BEAM EXTRACTION FROM THE SNS RING AND DESIGN OF EXTRACTION KICKERS*

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Abstract

The accumulator ring of the Spallation Neutron Source (SNS) [1] will accumulate a proton beam, injected from a LINAC, into a single bunch containing ~2.1×10^{14} protons at a maximum energy of 1.3 GeV. The single bunch with length ~650 nsec and a gap of ~290 nsec will circulate into the accumulator ring for ~1.0 msec before it is extracted into the RTBT transfer line. The accumulation, extraction frequency is set at 60 Hz. This paper discusses the extraction process and the requirements of the fast beam extraction system.

1 THE EXTRACTION PROCESS

With the completion of the beam-injection/accumulation process, ("painting" [3]) which requires a time interval of ~1 ms the fast beam extraction process is initiated. The extraction scheme is a "single turn, two-step" process which employs two types of extraction devices; first the fast extraction kickers that will deflect the beam vertically (first step) into the extraction channel of a Lambertson type septum magnet and second the Lambertson type septum magnet which will bend the beam horizontally (second step) by 16.8^0 into the RTBT transfer line [2] and to the SNS target. The extraction process is completed in a single turn ~1 μsec, and takes place in one of the straight sections of the accumulator's ring. The physics of extraction can be described by the equation 1 below.

$$y_{cod}=y'_1(\beta_1\beta_2)^{1/2}\sin(\Delta\phi) \qquad 1$$

The symbols y'_1 and β_1 in equation 1 are the kick strength, and the value of the beta function at the location of the kicker, and β_2 and y_{cod} are the values of the beta function, and the central orbit displacement (cod) of the beam at the entrance of the Lambertson septum magnet, $\Delta\phi$ is the phase advance between the kicker and the septum.

The plot of the functions $\beta_{x,y}$, along a superperiod of the ring is shown in Fig. 1 (top). Present technology cannot provide a single kicker to displace the central orbit (y_{cod}) of 1.0 GeV proton beam by the required amount of 167 mm at the entrance of the Lambertson magnet, therefore a set of 14 kickers (see Fig.1), each delivering the maximum possible kick, are being used for the extraction. The computer code MAD [4] was used to calculate the strength of each of the 14 kickers in order to achieve the required y_{cod} at the entrance of the septum. The plot of the y_{cod} and the phase advance $\phi_{x,y}$ along the extraction straight section are shown in Fig. 2. The value of y_{cod} at the entrance of the septum is 167 mm and this displacement depends on beam size considerations and safety margins during extraction that are discussed in the next section.

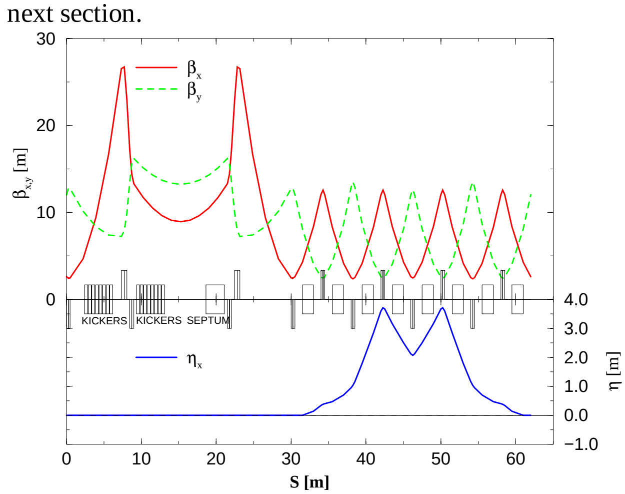

Figure 1: The functions $\beta_{x,y}$ (top) and η_x (bottom) along a superperiod. Shown are the kickers and septum location.

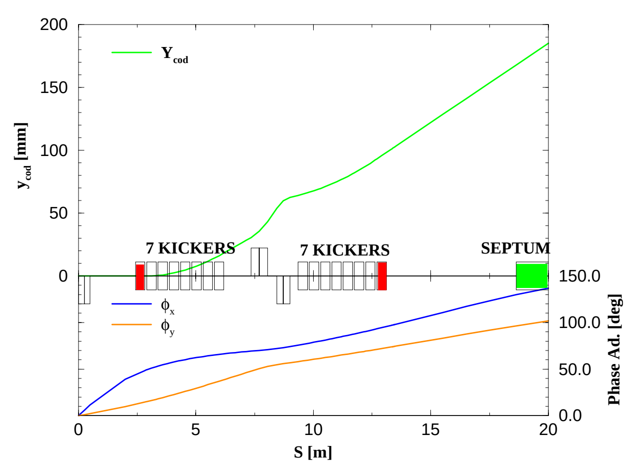

Figure 2: The y_{cod} (top) and $\phi_{x,y}$ (bottom) along the straight section. Two more kickers (red boxes) are needed to extract a 1.3 GeV proton beam.

2 APERTURE REQUIREMENTS FOR THE FAST BEAM EXTRACTION

The apertures of the extraction devices (kickers,and septum) depend on the acceptance of the ring and the acceptance of the extraction channel. Both acceptances are based on safety margins for reliable, beam accumulation and extraction with minimum beam losses.

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The aperture consideration of the extraction devices as well as the apertures of other magnets involved during the beam extraction are discussed here.

1. Lambertson septum magnet.

The septum magnet separates the circulating beam region from the extraction beam region. The circulating beam region should provide an acceptance of 480π.mm.mrad which is the same with the ring acceptance, except at the locations of the collimators [2] where the acceptance is 300π.mm.mrad and the beam losses are controlled. Simulations show that the uncontrolled losses in the ring are 10^{-4} for beam of $\varepsilon_{x,y}$=160π.mm.mrad (after painting). The extraction beam channel at the region of the septum magnet provides an acceptance of 400π.mm.mrad which equals the minimum acceptance of the RTBT transport line, and allows a "no loss" beam transport from the ring to the RTBT target even if one of the 14 extraction kickers fails to fire. In fact failure of two kickers, one from the first group upstream of the quad-doublet shown in Fig, 2 and the other from the second group downstream of the quad-doublet, (or both from the second group), still maintain the extraction beam within the 400π.mm.mrad acceptance of the septum magnet. In order to satisfy the above acceptance requirements for the circulating beam region and the extraction beam region the displacement of the central orbit at the entrance of the septum should be 167 mm. This displacement allows for a 10 mm septum thickness. The lower acceptance (400π) for the extraction channel is based on the beam collimation that has cleaned up the beam from "beam halo" during the accumulation period, and has prepared a beam which may not cause uncontrolled losses during extraction.

2. Extraction kickers

The physical aperture of the extraction kickers is defined by two main requirements:

a)The kickers should provide a 480π.mm.mrad acceptance for the circulating beam in the ring in the horizontal direction.

b)The acceptance of the kickers in the vertical direction however should be larger than 480π.mm.mrad depending on the location of the kicker. This is because during the extraction time, the central orbit of the extracted beam is displaced vertically with respect to the ideal orbit of the ring. This beam displacement requires a kicker with larger vertical aperture in order to accommodate the extracted beam. The extracted beam however has already been cleaned up by most of the halo, and therefore it is reasonable to decide an acceptance of 400π.mm.mrad (with respect to the displaced central orbit) during the extraction. Table I shows the maximum vertical beam displacement ($y_{k,cod}$)at the location of each kicker.

3. Quad-doublet located in the extraction region.

In order to optimize the kick delivered by each of the kickers the 14 kickers are separated into two groups,. The first group is located upstream of the quad-doublet (Fig. 2) and the second downstream. As in the case of the kickers, the available aperture of the quadrupole doublet should provide an acceptance of 480π.mm.mrad for the circulating beam, and an acceptance of 400π.mm.mrad for the extracted beam (the acceptances are measured with respect to the central orbit). These constraints set an upper limit of 7 cm on the maximum displacement of the central orbit (y_{cod}) in the region of the doublet quads during the extraction.

Table 1: Kicker apert (HxV), kicker (Kick), y_{cod} at kicker ($y_{k,cod}$), Δy_{cod} at septum ($y_{ks,cod}$), y_{cod} at septum ($y_{ts,cod}$)

	HxV[mm]	Kick mrad	$y_{k,cod}$ mm	$y_{ks,cod}$ mm	$y_{ts,cod}$ mm
K1	143x131	1.65	0.46	18.4	18.4
K2	143x131	1.65	1.45	17.8	36.2
K2	143x131	1.65	3.37	17.1	53.3
K3	168x131	1.48	6.04	14.7	68.0
K4	168x131	1.48	9.42	14.1	82.1
K5	195x135	1.35	13.49	12.3	94.4
K6	195x135	1.35	18.20	11.8	106.2
K7	157x235	1.13	66.14	10.3	116.5
K8	157x235	1.13	69.09	9.7	126.2
K9	157x235	1.16	72.58	9.4	135.7
K10	146x250	1.16	76.63	8.9	144.5
K12	146x250	1.16	81.24	8.3	152.9
K13	146x250	1.16	86.40	7.8	160.6
K14	146x250	1.16	92.12	7.1	167.8

3 SEPTUM MAGNET REQUIREMENTS

In order to obtain the maximum displacement of the extracted central trajectory, the septum magnet was placed as far downstream as possible. Beam acceptance constraints at the location of the septum (discussed earlier) and field quality of the septum magnet, generate the following list of parameters for the septum magnet.

Length ~2.44 m, Septum thickness=1 cm

Vert. and Hor. aperture at circulating beam region=17 cm

Vertical aperture at beam extraction region=16 cm

B-field in circulating beam region ~1 G.

B-field in beam extraction region ~6.76 kG.

4 KICKER MAGNET REQUIREMENTS

Apart from the aperture requirements of the kickers, discussed in section 2, there are additional requirements to be fulfilled by the kickers. One of them is the rise time (~200 ns) within which the kicker will be excited to the maximum field, and subsequently remain at this maximum field for ~700 nsec. Electrically however, the kicker is considered as an inductor powered by a Pulse Forming Network (PFN), and both kicker and PFN, form a resonant circuit. A thyratron, which is part of the PFN, and acts as a fast switch to power the kicker, operates at 25 kV and 3 kA. The voltage/current limitations of the thyratron and the rise time of the kicker (~200 ns) set an upper limit on the inductance, and therefore the physical length of the kicker which in turn limits the kick that each kicker can deliver to the beam. This upper limit in the length of the kicker, increases the number of the required

kickers to 14. An horizontal extraction scheme reduces the number of kickers to 12 but extraction septum considerations favor the vertical extraction scheme.
Table I shows few of the kicker parameters and the beam displacement at the location of the kickers and septum.
This large number of kickers prompted a study [5] of the longitudinal and transverse beam impedance due to the kickers.

5 KICKER DESIGN AND FIELD CALCULATIONS[6]

A single kicker is a window frame magnet made of ferrite with a frame ~2.5 cm thick in the transverse dir. Fig. 3.

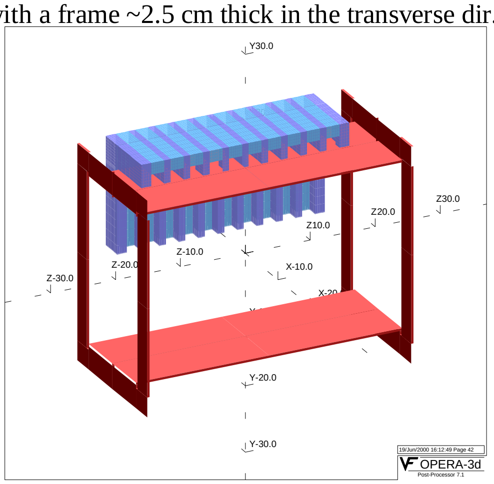

Figure 3: A 3-dimensional view of the kicker. The red material is the copper conductor shown in full. For a good view, of the segmented ferrite (dark-blue 1cm thick in z-dir.) and the material (light blue 2cm thick in z) between the ferrite, only one quarter of the kicker is shown.

The ferrite in the z-direction along the beam can be continuous or segmented as shown in Fig. 3. The dark blue material represents 1cm thick ferrite, followed by 2 cm air or copper (light-blue in Fig. 3). The ferrite type is CMD5005 that can be used inside high vacuum. The segmentation of the ferrite, (Fig. 3), reduces the μ_{eff} that may benefit[5] the beam impedance. The current carrying conductor is ~3 mm thick copper shown in red in Fig 3 with the whole structure placed in vacuum.
The length of each kicker, measured along the beam from one end of the ferrite to other, is 30 cm and the coil of each kicker is 40 cm long. Such a geometry (30cm ferrite/40cm coil) reduces the inductance (L~0.9 μH) to kick ratio, of the kicker and provides the required kick. The center to center distance between two adjacent kickers is 48 cm. The available aperture of the kicker is 14.6 x 25 cm for the horizontal and vertical dimensions.
The field of a kicker with segmented ferrite at the maximum current of the coil is shown in Fig. 4. This figure plots the main field component B_x over a rectangular area bounded by the following (x,y,z) coordinates: a)(-5,0,-35) b)(-5,0,35) c)(5,0,35) d)(5,0-35). The beam is along the z-direction. The discontinuities of the ferrite material does not affect the central field region which is "smooth" as shown in Fig. 4.

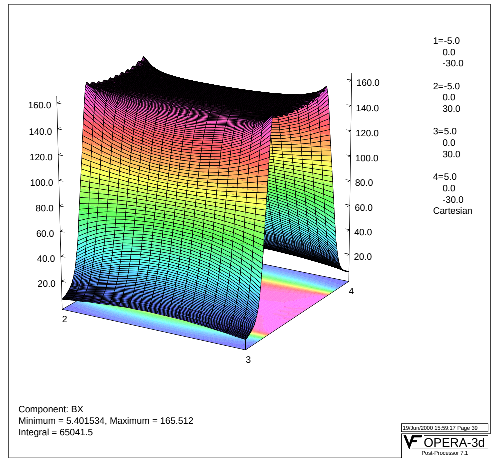

Figure 4: Plot of the field component B_x over the rectangular area defined by the four coordinates shown on the upper-right corner of the graph.

The kicker is excited by a current pulse that rises to its maximum in ~200 nsec, remains constant for ~700 nsec and falls off to zero in ~200 nsec. This current pulse is generated by the PFN and excites eddy currents in the kicker conductor which is one of the major sources of power loss. The high resistivity of the ferrite does not allow significant eddy currents in this material and does not contribute to the power losses. The ferrite however is a source of power loss through the magnetic hysterisis of the ferrite when it is excited by the beam bunch which circulates in the ring with a revolution frequency of ~1 MHz. To reduce the hysterisis losses and subsequently reduce the beam-ferrite interaction, a copper stripe 1 mm thick is inserted in the magnetic circuit of the ferrite creating a discontinuity in the magnetic circuit of the ferrite window frame. This copper stripe generates eddy currents (excited by the circulating beam) thus opposing the magnetic flux which circles the ferrite material.
Transient field calculations in 3D show that the power loss in the 2 cm thick copper material placed between the ferrite slabs (shown in Fig. 3) is also insignificant. This is due to the low field in this region.

6 CONCLUSIONS

The SNS ring beam extraction optics and the mechanical, electrical, and magnetic design of the kickers and septum magnet present no problem. Both the transverse and longitudinal impedance of the kickers as seen by the beam are under theoretical and experimental study.

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