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To cite this article: Masahito Tomizawa *et al* 2018 *J. Phys.: Conf. Ser.* **1067** 042004

IOP Conf. Series: Journal of Physics: Conf. Series **1067** (2018) 042004 doi:10.1088/1742-6596/1067/4/042004

Beam Optics Design of Stretcher Ring and Transfer Line for J-PARC Slow Extraction

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Abstract. The main ring (MR) at the Japan Proton Accelerator Research Complex (J-PARC) provides 30 GeV high-intensity protons to the neutrino experimental facility (NU) by fast extraction and to the hadron experimental facility (HD) by slow extraction. A stretcher ring (SR) has been proposed to ensure that the integrated proton number on target from the slow extraction is sufficient. A beam accelerated at 30 GeV in the MR is transferred to the SR and is slowly extracted over several seconds. While the slow-extraction procedure is performed, a beam can be accelerated in the MR and delivered to the NU. The arc sections of the SR consist of superconducting combined-function magnets and separated-function magnets (a hybrid lattice configuration). A 30 GeV beam transfer line from the MR to the SR uses superconducting combined magnets with dipole and quadrupole functions. The transferred beam is injected into an arc section of the SR.

1. Introduction

The main ring (MR) at the Japan Proton Accelerator Research Complex (J-PARC) provides 30 GeV high-intensity beams to the neutrino experimental facility (NU) by fast extraction, and to the hadron experimental facility (HD) by slow extraction. It is a serious problem to ensure a sufficient integrated proton number on target (POT) for the HD with limited operation time. The use of a stretcher ring (SR)[1] can solve this problem. A beam accelerated by the MR is transferred to the SR, and is slowly extracted over several seconds after debunching. While the slow-extraction procedure is performed, the MR can accelerate and deliver a beam to the NU. We show here a specific example. The repetition time of the MR for the NU is assumed to be 1.2 s, which will be upgraded in 2019 mainly for the NU. A flat-top time of 2.4 s with a repetition time of 3.6 s is possible for the slow extraction in the present mode. The ratio of the integrated operation time for the NU and the HD is expected to be roughly 2:1. Figure 1 shows the proposed SR scheme. The beam injection from the MR to the SR is conducted every 3.6 s, and almost all of the 3.6 s can be assigned to the slow beam spill. During the slow beam spill time, two beam pulses can be delivered to the NU. If the total integrated beam operation time is same for both modes, the POT from the slow extraction using the SR scheme triples while the POT at the NU remains the same for both modes. Furthermore, the duty factor of the beam spill for the SR scheme can be improved from 67 to 100% at a theoretical maximum.

The SR and the beam transfer line (BTL) from the MR to the SR have been designed. The following design principles were implemented: i) The SR is suspended from the ceiling of the

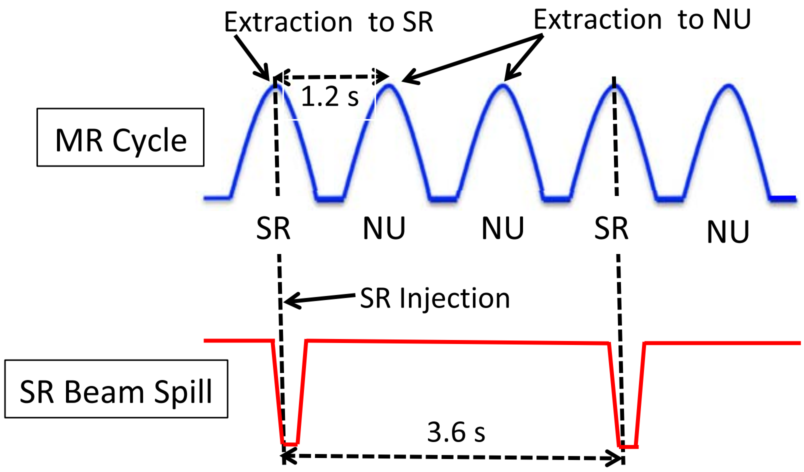

Figure 1. Stretcher ring scheme for the slow extraction.

MR tunnel. The SR is designed so as to fit into the MR tunnel. ii) The main magnets of the SR and the BTL are superconducting combined-function magnets using dipole fields and quadrupole fields to limit operating costs and to ensure magnet-free spaces. The beam optics for the SR and the BTL will be described in this paper.

2. J-PARC main ring

The 1567.5-m-long MR has a three-fold symmetry with three arc sections and three long straight sections. The transition γ (γ_t) of the MR is imaginary [2]. Each arc section consists of eight identical modules. One module consists of four identical bending, four quadrupole (referred to as QFN, QDN, QFX, and QDX), and three chromaticity-corrected magnets. Each 116.1-m-long straight section, which is dispersion free, consists of seven groups of quadrupole magnets. Steering magnets are distributed near the quadrupole magnets throughout the whole ring. Each of the three long straight sections is dedicated to injection and beam collimation, slow extraction, and fast extraction, respectively. Electrostatic and magnetic septa, bump magnets, and a slow collimator are placed inside the long straight section dedicated to the slow extraction. A horizontal tune approaches the $3Q_x = 67$ resonance line for the slow extraction. Eight resonant sextupole magnets are distributed in the arc sections. Note that all of the magnets in the MR are of the normal conducting type and of separated-function type.

3. Stretcher ring

The designed ST has the same circumference of 1567.5 m as the MR does. Similar to the MR, each arc section in the SR consists of eight identical modules. As shown in Fig. 2, each module has combined-function magnets that generate dipole and quadrupole fields (BMNDCMB and BMNFCMB). In addition, each module also has separated-function quadrupole magnets (QFX and QDX). The beam optics of the module are shown in Fig. 2. As will be described later, this design creates a space for the injection of the beam into the ring. The beam optics of each long straight section consisting of seven quadrupole groups is identical to those in the MR (see Fig. 2). Furthermore, the horizontal and vertical tunes are chosen to be $(Q_x, Q_y) = (22.295, 20.780)$, which are the same as those used in the MR slow-extraction procedure. Thus, the SR can have the same slow extraction scheme just as the MR does [2]. The SR has γ_t=21.7 in the proposed optics design. The optics of the SR have been carefully designed to suppress the horizontal orbit deviation between the SR and the MR to the acceptable level of $\sim$30 cm in order to fit the SR into the MR tunnel.

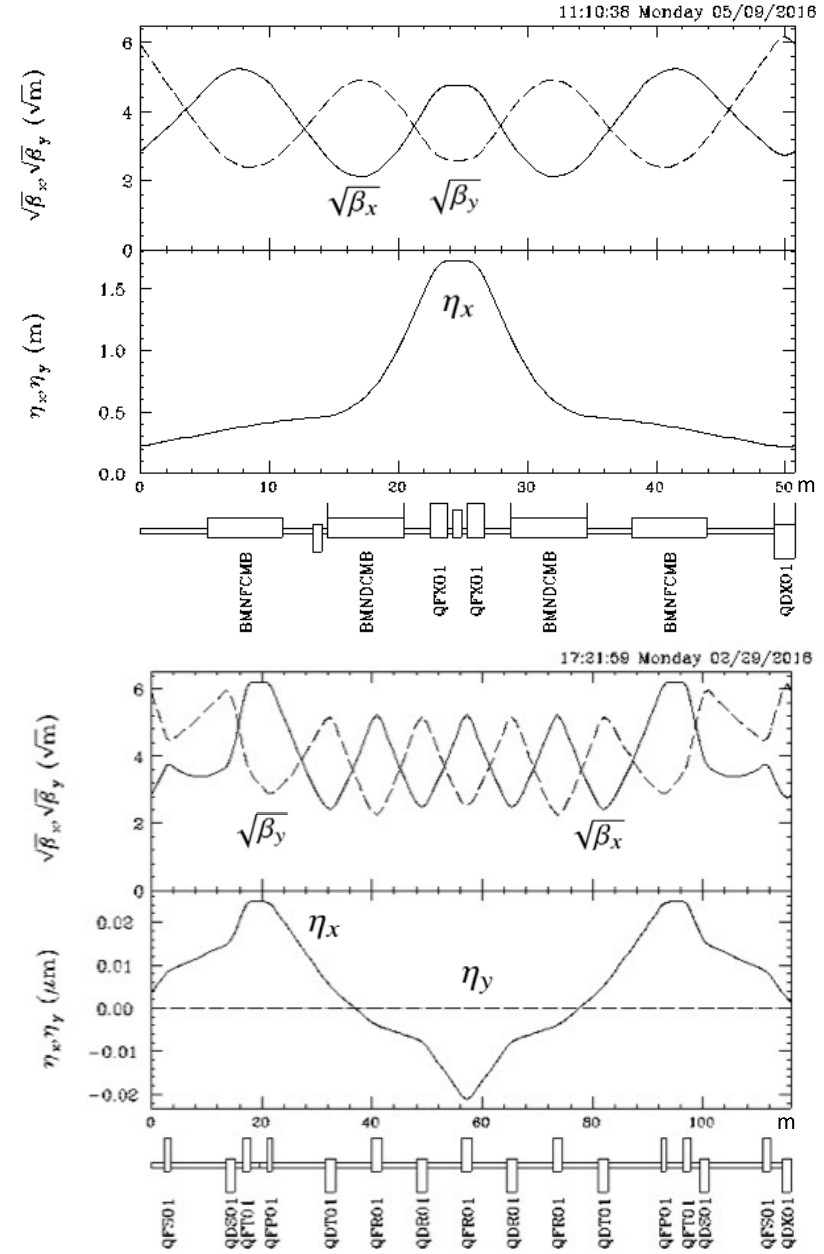

Figure 2. Beam optics of a module in an arc section (upper) and of a long straight section (lower).

The superconducting combined-function magnets in the arc sections are of superferric type with a transmission line or of cosθ-coil type [3]. The quadrupole fields of BMNDCMB and BMNFCMB are 3.94 and 3.41 T/m, respectively, for a dipole field of 1.15 T corresponding to 30 GeV energy. These magnets can produce a sextupole field of 17 T/m^2 for the chromaticity corrections. The sextupole field is created by the pole shape design in the superferric-type magnets. The cosθ-coil-type magnets, however, have an independent coil to produce the sextupole fields[3]. The QFX and QDX magnets in the arc section are of cos2θ-coil type and have a coil to generate a sextupole field for corrections. It should be noted that several magnets in the long straight sections may be exposed to a high radiation dose as a result of the beam loss due to the slow extraction or the beam collimation. Under these conditions, quadrupole magnets of the normal conducting type should be chosen. A full chromaticity correction for the SR can be performed using sextupole fields in the defocusing combined-function magnets (BMNDCMBs) and the focusing QFXs. For a shift from the full correction, sextupole fields in the QDXs and QFXs can be adjusted for the superferric type. The slow-extracted beam from the SR is deflected downwards and merged with the present beam line for transportation to the HD.

4. Beam transfer and dump lines

The bipolar kickers and bipolar magnetic septa in the long straight section for the fast extraction in the MR can deflect the beam to the inner neutrino beam line or to the outer beam dump line [4]. The present beam dump line will be rebuilt to allow for beam transfer from the MR to the SR. The BTL to the SR comprises combined-function superconducting magnets with cosθ and cos2θ coils as well as separated-function cos2θ quadrupole magnets. The maximum dipole and quadrupole fields for the combined-function superconducting magnets are 1.36 T and 15.8 T/m, respectively. The beam optics of the BTL are shown in Fig. 3. A layout of the BTL magnets is shown in Fig. 4 together with the MR, SR, and abort magnets (QFAB and QDAB). The beam to the SR or the beam dump passes through beam ducts of two magnets (BMHF01 and BMHD01) just downstream of the MR. These magnets are excited with the acceleration pattern of the MR. The dipole fields are turned off in case the beam is delivered to the dump. The beam being delivered to the dump passes through a field-free region in a cryostat module in the third magnet (BMHF02) and is delivered to the dump through a quadrupole doublet (QFAB and QDAB) as shown in Fig. 4. However, the beam being delivered to the SR is deflected upwards by a vertical combined magnet (BMVD01), passes through some horizontal combined magnets, and is then deflected back by another vertical combined magnet (BMVD02). The beam line

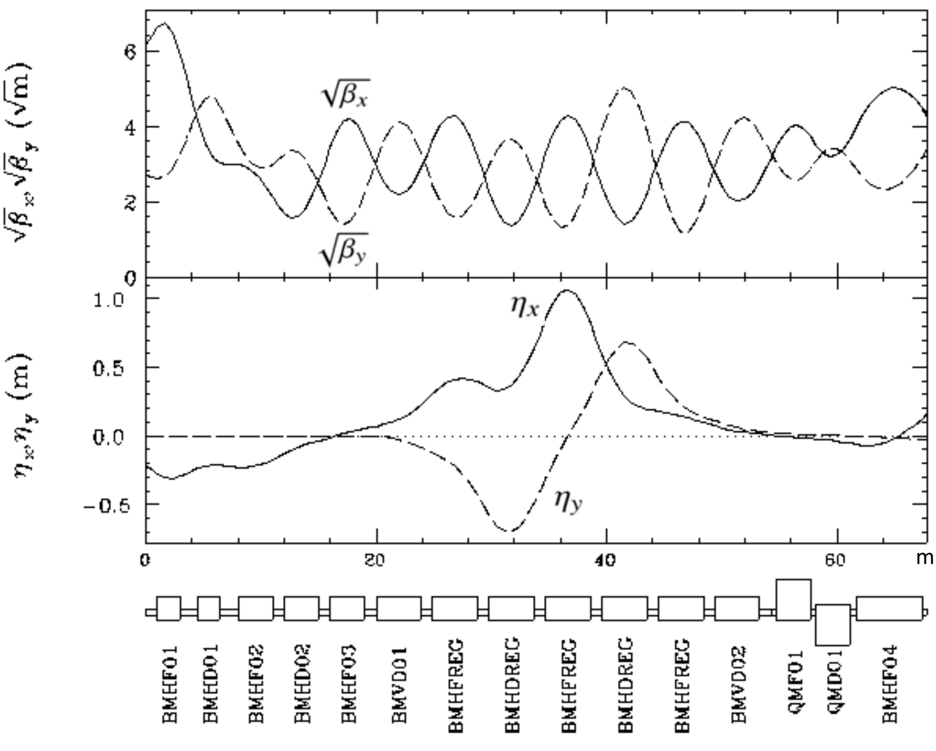

Figure 3. Beam optics of the BTL from the MR to SR.

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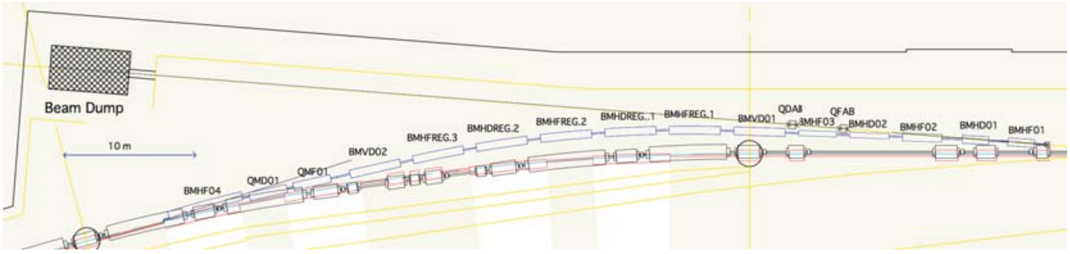

Figure 4. Layout of the MR (black), SR (red), BTL (blue), and abort magnets (QFAB and QDAB).

level is elevated by 1.5 m. The vertical dispersion function in the slope can be suppressed by choosing a suitable phase advance in the slope. The beam is optically matched by the following quadrupole and horizontal combined-function magnets and is injected into the SR. Since the last horizontal combined magnet BMHF04 (with $B = 1.58$ T, $B' = 4.15$ T/m) is placed fairly close to the combined magnet BMHF04 in the SR, it has a special structure. An internal dump should be placed downstream of the MR kickers to enable a fast beam-stopping function in the MR since the response time of the magnets required to deliver the beam to the external dump mentioned above is not fast enough for emergency machine protection. In the SR, the beam can be fast extracted and delivered to the present external dump. The beam line to the dump comprises a quadrupole doublet and a vertical bending magnet to deflect the beam downwards.

5. Injection

The beam from the BTL is injected into an arc section in the SR, which is located just downstream of the extraction point from the MR (see Fig. 4). Figure 5 shows beam envelopes in the injected area of the SR. The beam is injected by magnetic septa (MS1 and MS3) and

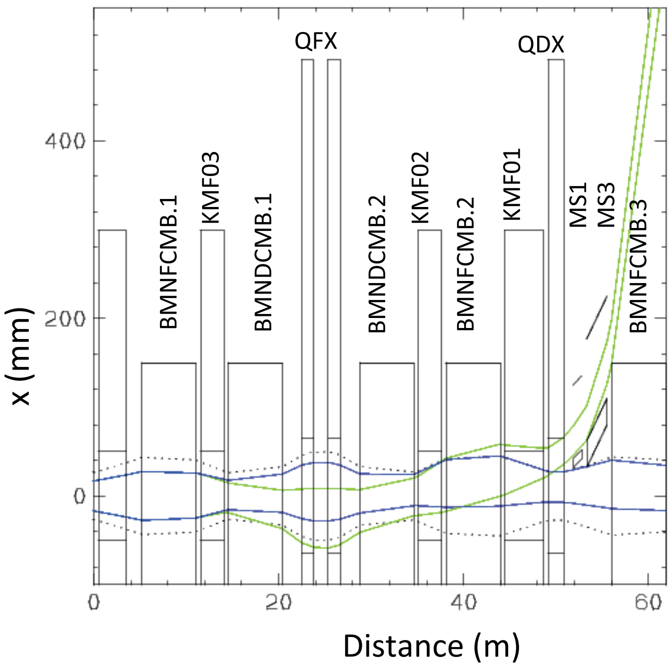

Figure 5. Beam envelopes of the beam injected into the SR.

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kicker magnets (KMF01−03). The green lines indicate the injection envelope with an emittance of 30 πmm·mrad. A bump orbit is produced by steering fields in the combined-function magnets (BMNFCMBs and BMNDCMBs) and the field strength for the kickers is 0.074 T. The blue lines indicate an envelope of the beam circulating with the bump orbit. The dotted lines indicate a 54 πmm·mrad envelope of the circulating beam without exciting the bump orbit.

6. Conclusion

The J-PARC main ring provides 30 GeV high-intensity beams to the NU by fast extraction and to the HD by slow extraction. It is difficult, but also of utmost importance, to ensure that the integrated POT is sufficient for each facility. An SR that addresses this problem has been proposed. The designed SR has a unique hybrid lattice configuration with combined- and separated-function superconducting magnets and fits well into the existing MR tunnel. The compact BTL from the MR to the SR using superconducting combined-function magnets has also been designed. However, the work described in this paper is in the conceptual desgin stage. Further studies including applications for possible future requirements as variable output energies and a bunched-beam extraction will be conducted in the next step.

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