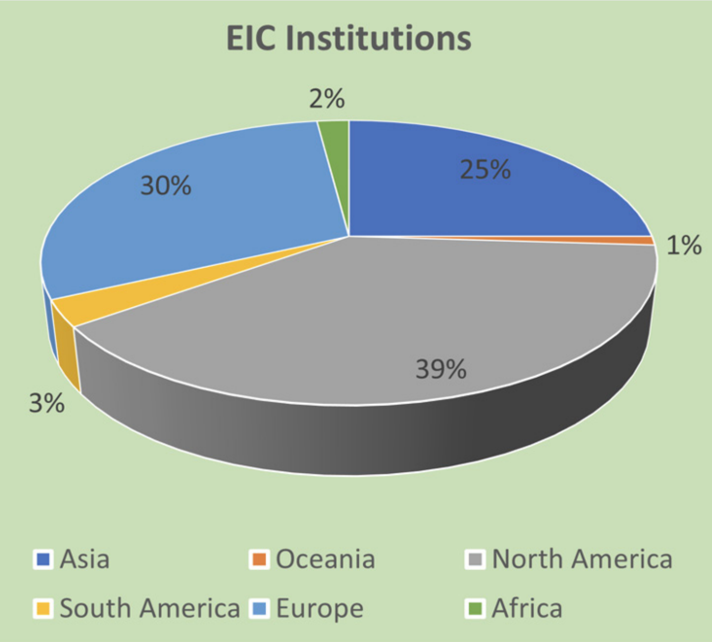
THE ELECTRON-ION COLLIDER

The Benefits of Two Detectors

The Electron-Ion Collider (EIC) is a transformational and unique accelerator that will enable studies of nuclear matter with unprecedented precision. The EIC is required to address fundamental open questions in physics, such as the origin of mass and spin of protons and neutrons, the details of the "glue" that binds them, and the nature of very dense gluon systems in nuclei. This ambitious collider could not deliver physics results without powerful "cameras" capable of taking the most detailed snapshots of the collisions produced at the EIC. Novel particle detectors must be designed and constructed to capitalize on the investment made on the accelerator side, so that the deepest secrets of the building blocks of matter in our visible universe may be unlocked.

The EIC Project was launched by the U.S. Department of Energy (DOE) in January 2020 and is on track to begin operation in the early 2030s. Located in the U.S., the EIC will be a premier international facility, the success of which hinges on both U.S. and international engagement in advancing accelerator science and fundamental research. The DOE has committed to funding the construction of the collider and a state-of-the-art multipurpose detector at one of two possible interaction points. Historically, projects of similar scientific impact and scope were designed to include two or more complementary detectors. Multiple detectors expand scientific opportunities, draw a more vivid and complete picture of the science, and mitigate the inherent risks that come with exploring uncharted territory by providing independent confirmation of discovery measurements. The physics community behind the EIC project has emphasized the need for at least two detectors for many years. Several community reports, such as the 2007 and 2015 U.S. Long Range Plan reports for Nuclear Science, reference "as many as four interaction points" or the need for collisions "at two interaction points." This is echoed in the 2018 National Academies of Sciences, Engineering, and Medicine report on an Assessment of U.S.-Based Electron-Ion Collider Science.

The need for and ultimate success of a multi-detector standard have both been demonstrated historically over many decades across multiple subfields of physics. Some 40 years ago, the strong force carrier, the gluon, was discovered by the TASSO, JADE, Mark J, and PLUTO collaborations at the Deutsches Elektronen-Synchrotron (DESY, Germany). Nearly two decades later, the H1 and ZEUS collaborations, also at DESY (Germany), both demonstrated that deep inside a proton, its structure is overwhelmingly dominated by gluons. At the turn of this century, the CLAS collaboration at Thomas Jefferson National Accelerator Facility (Jefferson Lab, USA) and the HERMES collaboration at DESY (Germany) independently performed the first measurements that opened the way to the spatial imaging of quarks inside the proton. Meanwhile, at the European Organization for Nuclear Research (CERN , France and Switzerland) the NA-35 experiment was detecting the first hints of the Quark-Gluon-Plasma (QGP), a new state of matter composed of deconfined quarks and gluons that was ultimately observed simultaneously by the BRAHMS, PHOBOS, PHENIX, and STAR collaborations at Brookhaven National Laboratory (BNL, USA). More recently, the discovery of the Higgs boson, the final piece of the Standard Model of particle physics, was independently confirmed by the ATLAS and CMS collaborations at CERN (France and Switzerland), and the first observation of gravitational waves was made concurrently at the Hanford and Livingston detectors by the Laser Interferometer Gravitational-Wave Observatory (LIGO in USA) collaboration and soon after by the Virgo detector at the European Gravitational Observatory (EGO, Italy and France). In each case, the capability of near-simultaneous discovery by multiple detectors was essential for establishing the validity of the newly emerging paradigm.



The distribution of the institutional members of the EIC Users Group per region of the world.

The multiple detector efforts discussed above were made possible by engaging resources on a national and international level. The EIC project is well positioned to follow this model and is already attracting interest and expertise from around the world. The international community began self-organizing in late 2015 by forming the EIC Users Group (EICUG), which rapidly grew to over 1,300 physicists at more than 250 institutions in 35 countries world-wide. Now is the time for international collaborators to seize the opportunity for leadership in the many scientific and technical challenges presented by the design and construction of a second interaction region and detector.

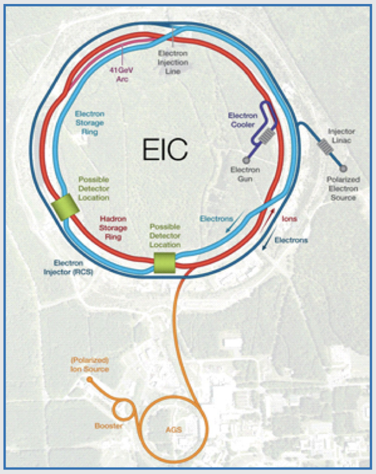
THE ELECTRON-ION COLLIDER’S GOLDEN OPPORTUNITY FOR TWO DETECTORS

Taking Advantage of the RHIC/EIC Collider Layout

The scientific mission of the Electron-Ion Collider includes a diverse set of open physics questions about the nature of matter in our universe. Answering these questions requires state-of-the-art experimental apparatus that would, ideally, detect all particles produced in electron-ion collisions.

This presents unique challenges to the design of an EIC detector and its integration in the collider, with two different beam species moving in opposite directions. The device must cover a large area, extending from the central region, where the remnants from the most energetic collisions are scattered, to the regions very close to the incoming beamlines. The EIC will repurpose the existing layout of the Relativistic Heavy Ion Collider, which currently weaves the beams from varying ring-inside and ring-outside locations at the two possible interaction points. This geometric constraint provides an opportunity to optimize the complementarity of the two detector systems, so that the necessary gaps in coverage occur in different regions, allowing one detector to see particles where the other is blind.

It is also possible to tune the beam optics for each detector to emphasize different physics processes, satisfying what would otherwise be mutually exclusive demands. The flexibility will allow, for example, the EIC to access rare scattering processes, which are critical for imaging the deep internal structure of nucleons and nuclei. The EIC's science reach will be significantly enhanced by leveraging the variations of the beamline optics and interaction region design for the two detectors. Further, the separate scientific focus opportunities provided by two customized detectors naturally leads to two independent yet complementary collaborations.



The EIC will be the only electron-nucleus collider operating in the world and will delve deeper than ever before into the building blocks of matter. The EIC will consist of two intersecting accelerators, one producing an intense beam of spin-polarized electrons, the other a high-energy beam of spin-polarized protons or heavier atomic nuclei, which are steered into head-on collisions at two possible detector locations.

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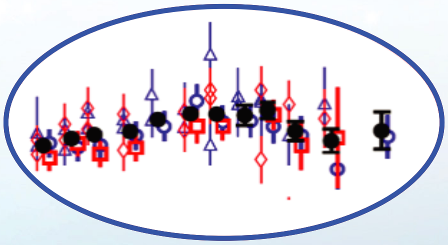
Detector Redundancy and Complementarity

The detector demands an onion-like structure, composed of multiple layers of detector technologies that can be used to determine the type of particles produced and reconstruct their momenta and energy. As detector design for the world's only Electron-Ion Collider facility continues, it is only natural that each subsystem will explore multiple performance optimization routes and push for the most advanced, state-of-the-art technologies that will satisfy the required functionality. Varying design decisions and technology choices between two complementary detector concepts will ensure the necessary redundancy.



The complementary technologies of the two H1 and ZEUS detectors at DESY in Germany showed that the combined proton cross section data (black) are much better than one would naively expect from the independent H1 and ZEUS data (red and blue).

Data are from Eur. Phys. J. C75 (2015) 12, 580 (https://arxiv.org/abs//1506.06042).

Alternative technology choices will also allow each experiment to optimize for different types of measurements while still preserving the ability to perform independent cross-checks. Possible optimization areas include consideration of different magnetic field strengths and associated trade-offs between detector coverage, particle identification capabilities and tracking performance at high particle momenta. These design choices impact the precision with which different physics can be accessed.

The complementarity of multiple detectors enhances the science scope and ultimately leads to higher scientific impact. A prime example is the final dataset from HERA (the Hadron-Electron Ring Accelerator at DESY), which was combined from the independent datasets simultaneously recorded by two different detector configurations, H1 and ZEUS. The combined black points depict a much clearer picture of the proton cross section data than the scatter of individual red (H1) and blue (ZEUS) points. This jump in precision exceeds the gains made by simply doubling the amount of data collected; it is driven by the unique view each detector has into the same measurement, reducing the inherent uncertainties associated with a single configuration.

Two complementary detectors with different coverage, optimizations, and sub-detector technologies will ensure redundancy, cross-calibration, and independent validation of the most important results, providing higher-impact science for this significant investment.

Lessons from History

Large-scale scientific endeavors like the EIC are tremendously exciting but also inherently risky. Wrong turns, dead ends, and temporary setbacks are unavoidable parts of the scientific process, particularly when charting new territory and tackling the big mysteries about the nature of matter in our universe. History holds numerous examples of scientific dead ends, of seemingly apparent signals for new phenomena resulting from misinterpretation, from Pons and Fleischmann's cold fusion, to 17 keV neutrinos in tritium decays, to superluminal neutrinos traveling between CERN and Gran Sasso. Several premature discoveries were announced by collider experiments as well, including leptoquarks at HERA and various pentaquarks at labs across the world. These examples illustrate a compelling need for independent cross-checks of experimental results that challenge current scientific theories; only through this process can science evolve and progress be achieved.

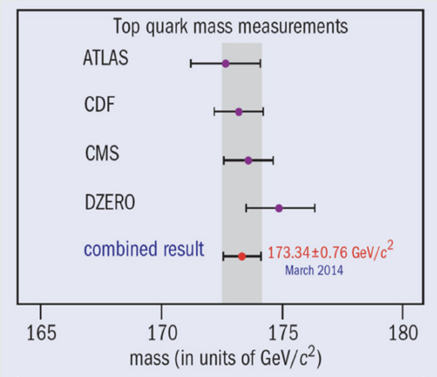


Illustration of the power of multiple experiments. The top quark was discovered in 1995 by the CDF and D0 experiments at Fermilab in the USA.

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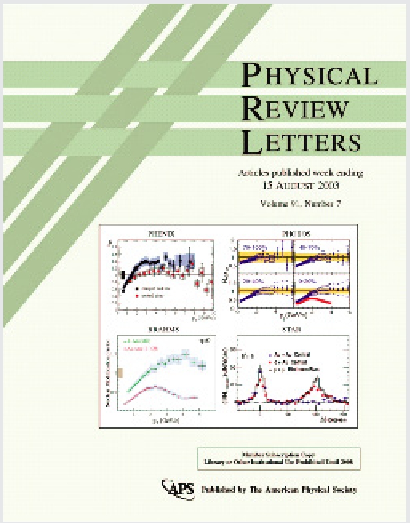
History holds many examples of such scientific progress. One example is the evidence of the creation of the Quark-Gluon-Plasma, simultaneously demonstrated by the BRAHMS, PHOBOS, PHENIX and STAR collaborations, all located at BNL (USA). A second example is the discovery of the top quark and measurement of its mass by the CDF and D0 experiments at Fermilab (USA), followed by the ATLAS and CMS Collaborations at CERN (France and Switzerland). The scientific community can only become truly convinced of discovery if independent cross-checks by at least two different experiments (with different setups and/or approaches) are available for such critical new measurements.

The most robust and productive scientific endeavors build in avenues for redundancy and complementarity. Only if the scientific question is illuminated from multiple angles does our understanding of nature tend to an ever-more accurate description. The EIC project is particularly well suited for two separate collaborations, as it provides room for optimization of each detector for a specific scientific focus and the customization of the surrounding interaction region. The gains in innovation and accountability made by investing in a second detector will more than double the return.



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Science Discovery Relies on Independent Experimental Confirmation

Multiple examples illustrate the importance of independent experimental confirmations at the discovery facilities. Tackling a scientific issue from different angles with different experimental set-ups is the most reliable way to confirm a novel phenomenon, particularly for most groundbreaking unexpected discoveries. An example highlighting the independent yet coherent effort of four experimental collaborations at the Relativistic Heavy Ion Collider is presented in the Figure above. The four experimental results depicted on the cover of a Physics Review Letters issue firmly established the discovery of the jet quenching as a signature of quark-gluon plasma. These independent validations erased any doubts in the finding and quickly propelled jet tomography from novelty to one of the most versatile tools for studying properties of the quark-gluon plasma.

A GATEWAY TO INNOVATION AND INTERNATIONAL COLLABORATION

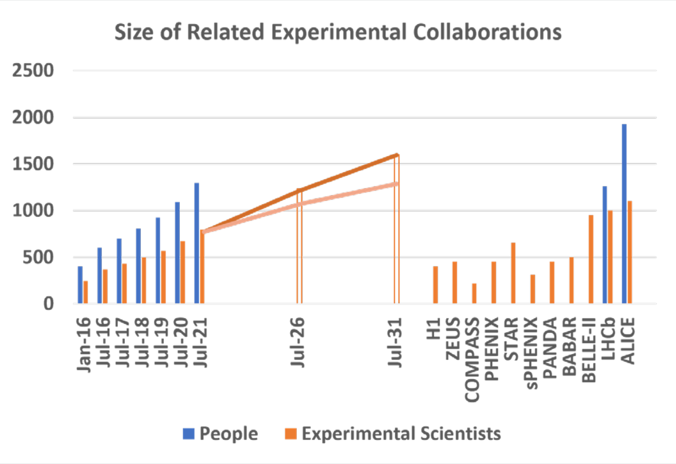
Two Detectors are More than 1+1

The EIC project has generated immense interest and support from the international community. The current size of the EIC Users Group has surpassed 1,300 scientists, easily achieving the critical mass of physicists and engineers needed for a highly active and successful detector collaboration at this scale. The growth of this community shows no sign of slowing and could perhaps double by the start of data collection in 2030. The fact that the EIC project continues to attract scientists, many of them leaders in their fields, reflects the substantial scope and physics potential of the EIC. Establishing two detector collaborations at two interaction points now provides the opportunity to harness this growth to the benefit of the EIC, attracting international talent and the resources they will bring. This makes best use of the complementary strengths of various international communities.

A detector at the second interaction point presents a second unique and high-impact point of entry for the international community to bring a wealth of technical expertise and leadership to the EIC project. Two collaborations will also expand the opportunities for a new generation of scientists, providing avenues for the best amongst them to contribute and develop into the next generation of scientific leaders. It is imperative that the community seize this rare opportunity to significantly broaden and strengthen the scientific workforce worldwide.

The Path to New Ideas

In addition to developing the scientific workforce, two detectors will foster a natural and healthy competition between the collaborations, which will in turn encourage innovation and drive technological development. A case in point is the design of the two EIC interaction regions, which are not identical but rather housed in existing halls of different dimensions and with beams colliding at different angles. Unique constraints require unique solutions, and these solutions often manifest in the form of new technologies designed to specifically address the challenges presented by each of these two different interaction regions.



The growth of the international Electron-Ion Collider User Group since its inception in 2016. Presently, the EIC User Group consists of about 1300 physicists of which 800 are experimental scientists. This already surpasses or compares with the size of similar experimental collaborations. With conservative projections of the further growth that is expected through the construction era (~2026) to the time of early operations (~2031) the EIC User Group can comfortably support two experiments. Having the entire EIC experimental community work on one experiment is beyond the scale of the effort required and diminishes scientific productivity.

Concurrent development of complementary technologies for the two detectors is an asset that cannot be overstated: it broadens the opportunities for societal impact of the EIC, allows for verification of measurements in two truly independent ways, and provides the scope to capitalize on the complementary strengths of different solutions. Jefferson Lab (USA), for example, has one hall with an almost fully hermetic detector that provides excellent coverage of phase space and another hall with detectors that cover a small angular range but with phenomenal precision; the complementarity of this design has been invaluable in the tomographic study of quark distributions inside the nucleon.

Most importantly, perhaps, friendly competition provides the most fertile ground for the emergence of the best new ideas. The existence of two collaborations opens a natural dialogue and encourages critical assessment of methods and solutions by the most qualified and uniquely invested audience. The healthy discussion and questioning of approaches provide objectivity and drives the desire to improve. The different needs and focus of the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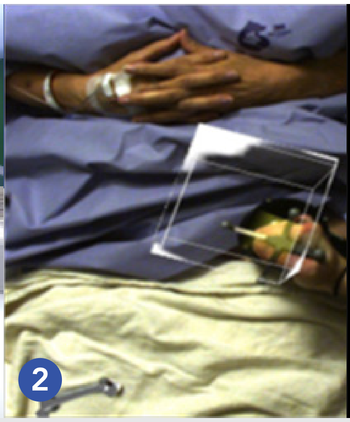
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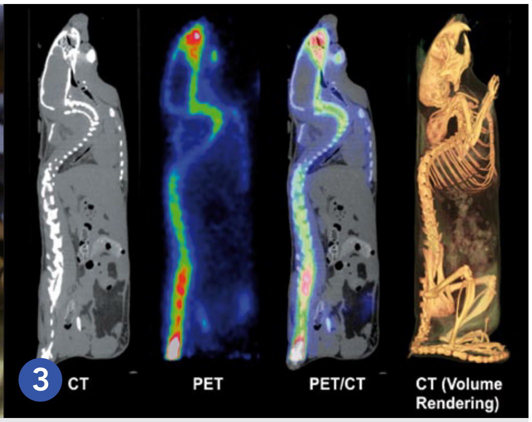
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RADIATION THERAPY

Pushing the Envelope of Nuclear Physics Technology

The tools and results of nuclear physics research, coupled with research into the chemical properties of radioactive nuclear isotopes, are essential ingredients of any modern healthcare strategy for diagnosing and treating cancer and other diseases. Worldwide, many techniques used today are an alliance of nuclear physics and medicine.

A wireless and wire-free handheld single-photon emission computed tomography (SPECT) gamma camera with position tracking is presently undergoing clinical trials. The device is based on silicon photomultipliers that saw first large-scale use in the GlueX experiment in Hall D at Jefferson Lab. The camera has demonstrated high sensitivity for detection of spreading cancer in a preoperative surgery setting.

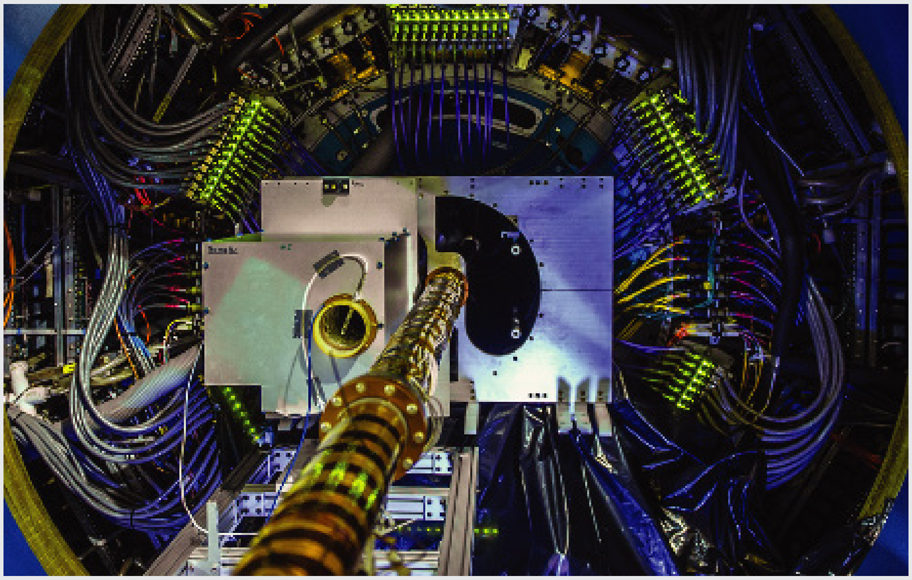
Gastrointestinal tumors, such as pancreatic cancer, require ion beams with more cell-killing energy than proton beams provide. Sensitivity to such tumors can vary widely. Because of this variation, six of the present 12 operating carbon ion therapy centers worldwide are located in Japan and eight in Asia, with more under construction (https://www.ptog.ch/).

Positron Emission Tomography (PET) is a widely used diagnostic and cancer-monitoring technique. Improvements in PET are sought by use of different and optimized calorimeter materials, use of silicon photomultipliers, integration of artificial intelligence in molecular imaging, and by use of time-of-flight techniques, in strong synergy with nuclear physics technologies. For example, the sensitivity gain of time-of-flight based PET scans is proportional to the size of the object that is being scanned and the time resolution. Gains in sensitivity thus allow a reduction of the dose rate and exposure time for medical diagnosis and treatments.

The Australian Bragg Centre for Proton Therapy and Research is aptly named after Adelaide-born Sir William Lawrence Bragg and his father Sir William Henry Bragg who together won the Nobel Prize for Physics in 1915 for 'services in the analysis of crystal structure by means of X-ray'. The new science of X-ray crystallography led to huge leaps in understanding and societal applications over the last century. This can be seen as a precursor of the EIC, which images structures over a million times smaller!

Rendering of the Bragg Centre under construction, Australia's first proton therapy center and the first center of its kind in the Southern Hemisphere.

1. *Accelerator Room at Osaka Heavy Ion Therapy Center, Osaka, Japan. The insert shows a horizontal fixed beam treatment room at East Japan Heavy Ion Center, Yamagata University.*
2. *SPECT gamma camera with position tracking in use for a clinical trial. copyright: JLab*
3. *Typical Computer Tomography (CT) image of a mouse. From left to right: CT, PET image (F18-), fused PET-CT image, CT image volume rendering. NuPECC Report "Nuclear Physics for Medicine" (eds. F. Azaiez et al., 2014), ISBN: 978-2-36873-008-9*



The Heavy Flavor Tracker of the STAR experiment at Brookhaven National Lab. The detector enabled precision tracking measurements of particles that contain the heavy charm and bottom quarks. The detector was based on the silicon technology, with the innermost detector based on "Monolithic Active Pixel Sensors", the first collider detector worldwide to use this technology. The technology is further developed for experiments at the Large Hadron Collider at CERN and, in synergy with ongoing EIC detector R&D, is expected to make its return to the US for use in the future EIC detectors.

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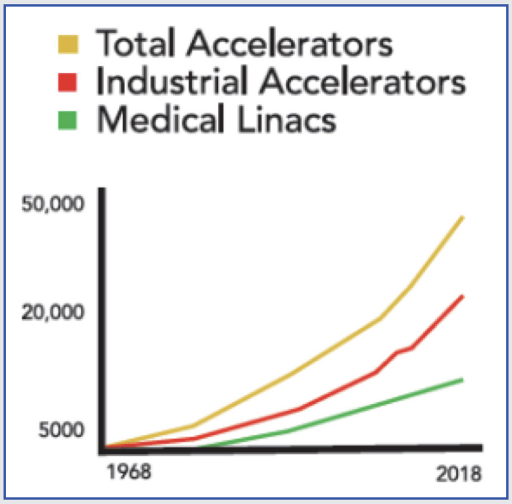
detectors may also lead to cross-fertilization of ideas, and improve technologies will simultaneously lead to a faster path for further technology development to meet societal needs.

A Long-Term Investment in a Country's Vitality

It is broadly acknowledged that Nuclear Physics has produced and continues to produce a growing number of significant applications that directly benefit society. Highly reliable, small accelerators are central to advances in cancer treatment and industry are central to advances in cancer treatment and the development and manufacturing of new materials, for example those used in computer chips, electronics, batteries, and pharmaceuticals. They already constitute a multibillion-dollar enterprise with more than 30,000 installations worldwide. Radioisotopes are used for diagnosis of heart disease and for tracking tumors. Facilities are provided for exploring the effects of space radiation to protect future astronauts and spacecraft. Detector technologies are used for deep screening of the human body, for security (from detection of dangerous substances at borders and ports to inspection and protection of the food supply), and for selecting the most appropriate technique for restoring works of art.

From these examples, it is evident that a highly qualified workforce trained in nuclear science is vital to a nation's health, economy, and security (including nuclear weapons control and counterterrorism). The EIC research frontier will provide an outstanding opportunity for students and junior scientists world-wide to access the hands-on training and unprecedented high-tech research exposure within the sub-fields of science that are crucial to technological progress, economic prosperity, and national security. In addition to fundamental research positions, nuclear and particle physicists serve in sovereign governments in leadership positions that address these critical issues. Financial organizations and private companies in all sectors seek out scientists trained in nuclear science for their quantitative skills, expertise in big data analysis and creative problem-solving abilities. The EIC will play a

X-Ray Fluorescence (XRF) study by INFN-CHNet Firenze on "L'Annunciazione" by Beato Angelico (Museum "San Marco" - Firenze, Italy).



Accelerators are key tools in (critical infrastructure for) industry and medicine.

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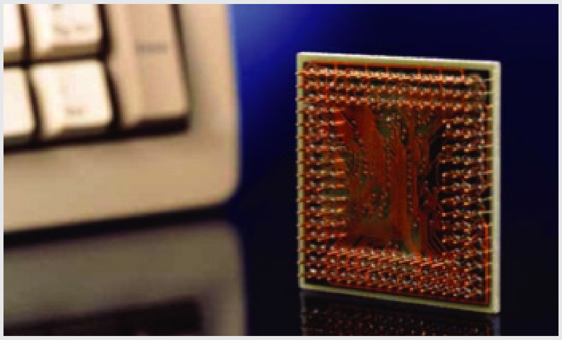

Nuclear physics has pushed the development of advanced computer power.

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crucial role in inspiring and training a new generation of highly skilled scientists that will explore physics further or find themselves applying their expertise in a range of careers that propel their home countries' economies.

EIC science requires experiment capabilities to measure a broad range of big data with numerous correlations and in multiple dimensions. An EIC will be among the first facilities to come online in the era of exascale computing. This era will see unprecedented integration of computing in the collider and experiments, combined with continued advances in machine learning and applications of Artificial Intelligence (A.I.). The EIC-related research will bring advances in a broad spectrum of science fields, including new A.I. algorithms for data processing, new quantum algorithms and computational methods and secure quantum key protocols for distributed data analysis. It will push forward new applications in particle detector technology, for example new sensors and materials for future detectors and quantum graph neutral networks for particle reconstruction. The EIC can open opportunities for truly new approaches to physics problems and analyses of scale, again to provide a unique and valuable training ground for a new generation of skilled workforce.

The EIC will revolutionize our understanding of the structure of protons and nuclei. This high-precision electron microscope will enable three-dimensional pictures of their internal structures at the finest quark-gluon levels, charting the rapidly moving gluon oceans, anti-quark seas, and quark continents. The EIC will provide nuclear science with an understanding of the internal structure of the proton and more complex atomic nuclei that is comparable to our knowledge and understanding of the chemical elements, which lies at the heart of modern technologies. Advances in technology are inevitable when we gain a better understanding of nuclear matter's innermost structures at sub-femtometer scales, which are a million times smaller than what is common in many of today's nanotechnology applications.

Ensuring this future implies that the time for decision making is now because of the long timescale of operations. For example, the Large Hadron Collider at CERN started its operations in 2008 and its schedule already shows plans for continued operations to 2038. At the Relativistic Heavy Ion Collider (BNL, USA), operations started in 2000 and are slated to continue to 2025 when the transition to the construction phase of the Electron-Ion Collider (EIC) is expected to begin.

The EIC project provides a unique opportunity for scientists and their home countries to rejoin or further their leadership in the endeavor of building colliders for fundamental science, a move that will bring a bounty of scientific and economic benefits. The time is now to capitalize on this scientific bounty with the decision to move forward with two complementary detectors at two different interaction points. Investing in the EIC early will ensure increased opportunity for countries to bring their expertise to the endeavor to help spark the future technologies and also enjoy the tangible benefits such advances bring for modern industry, medicine and society well into the future.

U.S. DEPARTMENT OF ENERGY

Jefferson Lab

Brookhaven National Laboratory