

First Experimental Demonstration of Beam Storage by a Three-Dimensional Spiral Injection Scheme for Ultracompact Storage Rings

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Three-dimensional spiral injection enables beam storage in ultracompact rings with nanosecond revolution periods. We report first storage of a 297 keV/c electron beam in a 22 cm weak-focusing ring with a 4.7 ns revolution period using a 140 ns kicker pulse. A scintillating-fiber detector observes signals $> 5\sigma$ above noise for $\geq 1 \mu\text{s}$, and varying the weak-focusing field potential shifts the stored-beam region, consistent with Monte Carlo predictions, validating beam storage. This proof-of-principle opens a path to ultracompact storage rings for next-generation precision measurements including short-lived particles.

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Introduction—Storage rings have played a central role in accelerator science since their first realization as colliders in the 1960s [1–3]. Their applications now span a wide range of fields, including particle and nuclear physics, synchrotron light sources, medical treatments, and various industrial applications. As these applications have expanded, injection methods have undergone continuous development. Conventional transverse injection relies on a pulsed kicker system that produces a localized dipole field which steers the injected beam toward the stored orbit. Advanced concepts, such as pulsed multipole kicker injection schemes [4–6], swap-out injection schemes [7], and longitudinal injection schemes [8], have also been developed to minimize the disturbance to the stored beam in modern strong-focusing rings for light sources. In the present Letter, the target device class is an ultracompact solenoidal weak-focusing storage ring, in which stored particles circulate on closed orbits with revolution periods on the nanosecond timescale. Such rings are relevant to precision experiments with short-lived particles because they allow

relativistic beams to be stored in a small and well-controlled measurement volume.

Injection and loading have also been studied in magnetic-confinement devices and particle traps [9–11]. In many such implementations, particles are captured by deceleration-based trapping and stored at low kinetic energies. The present Letter addresses a different regime. Here, the objective is momentum-preserving storage in an ultracompact weak-focusing ring, where the injected beam is guided into the storage region without deceleration. Related compact storage rings have also been developed in the synchrotron-light-source community, for example MIRRORCLE-type light sources employing resonant injection scheme [12]. In that class of electron storage rings, the literature reports large betatron oscillations associated with resonant injection scheme together with millisecond time scale postinjection radiation damping. By contrast, the present Letter targets momentum-preserving storage without relying on such postinjection radiation damping, which is relevant when considering applications to short-lived particles.

However, ultracompact storage rings face a fundamental difficulty. As the size of the ring becomes smaller, the revolution period of the circulating beam decreases to a few nanoseconds. Under these conditions, conventional injection schemes become challenging because they require strong pulsed magnetic fields with nanosecond-scale rise and fall times. Even state-of-the-art developments for the International Linear Collider (ILC) damping ring demonstrated switching times of approximately 3 ns [13], and achieving significantly faster performance remains technically demanding. This limitation has formed a major

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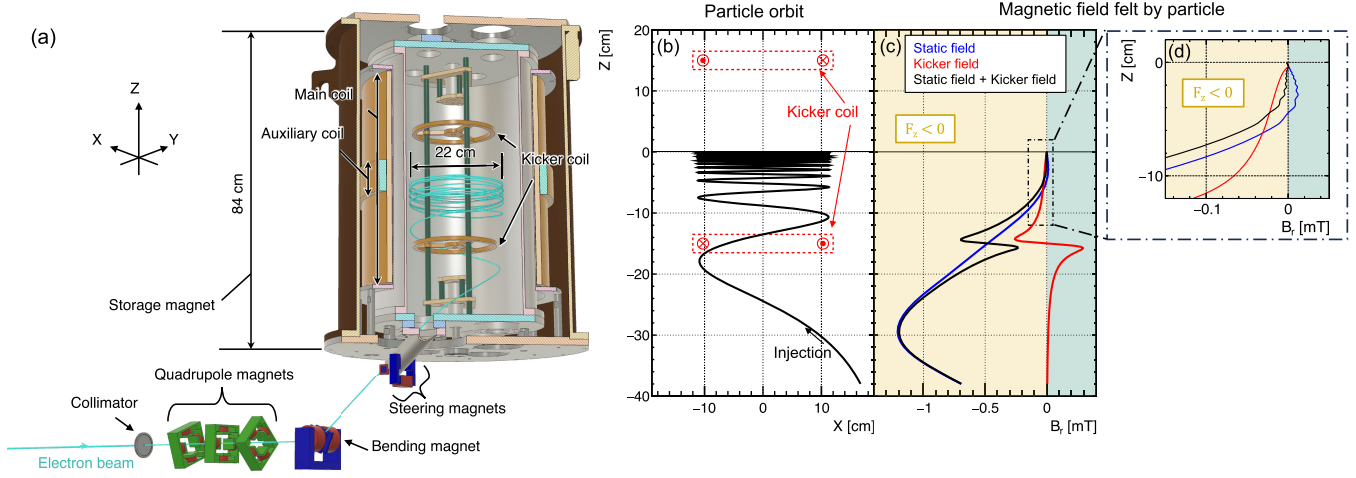


FIG. 1. (a) Overview of the demonstration beamline. The electron beam is generated by an electron gun and injected into the storage magnet through a transport line consisting of three rotatable quadrupole magnets, one bending magnet, and a pair of steering magnets. (b) X-Z projection of the reference particle orbit after injection. The storage midplane corresponds to $Z = 0$ cm. (c), (d) B_r components along the reference particle orbit. Blue line shows the static magnetic field by the storage magnet. Red line shows the time-varying magnetic field by the kicker. The $B_r < 0$ field during injection provides the downward steering to electrons required for beam storage in weak-focusing regime.

obstacle in the realization of ultracompact storage rings. For nanosecond revolution period, injection with minimal perturbation requires a kick confined to single turn, placing simultaneous demands on both switching speed and peak field that are difficult to meet with conventional pulsed-power systems.

A concept proposed in 2016 by Iinuma *et al.* [14] offers a solution. The idea is known as the *three-dimensional spiral injection scheme*, and it avoids the timescale limitation by extending the injection orbit into the vertical direction. Instead of injecting the beam parallel to the storage plane, the beam enters the solenoid-type storage magnet with a controlled pitch angle. This nonparallel injection causes the beam to experience the fringe field of the solenoid, which provides an initial vertical steering force. The storage region is defined by a weak-focusing potential [15,16] located near the midplane of the magnet. As the injected beam enters the weak-focusing potential region, the radial field component B_r changes sign due to the weak-focusing field, which reverses the vertical Lorentz force and steers the beam upward. To counteract this effect, the spiral injection concept employs a pulsed kicker and this supplies a small vertical kick to reduces pitch angle during many consecutive turns.

The accumulated effect of these repeated vertical kicks guides the injected beam into the weak-focusing potential, allowing stable storage. Because the required deflection is distributed over multiple turns, the beam and kicker system remain compatible with the nanosecond-scale revolution period, enabling a practical multiturn injection scheme in a regime where conventional single-turn injection is technically prohibitive. Thus, the method avoids the need for the extremely fast pulsed-power performance that limits conventional two-dimensional injection.

The ability to implement this scheme paves the way toward ultracompact storage rings in a regime that is difficult to access with conventional injection schemes. This is relevant to precision experiments with short-lived particles, for which compact storage in a small and well-controlled volume is advantageous. Examples include the muon $g - 2$ /EDM experiment at J-PARC [17] and the muEDM experiment at PSI [18]. No experimental demonstration had been reported so far. In this Letter we present the first successful storage of an electron beam using this method.

Experimental setup—A beamline was constructed [19] for the demonstration of the three-dimensional spiral injection scheme. Figure 1(a) shows an overview of the demonstration beamline. An electron beam with momentum is $p = 297$ keV/c, kinetic energy is $E_{\text{kin}} = 80$ keV, and pulsed width is 100 ns is generated using a thermionic electron gun [20] and a chopper system [21]. The transport line allows us to control the beam phase-space [22] and the injection orbit at the injection point. This transport line consists of three quadrupole magnets, one bending magnet, and a pair of steering magnets [19], then injected into the storage magnet with a 0.7 rad pitch angle, defined with respect to the horizontal (x-y) plane.

The storage magnet consists of two solenoidal coils [23], main coil and auxiliary coil shown in Fig. 1(a), which allow us to apply both the solenoidal field and weak-focusing field in the beam storage region. By setting the coil currents I_{MAIN} and I_{AUX} with opposite polarities, we adjust the weak-focusing field potential (field index $n \sim 10^{-2}$ in the storage region) while keeping the solenoidal field constant at $B_z = 8.77$ mT on the storage plane ($Z = 0$ cm). Figure 1(b) shows the projected reference particle orbit in the x-z plane and Figs. 1(c) and 1(d) show the corresponding B_r

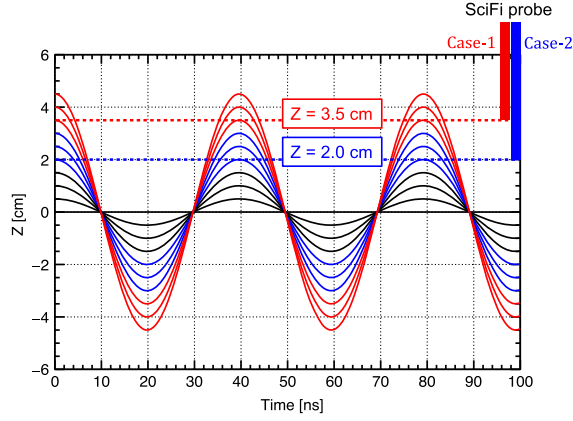


FIG. 2. Principle of SciFi probe measurement. Solid lines show the stored particle trajectories with vertical betatron oscillation. Stored particles with vertical betatron amplitude greater than $Z[\text{cm}]$, which is the tip position of the SciFi probe, generate signals. Case-1, SciFi probe is inserted up to $Z = 3.5$ cm, measures particles with vertical amplitude ≥ 3.5 cm shown by red lines. Similarly, Case-2, SciFi probe is inserted up to $Z = 2.0$ cm, measures those with amplitude ≥ 2.0 cm shown by red and blue lines.

component along the reference orbit. After injection, the beam follows a spiral orbit thanks to the B_z component and simultaneously being steered downward ($Z < 0$) thanks to the fringe field of $B_r < 0$. Inside the weak-focusing region, the $B_r > 0$ from static weak-focusing field applies an upward force. To counter this, a 45 A, 140 ns pulsed current is applied to the kicker coils, inductance $L = 1.3 \mu\text{H}$, at $Z = \pm 15$ cm, generating a $B_r < 0$ field that maintains the downward steering and enables beam storage.

A detector using a plastic-scintillating-fiber (SciFi), *SciFi probe* [24], which can be inserted into the storage region, is utilized to measure the storage beams. The SciFi probe consists of a 1 mm-diameter and 20 cm-long SciFi, which is long enough to cover the entire storage region vertically. The scintillation signal is read out with a photomultiplier tube. Because the continuous slowing down approximation (CSDA) range of a $p = 297$ keV/c electron in the SciFi is about $100 \mu\text{m}$ [25], the measurement is destructive.

In a measurement, the SciFi probe is inserted vertically from above with its tip positioned at an insertion depth Z , which is measured from the storage midplane ($Z = 0$ cm), and particle hits generate a signal. Because stored particles perform vertical betatron oscillations, the integrated signal at a given Z is proportional to the population whose vertical amplitude exceeds that depth (Fig. 2). Since the stored particles also perform betatron oscillations in the radial direction simultaneously with vertical betatron oscillations, the SciFi probe does not measure all stored particles within a single vertical betatron oscillation period. We thus integrate the SciFi probe signal over a sufficiently long time window to cover a wide range of betatron phases.

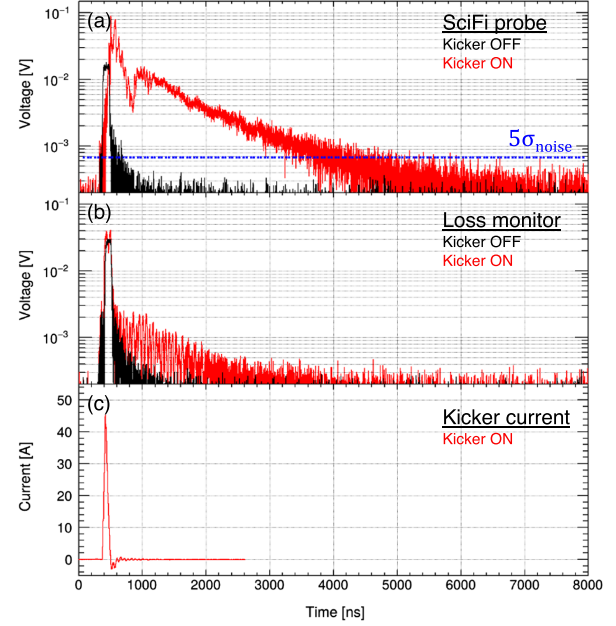


FIG. 3. Example of measured signals. (a): SciFi probe signal measured within the weak-focusing region. Blue line shows the threshold of $5\sigma_{\text{noise}}$. (b): Loss-monitor signal downstream of the storage region. (c): Kicker current waveform measured using a Rogowski coil. Red and black lines correspond to the with and without kicker conditions, respectively. In this example, the SciFi probe is inserted up to the storage midplane and SciFi covers the range from $Z = 0$ cm to $Z = 20$ cm. Each waveform is an average over 1000 shots.

In this Letter, we define beam storage operationally as observing a SciFi probe signal that exceeds $5\sigma_{\text{noise}}$ for $1 \mu\text{s}$ or longer, which is ten times longer than the injected pulse width of 100 ns and corresponds to more than 200 revolutions, where σ_{noise} is the standard deviation (rms fluctuation) of the voltage in a preinjection time window. This conservative criterion is introduced to distinguish true storage from nonstored or transiently circulating particles that may survive for only a few turns before escaping the weak-focusing region.

A plastic scintillator is installed on the bottom surface of the storage chamber as a beam loss monitor to observe time structure of reflected beams that are not captured in the storage region during injection. Information from this beam loss monitor is used for tuning beam injection trajectory.

Experimental results—Beam storage was confirmed using the operational criterion defined above based on the SciFi probe waveform. Figure 3 shows the waveforms from the SciFi probe, the beam-loss monitor, and kicker current for cases with and without the kicker. With the kicker activated, the SciFi probe signal remains above $5\sigma_{\text{noise}}$ for longer than $1 \mu\text{s}$, thereby satisfying our definition of beam storage and indicating successful beam storage in the weak-focusing region. The beam-loss monitor simultaneously detected a signal induced by reflected beams, at the expected timing relative to the kicker pulse.

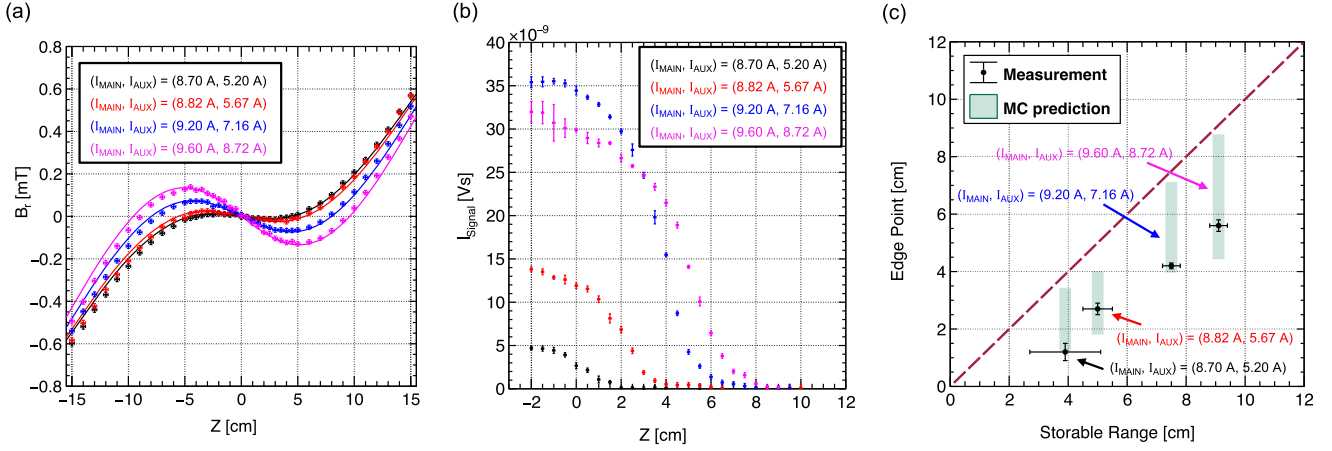


FIG. 4. Weak-focusing field dependence of the stored beam distribution. (a): Weak-focusing field configurations. Colored points denote measurement result, and colored lines denote finite element calculations performed with Opera [27]. (b): Z-scan results under the four field configurations. The vertical axis shows the time-integrated SciFi probe signal, $I_{\text{Signal}} = \int V_{\text{Signal}}(t)dt$, where $V_{\text{Signal}}(t)$ is the measured voltage as a function of time. The integral is evaluated over the time window from $t = 560$ ns to 9000 ns, starting just after the end of the kicker pulse. (c): Comparison of measured stored beam ranges with Monte Carlo predictions. Blue shaded regions show the expected region of MC simulation. Black points show the measurement result from field measurement and Z-scan measurement. Here the edge point is defined as the Z position where I_{Signal} decreases to 5% of its maximum value. For the measured points, the vertical uncertainty is dominated by the SciFi probe positioning uncertainty and shot-to-shot fluctuations, while the horizontal uncertainty is dominated by the magnetic-field measurement accuracy.

In contrast, without the kicker the SciFi probe signal has a duration of order 100 ns comparable to the injected pulse width and does not satisfy the $5\sigma_{\text{noise}}$ for 1 μs storage criterion, indicating that the beam is not stored under these conditions. This clear contrast demonstrates that three-dimensional spiral injection enables beam storage in ultra-compact storage rings.

During the first several hundred nanoseconds after injection, the stored particles perform coherent vertical betatron oscillations. This coherence produced a periodic modulation in the SciFi waveform. Although the modulation originates from the vertical betatron motion, its period does not correspond to the betatron oscillation period itself. The difference arises because the injected beam has a pulse width that is longer than one betatron period, so the SciFi probe samples particles with a wide distribution of betatron phases within each injection pulse. As time evolves, the periodic structure gradually decreases in visibility. This reduction is caused by the position dependence of the weak-focusing magnetic field, which introduces small variations in the betatron frequency and leads to phase mixing among the stored particles.

The measured storage signal persisted for $\geq 1 \mu\text{s}$, as shown in Fig. 3(a). This duration is more than one order of magnitude longer than the loss time observed without the kicker and demonstrates that multiturn vertical steering enables stable beam storage even when the revolution period is as short as 4.7 ns. The observed signal duration is largely limited by scattering in the SciFi probe, which is inserted into the storage region for measurement. It therefore provides a lower bound on the intrinsic storage lifetime

of the beam, which is expected to be longer than the observed value.

We verified that the accumulated beam is stored in the weak-focusing field by measuring its vertical distribution under four different field configurations. The corresponding magnetic-field distributions are shown in Fig. 4(a). For each configuration, we performed a scan of the SciFi probe insertion depth Z , which is measured from the storage midplane, hereafter referred to as a *Z-scan*: the SciFi probe was inserted from above in steps of 5 mm, and at each Z we measured a waveform averaged over 1000 shots. We then evaluated the time-integrated value I_{Signal} , the definition given in the caption of Fig. 4, which yields the Z-scan curve shown in Fig. 4(b). In Fig. 4(c), we define the upper edge of the stored-beam distribution as the Z position where I_{Signal} decreases to 5% of its maximum value, and compare it with Monte Carlo (MC) predictions of the storable range for each configuration. The vertical uncertainty of the measured points includes (i) the positioning uncertainty of the SciFi probe and (ii) shot-to-shot fluctuations of the I_{Signal} , whereas the horizontal uncertainty is dominated by the measurement accuracy of the weak-focusing field distribution used to determine the storable range for each configuration. In the MC predictions, the shaded region represents the spread obtained by including the injection-trajectory uncertainty, which is the dominant systematic contribution. The measurements for all configurations agree with the MC predictions, demonstrating that the observed stored-beam distribution is governed by the intended weak-focusing field configuration rather than accidental trapping or experimental artifacts.

The present storage efficiency, defined as the fraction of electrons stored from one injected bunch, is well below 1% under the current injection conditions based on Monte Carlo simulations. The storage efficiency can be improved by XY-coupled transverse phase-space matching and a shorter injected bunch length achievable through upstream radio frequency (rf) beam manipulation. Studies are also underway to improve storage efficiency and control the phase space of the stored beam by tuning injected beam phase space [22,28,29].

Conclusions—We have achieved the first experimental demonstration of beam storage by the three-dimensional spiral injection scheme in an ultracompact solenoidal weak-focusing storage ring. This result establishes the experimental feasibility of beam storage in a regime in which conventional single-turn injection is technically difficult because of kicker response constraints. It provides an essential step toward realizing ultracompact storage rings for short-lived particles. The technique is a key enabling technique for the planned muon $g - 2$ /EDM experiment at J-PARC and the muEDM experiment at PSI, and may also open new opportunities for precision studies using other short-lived particles.

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Data availability—The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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