PRESS RELEASE

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Ibaraki University
High Energy Accelerator Research Organization
The Graduate University for Advanced Studies

First Experimental Demonstration of 3D Spiral Injection in an Ultracompact Storage Ring

A New Beam Injection Scheme Opens Opportunities for Next-Generation Accelerator Technologies

A research group led by Associate Professor Hiromi Iinuma of the College of Science, Ibaraki University, and Ryota Matsushita of the Graduate School of Science, The University of Tokyo, has achieved the world's first experimental demonstration of beam storage in an ultracompact storage ring using a three-dimensional spiral injection scheme.

Precise measurements of spin precession in charged particles require particle beams to be stored stably for long periods in a highly uniform magnetic field. However, as storage rings become smaller, it becomes increasingly difficult to secure sufficient space for beam injection from outside the ring. To address this challenge, the research team developed a novel injection scheme that guides beams into the axisymmetric field of a solenoidal magnet, similar to those used in MRI systems, along a three-dimensional spiral trajectory.

Furthermore, the team experimentally demonstrated stable beam storage for more than 200 revolutions in a storage ring with a revolution period on the order of nanoseconds, using a pulsed magnetic kicker system. Such beam storage is extremely challenging with conventional injection schemes. This achievement represents an experimental demonstration of beam storage using the three-dimensional spiral injection scheme.

The three-dimensional spiral injection scheme demonstrated in this work is expected to contribute not only to next-generation compact storage-ring technologies, but also to the development of novel beam-control techniques in complex magnetic-field environments. Future work will focus on generalizing the concept to beam transport and storage design in arbitrary magnetic fields and exploring its application to next-generation accelerator technologies.

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Research Background

Frequency-based measurements provide some of the highest levels of precision achievable in experimental science. A familiar example is magnetic resonance imaging (MRI), which places the human body in a highly uniform magnetic field and visualizes signals generated by the precession of hydrogen nuclear spins. The resulting signal frequencies are used to produce detailed images of internal structures.

The same principle is used in precision particle-physics experiments. By storing elementary particles in an extremely uniform magnetic field and precisely measuring their spin precession frequencies, researchers can test the predictions of the Standard Model of particle physics with high accuracy. Such measurements may also reveal evidence of physics beyond the Standard Model. To achieve this goal, however, the particles must be stably stored within an ultra-uniform magnetic field for extended periods of time.

This research was motivated by the need to inject and store charged-particle beams in an ultra-uniform magnetic field with a field uniformity of 0.1 ppm (1 part in 10 million), a requirement that ultimately led to the development of the three-dimensional spiral injection scheme. While ultra-uniform static magnetic fields have been realized in medical MRI systems, the region over which such field uniformity can be guaranteed is typically limited to the size of a human body. In contrast, storage rings used in high-energy physics experiments often have diameters of several kilometers.

As illustrated in **Figure 1**, reducing the scale of a storage ring by a factor of one thousand—from kilometers to less than one meter—fundamentally changes the technical requirements.

For example, a particle traveling at nearly the speed of light completes one revolution in approximately 10 microseconds in a 3-kilometer ring, whereas the revolution period becomes only about 3 nanoseconds in a 1-meter ring. Such extreme timing requirements make conventional beam injection and control techniques exceedingly difficult to implement.

To overcome these challenges, the research team developed new beam-injection and beam-control technologies specifically designed for ultracompact storage rings.

The first challenge was to design both the magnetic structure and the beam-injection trajectory so that the beam could be smoothly transferred from the injection point into the storage region, while ensuring that no stray magnetic fields were introduced into the highly uniform storage field.

A viable solution was found by designing an injection trajectory through the fringe field of a solenoidal magnet, a configuration commonly used in medical MRI systems.

The second challenge was how to retain the injected beam within the uniform-field region of the solenoidal storage magnet. To address this issue, the research team devised a beam-optics scheme in which the injected beam follows an axisymmetric three-dimensional trajectory and gradually spirals toward the storage region over several tens of revolutions.

After injection, the beam is controlled by axisymmetric pulsed magnetic kicks generated by a set of solenoidal kicker coils (the vertical kick shown in **Figure 2**). Because these pulsed kicks are produced by driven currents, any residual magnetic fields that could disturb the highly uniform storage field are rapidly suppressed after the kick is applied.

The research team named this approach the "three-dimensional spiral beam injection scheme" and has pursued its development and experimental validation over the past several years.

As described above, the concept was motivated by the need to miniaturize accelerator systems while minimizing stray magnetic and electric fields. The central idea is to control the beam using only the axisymmetric magnetic fields generated by circular currents, thereby avoiding additional field sources that could compromise the precision of the storage region.

A key advantage of this approach is that the radial beam motion naturally remains axisymmetric. As a result, beam control can be simplified to managing only the beam distribution along the solenoid axis, significantly reducing the complexity of the injection and storage process.

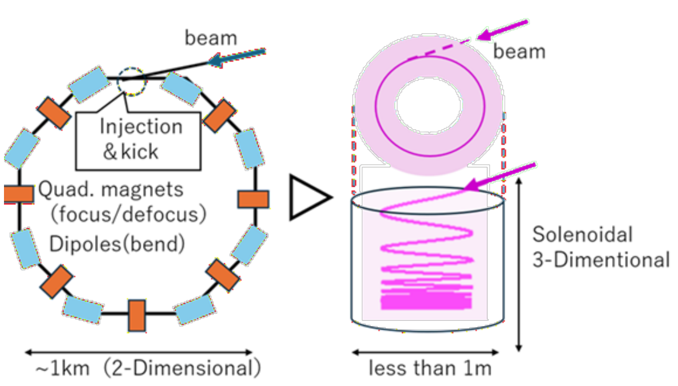

Figure 1. Conceptual size comparison between conventional accelerator storage rings and the ultracompact storage ring used in this study (22 cm in the present experiment).

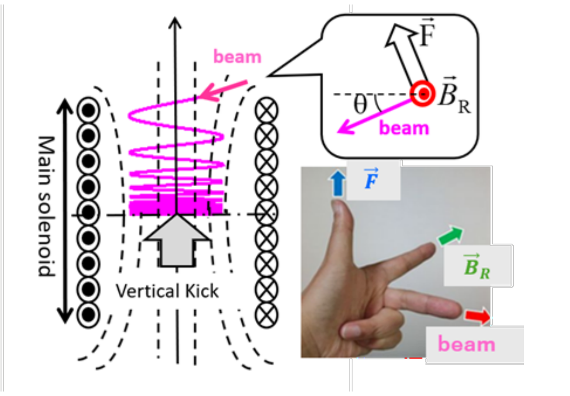

Figure 2. Schematic illustration of the three-dimensional spiral beam injection scheme into an axisymmetric solenoidal magnetic field.

Research Method and Results

Experimental Method

After proposing the concept of the new injection scheme in a 2016 publication, the research team constructed a dedicated experimental beamline at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan, to demonstrate beam storage using the three-dimensional spiral injection scheme (**Figure 3**).

In the experiment, an electron beam with a momentum of 297 keV/c and a pulse width of 100 nanoseconds was injected obliquely into a solenoidal storage magnet, where the stored-beam orbit had a diameter of 22 centimeters. The beam was guided toward the storage orbit through a spiral trajectory while receiving vertical kicks from a pulsed kicker system.

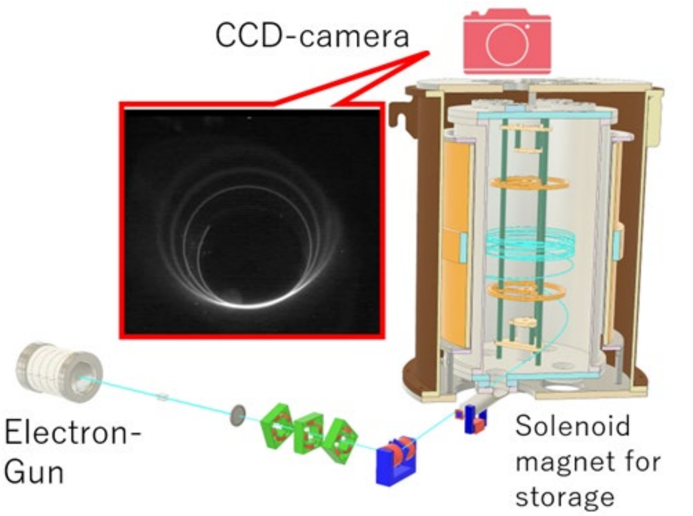

Figure 3. Experimental setup and wide-angle view of the beam trajectory in the ultracompact storage ring. The ring diameter is 22 cm, corresponding to a beam revolution period of approximately 5 nanoseconds.

The first stage of the experiment focused on beamline commissioning using a continuous electron beam. This confirmed that the beam could be injected into the storage region of the solen oidal magnet along the designed three-dimensional spiral trajectory, thereby addressing the first technical challenge described above.

In the second stage, the electron beam was chopped into short pulses using an electromagnetic chopper and synchronized with the kicker system. The experiment then proceeded to the second challenge: demonstrating that the injected beam could be retained within the storage region.

Main Results

In this storage ring, the beam completes one revolution in only 4.7 nanoseconds. As a result, conventional beam-injection techniques commonly used in large accelerator facilities—where the beam is transferred from the injection orbit to the storage orbit within a single revolution—become extremely difficult to implement because of the technical limitations of pulsed-power systems used to drive kicker magnets.

To overcome this challenge, the research team took advantage of the axisymmetric beam trajectory. Rather than completing the injection process within a single turn, axisymmetric magnetic kicks were applied over multiple revolutions, gradually guiding the injected beam into the storage region of the solenoidal magnet and maintaining the beam within the storage region.

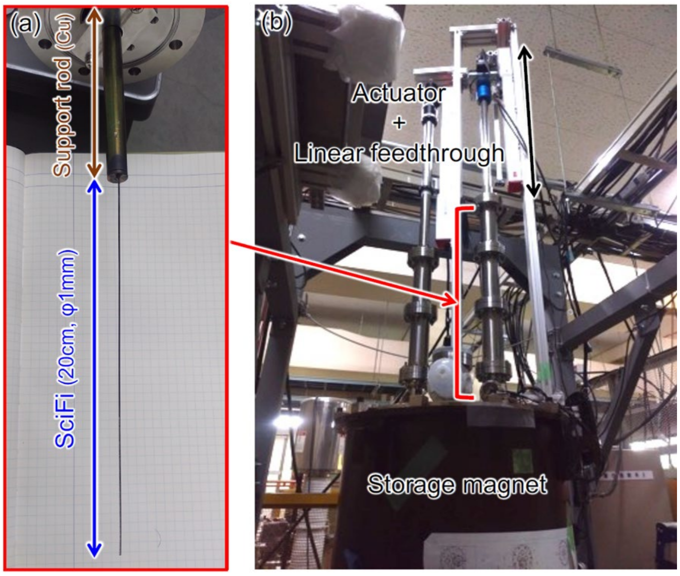

Figure 4. Plastic scintillating fiber (SciFi) detector installed above the solenoidal storage magnet for detection of stored beams.

To detect signals originating from stored beams, the researchers used a detector based on plastic scintillating fibers (SciFi) (**Figure 4**). The detector was inserted into the storage region, where circulating electrons passing through the SciFi generated scintillation light. This light was then read out by photomultiplier tubes, allowing signals from the stored beam to be observed.

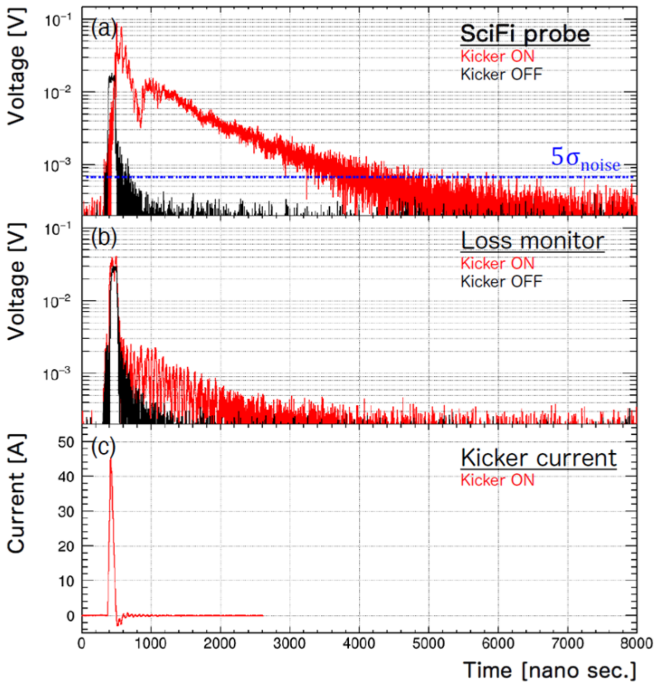

Figure 5. Time evolution of detector signals with and without operation of the kicker system. (Top) SciFi detector signal used to identify stored beams. (Middle) Beam-loss detector signal. (Bottom) Kicker pulse waveform.

To establish an objective criterion for beam storage, the team defined successful storage as a signal exceeding five standard deviations (5σ) above the pre-injection background noise level and persisting for more than 1 microsecond. This duration is substantially longer than the approximately 100-nanosecond width of the injected beam pulse and corresponds to more than 200 revolutions of the beam around the storage ring.

Using this criterion, the researchers compared detector signals recorded with and without operation of the kicker system (**Figure 5**).

When the kicker system was activated, the SciFi detector signal remained above the 5σ threshold for more than 1 microsecond, satisfying the criterion for beam storage. In contrast, when the kicker system was not operated, the signal duration was limited to approximately 100 nanoseconds, comparable to the width of the injected beam pulse, and therefore failed to satisfy the storage criterion.

This clear difference demonstrated that the beam was successfully stored through the action of the repeated vertical kicks provided by the kicker system over multiple revolutions. In other words, the experiment provided the first direct demonstration of beam storage achieved using the three-dimensional spiral injection scheme.

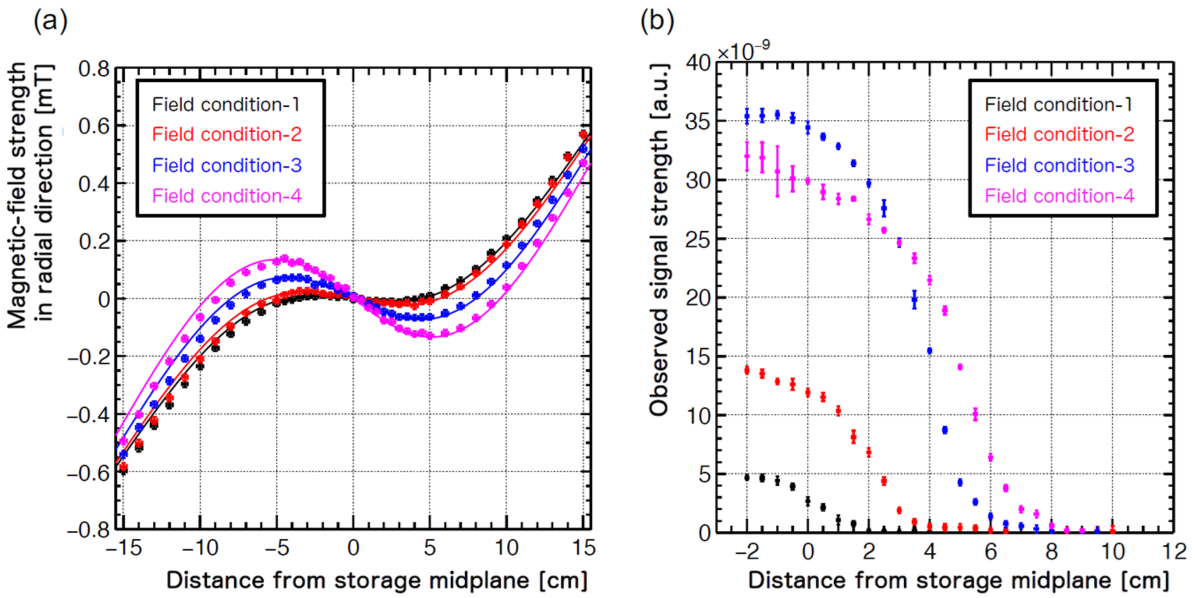

Figure 6. Measured distribution of stored-beam signals under different magnetic-field configurations. The observed signal region changes systematically with the magnetic-field conditions, consistent with numerical simulations.

To further verify that the observed signals originated from stored beams rather than from transient particles or accidental detector-related events, additional measurements were performed under different magnetic-field configurations.

The magnetic-field distribution of the solenoidal storage magnet was varied, and the spatial distribution of beam-related signals was measured while changing the detector position. The results showed that the region in which stored-beam signals were observed changed systematically in response to changes in the magnetic-field configuration (**Figure 6**).

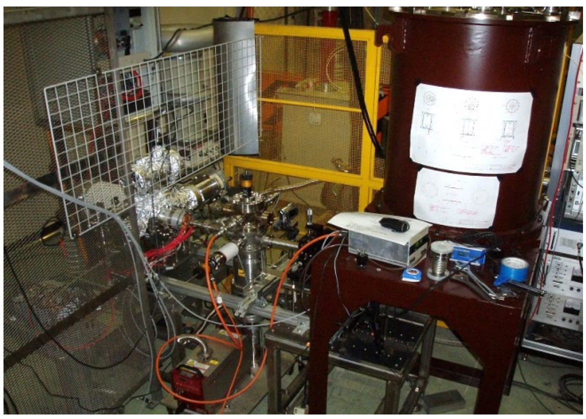

Figure 7. Experimental apparatus at the KEK Tsukuba Campus.

These observations were consistent with predictions from numerical simulations, providing strong evidence that the detected signals originated from beams stored in the weak-focusing magnetic field through the three-dimensional spiral injection scheme.

Future Prospects

In principle, the three-dimensional spiral injection scheme can be applied to a wide range of charged-particle beams, regardless of particle lifetime. In particular, precision experiments using short-lived particles require beams to be accumulated within a compact and well-controlled region before the particles decay. The technique demonstrated in this work enables beam injection into compact storage rings that would be difficult or impossible to realize using conventional injection methods, thereby opening new opportunities for precision measurements based on next-generation compact storage rings.

More broadly, this research provides a practical example of a new beam-control paradigm for charged particles in complex magnetic-field environments. In particular, the approach highlights the importance of canonical momentum as a guiding principle for beam manipulation and orbit design in complex magnetic-field environments. By exploiting this concept, more flexible beam-transport and storage schemes may become possible than those available with conventional design approaches.

Future research will focus on generalizing these concepts to beam transport and storage design in arbitrary magnetic-field configurations. Beyond applications in fundamental physics experiments, the team also aims to explore their potential for improving the compactness and precision of accelerator systems used in medical and industrial applications.

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