MAGNET DESIGN FOR THE SNS LASER STRIPPING EXPERIMENT

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Abstract

The first step in the three-step laser assisted H- beam stripping for charge exchange injection is to remove one electron in a strong magnetic field. In order to preserve the beam emittance for the subsequent laser induced stripping of the second electron the magnetic field has to have large gradient of about 40 T/m along the beam trajectory. The required magnetic field strength for stripping a 1 GeV H- beam is 1.2 T. In order to allow for undisturbed passage of high power beam during the nominal SNS operation the stripping magnet made of permanent magnet material resides in a vacuum chamber and can move in and out of the beam line. This paper describes the requirements, design and magnetic field calculation results for a stripping magnet for the Laser Stripping Experiment at SNS.

INTRODUCTION

The goal of the laser stripping experiment at SNS is to demonstrate the feasibility of using the laser-assisted H- stripping process (converting an H- to proton by detaching both electrons) for real world beam and laser parameters as a possible replacement of thin foils for charge-exchange injection in circular accelerators [1].

The schematic layout of the laser assisted H- stripping process is shown in Fig. 1. The first, relatively weakly bound, electron is stripped in the transverse magnetic field of the first magnet. The remaining electron in the ground state has a much higher binding energy and would require an impractically large magnetic field strength for detachment. This electron can be excited to a higher energy state by a laser with proper wavelength. The excited electron has a lower binding energy and can be stripped in a magnetic field of a modest strength [2].

The efficiency of the electron excitation is proportional to the photon density at the interaction point (I.P.), therefore it is beneficial to focus the laser beam to as small a size as possible. Correspondingly, the ion beam must have the same or smaller size to overlap with the laser beam. Focusing the ion beam to small size requires preserving a small emittance in the process of the first electron detachment in the magnetic field. In addition, the magnetic field strength must be low at the I.P. for efficient photo-excitation process: less than 20 Gauss for the SNS experiment parameters. The electron has a finite lifetime of the order of nanoseconds in the excited state therefore the ion must reach the second magnet as quickly as possible, before the electron returns to the ground state. The magnet system for the experiment must satisfy all the above requirements, fit into the available space in the existing SNS beam line, and be compatible the nominal SNS operation when a high power beam passes through the same beam line.

As we will show in the next chapter, the magnetic field of the first magnet must have a gradient of the order of 40 T/m in order to preserve the ion beam emittance. The aperture of the beam line at the experiment location of .15 m must be clear for high power operation. A magnet with the field of about $40\,{}^{T}\!/_{m}\cdot .15m = 6T$ at the poles is required to achieve such a large gradient in such large aperture. We proposed a less expensive solution with movable magnets of a smaller aperture moving in for the stripping experiment and out for the normal SNS operation. The whole magnet system has to reside in vacuum to allow quick configuration switch without entering the beam tunnel. As the experiment is designed for a fixed ion beam energy of 1 GeV the magnetic system with a fixed magnetic field can be used. This allows the use of permanent magnets instead of electromagnets with a significant reduction of overall system size and cost.

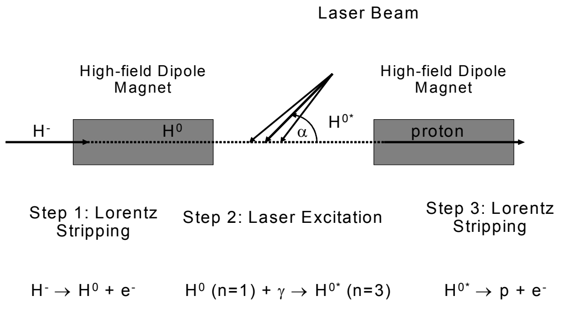

Figure 1: Schematic view of the three-step laser stripping process

MAGNETIC FIELD REQUIREMENTS

There is a finite probability for the electron to detach from an H^- ion in electric due to tunnelling effect. The lifetime τ of an H^- ion in a uniform electric field of strength E is

$$\tau\,[\,s\,] = \frac{a}{E\,[\frac{V}{m}]}\, e^{\frac{b}{E\,[\frac{V}{m}]}} \qquad (1)$$

where constants are $a \cong 2.5\cdot 10^{-6}\,\frac{sV}{m}$, $b \cong 4.5\cdot 10^{9}\,\frac{V}{m}$ [3].

An ion moving in a transverse magnetic field B with velocity v will experience an electric field $E = \gamma v B$ in its rest frame of reference and, therefore will neutralize with the probability described by (1). The stripping process is essentially probabilistic and, therefore, introduces an angular spread to the beam of ions: some ions move in the magnetic field for longer time than others thus accumulate larger deflection angles $\alpha \sim \gamma v \tau B$. Seemingly, the angular spread can be reduced by increasing the magnetic field strength, but in a real magnet the field will increase continuously from zero to maximum field in the gap and the angular spread will accumulate in the edge field of the magnet. This is illustrated in Fig. 2, where the stripping probability for a 1 GeV H^- ion is plotted versus distance travelled inside a linearly increasing magnetic field. The location of the maximum of the probability function near $B = 1.2\ T$ is almost independent of the field gradient. The probability function width is proportional to the field gradient. The angular spread at the magnet exit versus the field gradient is plotted in Fig. 3. We set the limit for the additional angular spread due to the stripping magnet not to exceed 1 mrad. This sets the required minimum magnetic field gradient of ~40 T/m at the point where the magnetic field strength is 1.2 T.

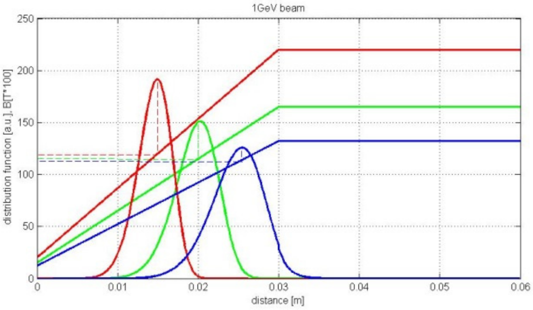

Figure 2: Distribution of the stripping probability along the beam path (bell shaped curves) inside a magnet with linearly ramping fringe field (magnetic field profile is shown on the same graph).

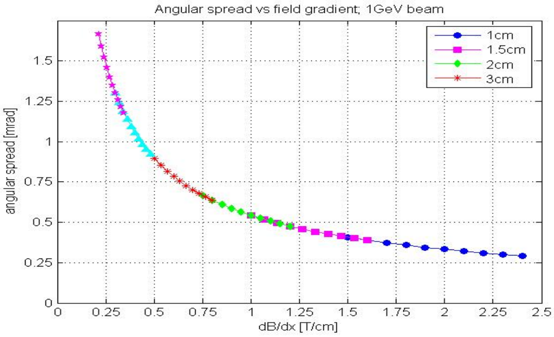

Figure 3: Dependence of the RMS value of the angular spread on the magnetic field gradient (linearly increasing magnetic fields with different maximum field strength and ramp length were used in the calculations).

The requirements for the second magnet, for stripping the remaining electron excited by the laser, are similar to the first one. The stripping process does not depend on the direction of the transverse magnetic field; therefore it is convenient to have the second magnet identical to the first one with opposite direction of the field. In this case the magnetic fields of the two magnets cancel each other at the midpoint between the magnets and the condition of zero field strength at the I.P is satisfied automatically.

The distance from the I.P. to the second magnet must be as small as possible to minimize the number of excited electrons relaxing to the ground state before they reach the second magnet. From other hand, it has to be large enough to allow an unobstructed passage of the laser beam through the I.P. at the required angle of ~40^{o}.

The H- ions are deflected in the edge field of the first magnet before the first electron is detached. Then the protons, created when the second electron is stripped, receive additional deflection in the same direction in the second magnet. In order to minimize the average deflection of the beam, two dipole field correctors are added before and after the stripping magnets. The field strength of the first corrector must be low enough not to cause premature stripping of the entering ions.

MAGNET DESIGN

We chose the Halbach Cylindrical Array configuration for the magnets [4], which does not require a heavy and bulky iron yoke for the return filed. –This results in compact and light design suitable for actuating inside a vacuum vessel. The magnetic field strength B inside the aperture of an infinitely long Halbach Cylindrical Array with continuously changing magnetization direction is given by

$$B = B_r \cdot ln\frac{R}{r}, \qquad (2)$$

where B_r is the remnant field of the permanent magnet (PM) material, R is the outer radius, and r is the inner radius of the annular magnet. A typical value of B_r is 1.3÷1.4 T for readily available PM material. The inner radius of 14.5 mm is defined by the ion beam transverse size. The outer radius of 60 mm we chose to satisfy the magnetic field strength and gradient requirements. The equation (2) gives a very good initial approximation for the magnet parameters. The CST Studio Suite code was used for final optimization of the design.

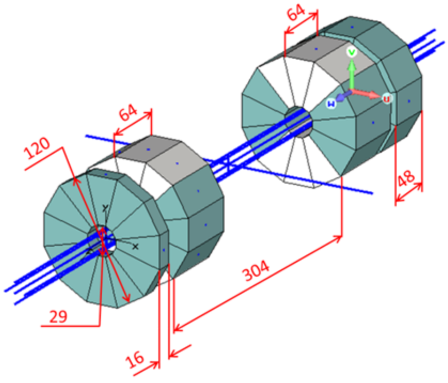

Figure 4: A layout of the magnets arrangement for the SNS stripping experiment. Dimensions are in mm.

A general layout of the magnet system satisfying all the requirements is shown in Fig. 4. The length of the stripping dipoles is chosen as a compromise between the field strength reduction due to the final length and the total volume of the PM material, which defines the weight and cost of the magnet. The length of the correcting dipoles is chosen to minimize the integral ion beam deflection in the system.

The transverse magnetic field strength along the beam path is shown in Fig.5.

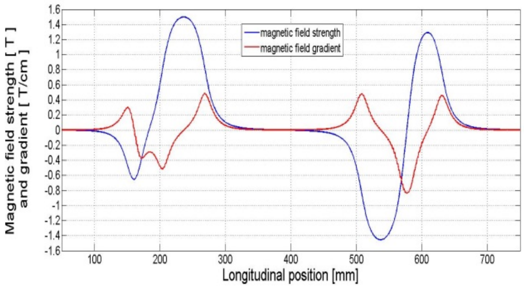

Figure 5: Plot of the magnetic field strength and gradient distribution along the beam path**.**

Each individual magnet is an assembly of 12 segments held by an aluminium ring as shown in Fig. 6. Two types of PM material are used. The sectors with magnetization collinear with the magnetic field are made of a higher B_r PM material (Dexter N4520, $B_r = 1.35\,T, H_{cI} = 20\,kOe$ [5]) to maximise the field in the gap. The sectors with magnetization opposite to the magnetic field direction are made of a higher initial coercitivity PM material (Dexter N3830, $B_r = 1.25\,T, H_{cI} = 30\,kOe$ [5]) to prevent PM material de-magnetization in high field areas. The magnet will be stabilized at 45°C and measures will be taken not exceed this temperature during transport and operation.

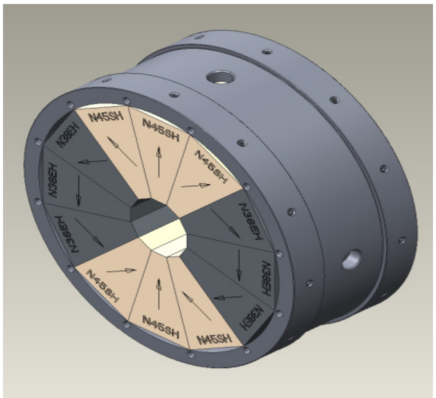

Figure 6: Model of the individual magnet assembly. Magnetization directions are shown by arrows. Different colours correspond to different PM material.

The stripping and corrector magnets in close proximity will attract with significant force of few hundreds kilograms therefore they are mounted in a strong aluminium holding block as shown in Fig. 7. The two blocks with pairs of magnets then mounted on a platform in vacuum vessel, which is movable up and down using a 200 mm stroke actuator as shown in Fig. 8.

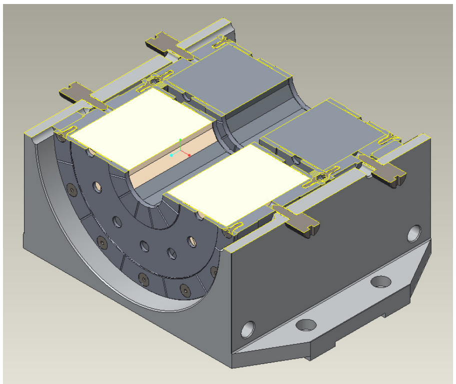

Figure 7: Model of a mounting block with the stripping and correcting magnets.

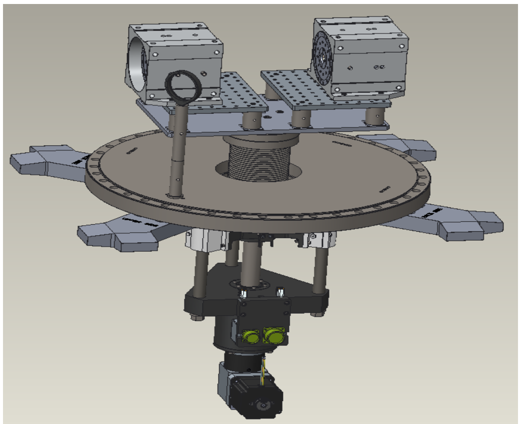

Figure 8: Magnet system with the actuator assembled on the vacuum flange**.**

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