LATEST RESULTS ON FAST KICKER FOR g-2 E-989 EXPERIMENT AT FERMILAB

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Abstract

We describe the latest results on fabrication and measurements of the injection kicker and pulser for the E-989 experiment at Fermilab for precision measurement of the anomalous magnetic moment of the muon.

OVERVIEW

In [1] we described the concept of the kicker magnets and current source for E-989 experiment at Fermilab. This E-989 experiment-[2] is a refinement of earlier E-821 experiment [3-5], that was performed at BNL to measure the anomalous magnetic moment of the muon $a_\mu=(g_\mu-2)/2$ where g_μ is the gyromagnetic ratio, $\vec{\mu}_\mu = g_\mu (e/2m)\vec{s}$, and $\vec{s}$ is the muon spin, with accuracy 0.54 ppm. At the muon "magic" momentum, 3.09GeV/c, the contribution of the spin precession from electric fields is synchronized with the cyclotron motion, so that the difference frequency is independent of the fields of vertically focusing electrostatic quadrupoles.

The (g-2) storage ring was moved from BNL and reassembled at Fermilab in the newly constructed MC-1 building, in preparation for the next-generation experiment E-989. The aim of the new experiment is to reduce both statistical and systematic errors for a measurement of the anomalous moment with an accuracy of better than 0.14 ppm, see Table 1.

Muon capture efficiency and amplitude of the coherent betatron oscillation of the stored beam depends on the performance of the injection kicker, see Fig. 1. Better capture efficiency reduces statistical errors, and smaller coherent betatron oscillations (CBO) to reduction of an important systematic measurement error.

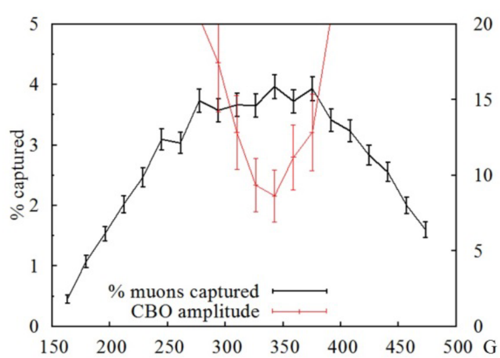

Figure 1: Dependence of capture efficiency and CBO amplitude on kicker field, Gauss.

A key component of the system is the kicker pulser, which provides the drive current to the kicker plates and the magnetic field over the storage volume required for a single-turn injection into the muon storage ring [6]. We have chosen a Blumlein-type pulser for these purposes.

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SYSTEM REQUIREMENTS

The muon beam enters the storage volume from through an inflector magnet. The beam emerges from the inflector magnet displaced tangentially 77mm from the center of the storage volume. The trajectory of the injected muons crosses the 7.11m radius design orbit at an angle of 10.8 mrad, ¼ betatron wavelength downstream from the inflector exit. The integrated 1.11 kG-m vertical field of the three 127cm long kicker magnets steers the beam onto the closed orbit.

The duration of the muon pulse is anticipated to be 120ns. Ideally, the kicker pulse turns on and off within a revolution period (149ns), so that muons are not kicked again on their second circuit. The muon pulses are extracted from the delivery ring at peak repetition rate of 100 Hz in two eight-pulses trains and 12Hz average, a rate that informs the specifications of the pulser power supply and charging electronics The required rise and decay time of the current pulse indicate a low impedance single turn magnet. The geometry of the magnet is chosen to maximize efficiency of converting current to field over the 9cm diameter storage volume.

NUMERICAL MODEL

3D codes were used to model the time dependence of the kicker field, when the skin depth is much less, than the thickness of the electrodes. We launched a full 3D time dependent analyses with FlexPDE and CST studio. Severe limitations for the stray field level <0.1 ppm, forced careful modeling of the problem. Calculations show that the current of 1 kA running in the kicker plates generates field $B \cong 65G$, (i.e. 65G/kA) at the center of chamber. The presence of the surrounding conducting surfaces drastically reduces the field/current ratio. Allegro/Cadence software was used for modeling the charging of the Blumlein and the pulse shape.

BLUMLEIN

The tri-axial Blumlein inner sections are joined with 1" long threaded cylindrical collars. The space between the conductors is filled with Castor oil, with permittivity $\varepsilon_r \approx 4.4$ within the relevant frequency range. The volume of the innermost tube was filled with polyurethane foam to displace any oil that leaks through the sealed threads. Each Blumlein is assembled from six 60"-long identical aluminum sections. The outer tubes with 6" OD, are connected with 8" aluminum flanges, Fig 2. For circulation of Castor oil in a line for cooling purposes an individual oil pump is appointed for each Blumlein.

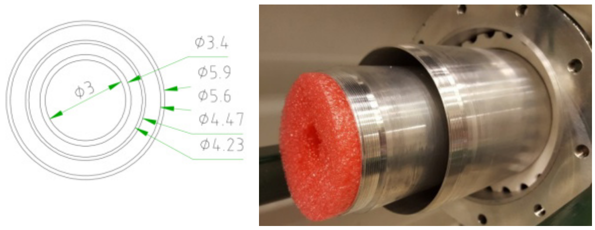

Figure 2: Blumlein tubing (Al). Dimensions are given in inches. Flanges are 8” in diameter. Sections are joined by 10 bolts evenly distributed at 7” diameter. Inner tubes are joined by 1”- long threaded strip-like collars. The Macor insulator that separators the conductors is visible inside.

Table 1: Muon Ring Parameters

Muon momentum [GeV/c]	3.09
R[m]	7.112
Index n	0.139
Qx, Qy	0.927; 0.373
β_x, β_y, η_x [m]	7.67, 19.1, 8.26
x_{max} , x_{min} [cm]	+4.5, -4.5
Energy aperture [%]	0.545
Offset at inflector exit [cm]	7.6

The tubing with the dimensions indicated in Fig. 1 yield to an impedance of 6.25Ω between adjacent conductor pairs (if the space is filled with Castor oil). The integrated field of 1.1 kG-m corresponds to 291G in each of the three 127cm long kickers. The required current is 291G/(65G/kA)= 4.5kA. The system was tested up to 5 kA to ensure adequate overhead. Loading resistors are shown in Figs. 3, 4.

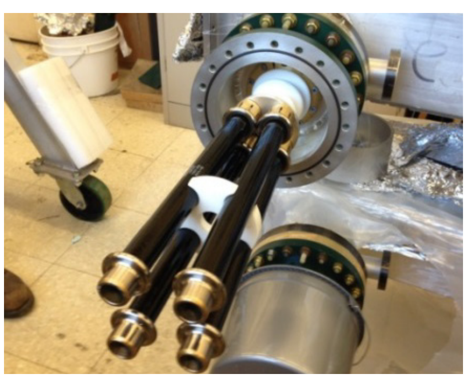

Figure 3: The Kicker input. Four load resistors are Kanthal tubular resistors, 50Ω each. Cylindrical protective cover removed. Inner volume is filled with Fluorinert FC-40.

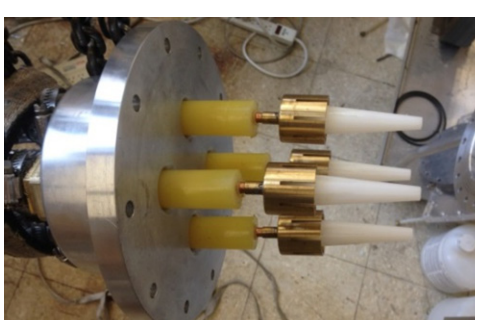

Figure 4: End of transmission line. Conical fingers serve for capturing theirs own resistor from Fig. 3 during insertion.

THE KICKER PLATES

One technical complication is the necessity to accommodate the trolley that carries the 17 NMR probes for measuring the field distribution in the beam aperture in vacuum, Fig. 2 (from time to time). Other requirement is that the kicker and all associated parts should not be magnetic. The outer diameter of the cartridge is ~90mm, with length ~500 mm, weight ~2kg. It travels on 18 wheels (total). The shape of the electrodes allows free passage of the cartridge between the kicker plates (see Figs. 5,6). The height of plates is ~5cm (see Fig. 5).

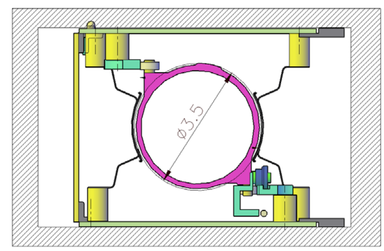

Figure 5: E-989 kicker cross-section. The NMR cartridge profile in measuring position is shown also. Diameter of circle is ~89 mm (3.5”).

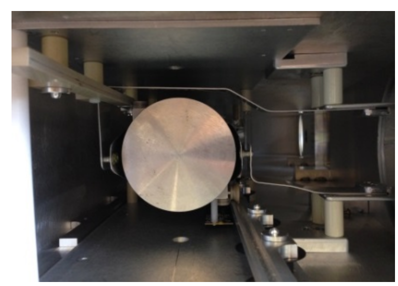

Figure 6: NMR cartridge is running on the rails between the kicker plates. Input jumper is visible at the top.

The current input is arranged at the upstream end of the plates, as shown in Fig. 6. This was done as the generator creates *negative* voltage at the output (μ^+ injected from outer radius). To reduce the current induced in the trolley rails, they made as 5” long sections. The rails near the jumpers are made from Peek and others from Aluminum. The kicker itself acts as a shorted loop, where the magnetic field is established after the wave front of feeding current travels to the shorted (downstream) end and back to the input. The length of each of the kicker plates is 50” (≅ 127cm). The width of the vacuum chamber in Figs. 5,6 is varies along the length of the kicker, and so does the impedance of the stripline.

THE CHARGING PULSER

For charging the Blumleins we appointed a system with an individual HV transformer for each Blumlein. The HV transformer ratio is 85 and the transformer is immersed in Corning 561 Silicon oil in the same cylindrical tank that was used in E-821. An electrostatic capacitive HV divider (Pearson VDE-305A) with coefficient 1:5000 to monitor voltage on the secondary and current monitor (Pearson P-411) 0.1V/A to measure secondary current are mounted inside the oil tank. The primary current derives from the

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discharge of a capacitor bank 5x50 μF with a PRX 2N4367 thyristor. These capacitors are charged by a TDK Lambda 802L power supply and capacitor charging device.

DESIGN AND REALIZATION

As described above the Blumlein generator is realized as a tri-axial line (of concentric conducting tubes). Each coaxial pair has impedance Z_0=6.25Ω so the output impedance of the Blumlein is 12.5 Ω. Four coaxial AA-5966 type 50 Ω cables, arranged in parallel, match the output impedance. The outer diameter of the coax cable is 2.1", allowing of bending it to a desirable shape. Each cable dressed in additional copper braid for reduction of leakage of EM field, Fig. 8. The HV transformer is linked to the Blumlein by an additional HV cable, see Fig. 11.

The thyratron CX1724X is chosen as the commutator. It allows up to 70 kV peak forward anode voltage with maximal current up to 15 kA with the rate of rise 300kA/μs, and a repetition rate limited at 2kHz. The parameters of the pulser are given in Table 2. Due to specifics of the operation of the Blumlein generator, the output voltage coincides with the charging voltage. At the same time, the current running through the thyratron is twice the output current.

Table 2: Parameters of the HV Kicker Pulser

Voltage	62.5kV
Current	5kA
Flat top	70ns
Load impedance	12.5Ω
Rep rate max	100Hz

Figure 7: Charging pulser tower (left), the control tower (center) and the thyratrons PS tower (right).

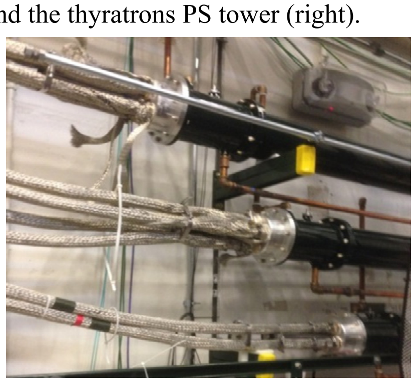

Figure 8: Output side of Blumlein generators.

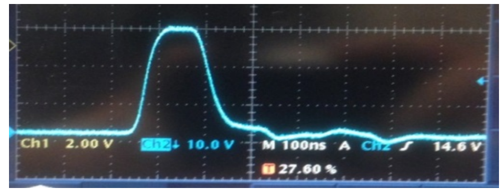

Figure 9: The current measured at the kicker input at Fermilab. 4 kA@max, 100ns/div.

Figure 10: The input into the g-2 ring chamber, kicker #3.

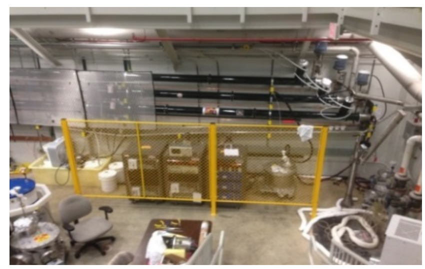

Figure 11: Blumlein generators allocation in MC-1.

SUMMARY

The Blumlein-type generator delivers a flat top pulse of width up to ~100 ns. The three kickers, charging power supplies and Blumleins were manufactured at Cornell, delivered to Fermilab MC-1, and installed in the g-2 storage ring with first tests performed in March 2017, see Figs. 7-11. The signal from a current monitor at the end of the ~10m long cable transmission line (4x50Ω cables) is shown in Fig. 9 corresponding to a charging voltage of 50 kV (administrative limit; at Cornell the system was tested up to 65kV, and 100Hz sequenced by two trains with eight pulses, 12 Hz average). The new kicker allows ~70% increase of kick as compared to the E-821 design with much improved temporal profile.

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