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Development of the CSNS Lambertson magnet with very low stray field

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A R T I C L E I N F O

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A B S T R A C T

In this paper, the magnetic and mechanical design of Lambertson are studied, and then magnetic field measurements are introduced. The results show that the integral field uniformity and effective length meet the physical requirements. The shielding measures shield the stray field effectively and the stray field along the circulating beam orbit is at a very low level.

1. Introduction

The China Spallation Neutron Source (CSNS) is a large scale science facility for multidisciplinary experiments. The accelerator at CSNS generally includes a H^- linac, a proton rapid cycling synchrotron (RCS) and two beam transport lines. As a key element of the accelerator, beam injection and extraction system directly relates to the beam loss [1,2]. The extraction system consists of eight fast Kicker magnets and one Lambertson septum magnet. Radiated from the linac, the H^- beam is injected into RCS by stripping injection, and then accumulated and accelerated to the energy benchmarks. Kickers [3] are fired to push the extracted beam vertically up to the entrance of Lambertson, and then Lambertson deflects the beam horizontally to the high energy beam transfer line. Difficulties in the magnetic design of the magnet lie in the requirement of a high magnetic field in the magnet gap (extracted beam orbit), also minimal the stray field along the circulating beam orbit. Moreover, the fact that both extracted beam and circulating beam pass through the magnet complicates the magnet structure design.

2. Requirements on CSNS/RCS extraction septum magnet

According to the requirements of accelerator physics, the magnetic field qualities of extraction septum magnet are very critical to the extracted beam as well as to the circulating beam. With effective shielding, a desirable magnet allows high-quality deflection of the extracted beam, and minimal stray field along the circulating beam orbit. The specifications of CSNS/RCS extraction septum magnet are listed in Table 1.

3. Septum magnet selection

There are two types of septum magnets often used in accelerator extraction system: C-type septum magnet and Lambertson septum magnet. Extraction system in RCS of J-PARC has eight Kicker magnets and three C-type septum magnets [4], while in SNS, it has fourteen Kicker magnets and one Lambertson septum magnet [5–7]. Table 2 shows the advantages and disadvantages of C-type magnet and Lambertson magnet, respectively. Since the difference in the deflection angle between Lambertson and Kicker is 90 degrees, dipole magnets downstream are needed for correcting the Kicker angle. Beam physics theory indicates that C-type magnet is more generally efficient than Lambertson magnet in beam extraction. However, in the case of high radiation environment, particularly high field in the magnet gap and the limited thickness of septum, C-type septum magnet has severe disadvantages: high current density, complex water cooling structure and beam bombardment induced the radiation damage of coil, etc. Lambertson magnet also is proven to be more reliable to high radiation environment, less fabrication difficulty, production cost and operation maintenance. Therefore, the CSNS extraction layout is determined with eight Kickers and one Lambertson, as Fig. 1 shows.

4. Lambertson magnet design

Unlike the conventional magnet, there is a common problem of stray field on the extraction septum magnet. For example, the relation

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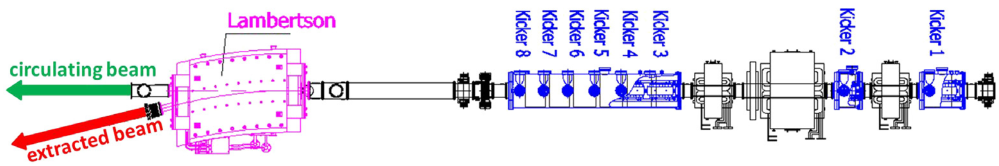
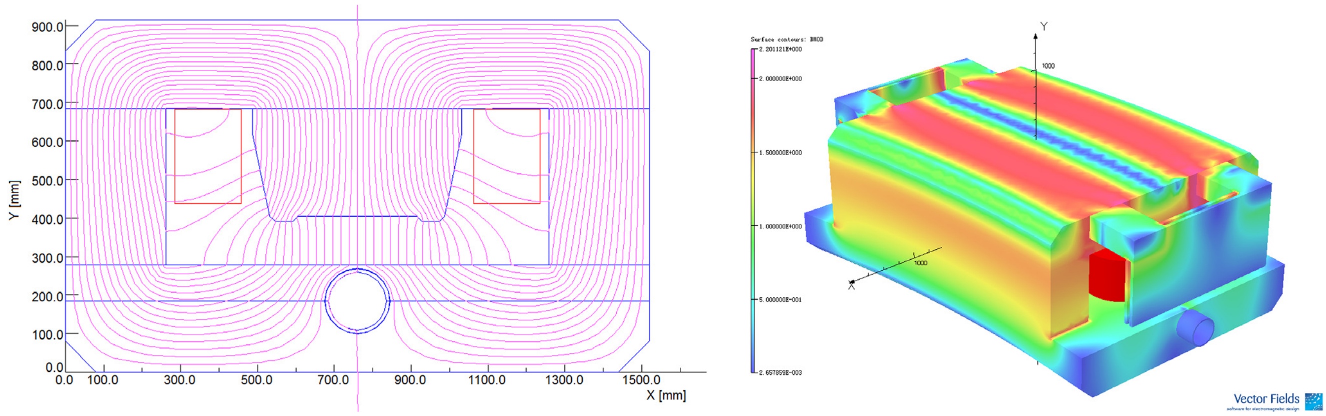


Fig. 1. Layout of CSNS extraction system.



(a) 2D magnetic field at the entrance of the magnet.

(b) 3D magnetic field intensity distribution.

Fig. 2. 2D and 3D simulation of Lambertson.

Table 1
Specifications of CSNS/RCS extraction septum magnet.

Extraction energy (GeV)	1.6
Bending angle (mrad)	228
Main magnetic field (Tesla)	0.9441
Effective length (m)	1.9
Magnet gap (mm)	128
Horizontal field uniformity (−60 mm to +60 mm)	$<1 \times 10^{-3}$
Vertical field uniformity (−50 mm to +50 mm)	$<5 \times 10^{-3}$
Stray field integral/main magnetic field integral	$<5 \times 10^{-4}$
Elevation angle of extracted beam vacuum tube (mrad)	12
Elevation angle of circulating beam vacuum tube (mrad)	6
Aperture for extracted beam (mm)	122
Aperture for circulating beam (mm)	150
Septum thickness (mm)	<20

between the stray field and the beam loss was studied at J-PARC [4]. The stray field ratio of SNS Lambertson magnet along the circulating beam orbit is as high as 4.6×10^{-3} (in this paper, the stray field ratio is defined as the ratio of the stray field integral along the circulating beam orbit and the main magnetic field integral along the extracted beam orbit). In order to reduce the stray field, SNS uses multilayer high permeability ferromagnetic materials as shields. Although the stray field ratio was suppressed to 1.89×10^{-3}, its impact was still found [8,9]. In CSNS, due to approximately 1 T main magnetic field in the gap of Lambertson magnet and short distance to the circulating beam orbit, the stray field affects the circulating beam significantly. Therefore, the stray field ratio requirement of CSNS is less than 5×10^{-4}. The magnetic field has been simulated and optimized by OPERA 3D/TOSCA [10] program. A variety of shielding measures have been adopted to effectively reduce the stray field along circulating beam orbit.

Many problems need to be considered in structure design. Due to the limitation on the thickness of the septum, the circulating beam vacuum tube and the extracted beam vacuum tube are very compact with the magnet core at the entrance of magnet, and vertical Kicker angle of about 20 mrad is also taken into account. Therefore, the structure of the core and the two vacuum tubes is very compact and complex, and magnet assembly is also difficult.

4.1. Magnetic field design

According to the relevant theory and experience to find the basic parameters of the magnet [11], the magnetic field and mechanical structure of the magnet are simulated and optimized by OPERA 2D/3D program. Fig. 2 shows the magnetic field simulation. Fig. 2(a) shows a 2D magnetic field at the entrance of the magnet and the yellow lines represent the magnetic loop. Fig. 2(b) shows a 3D magnetic field distribution, which derives the magnetic saturation of the magnet. Fig. 3 shows the field distribution along the extracted beam orbit. The central magnetic field is about 0.9441 T of design requirement and the effective length is 1.974 m. Fig. 4 shows the simulation results of field integral uniformity (the uniformity is defined as $(By{-}By_{(X,Y=0)})/By_{(X,Y=0)}$). The simulation of horizontal field uniformity is 6.37×10^{-4} in the range of −60 mm to +60 mm, which is 3.63×10^{-4} better than the physical requirement (1×10^{-3}) in Table 1. And the simulation of vertical field

Table 2
Comparison of Lambertson and C-type septum magnet.

		Lambertson	C-type septum magnet
1	Coil size	No limitation	Limited by the thickness of septum
2	Coil insulation	Conventional technology	Special insulation technology
3	Coil cost	Low	High
4	Reliability	Safe and long-lasting	The coil insulation is easier damaged by beam bombardment
5	Current density	Low	High
6	Water cooling	Conventional design	High water flow rate is required
7	Beam extraction	Additional magnets for correcting the Kicker angle	Convenient and simple