Abstract

Two identical fast beam kicker systems (FWHM ~ 2 μs) were installed at Hall C beam line girder 3C07 and 3C15. These systems provide versatile beam kick functions such as triangle (linear) and wedge shapes to generate few mm vertical beam excursion on Möller iron foil target [1]. The kick frequency, kick base width, and the length of flat top of wedge pulse can be independently adjusted by the kicker control electronics in Hall C counting house. Those functions are used to minimize the equilibrium temperature rise of Möller target below 100°k under 80 μA beam in order to guarantee the 1% accuracy of polarization measurement. This report introduces the basic principle of power electronics, the kick magnet, the operational procedure and the instruction of system calibration.

1. Linear power driver – the half H-bridge with dual trigger system

Evolved from continuous linear triangular current reciprocating of the target raster to an intermittent linear triangular current burst for kicker, the simplest way is to use half H-bridge as a re-triggerable one shot as shown in Figure 1 for an intermittent operation. As the trigger pulse comes, the half H-bridge is conducting. The current through the magnet increases with the function like \( (1 - e^{-t/\tau}) \). The time constant \( \tau = L/R \), here \( L \) is the inductance of the magnet plus parasitic loop, \( R \) is the serial DC resistance from upper shoulder through lower shoulder. As \( T_{1/2} \ll \tau \), \( \tau \) typically in this case is about 24 μs, the waveform of ramp up waveform is approximately linear. After current reaches the level of \( V/R \) (\( V \) – the voltage of power supply), it ramps down with the same slope to zero baseline level.

Due to the existence of parasitic inductance surround kicker magnet, a damping current oscillation appears at the end of ramping down interval. For a 2.9 μH magnet, the number of damping ripple is about 9. In order to eliminate the undesired ripple, a second trigger should be applied to force the bridge shutdown immediately. The time interval between the 1st trigger and the 2nd trigger is roughly equal to the starting point of the 1st ripple. In this way, the excitation current of kicker magnet are forced stays on real zero baseline level after a kick. Beam returns to a truly stationary state.
Figure 2 shows a comparison of current waveforms of free-ended kick with damping oscillation and force-ended kick. It is very clear that with assistance of the 2nd trigger, the damping oscillation completely disappears and the baseline of kick current could be immediately restored to zero level. Figure 3 shows the flexibility of kick waveform adjustment. Upper is triangular current burst by setting top width zero. Lower is a stretched wedge shape waveform. The top is approximately flat with a slow tilt slop. It makes beam stay inside the target foil for a while. Two identical HP8013B pulse generators are connected in master-slave configuration. The shape of kicker current is finally determined by four adjustable parameters - the widths of two trigger pulses, the time delay between two generators, and the frequency of the master generator.

2. Kicker magnet

The two kicker magnets were installed on 3C07 granite table and 3C15 G-10 girder as shown by the photos in Figure 4. G0 experiment is going to run 80 μA beam in 2006, Qweak requests 180 μA beam in 2008. Based on the thermal equilibrium calculation on iron foil Möller target, the kick base width should be in the order 2 ~ 4 μs, ie. FWHM ~ 1 ~ 2 μs. The significant difference between kicker and target raster magnet is the inductance. The original 12 turn FR magnet (88 μH) and a modified 6 turn Litz magnet (22 μH) were used for primary kicker function test in 2003 and 2004. The presently installed G0 kicker magnet is a bedstead shape four turn magnet made by silver plated solid copper strips with thickness 0.125". The net inductance is about 2.9 μH. To reduce the space distributed parasitic inductance, the power leads of kicker magnet consists of a tightly bonded parallel AWG #6 Litz cable. The cable contribution to the global inductance is about 0.323 μH. The total inductance measured at output connector of H-bridge is about 3.223 μH.

Two kicker magnets were mapped in magnet group in 07/08/2005. The mapping data showed the effective length $L_{\text{EFF}} = 26.031$ cm. $\Delta(Bdl)/\Delta I = 18.738$ Gauss cm per Ampere. The kicker magnets are installed on 1" ceramic duct (physical aperture ~ 1.95 mm). In order to eliminate the induced image current on the wall, the inner wall of the pipe was coated by conductive polymer layers to keep the resistance of flange-to-flange is about 1 M ohm [2].

3. Operational kicker parameters from thermal equilibrium calculation

The basic calculation of kicker operational parameters can be found from report [5]. The major constraints can be summarized as:
- From the condition of original Møller polarimeter operation under stationary beam [4], the beam current to run Møller measurement is about 1 μA. For Møller + kicker system, we should keep \( I_{\text{average}} = \Delta t_{\text{kick}} \times f_{\text{kick}} \times I_{\text{beam}} \approx 1 \text{ μA} \), where \( \Delta t_{\text{kick}} \) - average kick width, \( f_{\text{kick}} \) - kick frequency, and \( I_{\text{beam}} \) - applied beam current.

- Beam deposit power in Møller target \( P_1 \) [watt] = \( I_{\text{beam}} \) [μA] \( \times \Delta E \) [MeV], electron energy loss in target \( \Delta E = (dE/dx) \ dx \), here \( dE/dx \) is stopping power of iron target = 1.48 MeV/(g/cm²), \( dx \) the thickness of target (1 μm), \( I_{\text{beam}} \) - applied beam current (80 μA for G₀ experiment). \( ρ \) - the density of iron (7.87g/cm³). \( P_1 \approx 0.093 \text{ W} \).

- Cooling power by target frame \( P_2 = -k \times A \times \Delta T/\Delta x \). Here \( k \) – thermal conductivity of iron (0.73 w/(cm x °K)). \( A \) – contacting area between foil and frame boundaries. In equilibrium \( P_1 \times t_1 = P_2 \times t_2 \), \( t_1 \) – stay time inside the foil and \( t_2 \) the time beam keeps away from target. At least \( t_2 \gg 5t_1 \) is the primary condition of equilibrium.

- The maximum retention period of 80 μA beam inside the foil target is determined by the temperature rise rate \( \Delta T/\Delta t = P_1 \) [watt]/(\( C_ρ \times ρ \times V \)), where \( P_1 \) is beam deposit power, \( C_ρ \) the specific heat of iron (0.448 Joule / (g°K)), \( ρ \) the density of iron, \( V \) the volume of conductor (beam size x thickness of foil). In order to restrict depolarization caused by beam heating below 1%, the equilibrium temperature rise should be less than 100 °K [4].

Let us combine the information from above calculations, to run 80 mA beam on 1 μ planar iron foil target, the kick frequency is about 5 kHz while 2 μs FWHM kick pulse is established.

4. Description of system adjustment procedure

The control electronics was installed in the raster rack of Hall C counting house as shown in Figure 5. Figure 6 shows the two kick current waveforms from kicker 3C07 and 3C15 were displayed on the oscilloscopes together with gate signals. Several adjustable vernier knobs on panels of two Tektronix pulse generators are marked with the function of adjustment.

“Frequency” (frequency vernier of the master generator) – determine kick frequency which is displayed by the frequency counter below oscilloscopes.

“Shape” (pulse width vernier of the master generator) – determine the base width of kick burst. It controls the arriving time of peak current to set up desired base width (for example 4 μs for G₀ and 2 μs for Qweak).
“Top Width” (pulse delay vernier of the slave generator) – determine the width of top of kick burst, control the width of either triangular or wedge kick burst.

“Baseline” (pulse width vernier of the slave generator) – Control pulse width of second trigger, eliminate ripples and restore baseline to zero level.

5. Determination of kick direction

A Pearson current sensor is inserted between kicker magnet and the lower shoulder of H-bridge. On the probe the arrow direction indicates a positive output for electron current. When a positive kick pulse is observed from Pearson probe, a reversed path should be positive current as shown in Figure 7. The current path through the winding is anticlockwise. The field direction points outwards (against tunnel wall). In this way, the bending direction for electron beam is upwards.

6. Maximum operational parameters

The limit of setting operational parameters come from two constraints: The maximum output power of high voltage unit and the amplitude of high voltage spikes which appear at source and drain of power MOSFETs. The HV unit is rated by 500V 250 mA. So the major limit comes from HV spikes.

A series of snubber chains are connected between all sources and drains of all MOSFETs. Due to the parasitic inductance of circuit mechanical configuration, specially at an equivalent high frequency domain (narrow pulse width ≈ 2 μs), it is very difficult to suppress HV spikes effectively. The maximum height of spikes is almost about one third of applied voltage. For G0 application, the HV limit is set at 100V. No hardware control is designed for limitation of applied HV unit. I suggest all Möller operators and Hall C users should remember this value during manual adjustment procedure.

The maximum output current of HV unit is determined by kick frequency, base width, and top length of kick burst. The HV unit will automatically hold when HV current is equal or greater than 250 mA.
7. System calibration procedure

- From mapping data of kicker magnet, find the $\Delta(Bdl)/\Delta I = 18.738$ Gauss cm/A
- From beam line optics [5], $\Delta(Bdl)/\Delta y = 100$ Gauss cm/mm
- From Dynamic calibration of 4 turn magnet and the power driver (for triangular kick burst only), we found $\Delta I_{\text{PEAK}} / \Delta V_{HV} = 0.535$ A/V
- Finally, we have $\Delta V_{HV}/\Delta y \approx +10$V/mm (+ means kick up).

Figure 8 is a block diagram of system configuration.

8. References

[1] Chen Yan, Jlab-TN-04-002, 02/19/2004
[5] Jay Benesch, E-mail communication, 12/06/2005

9. Figure captions

Fig. 1 The principle circuit configuration of half H-bridge kick magnet power driver electronics
Fig. 2 Comparison of the current burst waveforms of free-ending kick and a forced-ending kick.
Fig. 3 With dual trigger system either triangular kick current burst or Wedge shape waveform can be obtained by adjusting the 4 Operational parameters.
Fig. 4 Photographs of $G_0$ kicker magnets on the 3C07 granite table (upper) and on the G-10 girder 3C15 (lower).
Fig. 5 Photograph of control electronics installed in Hall C counting house
Fig. 6 Kick waveforms displayed on Tektronix oscilloscopes in Hall C Counting house
Fig. 7 Sketch of cable connection for verification of beam kick direction
Fig. 8 Block diagram of $G_0$ kicker system
Figure 1. The principle circuit configuration of Half H-bridge kicker magnet Power driver electronics
Figure 2. Comparison of free-ending and forced-ending kick current bursts.
Figure 3. With dual trigger system either triangular kick current burst or wedge shape waveform can be obtained by adjusting the 4 operational parameters.
Figure 4. Photographs of G2 kicker magnets on 3C07 superharp granite table (upper) and 3C15 G-10 girder (lower).
Figure 5. Control electronics installed in Hall C counting house

Figure 6. Kick waveforms displayed on Tektronix oscilloscopes in Hall C counting house
Figure 7. Sketch of cable connection for verification of beam kick direction.
Figure 8. Block diagram of G, kicker system.