Development of a Nonlinear In-Vacuum Kicker at the TPS

To improve beam injection performance and reduce perturbations of the stored electron beam, the development of a novel nonlinear in-vacuum kicker (NIK) system for the Taiwan Photon Source (TPS) has been initiated. This effort aims to upgrade the injection process by replacing the traditional four-kicker method with an advanced, low-disturbance solution.

At present, TPS uses a conventional four-kicker injection system, which consists of four identical kicker magnets and two septa to guide the injected beam into the storage ring, as illustrated in **Fig. 1(a)**. Although this method is widely adopted, it introduces oscillations and positional shifts in the stored beam, which are especially problematic under the tight dynamic aperture conditions required by next-generation light sources. In response to these limitations, the TPS team is developing a nonlinear injection scheme, as illustrated in **Fig. 1(b)**.[1] This scheme includes a custom-designed NIK that generates a strong, localized magnetic field to bend the incoming beam while maintaining a nearly zero field along the trajectory of the stored beam. A major innovation of this system is its in-vacuum design, which differs from the more common out-of-vacuum setups used in other facilities. During testing, the four-kicker system and the NIK scheme will coexist. In this phase, the NIK will operate while the four-kicker system is switched off. Once the injection efficiency meets the required performance targets and the operational reliability of the NIK is fully demonstrated, the NIK scheme will replace the existing four-kicker configuration in the final implementation.

The NIK provides several unique advantages:

- Compact geometry: the vacuum-integrated configuration allows for a reduced vertical gap between the copper coils, which increases the magnetic field strength available to deflect the injected beam.
- Lower cost and simplified construction: by using multiple ceramic components instead of a monolithic coated ceramic chamber, the system eliminates the need for complex coating processes and reduces costs.

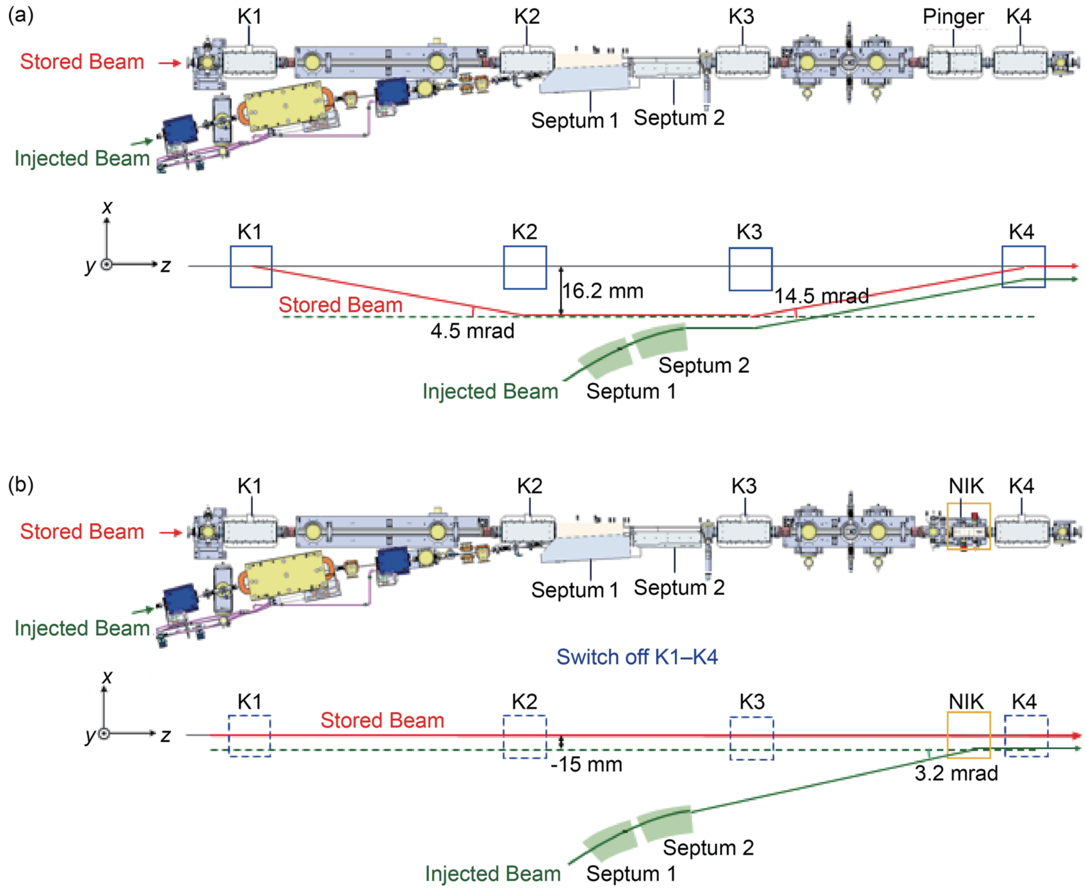

Fig. 1: (a) Existing injection scheme using four bumper kickers, and (b) proposed injection scheme with a NIK kicker in the TPS injection section. [Reproduced from Ref. 1]

- Improved coating uniformity: titanium coatings applied to flat ceramic substrates offer better thickness control while maintaining variation within 5% compared to coatings on the inner walls of cylindrical chambers.
- Lower inductance: the internally routed coil connection reduces the system's total inductance compared to conventional external wiring, thereby increasing efficiency during pulsed operation.

The NIK assembly comprises a titanium vacuum chamber, ceramic substrates, support blocks, and end plates. As shown in **Figs. 2(a) and 2(b)**, the structure contains eight copper coils embedded in grooves on the ceramic substrates, resulting in a significantly more compact design compared to the original kicker shown in **Fig. 2(c)**.[1,2] Precise assembly is achieved using ceramic clamping blocks and titanium screws to ensure accurate coil placement and mechanical robustness under vacuum conditions. The vacuum chamber is made from Grade 2 titanium, which has been selected for its low thermal outgassing, non-magnetic behavior, and light weight. Titanium plates are welded together to form the chamber, including two DN35CF flanges on each side for installing K-type thermocouples, vacuum gauges, and NEXTorr Z 200 vacuum pumps. Additionally, eight DN16CF ports (four on the top and four on the bottom) are provided, with designated ports used as electrical feedthroughs for the kicker coil connections.

To ensure adequate electrical conductivity for the passage of beam image currents, a titanium coating is applied to the ceramic substrates. Increasing the coating thickness can reduce ohmic heating and thermal stress, but it also increases eddy current losses, which raises power deposition, attenuates the magnetic field, and slows the temporal response of the pulsed field. Therefore, achieving an optimal balance is critical. The selected coating thickness of 5 μm provides sufficient electrical conductivity while minimizing heating from both image and eddy currents, thereby ensuring stable magnetic field performance and effective thermal management.

The core design of the NIK generates a nonlinear pulsed magnetic field that peaks at the injected beam position while maintaining a flat zero-field region around the stored beam. This field-free zone spans ±1.5 mm centered on the stored beam trajectory. The nominal peak field is 890 G at an offset of 15 mm. However, the nonlinear characteristics of conventional magnetic yoke materials can induce unwanted residual fields near the center. To avoid these fields, the NIK is designed without a yoke. Consequently, a high current is required to generate the necessary field strength. Therefore, the entire NIK is implemented as an in-vacuum type structure, which allows the magnet gap to be minimized, thereby improving magnetic efficiency and field control.

Magnetic field simulation studies highlight the impact of return conductor configuration. A symmetric return path, as shown in **Fig. 3(a)**, produces opposing vertical fields in the upper and lower conductors, which effectively cancel each other and expand the field-free region at the beam axis. By contrast, an asymmetric design, as shown in **Fig. 3(b)**, leaves residual magnetic fields that may introduce undesirable quadrupole components. Positioning errors in conductor placement further compromise field uniformity, as shown in **Fig. 3(c)**.[3]

An in-house measurement system was developed to verify the field characteristics of the NIK, as shown in **Fig. 4**.[3] The setup included a function generator (DG 535), digital oscilloscope (TDS3054B), current transformer, and long coil probe with an RC integrator circuit. The long coil probe was constructed using printed circuit board (PCB) technology to ensure precise conductor positioning. This system was used to capture the dynamic magnetic response of the kicker during pulsed operation.

Figure 5 presents a comparison between the simulated and measured profiles of the kicker's first magnetic field integral. At the center of the beam trajectory, the ideal value is zero, and the measured deviation is approximately 250 G·cm. At the design injection point (-15 mm), the simulated and measured values of the field integral are approximately -32,100 G·cm, with a relative error of just 0.124%, which is well within the expected tolerance range.[3]

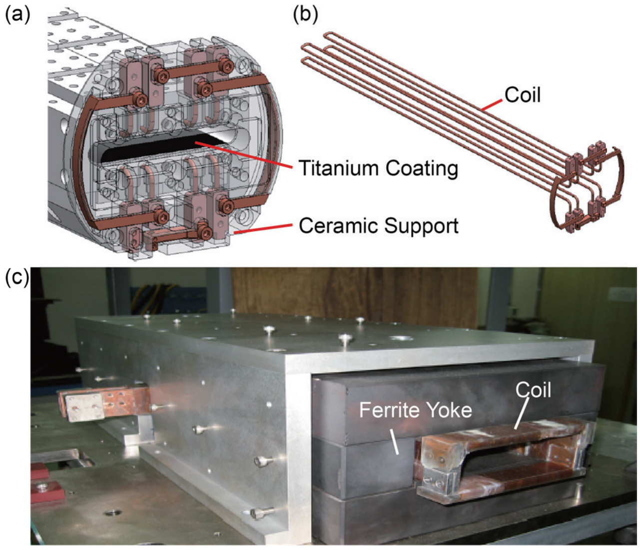

Fig. 2: Routing of copper coils (a) with and (b) without the surrounding ceramic support structure, and (c) one of the four-kickers. [Reproduced from Refs. 1 and 2]

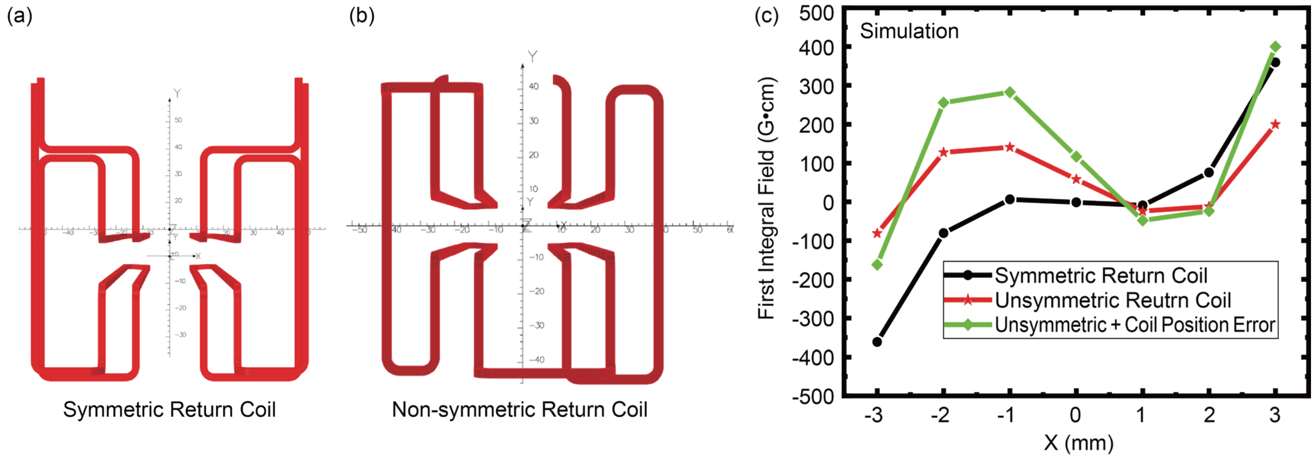

Fig. 3: Symmetric and non-symmetric coil designs. [Reproduced from Ref. 3]

To evaluate the vacuum compatibility of the NIK system, which is composed of ceramics, titanium, copper, stainless steel, aluminum alloy, and Kapton, we measured its outgassing rate using the pressure-rise and throughput methods. A dedicated test bench was built, and the NIK was connected to an aluminum orifice chamber *via* a gate valve and pumped using a turbo molecular pump. Two ion gauges were used to monitor pressure changes in both chambers. After 120 h of pumping, the pressure dropped below 5×10^{-7} mbar, indicating good initial vacuum performance. Subsequently, a bake-out at 150 °C for 24 h was conducted to further reduce gas release. The measured thermal outgassing rate was 1.9×10^{-8} mbar·L/s, consistent across both measurement methods. After the bake-out, two NEXTorr Z200 pumps were installed and activated. The final pressure reached the 10^{-10} mbar range, confirming the system's suitability for ultrahigh vacuum applications.

To minimize interference with user experiments during injection, the NSRRC is committed to developing a transparent injection approach using this nonlinear in-vacuum kicker. A key achievement is the system's low inductance value of 1.56 μH, which allows for faster current rise times and improved pulse shaping.

This development represents a major step forward for TPS and contributes to the long-term goal of upgrading the injection system for TPS-II, the next-generation storage ring. With its improved field characteristics, reduced beam disturbance, and robust vacuum performance, the nonlinear kicker will support future high-brightness and low-emittance beam operations. (Reported by Chin-Kang Yang and Chin-Chun Chang)

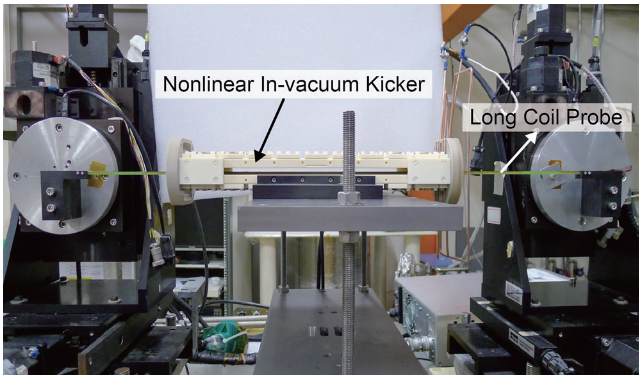

Fig. 4: NIK field measurement setup. [Reproduced from Ref. 3]

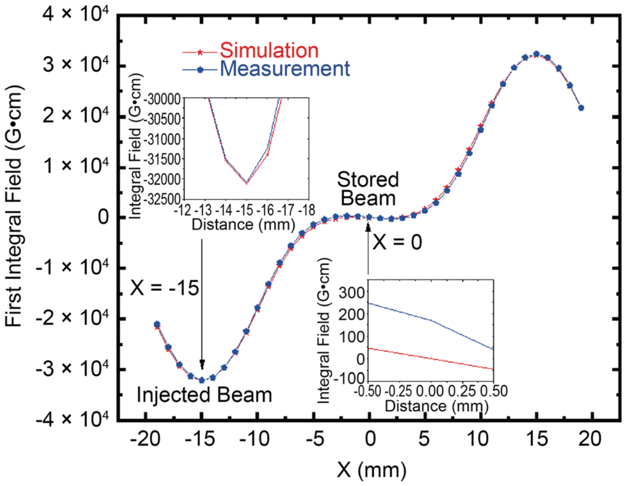

Fig. 5: Simulated and measured first magnetic field integral profiles. [Reproduced from Ref. 3]

References

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