAN and KEKB collider projects, with the sum of the two construction budgets about one-tenth of that of the ILC, and the J-PARC project budget was of about one fifth of that of the ILC.

The ILC has been designed so that future technological advances can always be incorporated, allowing the machine performance to be upgraded with respect to the present design when appropriate.

2. Specific Comments on “Overview Discussions” for verifying the TDR

The overall “uncertainty” of 25 % in the TDR total cost-estimates includes only the pure cost-estimate uncertainty and does not include such contingencies as risks in technical performances, market conditions and time-delay in construction. Those risks strongly depend on site-specific conditions, which could not be taken into account in the TDR process. They will be carefully evaluated after receiving clear site-specific information during the ILC preparation period.

However, the ILC-TDR cost estimate has included the experience from the European XFEL project preparation, as noted earlier, for component production. The construction of the XFEL accelerator is approaching completion and can be considered to be a one tenth scale ILC prototype. This project is more mature than any other large project ever built using SRF accelerator technology including industrial mass-production of components. The European XFEL project has successfully manufactured cryomodules at the required production rate with the performance level reaching 30 MV/m, This is now very close to that needed for the ILC (31.5 MV/m). The XFEL experience will certainly reduce the cost uncertainty of the SRF cavity and cryomodule system which is one of the largest cost drivers in the ILC.

The LCC plans to increase the SRF safety margin by increasing the main linac tunnel length. If necessary, this will enable the nominal energy to be reached with reduced accelerating gradient by installing additional cryomodules. This may be realized in an overall tunnel-cost neutral/lower way by combining with other design optimisations. The overall accelerator tunnel width may be reduced using an optimised central radiation-shield (wall) thickness. This would allow personnel access only for hardware commissioning/maintenance, with no access during accelerator beam operation. It would also improve radiation-safety during accelerator operation. The increased safety margin will result in less access requirements for the accelerator components and associated powering system. The best cost-effective solution will be evaluated in the ILC construction stage, and will also depend on further SRF performance progress.

Another ILC critical technology, large-scale cryogenics, is very similar in size and scope to the CERN-LHC, where costs are accurately known. The ILC civil construction cost-estimate benefits from the known cost of many tunneling projects in Japan, in similar geological conditions.

There are a limited number of vendors of niobium and helium, two critical materials for the ILC. However, the ILC global collaboration should be able to make purchases from the vendors in the many countries of the collaboration. The LCC has already launched a technical cooperation with one of the largest niobium mining and refining companies in the world, which will provide significant ability to increase the number of suppliers. The LCC has been learning from the experience of the CERN-LHC program, which has already managed to contract with multiple vendors for helium resources in the wider European and surrounding countries market. The ILC project will learn from the experience of the LHC program and may maximise the number of helium resource vendors by taking advantage of the ILC global collaboration, as mentioned above.

Water-proofing of the accelerator tunnel has been already incorporated in the basic tunnel design by having a multiple-layered outer tunnel-wall, following a risk management study and as a counter measure against possible earthquakes. Further detailed studies, including earthquake risks, will need to be carried out following clearer site-specific information.

Components manufactured in different world regions will be tested and qualified before being transported to the ILC site. A mechanism already exists to exchange technical information between laboratories and to discuss standardization and quality control for the SRF cavity technology. Quality assurance will be the responsibility of each “Hub Laboratory (regional core-laboratory)” following a centrally established and agreed quality plan. During the project preparation phase the qualification and safe transportation of the completed SRF cryomodule systems from one region to another will be demonstrated, including legal and safety issues, and the performance stability. Three to five regional “Hub-Laboratory” consortiums may be expected in the ILC global collaboration. Each “Hub-Laboratory” will be responsible for its own quality assurance and risk management as discussed above.