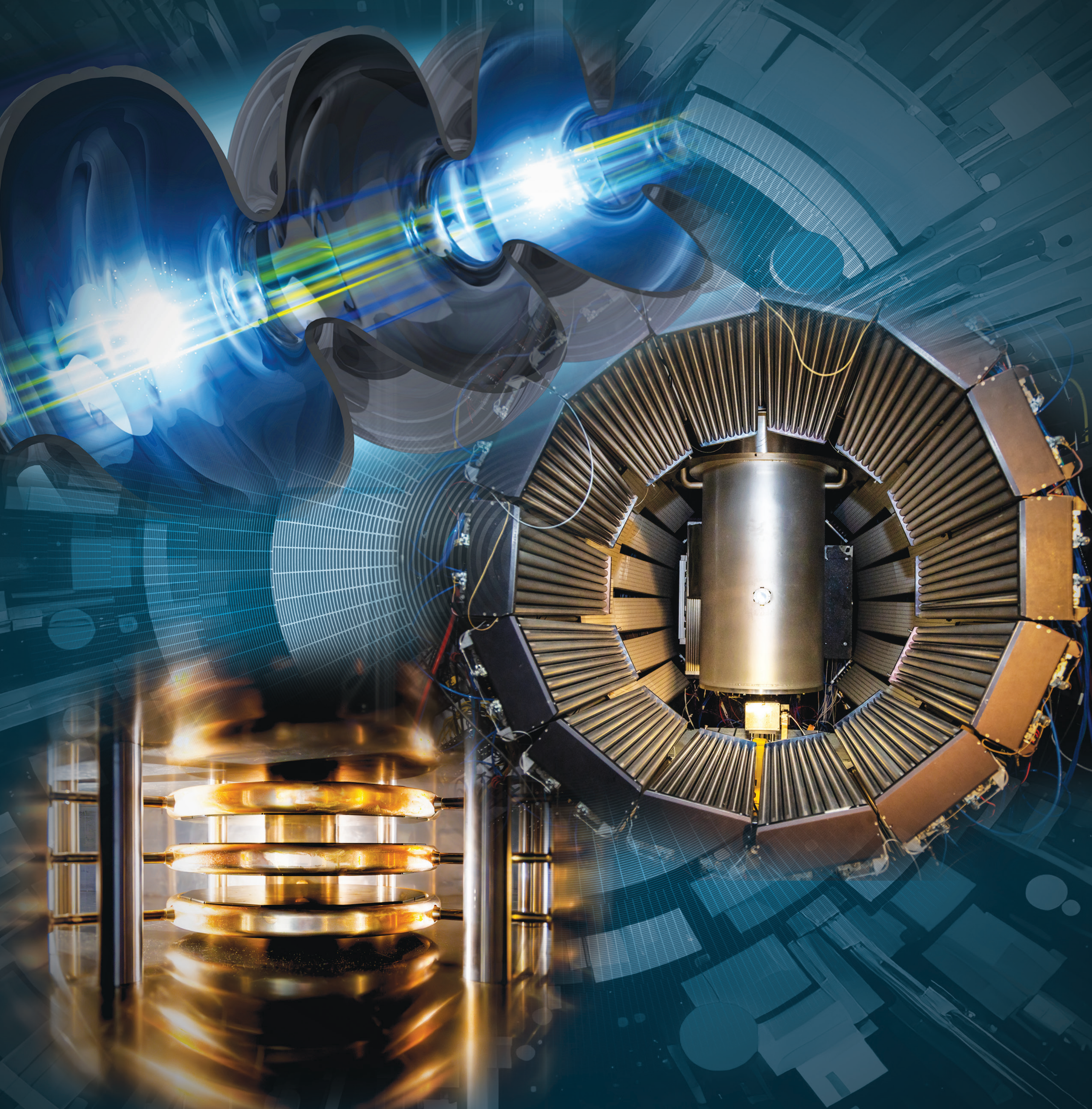
BASIC RESEARCH NEEDS FOR ACCELERATOR-BASED INSTRUMENTATION



RESEARCH TO ACCELERATE INNOVATION FOR FUTURE SCATTERING FACILITIES

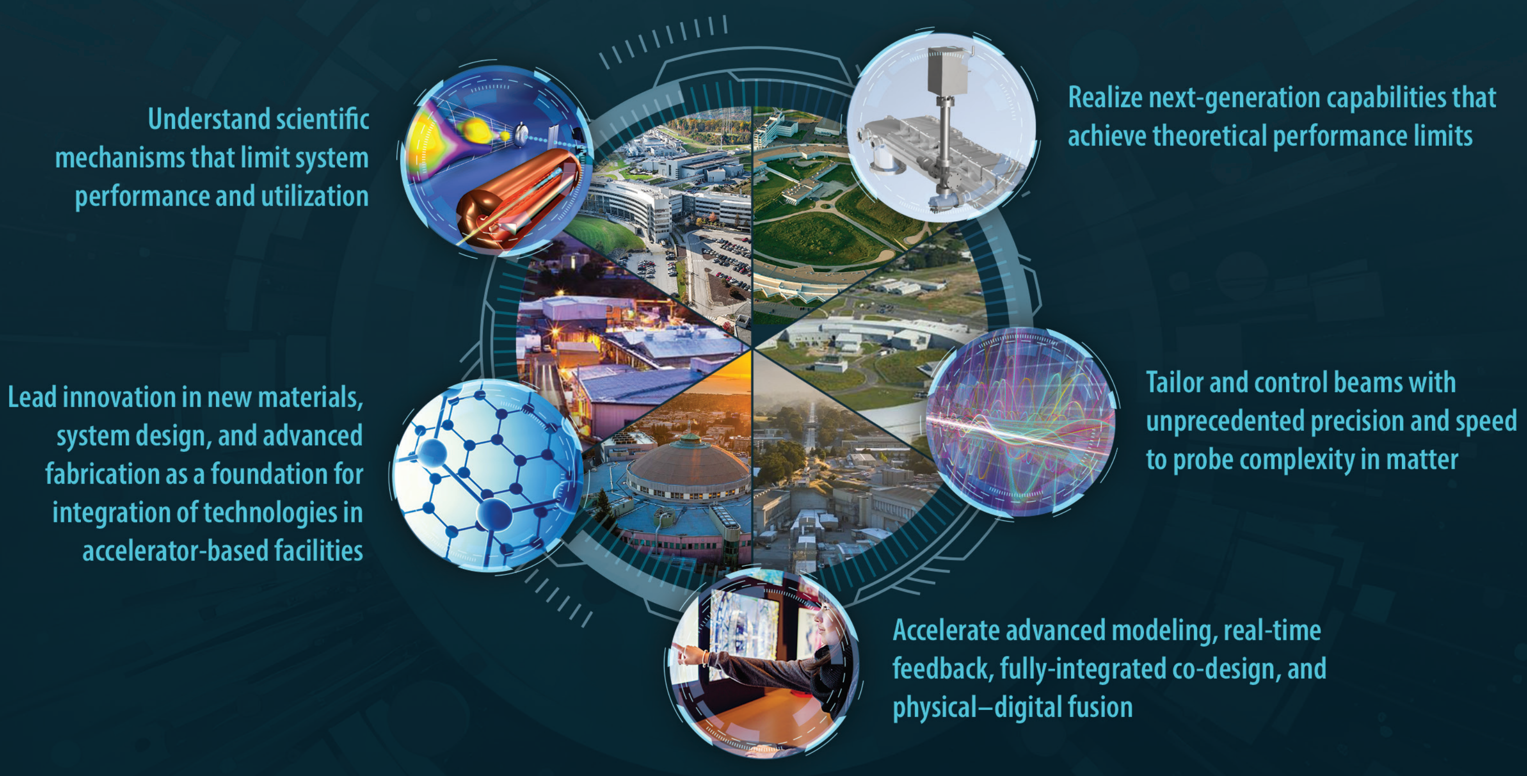
Accelerator-based instrumentation—Fundamental science for innovation of next-generation scattering facilities

Accelerator-based light and neutron sources are research powerhouses, providing unique analytical tools for decoding complex materials and systems. They contribute directly to societal grand challenges and serve an incredibly broad range of applications from elucidating the fundamental mechanisms at play in biological or physical systems, including their evolution over time, to providing high-throughput discovery platforms for new and increasingly complex materials with specialized properties required by technology and the U.S. economy. New accelerator concepts, new materials such as next-generation semiconductors, advanced techniques for fabrication and processing, miniaturization, and increased computing power, have enabled decades of scientific and technological innovation. As a result, the research capabilities of photon and neutron facilities have grown exponentially.

The full breadth of instrumentation at these facilities will benefit from research advances, which have the potential to transform existing light and neutron sources and pave the way for new facilities with unprecedented capabilities that will impact broad areas of science. Research in instrumentation will yield sources and accelerator systems that produce much brighter beams, deliver efficient beam transport and detection systems, and allow for co-designing future instruments with autonomous closed-loop workflows in mind from the outset. These capabilities will revolutionize the way scientists understand matter and control phenomena occurring at multiple length- and timescales at or near realistic operating conditions and will enable discovery at unprecedented scales.

In 2023, a team of experts from national laboratories, academia, and industry convened for a workshop to address Basic Research Needs for Accelerator-Based Instrumentation. Five Priority Research Directions were identified (illustrated below) across multiple accelerator science and technology domains, complementing each other to provide—individually or collectively—transformative capability improvements. The full workshop report will be posted at http://science.osti.gov/bes/Community-Resources/Reports.

Priority Research Directions to revolutionize accelerator-based instrumentation



Priority Research Directions

- ## Realize next generation capabilities that achieve theoretical performance limits

  Key Question: *How can research breakthroughs lead to new, accelerator-based capabilities that perform at or near theoretical limits?*

  Progress in high-power and high-brilliance sources depends on advances that push the performance of high-power electronics, lasers, optics, detectors, and diagnostics towards physical and technological limits. Research to understand the fundamentals of beam generation and to probe parameters' behavior near or at their theoretical limits should provide a pathway that leads to overall maximum performance.

- ## Tailor and control beams with unprecedented precision and speed to probe complexity in matter

  Key Question: *What are the most promising avenues to manipulate and multiplex beams to support a wide range of experiments across multiple research fields?*

  Accelerator-based neutron and x-ray light sources are enabling more and more complex, often multimodal, experiments in which the beam characteristics (e.g., size, shape, polarization) are manipulated in real time to probe materials and systems over a wide range of experimental conditions. Expanding the research capacity requires developing methods and techniques to improve beam quality and tunability.

- ## Accelerate advanced modeling, real-time feedback, fully-integrated co-design, and physical–digital fusion

  Key Questions: *Can scientists build true, actionable, shareable digital twins that enhance development and control of accelerator, optical, and detection systems? How can the revolution in artificial intelligence, machine learning, and exascale computing be used to transform the research paradigm?*

  Advanced modeling and digital representation of individual instrumentation components and systems are becoming key to innovation and essential for increased operational efficiency of state-of-the-art facilities. Research opportunities include advances in probabilistic digital twins that incorporate errors present in physical systems and real-time integration to predict outcomes of specific experiments (with real-time parameter optimization). These digital twins can also be used in high-efficiency accelerator operations.

- ## Lead innovation in new materials, system design, and advanced fabrication as a foundation for integration of technologies in accelerator-based facilities

  Key Questions: *Which critical technologies can benefit most from research programs in new materials and advanced synthesis and manufacturing? How can Small Business Innovation Research or other technology-transfer mechanisms accelerate exploitation of this research in implemented technologies?*

  From particle sources to optics to detectors, accelerator-based facilities rely heavily on new materials with controllable properties on atomic to mesoscales, innovative designs/architectures, and advanced fabrication processes. Coupling precision design of complex components with modeling and optimization will lead to new paradigms for fabrication and component integration.

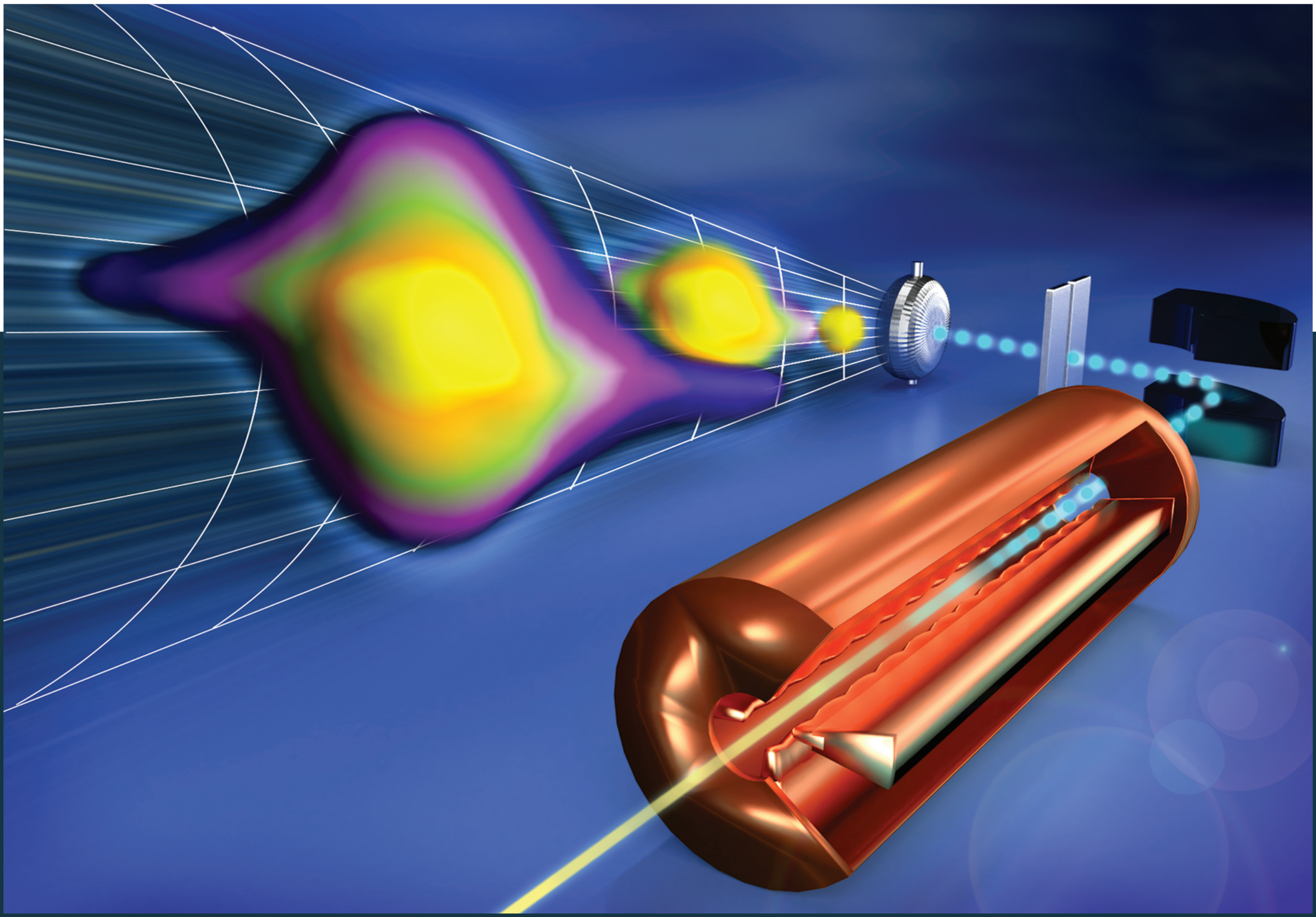
- ## Understand scientific mechanisms that limit system performance and utilization

  Key Question: *What are the key phenomena hindering transformative changes in capabilities at accelerator-based facilities?*

  Multiple factors place practical limits on the performance of key technologies used in accelerator-based facilities and require an in-depth understanding of the mechanisms at play, a clear analytical formulation, and/or the ability to compute realistic simulations of the system.

Summary

Continuing to increase the impact of accelerator-based light sources and neutron sources requires research to innovate throughout the instrumentation ecosystem. This research includes investigating ways to overcome current practical limits; developing new materials and devices for accelerator components, detectors, and optics; leveraging innovative fabrication processes to boost beam performance; tailoring probes' functions dynamically; employing computational tools in the design of experimental capabilities; and using systems engineering approaches augmented by artificial intelligence to keep pace with fast-changing technologies. The multiplicative gain obtained by system-level optimization has the potential to radically transform research capabilities at scattering facilities and to further enhance their scientific reach and impact. These Priority Research Directions lay the scientific foundation for innovations that will revolutionize the suite of advanced light and neutron sources that are the backbone of the BES scientific user facilities.



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