A WIDEBAND SLOTTED KICKER DESIGN FOR SPS TRANSVERSE INTRA-BUNCH FEEDBACK*

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Abstract

In order for the SPS to meet the beam intensity demands for the HL-LHC upgrade, control and mitigation of transverse beam instabilities caused by electron cloud and TMCI will be essential. For this purpose a wideband intra-bunch feedback method has been proposed, based on a 4 GS/s front end data acquisition and processing, and on a back end frequency response extending to at least 1 GHz. A slotted type kicker, similar to those used for stochastic cooling, as well as an array of stripline kickers have been considered as the terminal elements of the feedback system. A slotted TEM type kicker has been designed fulfilling the bandwidth and kick strength requirements for the SPS application. In this paper we present an updated version of the design and electromagnetic characteristics, leading into the mechanical design and construction of the kicker occurring later this year.

INTRODUCTION

Intensity dependent effects like electron cloud (Ecloud) and transverse mode coupling instabilities (TMCI) cause intra-bunch motion that can lead to emittance blowup and ultimately loss of beam in the SPS. For the HL-LHC phase of the LHC, the SPS must be able to provide beams with the appropriate intensity [1]. A 4 GS/s feedback demonstration prototype has been developed as a potential method to mitigate these intensity dependent effects [2]. Measurements using the new feedback system have been successfully performed in 2012 – 2013 at the SPS with a limited bandwidth 200 MHz stripline kicker [3]. For the system to be complete, a kicker operating across a very broad bandwidth is necessary. An effort to evaluate the most suitable type of kicker technology available was pursued, investigating striplines, cavities, and slotted structures. The effort culminated in a design report detailing each type of technology [4, 5]. The technologies were reviewed as part of the LIU Project framework at CERN, and a decision was made to build an array of striplines and a slotted kicker for installation in the SPS. This paper focuses on the electromagnetic design of the slotted kicker (slotline) [6] exhibiting desirable characteristics in bandwidth and shunt impedance as well as the initial design for the feedthrough ports for power handling. The initial designs have been sent to CERN for detailed mechanical development of a prototype to be built this year.

SLOTLINE CHARACTERISTICS

The transverse kicker must be able to provide kick deflections of the order of $10^{-5}\,\frac{\mathrm{eV\cdot s}}{\mathrm{m}}$ over a bandwidth up to 1 GHz to mitigate such Ecloud and TMCI effects [5]. Factors such as these and beam stay clear requirements (> ±20 mm vertical) make it essential for the kicker to possess high shunt impedance characteristics to minimize the cost of broadband power amplifiers. The slotted type kicker is very attractive for this reason and is consistent with keeping the beam coupling impedance at a minimum. The slotted-coaxial kicker resembles that of Ref. [7], having a coaxial transmission line within the waveguide. Figure 1 shows a model of the design complete with ports, transmission lines, waveguides, beam pipe, and slotted interfaces. The x-axis direction in Fig. 1 corresponds to the physical y-axis (vertical) of the beam motion. The kick signal supplied by the amplifiers co-propagate with the beam (two power amplifiers would be located at the upstream ports of the structure, with 180° phase difference).

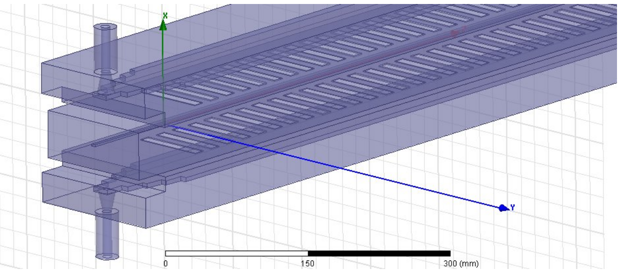

Figure 1: Model of the slotted kicker. The model shows one end of the slotted kicker, with the other end being a mirror image. The model contains the power ports, transmission lines, waveguides, beam pipe, and slotted interfaces. The x-axis is physical vertical direction of the beam motion.

The structure was modeled and the fields were generated by numerical simulations performed in HFSS [8] at frequencies in the operating band obtaining the transfer function. The dimensions of the slotted kicker were parameterized for optimization, maximizing the often competing characteristics of shunt impedance and bandwidth. The main parameters of the optimized geometry are summarized in Table 1.

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Figure 2 shows the magnitude and phase of the transfer function for the slotted kicker. The integrated transverse voltage corresponds to powering the structure with $P = 1$ W. One can easily convert the magnitude of the transverse voltage to shunt impedance using the expression [9]

$$R_\perp T^2 = \frac{V_\perp^2}{2P} \tag{1}$$

where P is the input power to the structure, T represents the reduced energy gain from the beam's finite transit time through the kicker, and $V_\perp$ is the transverse voltage. Thus, the shunt impedance is minimum at 100 MHz at 5 kΩ and as high as 11 kΩ at 950 MHz. Notice the smooth phase response, easy to equalize, preserving correct feedback loop phase.

Table 1: Parameter dimensions of the slotted kicker after optimization for bandwidth and shunt impedance. These parameters correspond to those used to calculate the transverse deflecting voltage in Fig. 2. The 1000 mm slotted section with 12.5 mm slot width and 12.5 mm slot spacing corresponds to 40 slots.

Parameter	Dimension (mm)
Length of slotted section	1000
Beam pipe height	45
Beam pipe width	132
Slot interface thickness	1
Waveguide height	66
Waveguide width	150
Slot spacing	12.5
Slot length	80
Slot width	12.5
Coaxial line thickness	5
Coaxial line width	80

PORT MODELING

Additional studies over the last year have included adding coaxial power coupling ports to make the model more realistic by matching the transmission line within the waveguide to the external 50 Ω system of the power system. The initial design with ports from Fig. 1 showed a $|S_{11}|$ parameter of less than 0.25 across the 1 GHz band. However, modeling of the longitudinal beam coupling impedance with GdfidL [10] showed evidence of periodic higher order modes. Gradual tapering and introducing the ports in the longitudinal direction so that they are collinear with the transmission line helped to minimize the peaks observed in the beam coupling impedance spectrum. Figure 3 shows a symmetry, quarter geometry model of the slotted kicker with longitudinal ports and Fig. 4 shows the longitudinal transverse impedance up to 5 GHz. The characteristic impedance of the 5 mm diameter coaxial port is 50 Ω, similarly for the transmission line. A linear taper between the coax and transmission line was used to maintain the 50 Ω impedance as closely as possible, showing at most 2.5 Ω of variation. The $|S_{11}|$ parameter was ≤0.10 over the entire 1 GHz band.

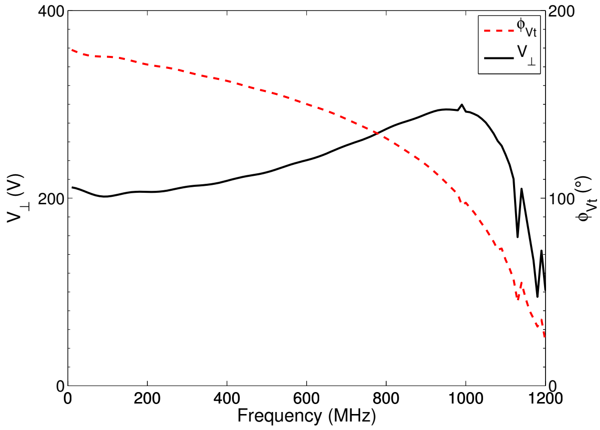

Figure 2: Transfer function of the slotted kicker, both magnitude and phase. The magnitude displays the integrated transverse voltage normalized to 1 W input power to the structure.

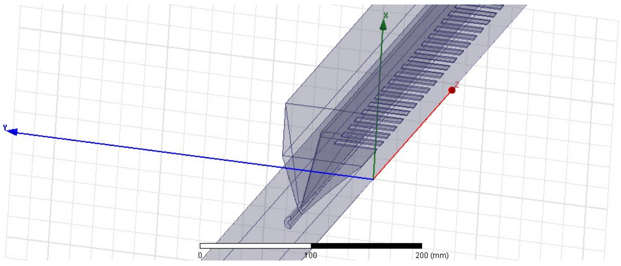

Figure 3: Slotted kicker with longitudinal ports and a linear taper from the cylindrical coax to the rectangular transmission line.

An additional model with 90° ports to the transmission line and linear tapers was developed as well and also shows improvement over the initial design. The mechanical advantages and challenges of each layout is being weighed and the most robust mechanical layout will be developed.

The directivity of the slotted kicker was studied in HFSS using a plane wave excitation method described in Ref. [11]. Understanding where beam induced power is directed and how to protect elements like power amplifiers is essential. Initial estimates show that at 1 GHz, the power induced upstream to downstream is 1 to 300. Fortunately, most power is directed downstream, i.e., not towards the power amplifiers. When the specific port design is chosen, additional computations with a time domain transient technique will be necessary to verify these results.

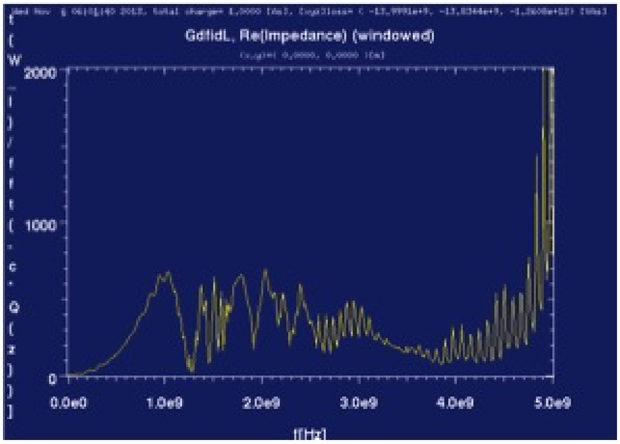

Figure 4: Longitudinal transverse impedance of the slotted kicker with longitudinal ports.

POWER ESTIMATES

Since the bandwidth being covered for this application is so broad, power amplifiers with 1 GHz bandwidth and power range from 100 – 500 W are also necessary. Active search and evaluation for power amplifiers with instantaneous bandwidth, 100% amplitude modulation, and linearity across the 1 GHz band is ongoing. For the two kicker systems proposed for the SPS, the array of two 10 cm long striplines and the 1 m long slotline, Fig. 5 shows the transverse deflecting voltage using 500 W amplifiers. For the striplines, 4× 500 W amplifiers are needed to power the system and for the slotline 2× 500 W amplifiers are needed. Where the striplines lack in kick strength beyond 500 MHz, the slotline provides kick response up to 1 GHz.

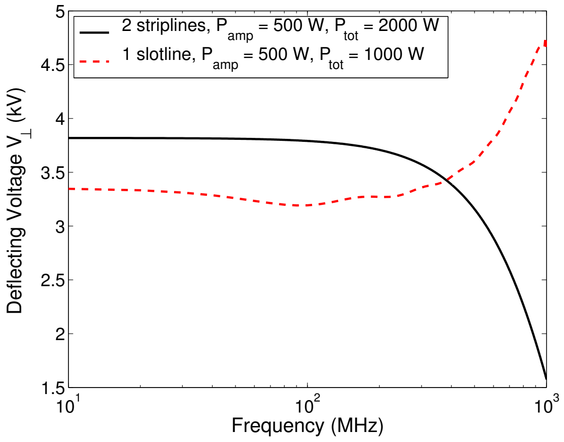

Figure 5: Deflecting voltage of the proposed kicker systems in the SPS. Note that the stripline array requires 4× 500 W power amplifiers, while the slotted kicker requires 2× 500 W.

SUMMARY

The slotted kicker is an attractive technology to use as an intra-bunch kicker in the SPS. With deflecting voltages of 3 – 5 kV for modest amplifier powers and with bandwidth from near DC up to 1 GHz, it possess the characteristics desired as the backend element of the 4 GS/s feedback system. The design has been refined and is ready for mechanical development and prototyping, both of which are scheduled for this year.

ACKNOWLEDGMENT

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