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

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Abstract

Control and mitigation of transverse beam instabilities caused by electron cloud and TMCI will be essential for the SPS to meet the beam intensity demands for the HL-LHC upgrade. A wideband intra-bunch feedback method is in development, based on a 4 GS/s data acquisition and processing, and with a back end frequency structure extending to 1 GHz. A slotted type kicker, similar to those used for stochastic cooling, has been considered as the terminal element of the feedback chain. It offers the most promising deflecting structure characteristics to meet the system requirements in terms of bandwidth, shunt impedance, and beam coupling impedance. Different types of slotted structures have been explored and simulated, including a ridged waveguide and coaxial type waveguide. In this paper we present our findings and the conceptual design of a vertical SPS wideband kicker consistent with the stay clear, vacuum, frequency band coverage, and peak shunt impedance requirements.

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 4.0 GS/s feedback demonstration prototype has been developed as a potential method to mitigate these intensity dependent effects [2]. First measurements using the new feedback system have been successfully performed this past year 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 has been on going, investigating striplines and cavities [4], and slotted type structures. Striplines characteristically have linear phase response and high shunt impedance at low frequencies. The bandwidth of a stripline can be increased by decreasing the length, but the shunt impedance is reduced. Cavities can provide high shunt impedance at characteristic frequencies,

but are relatively narrowband. This paper details the conceptual models of three types of slotted type kickers with focus on a slotted-coaxial kicker, which exhibits desirable characteristics in bandwidth and shunt impedance.

The transverse kicker must be able to provide kick deflections of the order of 10^{-5} $\frac{eV \cdot s}{m}$ over a bandwidth up to 1 GHz to mitigate such Ecloud and TMCI effects. Factors such as these and beam stay clear requirements 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 in keeping the beam coupling impedance at a minimum.

The geometry of the structure can be tuned in such a way as to yield the necessary bandwidth. The slotted-type kicker geometries evaluated in this study are similar to those used for stochastic cooling of Refs. [5] and [6]. The slotted-waveguide kicker consists of a waveguide coupled to a beam pipe via slots and is most similar to that of Ref. [6]. The slotted-ridged waveguide is an extension of the slotted-waveguide kicker, with a ridge incorporated to the waveguide to concentrate the field in the ridge region. The slotted-coaxial kicker resembles that of Ref. [5], having a coaxial transmission line within the waveguide. Figure 1 shows 1/4 geometrical models of the three slotted type kickers explored.

SHUNT IMPEDANCE

The transverse shunt impedance is defined as [7]

$$R_\perp T^2 = \frac{V_\perp^2}{2P} \qquad (1)$$

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. The transverse voltage for a vertical kick is calculated using the following expression

$$V_\perp = \left| \int_0^L [E_y(z) + cB_x(z)] \, e^{\frac{j\omega z}{\beta c}} \, dz \right| \qquad (2)$$

where the beam propagates in the z-direction, $E_y(z)$ and $B_x(z)$ are complex fields in the vertical and horizontal directions, respectively, $e^{\frac{j\omega z}{\beta c}}$ accounts for the beam transit time and has positive argument since the electromagnetic
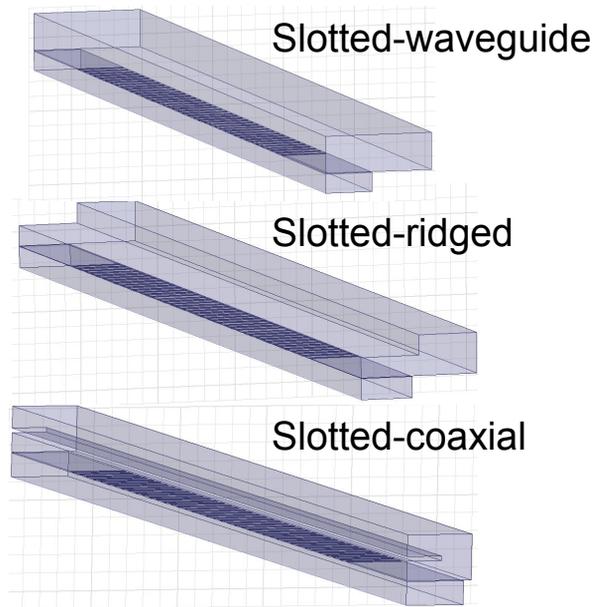
Figure 1: Quarter model geometries of the three slotted type kickers evaluated in this study.

Figure 2: Transverse shunt impedance calculations for the three variations of the slotted type kicker. The slotted-coaxial kicker shunt impedance is plotted for two different slot lengths (SL).

Figure 3: Phase of the transverse voltage. Color and symbol coding reference is the same as in Fig. 2.

field co-propagates with the beam, and L is the length of the structure. The structures were modeled and the fields were generated by modal numerical simulations performed in HFSS [8] at frequencies in the operating band. Upon integrating the fields along the beam trajectory, $V_\perp$ can be computed and subsequently $R_\perp T^2$ for a constant input power.

Figure 2 shows the transverse shunt impedance for the three slotted type kickers. The slotted-waveguide kicker exhibits the most narrowband response with a peak in shunt impedance at about 950 MHz. Introducing a ridge into the waveguide slightly increases the bandwidth and shifts the operating point to lower frequency, peaking at about 800 MHz. The peak shunt impedance is down by about a factor of two (or 6 dB). Arguably the most interesting of the three structures is the slotted-coaxial kicker. It has extremely wide bandwidth response spanning from nearly DC to greater than 1200 MHz for the 80 mm slot length case. The shunt impedance is significantly reduced for this kicker, 5 kΩ for an 80 mm slot length case at low frequencies, but remains at reasonable levels. With a shunt impedance of 5 kΩ, we estimate the peak power needed to be about 600 W total or 300 W per top and bottom waveguide in order to generate a transverse momentum of $5 \times 10^{-5} \frac{eV \cdot s}{m}$ to drive the beam.

Since the transverse voltage, $V_\perp$, is complex its phase response has important implications for the overall transfer function of the feedback system. As shown in Fig. 3, the slotted coaxial kicker has linear phase response at low frequencies as compared to the slotted-waveguide and ridged kickers. The linearity deviates as the frequency approaches the peak in the shunt impedance, which corresponds to about 1000 MHz for the 80 mm slot length case.

The dimensions of the entire slotted-coaxial kicker were parameterized for optimization, maximizing the shunt impedance of the kicker. The periodicity of the slots was explored and showed an optimal slot width to slot spacing (along the beam axis) aspect ratio of about 1 to 1. For a fixed 1 m long structure of 40 slots, the number of slots were doubled to 80, which increased the shunt impedance by about 25%. This could be a method to increase the shunt impedance further, if necessary (at the expense of increased beam coupling impedance). The uniformity of the fields and ultimately the kick were explored by computing the shunt impedance off axis. For a beam trajectory 20 mm horizontally off axis, the shunt impedance was reduced by 40% in the 80 mm slot length case. Further studies include simulating a more realistic model by adding coaxial power coupling ports, which must match the stripline within the waveguide to the external 50 Ω system.
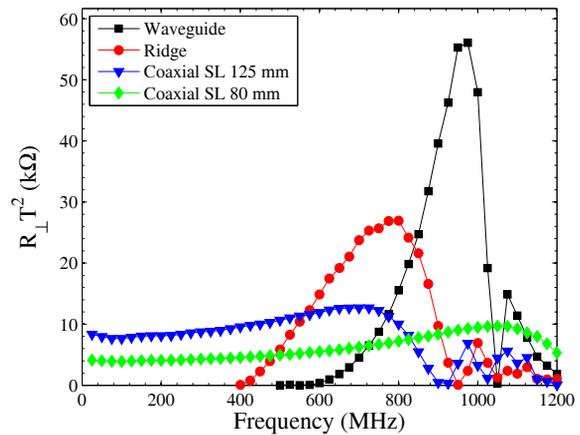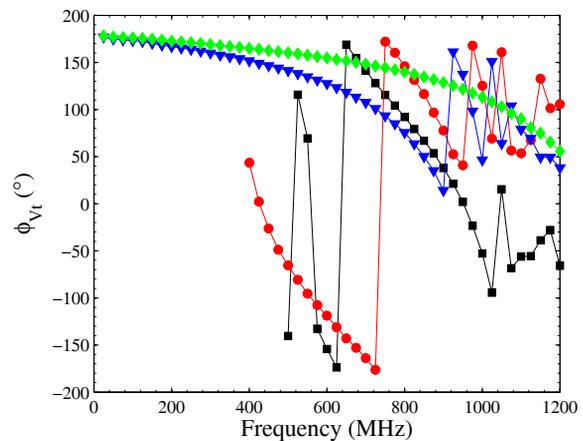
BEAM COUPLING IMPEDANCE

In order to evaluate the contribution of the slotted-coaxial kicker (80 mm slot length) into the overall SPS impedance budget, we have carried out numerical simulations with GdfidL [9]. We found that for the perfectly matched coaxial waveguides, both longitudinal and transverse impedances remain essentially broadband (without very narrow HOM-like peaks) until rather high frequencies. As an example, Fig. 4 shows the real and imaginary transverse impedance components, Z_y, of the slotted kicker. The broadband kicker impedance is expected to be
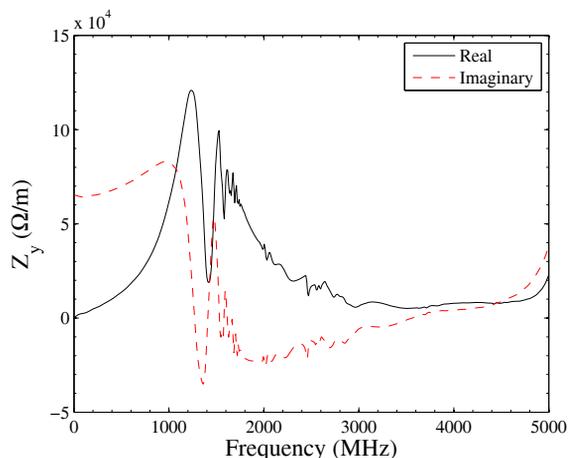
Figure 4: Real and imaginary parts of the transverse beam coupling impedance for the coaxial slotted kicker with a slot length of 80 mm for a simulated beam transverse offset of 4 mm.

a small fraction of the total SPS impedance. For example, the estimated transverse broadband impedance is less than 150 kΩ/m, to be compared with 8 – 9 MΩ/m, which is the contribution of all other installed SPS kickers.

The resulting wake fields decay very fast. For shorter bunches than the nominal ones, the wakes almost disappear before the arrival of successive bunches (blue vertical line corresponding to 25 ns bunch spacing), as seen in Fig. 5 for the case of the longitudinal wake, W_z. This helps in avoiding harmful multibunch effects such as conventional multibunch instabilities and a power loss enhancement due to interaction with higher-order modes.

SUMMARY

The bandwidth and shunt impedance characteristics of three slotted type kickers have been presented for consideration as a transverse kicker for the SPS feedback project. Among the three, the slotted-coaxial kicker stands out for its wideband coverage, high shunt impedance, and nearly linear phase response below peak frequency. A kicker with these characteristics could be used alone and would not require another type of device to be used in conjunction with it, as would be required with a stripline or cavities [4]. Beam coupling impedance simulations show that
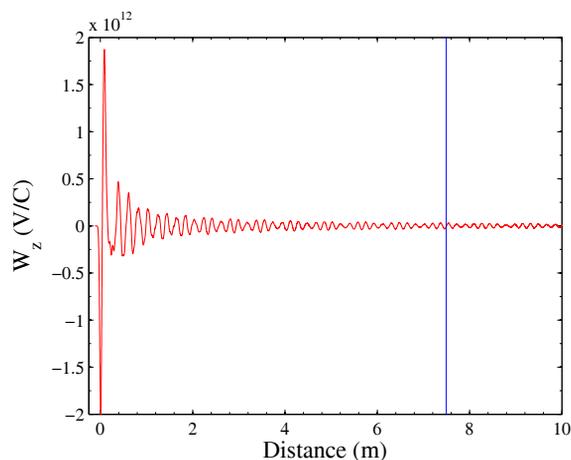
Figure 5: The longitudinal wake potential of a 2 cm long bunch. The blue line marks the 25 ns bunch separation.

the addition of the slotted-coaxial kicker to SPS would contribute a fractional amount to the overall transverse kicker impedance of the SPS. Studies are on going for a more detailed design of the slotted type kickers.

ACKNOWLEDGMENT

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