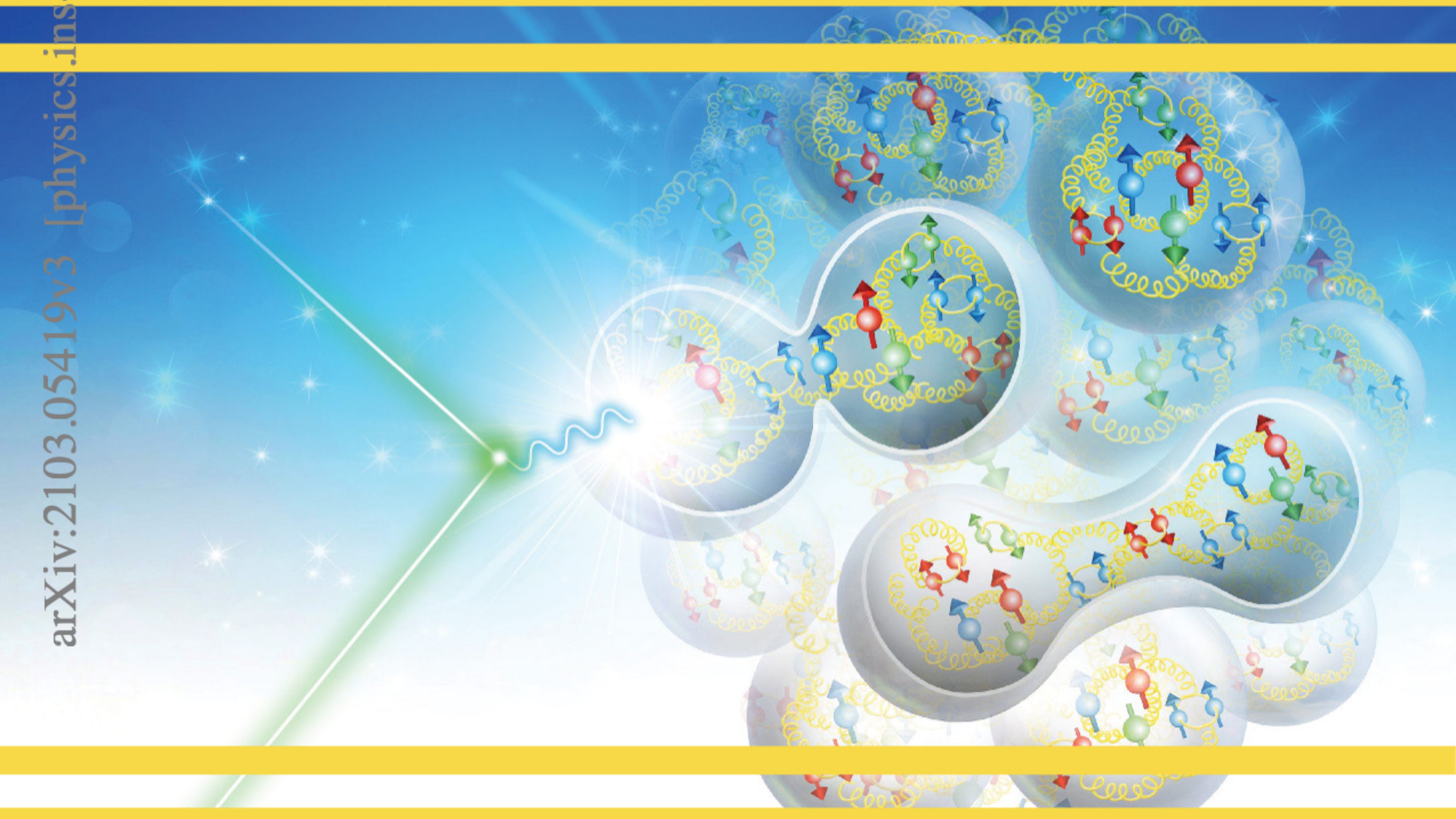
SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report



Cover Art by Yulia Furletova and Shannon West

BNL-220990-2021-FORE
JLAB-PHY-21-3198
LA-UR-21-20953

Science Requirements and Detector Concepts for the Electron-Ion Collider

EIC Yellow Report

October 2021

Author List

R. Abdul Khalek[1,2], A. Accardi[3,4], J. Adam[5], D. Adamiak[6], W. Akers[4], M. Albaladejo[4], A. Al-bataineh[7], M.G. Alexeev[8,9], F. Ameli[10], P. Antonioli[11], N. Armesto[12], W.R. Armstrong[13], M. Arratia[14,4], J. Arrington[15,$], A. Asaturyan[16], M. Asai[17], E.C. Aschenauer[5,+], S. Aune[18], H. Avagyan[4], C. Ayerbe Gayoso[19], B. Azmoun[5], A. Bacchetta[20,21], M.D. Baker[5], F. Barbosa[4], L. Barion[4,22], K.N. Barish[14,*,$], P.C. Barry[23], M. Battaglieri[4,24], A. Bazilevsky[5], N.K. Behera[25], F. Benmokhtar[26], V.V. Berdnikov[27,+], J.C. Bernauer[28,29,30], V. Bertone[18], S. Bhattacharya[31], C. Bissolotti[20,21], D. Boer[32,$], M. Boglione[8,9], M. Bondì[24], P. Boora[33], I. Borsa[34], F. Bossù[18], G. Bozzi[20,21], J.D. Brandenburg[5,30], N. Brei[4], A. Bressan[35,36,+], W.K. Brooks[37,+], S. Bufalino[9,38], M.H.S. Bukhari[39], V. Burkert[4], N.H. Buttimore[40], A. Camsonne[4], A. Celentano[24,+], F.G. Celiberto[20,41,42,43], W. Chang[5,44], C. Chatterjee[36], K. Chen[5], T. Chetry[19], T. Chiarusi[11], Y.-T. Chien[30], M. Chiosso[8,9], X. Chu[5], E. Chudakov[4,+], G. Cicala[45,46], E. Cisbani[47,10], I.C. Cloet[13], C. Cocuzza[31], P.L. Cole[48], D. Colella[45,49], J.L. Collins II[50], M. Constantinou[31], M. Contalbrigo[22], G. Contin[35,36], R. Corliss[28,30], W. Cosyn[51,+], A. Courtoy[52], J. Crafts[27], R. Cruz-Torres[15], R.C. Cuevas[4], U. D'Alesio[53,54], S. Dalla Torre[36,*,$], D. Das[55], S.S. Dasgupta[36], C. Da Silva[56], W. Deconinck[57,$], M. Defurne[18], W. DeGraw[58], K. Dehmelt[28,30], A. Del Dotto[59], F. Delcarro[4], A. Deshpande[28,5,30], W. Detmold[60], R. De Vita[24], M. Diefenthaler[4,*,$], C. Dilks[61], D.U. Dixit[58], S. Dulat[62], A. Dumitru[63,*,$], R. Dupré[64,+], J.M. Durham[56], M.G. Echevarria[65], L. El Fassi[19], D. Elia[45,+], R. Ent[4,$], R. Esha[28,30], J.J. Ethier[2], O. Evdokimov[66,*,$], K.O. Eyser[5], C. Fanelli[60], R. Fatemi[67,+], S. Fazio[5,30,+], C. Fernandez-Ramirez[52], M. Finger[68], M. Finger Jr.[68], D. Fitzgerald[69], C. Flore[64], T. Frederico[70], I. Friščić[60,4], S. Fucini[71,72], S. Furletov[4], Y. Furletova[4,+], C. Gal[30,28], L. Gamberg[73], H. Gao[61], P. Garg[30], D. Gaskell[4,+], K. Gates[74], M.B. Gay Ducati[75], M. Gericke[57], G. Gil Da Silveira[75], F.-X. Girod[76,77], D.I. Glazier[74], K. Gnanvo[78,+], V.P. Goncalves[79], L. Gonella[80], J.O. Gonzalez Hernandez[8,9], Y. Goto[81], F. Grancagnolo[82], L.C. Greiner[15,+], W. Guryn[5], V. Guzey[83], Y. Hatta[5], M. Hattawy[84], F. Hauenstein[84,60], X. He[85], T.K. Hemmick[30,28,+], O. Hen[60,+], G. Heyes[4], D.W. Higinbotham[4,+,#], A.N. Hiller Blin[4], T.J. Hobbs[4,86,87], M. Hohlmann[50], T. Horn[27,4,*,$], T.-J. Hou[88], J. Huang[5], Q. Huang[18], G.M. Huber[89], C.E. Hyde[84], G. Iakovidis[5], Y. Ilieva[90], B.V. Jacak[58,15,$], P.M. Jacobs[15], M. Jadhav[13], Z. Janoska[91], A. Jentsch[5,+], T. Jezo[92], X. Jing[86], P.G. Jones[80,*,$], K. Joo[76], S. Joosten[13], V. Kafka[91], N. Kalantarians[93], G. Kalicy[27], D. Kang[94], Z.B. Kang[95], K. Kauder[5,30], S.J.D. Kay[89], C.E. Keppel[4], J. Kim[13], A. Kiselev[5,+], M. Klasen[96], S. Klein[15,+], H.T. Klest[28], O. Korchak[91], A. Kostina[91], P. Kotko[97], Y.V. Kovchegov[6], M. Krelina[91], S. Kuleshov[98], S. Kumano[99], K.S. Kumar[100], R. Kumar[101], L. Kumar[102], K. Kumerički[103], A. Kusina[104], K. Kutak[104], Y.S. Lai[15], K. Lalwani[33], T. Lappi[105,106,+], J. Lauret[5], M. Lavinsky[50], D. Lawrence[4], D. Lednicky[91], C. Lee[56], K. Lee[15], S.H. Lee[69], S. Levorato[36], H. Li[107], S. Li[15], W. Li[108], X. Li[56], X. Li[61], W.B. Li[109,4], T. Ligonzo[110,45], H. Liu[100], M.X. Liu[56], X. Liu[111], S. Liuti[78], N. Liyanage[78], C. Lorcé[112], Z. Lu[113], G. Lucero[34], N.S. Lukow[31], E. Lunghi[114], R. Majka[115], Y. Makris[21], I. Mandjavidze[18], S. Mantry[116], H. Mäntysaari[105,106], F. Marhauser[4], P. Markowitz[51], L. Marsicano[24], A. Mastroserio[117,45], V. Mathieu[118], Y. Mehtar-Tani[29], W. Melnitchouk[4], L. Mendez[119,+], A. Metz[31,*,$], Z.-E. Meziani[13], C. Mezrag[18], M. Mihovilovič[120], R. Milner[60,$], M. Mirazita[59], H. Mkrtchyan[16], A. Mkrtchyan[16], V. Mochalov[121,122], V. Moiseev[121], M.M. Mondal[30,28], A. Morreale[56], D. Morrison[5], L. Motyka[123], H. Moutarde[18], C. Muñoz Camacho[64,*,$], F. Murgia[54], M.J. Murray[124,+], P. Musico[24], P. Nadel-Turonski[28,30], P.M. Nadolsky[86], J. Nam[31], P.R. Newman[80,+], D. Neyret[18,+], D. Nguyen[4], E.R. Nocera[125], F. Noferini[11], F. Noto[126], A.S. Nunes[5], V.A. Okorokov[122], F. Olness[86], J.D. Osborn[119], B.S. Page[5,30,+], S. Park[28], A. Parker[26], K. Paschke[78], B. Pasquini[20,21,+], H. Paukkunen[105], S. Paul[14], C. Pecar[61], I.L. Pegg[27], C. Pellegrino[127], C. Peng[13], L. Pentchev[4], R. Perrino[45], F. Petriello[13,128,+], R. Petti[90], A. Pilloni[10], C. Pinkenburg[5], B. Pire[112], C. Pisano[53,54], D. Pitonyak[129], A.A. Poblaguev[5], T. Polakovic[13], M. Posik[31], M. Potekhin[5], R. Preghenella[11], S. Preins[14], A. Prokudin[73,4], P. Pujahari[130], M.L. Purschke[5], J.R. Pybus[60,4], M. Radici[21,$], R. Rajput-Ghoshal[4], P.E. Reimer[13], M. Rinaldi[71,72], F. Ringer[15], C.D. Roberts[131], S. Rodini[20,21], J. Rojo[1,2], D. Romanov[4], P. Rossi[4,59,+],

E. Santopinto[24], M. Sarsour[85], R. Sassot[34], N. Sato[4,+], B. Schenke[5], W.B. Schmidke[5], I. Schmidt[37], A. Schmidt[77], B. Schmookler[30,28,+], G. Schnell[132,133], P. Schweitzer[76], J. Schwiening[134], I. Scimemi[118], S. Scopetta[71,72], J. Segovia[135], R. Seidl[81,29,+], S. Sekula[86], K. Semenov-Tian-Shanskiy[83], D.Y. Shao[94], N. Sherrill[114], E. Sichtermann[15,+], M. Siddikov[37], A. Signori[20,21,4], B.K. Singh[136], S. Širca[137,120], K. Slifer[138], W. Slominski[123], D. Sokhan[74,+], W.E. Sondheim[56], Y. Song[58], O. Soto[59], H. Spiesberger[139], A.M. Stasto[140,+], P. Stepanov[27], G. Sterman[28,30], J.R. Stevens[109,+], I.W. Stewart[60], I. Strakovsky[77], M. Strikman[140], M. Sturm[61], M.L. Stutzman[4], M. Sullivan[17], B. Surrow[31,$], P. Svihra[91], S. Syritsyn[28,30], A. Szczepaniak[114], P. Sznajder[141], H. Szumila-Vance[4], L. Szymanowski[141], A.S. Tadepalli[4], J.D. Tapia Takaki[124], G.F. Tassielli[82], J. Terry[95], F. Tessarotto[36], K. Tezgin[76], L. Tomasek[91], F. Torales Acosta[58], P. Tribedy[5], A. Tricoli[5], Triloki[36], S. Tripathi[142], R.L. Trotta[27], O.D. Tsai[95], Z. Tu[5,30], C. Tuvè[143,144], T. Ullrich[5,30,115,$], M. Ungaro[4], G.M. Urciuoli[10], A. Valentini[110,45], P. Vancura[91], M. Vandenbroucke[18], C. Van Hulse[64], G. Varner[142], R. Venugopalan[5,30], I. Vitev[56,+], A. Vladimirov[145,+], G. Volpe[110,45], A. Vossen[61,4,+], E. Voutier[64], J. Wagner[141], S. Wallon[64], H. Wang[4], Q. Wang[124], X. Wang[146], S.Y. Wei[41,42], C. Weiss[4], T. Wenaus[5,+], H. Wennlöf[80], N. Wickramaarachchi[27], A. Wikramanayake[50], D. Winney[114], C.P. Wong[56], C. Woody[5], L. Xia[147], B.W. Xiao[148,+], J. Xie[13], H. Xing[107], Q.H. Xu[149], J. Zhang[30,149], S. Zhang[4], Z. Zhang[5], Z.W. Zhao[61], Y.X. Zhao[150], L. Zheng[151], Y. Zhou[109], and P. Zurita[145]

[1]*Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands*
[2]*Nikhef Theory Group, 1098 XG Amsterdam, The Netherlands*
[3]*Hampton University, Hampton, Virginia 23668, USA*
[4]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[5]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[6]*Ohio State University, Columbus, Ohio 43210, USA*
[7]*Imam Abdulrahman Bin Faisal Univ., Dammam 34212, Saudi Arabia*
[8]*Università di Torino, I-10125 Torino, Italy*
[9]*INFN - Sezione di Torino, I-10125 Torino, Italy*
[10]*INFN - Sezione di Roma, I-00185 Roma, Italy*
[11]*INFN - Sezione di Bologna, I-40127 Bologna, Italy*
[12]*Universidade de Santiago de Compostela, E-15705 Santiago de Compostela, Spain*
[13]*Argonne National Laboratory, Lemont, Illinois 60439, USA*
[14]*University of California at Riverside, Riverside, California 92521, USA*
[15]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[16]*A. Alikhanian National Science Laboratory, Armenia*
[17]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[18]*IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[19]*Mississippi State University, Starkville, Mississippi 39762, USA*
[20]*Università di Pavia, I-27100 Pavia, Italy*
[21]*INFN - Sezione di Pavia, I-27100 Pavia, Italy*
[22]*INFN - Sezione di Ferrara, I-44122 Ferrara, Italy*
[23]*North Carolina State University, Raleigh, North Carolina 27607, USA*
[24]*INFN - Sezione di Genova, I-16146 Genova, Italy*
[25]*Central University of Tamil Nadu, Tamil Nadu 610005, India*
[26]*Duquesne University, Pittsburgh, Pennsylvania 15282, USA*
[27]*The Catholic University of America, Washington, DC 20064, USA*
[28]*Stony Brook University, Stony Brook, New York 11794, USA*
[29]*RIKEN BNL Research Center - Brookhaven National Laboratory, Upton, New York 11973, USA*
[30]*CFNS, Stony Brook, New York 11794, USA*
[31]*Temple University, Philadelphia, Pennsylvania 19122, USA*
[32]*University of Groningen, 9712 CP Groningen, The Netherlands*

[33]*MNIT Jaipur, Jaipur, Rajasthan 302017, India*
[34]*Universidad de Buenos Aires, C1053 CABA, Argentina*
[35]*Università di Trieste, I-34127 Trieste, Italy*
[36]*INFN - Sezione di Trieste, I-34149 Trieste, Italy*
[37]*Universidad Técnica Federico Santa María, Valparaiso, Chile*
[38]*Politecnico di Torino, I-10129 Torino, Italy*
[39]*Jazan University, Jazan, Saudi Arabia*
[40]*Trinity College, Dublin 2, Ireland*
[41]*ECT*, I-38123 Villazzano (Trento), Italy*
[42]*Fondazione Bruno Kessler (FBK), I-38123 Povo (Trento), Italy*
[43]*INFN - TIFPA, I-38123 Povo (Trento), Italy*
[44]*Central China Normal University, Wuhan, Hubei 430079, China*
[45]*INFN - Sezione di Bari, I-70126 Bari, Italy*
[46]*CNR-ISTP Bari, I-70126 Bari, Italy*
[47]*Istituto Superiore di Sanità, I-00161 Roma, Italy*
[48]*Lamar University, Beaumont, Texas 77705, USA*
[49]*Politecnico di Bari, I-70126 Bari, Italy*
[50]*Florida Institute of Technology, Melbourne, Florida 32901, USA*
[51]*Florida International University, Miami, Florida 33199, USA*
[52]*Universidad Nacional Autónoma de México, 36 01000 Ciudad de México, Mexico*
[53]*Università di Cagliari, I-09042 Monserrato (Cagliari), Italy*
[54]*INFN - Sezione di Cagliari, I-09042 Monserrato (Cagliari), Italy*
[55]*Saha Institute of Nuclear Physics, Kolkata, West Bengal 700064, India*
[56]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[57]*University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada*
[58]*University of California Berkeley, Berkeley, California 94720, USA*
[59]*INFN - LNF, I-00044 Frascati (Roma), Italy*
[60]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[61]*Duke University, Durham, North Carolina 27708, USA*
[62]*Xinjiang University, Urumqi, Xinjiang 830046, China*
[63]*Baruch College - The City University of New York, New York City, New York 10010, USA*
[64]*Université Paris-Saclay, CNRS - IJCLab, F-91406 Orsay, France*
[65]*Universidad de Alcalá, 28805 Alcalá de Henares, Madrid, Spain*
[66]*University of Illinois at Chicago, Chicago, Illinois 60607, USA*
[67]*University of Kentucky, Lexington, Kentucky 40506, USA*
[68]*Charles University, 116 36 Prague 1, Czech Republic*
[69]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[70]*Instituto Tecnológico de Aeronáutica, 12.228-900 São José dos Campos, Brazil*
[71]*Università di Perugia, I-06123 Perugia, Italy*
[72]*INFN - Sezione di Perugia, I-06123 Perugia, Italy*
[73]*Penn State Univ.-Berks, Reading, Pennsylvania 19610, USA*
[74]*University of Glasgow, Glasgow G12 8QQ, Scotland, United Kingdom*
[75]*Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, RS, Brazil*
[76]*University of Connecticut, Storrs, Connecticut 06269, USA*
[77]*The George Washington University, Washington, DC 20052, USA*
[78]*University of Virginia, Charlottesville, Virginia 22904, USA*
[79]*Universidade Federal de Pelotas, CEP 96010-900 Pelotas, RS, Brazil*
[80]*University of Birmingham, Birmingham B15 2TT, United Kingdom*
[81]*RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan*
[82]*INFN - Sezione di Lecce, I-73100 Lecce, Italy*
[83]*Petersburg Nuclear Physics Institute, Gatchina 188300, Russia*

[84]*Old Dominion University, Norfolk, Virginia 23529, USA*
[85]*Georgia State University, Atlanta, Georgia 30302, USA*
[86]*Southern Methodist University, Dallas, Texas 75275, USA*
[87]*Illinois Institute of Technology, Chicago, Illinois 60616, USA*
[88]*Northeastern University, Shenyang, Liaoning, China*
[89]*University of Regina, Regina, Saskatchewan S4S 0A2, Canada*
[90]*University of South Carolina, Columbia, South Carolina 29208, USA*
[91]*Czech Technical University, 115 19 Prague 1, Czech Republic*
[92]*Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany*
[93]*Virginia Union University, Richmond, Virginia 23220, USA*
[94]*Fudan University, Shanghai 200433, China*
[95]*University of California at Los Angeles, Los Angeles, California 90095, USA*
[96]*Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany*
[97]*AGH University of Science and Technology, 30-059 Krakow, Poland*
[98]*Universidad Andres Bello, Sazié 2212, Piso 7, Santiago, Chile*
[99]*KEK, Tsukuba, Ibaraki 305-0801, Japan*
[100]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[101]*Akal University, Talwandi Sabo, Punjab 151302, India*
[102]*Panjab University, Chandigarh 160014, India*
[103]*University of Zagreb, 10000 Zagreb, Croatia*
[104]*Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland*
[105]*University of Jyväskylä, 40014 Jyväskylä, Finland*
[106]*Helsinki Institute of Physics, FI-00014 Helsinki, Finland*
[107]*South China Normal University, Guangzhou 510631, China*
[108]*Rice University, Houston, Texas 77005, USA*
[109]*The College of William and Mary, Williamsburg, Virginia 23185, USA*
[110]*Università di Bari, I-70121 Bari, Italy*
[111]*Beijing Normal University, Beijing 100875, China*
[112]*CNRS - CPHT, École Polytechnique, I.P. Paris, F-91120 Palaiseau, France*
[113]*Southeast University, Nanjing, Jiangsu 211189, China*
[114]*Indiana University, Bloomington, Indiana 47405, USA*
[115]*Yale University, New Haven, Connecticut 06520, USA*
[116]*University of North Georgia, Dahlonega, Georgia 30597, USA*
[117]*Università di Foggia, I-71122 Foggia, Italy*
[118]*Universidad Complutense de Madrid, E-28040 Madrid, Spain*
[119]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA*
[120]*Jožef Stefan Institute, 1000 Ljubljana, Slovenia*
[121]*NRC "Kurchatov Institute" - IHEP, Protvino, Moscow region 142280, Russia*
[122]*National Research Nuclear University MEPhI, Moscow 115409, Russia*
[123]*Jagiellonian University, PL-31007 Krakow, Poland*
[124]*University of Kansas, Lawrence, Kansas 66045, USA*
[125]*University of Edinburgh, JCMB, KB, Edinburgh EH9 3FD United Kingdom*
[126]*INFN - LNS, I-95123 Catania, Italy*
[127]*INFN - CNAF, I-40127 Bologna, Italy*
[128]*Northwestern University, Evanston, Illinois 60208, USA*
[129]*Lebanon Valley College, Annville, Pennsylvania 17003, USA*
[130]*IIT Madras, Chennai, Tamil Nadu 600036, India*
[131]*Nanjing University, Nanjing, Jiangsu 210093, China*
[132]*University of the Basque Country UPV/EHU, E-48940 Bilbao, Spain*
[133]*IKERBASQUE, Basque Foundation for Science, E-48009 Bilbao, Spain*
[134]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*

[135]*Universidad Pablo de Olavide, E-41013 Sevilla, Spain*
[136]*Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India*
[137]*University of Ljubljana, 1000 Ljubljana, Slovenia*
[138]*University of New Hampshire, Durham, New Hampshire 03824, USA*
[139]*Johannes Gutenberg Universität, D-55122 Mainz, Germany*
[140]*The Pennsylvania State University, University Park, Pennsylvania 16802, USA*
[141]*National Centre for Nuclear Research (NCBJ), 02-093 Warsaw, Poland*
[142]*University of Hawaii, Honolulu, Hawaii 96822, USA*
[143]*Università di Catania, I-95124 Catania, Italy*
[144]*INFN - Sezione di Catania, I-95125 Catania, Italy*
[145]*Universitaet Regensburg, D-93040 Regensburg, Germany*
[146]*Zhengzhou University, Zhengzhou, Henan 450001, China*
[147]*University of Science and Technology of China, Hefei, Anhui 230052, China*
[148]*The Chinese University of Hong Kong, Hong Kong, Shenzhen 518172, China*
[149]*Shandong University, Qingdao, Shandong 266237, China*
[150]*Chinese Academy of Sciences, Lanzhou, Gansu Province 730000, China*
[151]*China University of Geosciences, Wuhan, Hubei 430079, China*

[$] Editor

[*] Working Group Convener

[+] Sub-Working Group Convener

[#] Technical Editor

Abstract

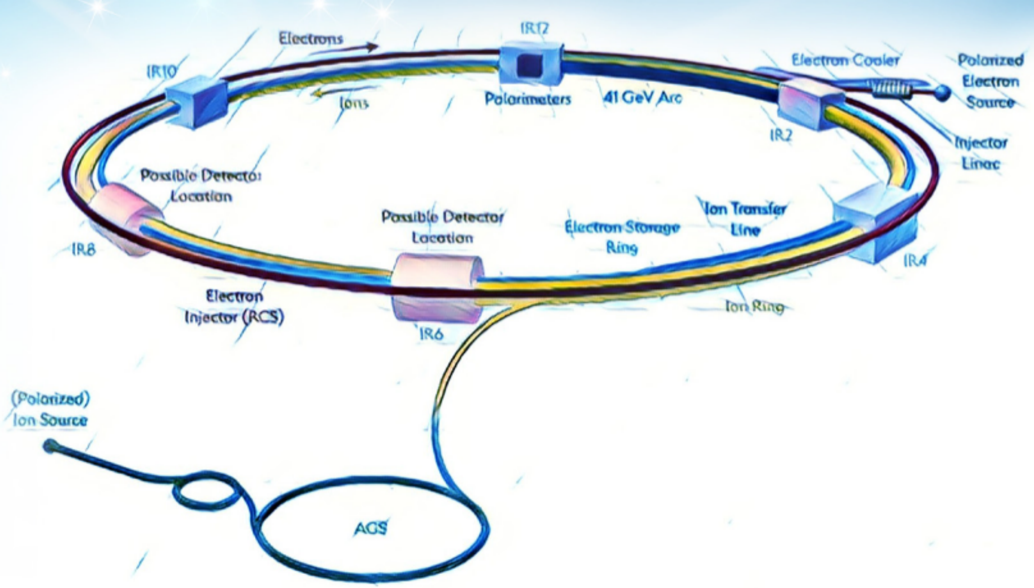
This report describes the physics case, the resulting detector requirements, and the evolving detector concepts for the experimental program at the Electron-Ion Collider (EIC). The EIC will be a powerful new high-luminosity facility in the United States with the capability to collide high-energy electron beams with high-energy proton and ion beams, providing access to those regions in the nucleon and nuclei where their structure is dominated by gluons. Moreover, polarized beams in the EIC will give unprecedented access to the spatial and spin structure of the proton, neutron, and light ions. The studies leading to this document were commissioned and organized by the EIC User Group with the objective of advancing the state and detail of the physics program and developing detector concepts that meet the emerging requirements in preparation for the realization of the EIC. The effort aims to provide the basis for further development of concepts for experimental equipment best suited for the science needs, including the importance of two complementary detectors and interaction regions.

This report consists of three volumes. Volume I is an executive summary of our findings and developed concepts. In Volume II we describe studies of a wide range of physics measurements and the emerging requirements on detector acceptance and performance. Volume III discusses general-purpose detector concepts and the underlying technologies to meet the physics requirements. These considerations will form the basis for a world-class experimental program that aims to increase our understanding of the fundamental structure of all visible matter.

Contents

EIC YELLOW REPORT

Volume I: Executive Summary



Chapter 1

The Electron-Ion Collider

The Electron-Ion Collider (EIC) is a new, innovative, large-scale particle accelerator facility conceived by U.S. nuclear and accelerator physicists over two decades and planned for construction at Brookhaven National Laboratory on Long Island, New York by the U.S. Department of Energy in the 2020s. The EIC will study protons, neutrons and atomic nuclei with the most powerful electron microscope, in terms of versatility, resolving power and intensity, ever built. The resolution and intensity is achieved by colliding high-energy electrons with high-energy protons or (a range of different) ion beams. The EIC provides the capability of colliding beams of polarized electrons with polarized beams of light ions, and this all at high intensity. The EIC was established as the highest priority for new construction in the 2015 US Nuclear Physics Long Range Plan, and was favorably endorsed by a committee established by the National Academy of Sciences in 2018 to assess the science case. In December 2019, the EIC was granted Critical Decision Zero (CD0) by the US Department of Energy, which launched the EIC as an official project of the US government.

The main design requirements of the EIC are:

- Highly polarized electron ($\sim$70%) and proton ($\sim$70%) beams
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium
- Variable e+p center-of-mass energies from 20$-$100 GeV, upgradable to 140 GeV
- High collision electron-nucleon luminosity $10^{33}-10^{34}$ cm^{-2} s^{-1}
- Possibility to have more than one interaction region

Several of the above performance parameters will be realized for the first time at EIC in a collider mode, such as the availability of nuclear beams and polarized nucleon beams along with the operation at high collision luminosity. Shown schematically in Fig. 1.1, the EIC will collide bright, intense counter circulating beams of

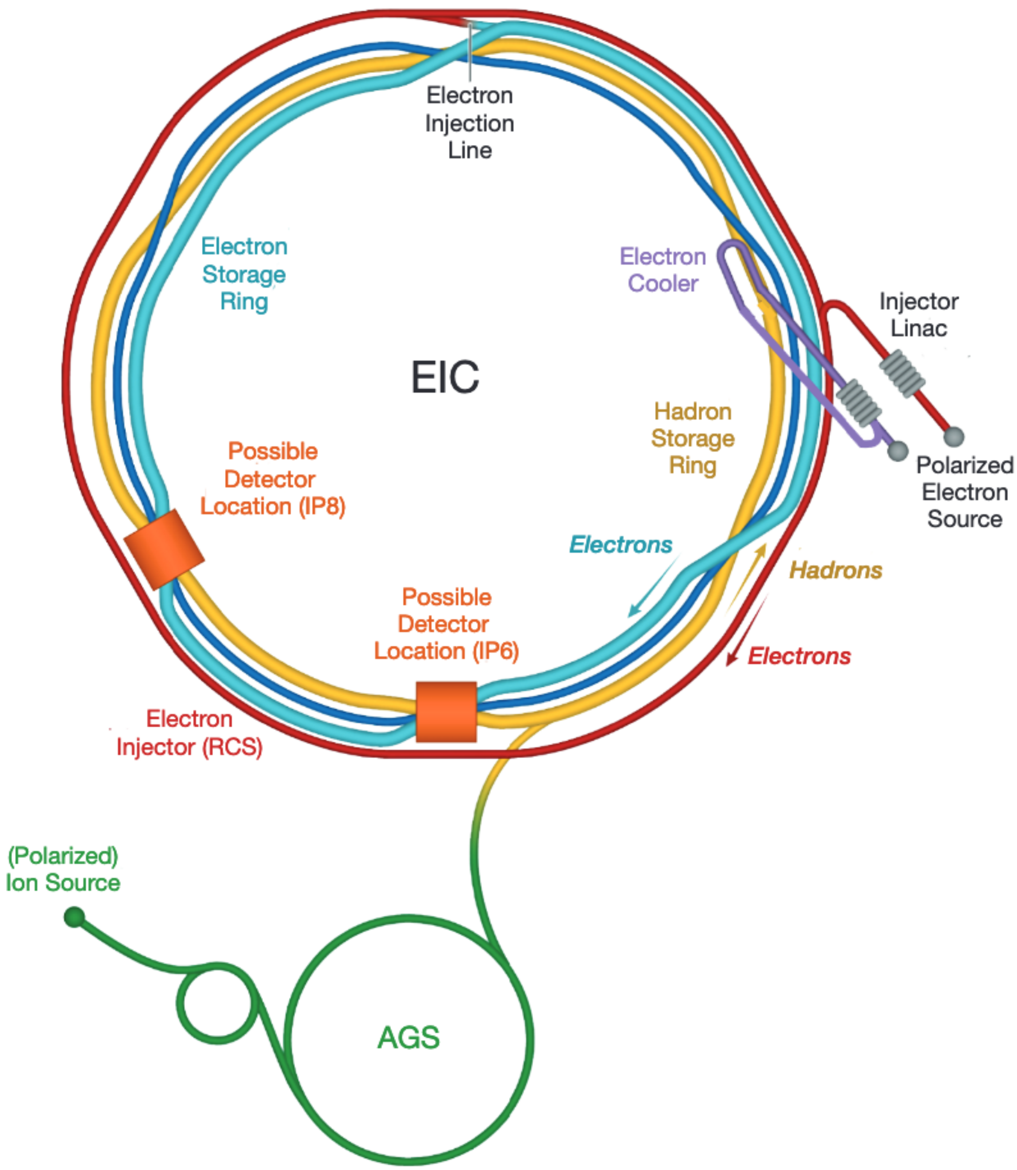


Figure 1.1: Schematic layout of the planned EIC accelerator based on the existing RHIC complex at Brookhaven National Laboratory.

electrons and ions and use sophisticated, large detectors to identify specific reactions whose precise measurement can yield previously unattainable insight into the structure of the nucleon and nucleus. The EIC will open a new window into the quantum world of the atomic nucleus and allow physicists access for the first time to key, elusive aspects of nuclear structure in terms of the fundamental quark and gluon constituents. Nuclear processes fuel the universe. Past research has provided enormous benefit to society in terms of medicine, energy and other applications. Particle accelerators and related technologies play a key role in the discovery sciences and it is estimated that about 30,000 worldwide are operating in industry. The EIC will probe the frontiers of nuclear science well into the twenty-first century using one of the world's most sophisticated particle accelerators and large detectors that will utilize cutting-edge technology.

The realization of the EIC is led jointly by Brookhaven National Laboratory and Thomas Jefferson National Accelerator Facility at Newport News, Virginia. It will involve physicists and engineers from other laboratories and universities in the U.S. and from around the world. This realization is expected to roughly take a decade, with beam operations to start in the early 2030s.

The EIC Users Group (EICUG, www.eicug.org) was founded in 2016. It now contains over 1200 members from 245 institutions located in 33 countries around the world. Late in 2019, the EICUG decided to organize an intensive, year-long consideration of the EIC physics measurements and scientific equipment by the members of the user group. This Yellow Report (YR) summarizes these studies and the conclusions that have been reached. The purpose of the Yellow Report Initiative is to advance the state and detail of the documented community physics studies (EIC White Paper, Institute for Nuclear Theory program proceedings) and detector concepts (Detector and R&D Handbook) in preparation for the realization of the EIC. The effort aims to provide the basis for further development of concepts for experimental equipment best suited for science needs, including complementarity of two detectors towards future Technical Design Reports. It is expected that this YR will be the cornerstone on which detector proposals will be developed by user collaborations beginning in 2021.

The work reported on here was organized by the EICUG at an in-person meeting in December 12-13, 2019 at the Massachusetts Institute of Technology, Cambridge, Massachusetts and was structured around four subsequent meetings in 2020: March 19-21, 2020 at Temple University, Philadelphia; May 20-22, 2020 at University of Pavia, Pavia, Italy; September 16-18, 2020 at the Catholic University of America, Washington, DC and November 19-21, 2020 at the University of California, Berkeley. This was a massive, international, sustained effort through the year 2020 and was overseen by 8 conveners and 41 sub-conveners. Because of the restrictions due to the pandemic, all of the EICUG meetings and interactions in 2020 were carried out remotely.

The EIC will be one of the largest and most sophisticated new accelerator projects worldwide in the next few decades, and the only planned for construction in the United States. It will address profound open questions in the fundamental structure of matter and attract new generations of young people into the pursuit of careers in science and technology. Its high design luminosity and highly polarized beams are beyond state-of-the-art and its realization will likewise push the frontiers of particle accelerator science and technology.

Chapter 2

Physics Measurements and Requirements

2.1 Introduction

The Electron-Ion Collider (EIC) will address some of the most fundamental questions in science regarding the visible world, including the origin of the nucleon mass, the nucleon spin, and the emergent properties of a dense system of gluons. The science program has been reviewed by the National Academy of Sciences (NAS) which concluded that ”the EIC science is compelling, fundamental, and timely.” [1]. The NAS review was based on a series of workshops hosted by the Institute of Nuclear Theory (INT) culminating in a whitepaper in 2012 and an update in 2014 entitled ”Understanding the glue that binds us all” [2]. The desire and need to construct a new collider facility were prominently featured in the 2015 US Long-Range Plan for Nuclear Science [3].

In this executive section, we present a selection of crucial physics topics that led to the recommendation for the construction of an EIC, and summarize the machine parameters and detector requirements needed to address them.

Key science questions that the EIC will address are:

- How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?
- How are partons inside the nucleon distributed in both momentum and position space?
- How do color-charged quarks and gluons, and jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?