DESIGN A FAST KICKER FOR SPEAR3 PSEUDO SINGLE BUNCH OPERATION[*]

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Abstract

Stripline kickers are widely used in particle accelerators. This paper presents the design of a fast stripline kicker operating at 1.28 MHz to enable pseudo-single-bunch mode in SPEAR3. The combination of the required kick strength and the high repetition rate creates significant challenges, primarily beam-induced heating of the kicker structure. The physics and mechanical designs were optimized to mitigate these effects. The final design approach and key performance considerations are discussed.

INTRODUCTION

SPEAR3 is a third-generation electron storage ring that provides a stable stream of intense x-rays for a large user community. To meet the needs of both timing and high-brightness users, SPEAR3 operates with a hybrid filling pattern in which a camshaft bunch is placed in a timing gap that is long enough for timing users to apply gated data acquisition. To further improve timing performance, we are developing pseudo single bunch (PSB) operational modes [1–4] to provide spatial separation between the main bunch trains and the camshaft bunch by applying a kick to the camshaft bunch with a dedicated fast kicker.

The kicker geometry must satisfy accelerator physics requirements for beam impedance and field quality and therefore requires optimization. The two kicker electrodes will be driven by two high-voltage pulsing power supplies in push–pull mode: one with a positive pulse, the other with a negative pulse. The pulser must supply high voltage when the camshaft bunch is inside the kicker and approximately 0 V when the remaining bunches pass through. At a repetition rate of 1.28 MHz, the average pulser power is at the kW level. Therefore, limiting heating of the structure, especially the electrodes, is a primary design concern.

PHYSICS SPECIFICATION

Kick Angle: The kick angle required from the PSB kicker is 85 μrad. Accounting for cable loss in the pulsing power supply, the specified maximum kick is 120 μrad, which corresponds to an electrode length of 90 cm, kick voltage of 1.6 kV, and an electrode separation of 15 mm.

Loss Factor k_l: We aim to keep the kicker contribution below $0.3\,\mathrm{V\,pC^{-1}}$.

Transverse Impedance: The horizontal and vertical coupled-bunch instability (CBI) thresholds for SPEAR3, considering radiation damping only, are $Z_x = 0.3\,\mathrm{M\Omega\,m^{-1}}$ and $Z_y = 0.5\,\mathrm{M\Omega\,m^{-1}}$.

Longitudinal impedance: The longitudinal CBI threshold is frequency-dependent; for SPEAR3 it is about 8.3 kΩ at 3 GHz and about 2.5 kΩ at 10 GHz.

Beam Stay Clear: Due to the high kick strength and reduced aperture, the beam stay-clear (BSC) requirement must be satisfied at the installation location. The vertical and horizontal values are $Y_{\mathrm{BSC}} = 4\,\mathrm{mm}$ and $X_{\mathrm{BSC}} = 16\,\mathrm{mm}$.

PHYSICS DESIGN

The physics design of the kicker involved multi-step simulations with both 2D and 3D tools. A multi-objective `sddsoptimize` process with a 2D simulation program [6] was used to optimize the characteristic impedance of the main cross section in both even and odd modes to complete the 2D design. Then, for the 3D design of the end transitions, simulations using several codes in the ACE3P suite [7] were carried out at NERSC [8] to balance beam-coupling impedance, loss factor, and RF heating from trapped HOMs.

2D Design

The main goal of the 2D stripline-kicker design is to match the odd-mode impedance Z_{odd} to 50 Ω for efficient power transfer, and to keep the even-mode impedance Z_{even} as close as possible to 50 Ω to reduce beam-coupling impedance. As shown in Fig. 1, after extensive optimization we selected a round chamber. Rib/vane structures are typically used to reduce the even-mode impedance. Flat electrodes were chosen to provide good field uniformity. The relatively large BSC aperture in the horizontal direction makes it challenging to reduce Z_{even}. Comparing with optimized results from other facilities, the design tends to have larger Z_{even} as b/gap increases. A global search found designs with Z_{even} as low as 60.58 Ω; however, many were impractical to manufacture. We selected a design with $Z_{\mathrm{odd}} = 49.9\,\Omega$ and $Z_{\mathrm{even}} = 67.1\,\Omega$.

3D Design

The 2D layout sets the basis for impedance matching, while the 3D design (including the feedthrough and end structures) largely determines the final kicker performance. In 3D, transitions for the chamber, electrodes, and vanes must be designed to minimize beam power loss (loss factor). Beam-coupling impedance, both transverse and longitudinal, is then evaluated for instabilities and beam heating.

In Fig. 2, we illustrate cross sections at different longitudinal positions along the kicker. To reduce the loss factor, the

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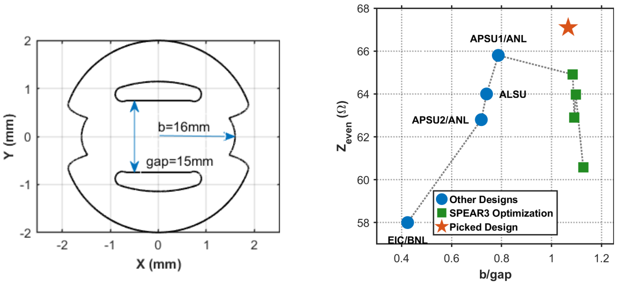

Figure 1: 2D design of the SPEAR3 PSB kicker: cross section of the selected design (left); challenge of matching Z_{even} with large b/gap (right).

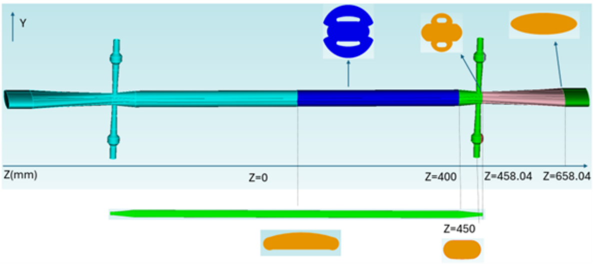

Figure 2: 3D design of the SPEAR3 PSB kicker.

end transitions should shield geometric discontinuities, especially those associated with the electrodes. In the first design iteration, we shielded the electrode using an end cap (Fig. 3). This helps reduce the loss factor when the gap between the electrode and chamber is sufficiently small. For example, with a 1 mm gap, the loss factor is about $0.11\,\mathrm{V\,pC^{-1}}$. However, the small gap increases manufacturing complexity and is less practical. When the gap is larger than 1 mm, the shielding cap provides less reduction in loss factor, and the smaller vertical aperture can also lead to trapped HOMs. After comparing the results, we decided not to use the shielding cap in the design.

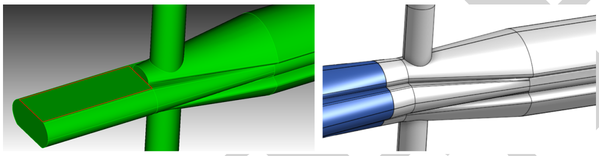

Figure 3: Kicker transition design with end cap (left) and without end cap (right).

Loss factor

The main short-range wakefield effect is characterized by the longitudinal loss factor in the time domain, which can be calculated using T3P. Because the kicker aperture is smaller than the beam pipe, indirect wakefield integration is no longer applicable. Direct integration is used instead, which requires a longer beam pipe to account for wakefield catch-up. As shown in Fig. 4, after extending the downstream beam pipe by 600 mm, the results converge and the loss factor is $0.207\,\mathrm{V\,pC^{-1}}$, which is acceptable.

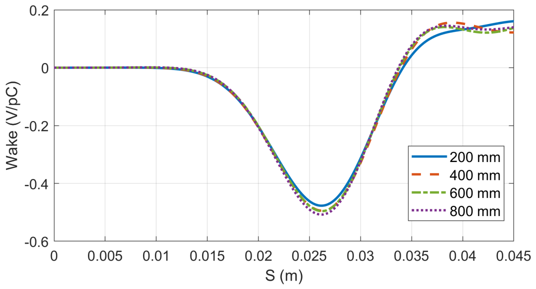

Figure 4: Short-range wakefield simulation results with direct integration using T3P using nonimal bunch length of 6 mm.

Trapped HOM Modes

Trapped HOM modes can cause beam instabilities; therefore, both dipole and monopole modes were examined to ensure their impedances are below the instability thresholds. We calculated the beam impedance using frequency-domain simulations to solve for all supported modes. As shown in Fig. 5, the impedances of all horizontal modes are below $0.1\,\mathrm{M\Omega\,m^{-1}}$, well below the $0.3\,\mathrm{M\Omega\,m^{-1}}$ threshold. For vertical modes, all are below $0.3\,\mathrm{M\Omega\,m^{-1}}$, satisfying the vertical limit of $0.5\,\mathrm{M\Omega\,m^{-1}}$. Monopole modes can contribute to longitudinal instability and RF heating since the beam loses energy to these modes. Simulation results in Fig. 5 shows that the impedance of most monopole modes up to 12 GHz is below 500 Ω. Two modes near 6.5 GHz have impedances of 1.4 kΩ and 870 Ω, respectively. They are not expected to limit beam stability, but they are potential sources of beam heating.

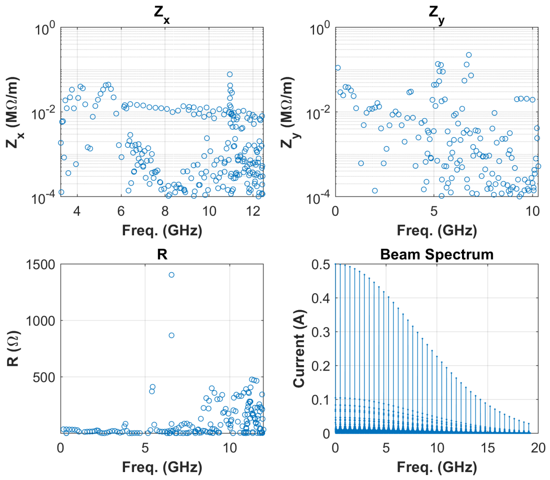

Figure 5: Beam-coupling impedance of the HOM modes: Horizontal Dipole Modes (top left); Vertical Dipole Modes (top right); Monopole Modes (bottom left); Beam Spectrum for SPEAR3 normal operation.

Electrode heating

A major concern for the PSB kicker is overheating of the electrodes. There are four heating sources. The first is the pulsing power supply. In many accelerators, a stripline kicker either operates at high voltage and low repetition rate (e.g., injection kickers, typically below 10 Hz) or at high repetition rate and lower voltage (e.g., feedback kickers). In contrast, the PSB kicker operates up to 1.28 MHz and 1.6 kV, so pulser-related heating is not negligible and depends on the pulse shape. With the current pulser design (about 60 ns pulse width), the average power of each HVPS is about 3.2 kW, and the resulting conductive loss is about 1.1 W per electrode. The second source is conductive loss from the image current when the electron beam passes through the kicker. Using a simplified model of the SPEAR3 filling pattern and assuming the aluminum skin depth at 8 GHz, the estimated heating from image current is about 1.06 W per electrode. The third contribution comes from short-range wakefields, a geometric effect that causes beam power loss. The numerical solution of the fields on the electrode surfaces in the time domain was used to estimate this heating, with uncertainty due to the skin depth. The result is about 2 W per electrode. The last contribution is from trapped monopole modes. To estimate this, we assume a Lorentzian distribution for the trapped monopole-mode impedances calculated in Fig. 5; multiplying by the quare of the beam spectrum gives the power spectral density of the modes. Integrating yields the frequency-range-dependent average power. Using the O3P eigenmode solver, we calculated the corresponding average power loss on the electrodes, as shown in Fig. 6. For the nominal design, the total HOM-related electrode heating up to 12 GHz is about 1 W per electrode. However, manufacturing tolerances can shift the mode frequencies. Assuming a ±0.2% frequency error for each mode and scanning for the worst case, the HOM contribution can reach up to 4 W per electrode. Adding all four contributions, the total heating is about 5.16 W per electrode for the nominal model and can reach about 8.16 W per electrode in the worst-case tolerance scenario. At 5 W per electrode, the hottest spot is estimated to reach about 60 °C, which is acceptable. This shows the importance of quantifying the impact of manufacturing tolerances on electrode heating. Studies of electrode misalignment and sag are in progress.

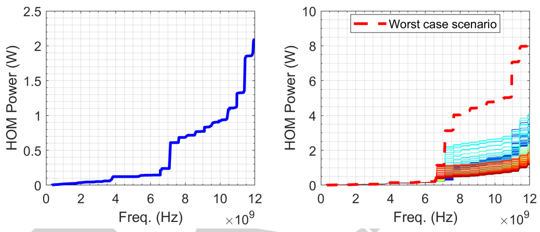

Figure 6: Total HOM power loss on two electrodes: ideal model(left); assuming frequency errors on each HOM mode(right).

MECHANICAL DESIGN

The kicker will be installed as a retrofit in the reconfigured straight section, as shown in Fig. 7. The design goals are a robust structure, reliable feedthroughs, a serviceable assembly approach to facilitate repair and upgrades, and a conservative electrode-cooling strategy. The chamber is a three-segment assembly with an overall length of 1019 mm, including the transitions. The electrode is a single piece with a length of 900 mm. The same type of feedthrough used for the BxB feedback kicker is adopted. Several viewports are included to monitor the electrodes. The mechanical design is still being finalized; current work focuses on electrode heating and the impact of manufacturing tolerances based on the RF-simulation results.

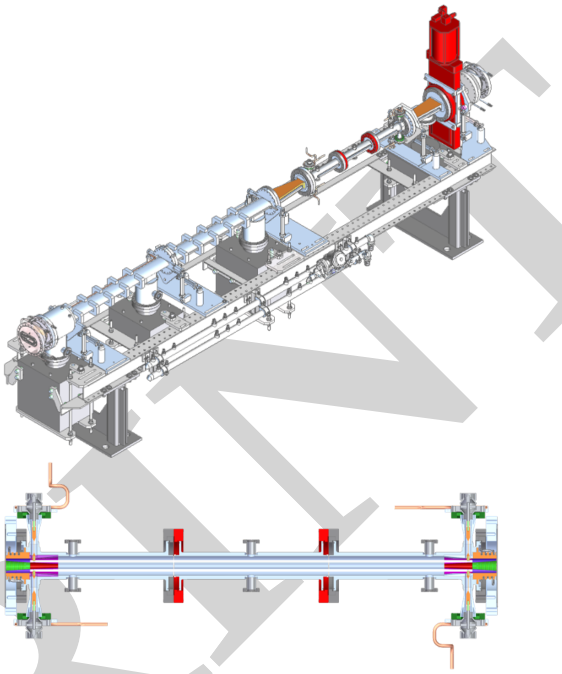

Figure 7: Mechanical design of the kciker: retrofit to the straight section (top) and the kicker deisgn(bottom).

CONCLUSION

A fast stripline kicker has been designed for pseudo-single-bunch operation in SPEAR3 at 1.28 MHz. The 2D and 3D electromagnetic designs were optimized to meet the required kick strength while controlling beam-coupling impedance and loss factor. Simulations indicate transverse and longitudinal impedances below SPEAR3 instability thresholds, while a few trapped monopole modes may contribute to heating. Electrode heating estimates give about 5.16 W per electrode nominally and up to 8.16 W per electrode in a worst-case tolerance scenario. Ongoing work focuses on finalizing the mechanical design and quantifying tolerance and alignment impacts.

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