Nuclear Instruments and Methods in Physics Research A 767 (2014) 26–33

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Beam injection with pulsed multipole magnet at UVSOR-III

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ARTICLE INFO

Article history:
Received 10 June 2014
Received in revised form
26 July 2014
Accepted 29 July 2014
Available online 14 August 2014

Keywords:
Electron storage ring
Beam injection
Storage ring

ABSTRACT

In this study, we designed and manufactured a pulsed multipole magnet for beam injection into the UVSOR-III ring. A sextupole-like magnetic field could be excited when using the multipole magnet. To compensate for the residual field at the center of the magnet caused by manufacturing imprecisions, thin ferrite sheets were used. The injection experiments at UVSOR-III demonstrated multi-turn injections with the pulsed multipole magnet. The injection efficiency was 23% and the electron beam was stored up to the normal operation current of 300 mA. Moreover, we confirmed that oscillations of stored beams caused by beam injection were drastically suppressed compared with conventional pulsed dipole injection.

1. Introduction

The pulsed multipole injection scheme was developed at KEK-PF and KEK-AR [1,2]. In this scheme, the injection beam is captured into the accelerator acceptance as a result of pulsed multipole kicks, and the stored beam passes through the center of the multipole magnet, where the field strength is almost zero. The scheme thus avoids exciting coherent oscillation in the stored beam and delivers a high-quality photon beam for synchrotron radiation users.

The KEK group developed the qaudrupole and sextupole type magnets and demonstrated to suppress the oscillation of the stored beam. At BESSY-II, the octupole type magnet was developed and the injection efficiency around 80% was obtained [3]. Recently the extensive beam dynamics have been studied for the MAX-IV storage ring [4–6].

For relatively small rings, such as UVSOR-III [7], the pulsed multipole injection scheme provides additional advantages. In conventional bumped injection, at least two pulsed dipole (bump) magnets are required, and the perturbed (bumped) orbit is quite long. UVSOR-III currently has three bump magnets at different straight sections, and the distance between the first and the third bump magnet is over one-fourth of the circumference. In contrast, only one pulsed magnet is required in the pulsed multipole scheme. This scheme thus minimizes the injection system and realizes additional straight sections for insertion devices or machine-improvement devices.

Another consideration is the "multiturn" effect during the magnet discharging, which needs to be considered when applying the pulsed multipole scheme to relatively small rings. In this case, the injection beam travels through several large-amplitude turns and is affected by nonlinear forces in the ring. In previous experiments conducted at KEK-PF and KEK-AR, injection beams were kicked less than third times [1,2]. At UVSOR-III, the number of kicks could not be reduced further than seven because the revolution period is three times less than that of KEK-PF and the pulse period of the magnet could not be shortened for technical and economic reasons. In this situation, we could not confirm whether the multipole injection method works; more complicated considerations are imposed to apply this scheme to UVSOR-III.

Furthermore, with pulsed multipole injection, the residual field at the magnet center, where the stored beam transits, should be minimized. The residual field is so sensitive to the position of the magnet assemblies that extremely accurate manufacturing is required, achieving which involves high costs. To address this problem, we developed a field-compensation technique in which a set of soft ferrites is applied to the pre-manufactured magnets.

In this paper, we report the design of the multi-turn pulsed multipole injection for the UVSOR-III storage ring and analyze its operation. The pulsed multipole magnet was modified by using the field-compensation technique and then used for multi-turn pulsed multipole injection.

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http://dx.doi.org/10.1016/j.nima.2014.07.059
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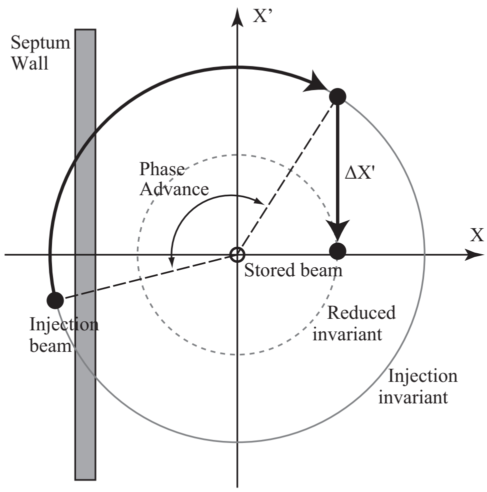

Fig. 1. Principle of pulsed multipole injection. Solid circles and open circle indicate injection beam and stored beam in phase-space, respectively.

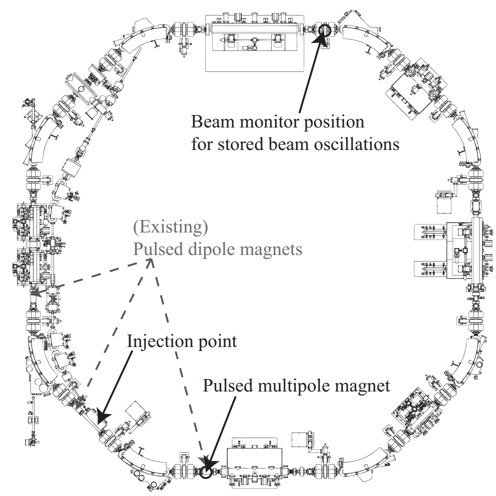

Fig. 2. Schematic image of the UVSOR-III storage ring.

2. Principle of pulsed multipole injection

The principle of pulsed multipole injection can be explained using Fig. 1, which shows the beam trajectories and the Courant–Snyder invariant in X–X' phase-space. The injection beam (solid circles) is transported from the exit of the septum magnet to the multipole magnet with a certain phase advance, while the invariant is maintained constant. At the multipole magnet, the injection beam receives the kick $\Delta X'$ and the invariant is reduced. When the reduced invariant, indicated by the dashed inner circle, is sufficiently smaller than the accelerator acceptance, the injection beam may be captured.

For convenience, we use the ratio of the reduced invariant to the accelerator acceptance as a dimensionless figure of merit (FOM) for the injection efficiency. It is defined as the ratio of the integrated areas, where a smaller ratio (i.e., a small FOM) indicates better injection efficiency. In contrast, the part of the injection beam with FOM >1 cannot be captured.

For the stored beam, indicated by the small open circle at the center of Fig. 1, the field strength of the multipole magnet is almost zero and coherent oscillations cannot be excited in the ideal case. In fact, the distribution of the stored beam should be considerable (see Fig. 2 in Ref. [2]).

3. UVSOR-III storage ring

UVSOR-III is an synchrotron light source at the Institute for Molecular Science in Okazaki, Japan. The accelerator complex was originally constructed as a second-generation VUV and soft x-ray source. The upgrades of 2003 [8] and 2012 [7] led to improved performance and qualified UVSOR-III as a third-generation source.

Top-up injection of the electron beam was started in 2010 to maintain a near constant beam current 300 mA during user experiments [9]. Because of the “close-bumped” orbit could not be realized due to poor magnet performance after the optics upgrades, the “open-bumped injection” scheme is now used for beam injection at UVSOR-III. Injecting the electron beam into the storage ring without using the closed bump orbit essentially requires kicking the stored beam horizontally, which induces betatron oscillations. These oscillations disturb user experiments and cause undesired spikes in the data. To solve this problem, we decided to use the pulsed multipole scheme instead of the conventional injection scheme.

Table 1
Main parameters of UVSOR-III storage ring for experiments.

Electron energy (MeV)	750
Circumference (m)	53.2
Revolution time (ns)	177
Natural emittance (nm rad)	16.9
Natural energy spread	5.4×10^{-4}
Horizontal tune	3.61
Vertical tune	3.26
Stored beam current	300 mA

Fig. 2 shows a schematic of the UVSOR-III storage ring, and Table 1 lists the main parameters. The electron energy is 750 MeV, and the circumference is 53.2 m. The lattice consists of four double-bend sections, four 4-m-long straight sections (long sections), and four 1.5-m-long straight sections (short sections). The beam emittance of 16.9 nmrad was achieved by distributing the dispersion function to all straight sections and by using combined-function dipole magnets [7]. The sextupole fields that serve to correct the chromaticity are introduced by the combined quadruple and dipole magnets. During the injection experiments, the storage ring was operated at the tune of $(\nu_x, \nu_y)=(3.61, 3.26)$, which is the designed operation point of the UVSOR-III ring.

The injection beam is provided by a 15 MeV-linac and a full energy booster synchrotron. During top-up, the injection rate is 1 Hz. An injection septum magnet, labeled as “injection point” in Fig. 2, is located at one of the short sections. For conventional dipole injection, three pulsed dipole magnets are used.

Numerical simulations indicate that only a few locations exist where the pulsed multipole injection scheme can be applied with adequate kick angle. We select the position about 4.42 m downstream from the injection point because it required the smallest kick angle for beam injection. The phase advance from the injection point to the location of the first kick was about 146°. In addition, an existing pulsed dipole magnet and a ceramic chamber were already located at this point. This configuration allowed us to examine the injection simply by replacing the magnet part; the vacuum system was not changed.

4. Construction of pulsed multipole magnet

4.1. Design of pulsed multipole magnet

Numerical calculations and cost studies led us to select a sextupole-like field. In ideal, a higher order field is more desirable