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# RENOVATION OF OFF-AXIS BEAM INJECTION SCHEME FOR NEXT-GENERATION PHOTON SOURCES

S. Takano†[1], K. Fukami[1], C. Kondo[1], M. Masaki, M. Oishi[1], M. Shoji, K. Tamura, T. Taniuchi, K. Yanagida, T. Watanabe[1], JASRI, 679-5198 Sayo, Japan
T. Hara, T. Inagaki, H. Tanaka, RIKEN SPring-8 center, 679-5148 Sayo, Japan
K. Hamato, J. Kataoka, K. Kusano, K. Ogata, Y. Saito, Tokin Corporation, 982-0003 Sendai, Japan
H. Akikawa, K. Sato, Nihon Koshuha Co., Ltd., 224-0054 Yokohama, Japan
[1]also at RIKEN SPring-8 center, 679-5148 Sayo, Japan

*Abstract*

Beam injection is one of the most crucial issues for the success of next-generation photon sources such as near diffraction-limited storage rings (DLSRs). We propose a new off-axis beam injection scheme, in-vacuum transparent off-axis beam injection, for the upgrade of SPring-8, SPring-8-II, which aims at the high brilliance and coherence enabling innovations in various scientific and industrial fields. The proposed scheme enables us to inject beams efficiently into narrow dynamic apertures with small amplitude, to minimize the degradation of the stored beam performance for transparent beam injection, and to stack and maintain by topping-up the required beam intensity. An overview of the renewed off-axis beam injection scheme and the development status of the three key components are presented: 1) permanent magnet based DC septum magnet, 2) in-vacuum pulse septum magnet, and 3) twin kickers driven by a single solid state pulser.

## INTRODUCTION

Photon sources are looking for performance upgrades by pursuing higher photon brilliance and coherence these years. The trend is pushing the lattice design to lower the beam emittance, which naturally results in narrower dynamic apertures of the rings. One bottleneck in the upgrades is the beam injection capable of accumulating and keeping the stored beam current by top-up operations with such narrow apertures. Beam injections with nonlinear kickers and transverse/longitudinal on-axis injections are now in the limelight. However, these techniques still need time to be put into practical use. We propose an in-vacuum transparent off-axis beam injection scheme for the SPring-8 upgrade, SPring-8-II [1], by renovating the present off-axis beam injection to address the requirements of the coming diffraction-limited storage rings (DLSRs): minimizing of both injected beam oscillation amplitude and perturbation to stored beams, and retaining of the topping-up functionality.

The three key components employed in the renewed off-axis injection are 1) permanent-magnet (PM) based DC septum magnet, 2) in-vacuum pulse septum magnet, and 3) twin kickers driven by a precision solid state pulser. We have been developing the prototypes of the key components. We plan to install the developed in-vacuum pulse septum magnet, twin kickers, and solid state pulser in the storage ring of the new 3GeV photon source project in Japan [2] and to verify the performance of beam injection.

This paper gives an overview of the in-vacuum transparent off-axis beam injection scheme and reports the development status of the three key components.

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† takano@spring8.or.jp

## IN-VACUUM TRANSPARENT OFF-AXIS BEAM INJECTION

The requirements of beam injection for the next-generation photon sources are i) injected beam oscillation amplitude of a few millimeters by one order of magnitude smaller than present, ii) stored beam oscillation amplitude smaller than 10 μm perturbed by beam injection for the more transparent beam injection to photon users than present, iii) capabilities of stacking and maintaining by topping-up the required beam intensity. To address the above requirements we renovate the current off-axis beam injection technique and propose an in-vacuum transparent off-axis beam injection scheme (Fig. 1) taking advantages of expertise and experiences acquired by accomplishing the stable and reliable top-up operation of SPring-8 [3].

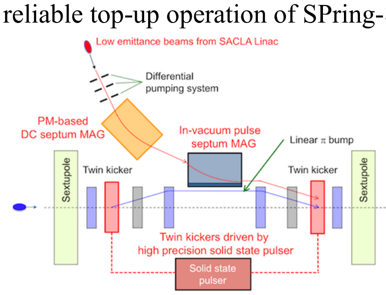


Figure 1: Schematic of in-vacuum transparent off-axis beam injection.

New features of the proposed in-vacuum transparent off-axis beam injection are as follows:

- windowless beam transport with differential pumping: free of degradation of low-emittance beam from the high-performance injector caused by vacuum windows, contributing to minimize the injected beam oscillation amplitude.
- PM-based DC septum magnet: cutting down on the electric power consumption in the current beam injection system dominated by DC septum electromagnets.

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- in-vacuum pulse septum magnet: no use of separated vacuum ducts for the injection beam and the stored beam, contributing to minimize the injected beam oscillation amplitude.
- linear π-bump orbit: linear bump orbit for beam injection by use of symmetric two kickers separated by 180 degrees of betatron phase in a section without any non-linear magnets such as sextupoles, contributing to the transparent beam injection.
- twin kickers driven by a common solid state pulser: identical kicker magnetic fields for closed π-bump orbit by parallel driving of the identical kicker magnetics, contributing to the transparent beam injection.

The key components of the new off-axis injection scheme are 1) PM-based DC septum magnet, 2) in-vacuum pulse septum magnet, and 3) twin kickers driven by a single solid state pulser. We have been developing them by carefully examining the defects of the counterpart in the current off-axis beam injection of each component.

## PERMANET MAGNET BASED DC SEPTUM MAGNET

The PM-based DC septum magnet provides the stable magnetic field free from the variation of power supply output. It enables stable beam deflection necessary for the small injected beam oscillation amplitude for both stacking and maintaining by topping-up the required beam intensity. The challenges of developing the PM-based DC septum magnet are compact design both to obtain high intensity magnetic field which deflects the injection beam and to minimize the stray magnetic field for the transparent beam injection.

We have designed and developed successfully a prototype of a PM-based DC septum magnet (Fig. 2) taking advantages of preceding developments of the permanent bending magnets for SPring-8-II [4]. The magnetic

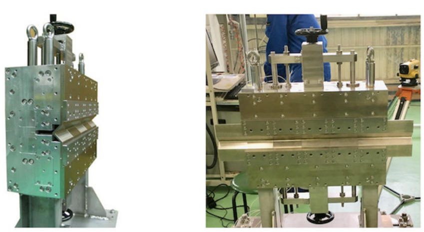

Figure 2: PM-based DC septum magnet.

circuit of the prototyped DC septum magnet is illustrated in Fig. 3. The intensity of the magnetic field can be changed by a mechanism of magnet shunt plates. The temperature dependence of the magnet is compensated by iron-nickel shut alloy. Samarium cobalt magnet is chosen to minimize demagnetization by radiation. The measured magnetic field intensity in the magnet gap was consistent with the design value of 1.2 T. The tunability of the field intensity by moving the shunt plates was confirmed successful. The temperature dependence of the magnetic field $\Delta B/B/\Delta T$ smaller than $1\times10^{-5}$ $K^{-1}$ was achieved by adjusting the thickness of iron-nickel shunt alloy. The stray

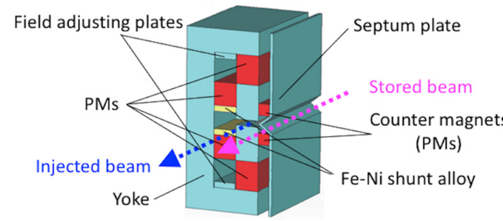


Figure 3: Magnetic circuit of the PM-based DC septum magnet.

magnetic field along the transverse direction was reduced after the strength of the counter magnetic field was adjusted by adding shut plates on the counter magnets. The stray magnetic field measured along the longitudinal direction had humps near the ends of the magnet pole. The septum plate was modified to extend the length longitudinally as shown Fig. 2, and the stray magnetic field was successfully reduced (Fig. 4).

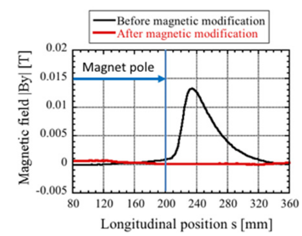


Figure 4: Measured stray magnetic field of the DC septum magnet.

We conclude that the stray magnetic field of the DC septum magnet after integrated in the beam injection section can be further reduced by using magnetic shields such as mu-metal to fulfill the requirement for transparent beam injection, the integrated value smaller than$10^{-5}$ T.m.

## IN-VACUUM PULSE SEPTUM MAGNET

The minimum possible amplitude of the injected beam oscillating around the stored beam is limited by both the emittance of the injected beam and by the characteristics of the pulse septum magnet placed at the end of the beam transport line. For our new off-axis beam injection, we utilize the low-emittance beam from a high performance injector linac and employ an in-vacuum pulse septum magnet. The in-vacuum septum magnet eliminates the walls of the injection beam duct and the stored beam duct limiting the minimum possible distance between the two beams. Our final goal is the injected beam oscillation amplitude of 1 to 2 mm. Design of the thin septum wall and the thin magnetic shield minimizing the stray magnetic field is crucial for the small injected beam oscillation amplitude and the transparency of the beam injection.

We have designed and developed a prototype of an in-vacuum pulse septum magnet (Figs. 5 and 6). To achieve the ultra-high vacuum necessary for use in storage rings, better than $10^{-7}$ Pa, suppression of outgassing from magnet yokes is crucial. We measured outgassing of laminated yoke models as well as silicon steel sheets to design the laminated yoke structure avoiding small gaps inside lead-

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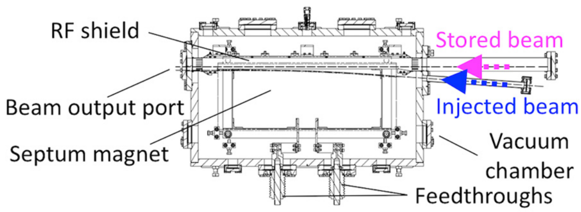


Figure 5: Schematic of in-vacuum pulse septum magnet.

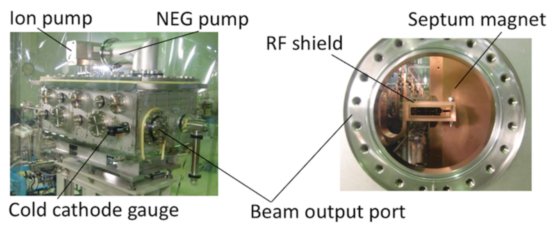


Figure 6: In-vacuum pulse septum magnet.

ing to slow leaks of trapped air. The shape of the magnet pole was designed to obtain flat magnetic field distribution near the septum wall, and the magnet gap of 2 mm was chosen. The septum wall made of cupper was designed to enclose the magnet yoke to suppress the stray field. The minimum thickness of the septum wall was 0.5mm. The pulse length of the half-sine exciting current was 10 µs taking account of the effects of eddy current on field flatness and stray field shielding. Ceramic blocks were adopted to isolate the high voltage of excitation coil up to 20 kV. The structure of the RF shield of the stored beam was determined to minimize the effect of coupling impedance and heating due to beam wall current. The heat sources in the in-vacuum pulse septum magnet are wall current on the RF shield, excitation current of the coil, and eddy current on the septum wall. Heat conducting structures for the coil, the septum wall, and the RF shield were designed to indirectly cool them by out-vacuum water flows. A combination of a cartridge NEG pump and an ion pump was adopted for evacuation.

The performance of the pulse septum magnet was evaluated in the atmosphere prior to installation into the vacuum chamber. The pulser developed for the twin kickers was used by temporarily replacing the condensers of the main charger fitted to the pulse septum magnet. The pulse septum magnet was successfully excited at the rated current without failures such as an electric discharge. The field intensity in the magnet gap and the stray magnetic field near the stored beam orbit were measured with a thin search coil and a long search coil, respectively. The magnetic field in the gap was consistent with the design of 1.4 T, and the stray field was small enough to be reduced by shielding with mu-metal down to the required level of $10^{-5}$ T.m or less. After the pulse septum magnet was installed in the vacuum chamber, the fully assembled in-vacuum pulse septum magnet was baked out. The temperature of the magnet was raised to 150 degrees centigrade. After the baking and activating the NEG pump, ultra-high vacuum of $5\text{x}10^{-8}$ Pa was successfully achieved.

We further plan to measure the detailed magnet performance of the in-vacuum pulse septum including the field distribution in the magnet gap and the stray field after shielded by mu-metal to verify the magnet performance for the new off-axis beam injection. We also plan to evaluate the vacuum performance on the excitation of the magnet and reliability through the long-term continuous operations to complete the prototype development.

## TWIN KICKERS DRIVEN BY SOLID STATE PULSER

To realize the transparent beam injection to photon users free of degradation of the stored beam performance, the magnetic field identity of kicker magnets used for the π-bump orbit is critical. The identity should be maintained throughout the repeated beam injection processes for stacking the required beam intensity. In the proposed twin kicker magnet system, two kicker magnets are parallelly connected to a common high-precision pulsed power supply switched by high-power solid state elements [5]. The timing jitter of the pulser output is common to the two kickers, and does not degrade the identity of the magnetic field waveforms of the kickers.

We have designed and assembled a prototype of a solid state pulser, and evaluation and improvement of the performance are in progress [5]. One of the remaining tasks for the pulser is reduction of the inductance to obtain the designed short pulse width of the kickers, 3 µs. Improvements of circuitry associated with the switching IBGTs and high-voltage diodes are in progress.

For the success of the twin kicker system, the identity of magnetic characteristics of the kickers such as inductance is mandatory up to the driving frequency. Detailed design of prototype kicker magnets is in progress. We plan to evaluate the performance of the prototyped twin-kicker system with the combination of the pulser and the kickers and also the reliability of the system through the long-term continuous operations.

## SUMMARY

A renewed off-axis beam injection scheme, in-vacuum transparent off-axis beam injection, is proposed to address the requirements for the next-generation photon sources. An overview of the new beam injection scheme and the development status of the prototypes of the three key components is presented: 1) PM-based DC septum magnet, 2) in-vacuum pulse septum magnet, and 3) twin kickers driven by a single solid state pulser. The prototype development will complete in 2019FY. The developed in-vacuum pulse septum magnet, twin kickers and solid-state pulser are planned to be installed in the storage ring of the new 3GeV photon source project in Japan [2], and the performance of beam injection will be verified.

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