QUANTITATIVE EVALUATION OF MAGNET HYSTERESIS EFFECTS AT LANSCE WITH RESPECT TO MAGNET POWER SUPPLY SPECIFICATIONS *

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Abstract

The proton beam in the LANSCE accelerator is guided and focused almost exclusively by electromagnets. Magnet hysteresis has had significant impacts on the tuning of the LANSCE accelerator [1]. Magnet hysteresis can also have an impact on Magnet Power Supply (MPS) control, regulation and repeatability requirements. To date, MPS performance requirements have been driven by the requirements on the magnetic fields as determined by the accelerator physicists. Taking hysteresis effects into account can significantly change MPS requirements, as some requirements become more stringent and some are found to be over specified. Overspecification of MPS requirements can result in significant increases in MPS cost. Conversely, the use of appropriate MPS requirements can result in significant cost savings. The LANSCE accelerator's more than three decades of operation provide a wide variety of MPS technologies and operational experience. We will survey the LANSCE MPS history and determine how performance specifications can be refined to both reduce costs and improve the operators abilities to control the magnetic fields.

PERFORMANCE REQUIREMENTS

Definition of Requirements

The required performance of the Magnet Power Supply (MPS) systems are quantified in MPS specifications. These specifications are determined by the type of magnet, the performance desired by the beam physicists and the technology available at the time.

The specifications of concern in this paper are: Stability, Regulation and Ripple. These quantify how the current changes with time and external conditions. They are usually defined as a percentage or parts per million (ppm) of the maximum current output.

Stability is defined as the ability of the MPS to maintain a certain output current for a period of time. The time period can range over 12 to 72 hours or as defined by the author of the specification.

Regulation is the ability of the MPS to hold a certain output current during changes in the input line power or the output load. Input line power changes include AC line voltage drift. This drift is assumed to be less than 5% of the line voltage. Load changes come from changes in the magnet coil's resistance which can be caused by magnet cooling water temperature variations. These changes are assumed to be less than 5% of the load resistance.

Ripple is defined as a periodic variation of the output.

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Stability and Regulation are independent of the inductance of the load, but Ripple is not. Ripple is usually specified to the MPS manufacturer as the ripple into a resistive load. Ideally the MPS would be tested at the factory into a load with the same impedance (resistive and inductive) as the magnet to which it will be connected. In most cases this is not practical. The current ripple into an inductive load is commonly assumed to be less than the ripple into a resistive load, but fine tuning of the feedback control loops in the supply after delivery is sometimes required to prevent oscillations. To compare different MPSs driving different magnets, we use the figure for ripple into a resistive load.

History of Requirements

The specifications for the MPSs at LANSCE evolved over the life of the accelerator. Commercially available MPSs with the required performance were available for the lower power magnets in the Low Energy Beam Transport (LEBT) region, and a performance based specifications were used to procure them. The specifications for the steering, quadrupole and bending MPSs in the LEBT are given in Table 1.

Table 1: LEBT MPS Specifications

Specification (ppm)	Steering Magnet	Quadrupole Magnet	Bending Magnet
Stability	1000	200	100
Regulation	200	200	100
Ripple	1000	500	80

Early specifications for the larger supplies date from the 1970s and specify construction rather than performance. At that time 200V, 3000A DC MPSs with the required performance were not commercially available, so the lab specified construction details of the major MPS components and procured them from outside vendors. The feedback and control systems were built at LANSCE and integrated with the supply after it was delivered. The MPSs for the Transition Region Bending Magnets (TRBMs) were built this way.

Table 2: Large MPS Performance

	Magnet Power Supply& Rating	
Performance (ppm)	TRBM02 (200V, 3000A)	LCQL01 (250V, 2500A)
Stability	181 (Meas.)	200 (Spec.)
Regulation	Not measured	200 (Spec.)
Ripple	8318 (Meas.)	1000 (Spec.)

As MPS technology advanced, output performance specifications were applied to the purchases of large supplies. The Line C Quadrupole Lens (LCQL) magnet

MPSs are of comparable size and their specifications are compared to the measured values for TRBM02 in Table 2.

Theoretical Basis for Requirements

Ideally, the requirements on the MPS current would flow down directly from the requirements on the magnetic fields in the magnets. The allowable changes of the field of a beamline magnet would be calculated by beam modeling and then applied to the MPS current. This method implicitly assumes that the magnet's current and field strength have a linear relationship, which makes sense given that all focusing and bending magnets at LANSCE are operated below saturation. Even when the magnet begins to slightly saturate, the linear approximation overestimates the change in the magnet's field for a change in the magnet's current. The end result is an MPS specification that is slightly better than required in order to meet the magnetic field specifications.

It was not be practical to derive all the performance parameters in this way, so the members of the LANSCE physics team provided desired lists based on their years of experience with the accelerator. The approximate medians of these values are given in Table 3. Note that the ripple is more stringent than the original specifications for the LEBT and the LCQLs and is much more stringent than the measured performance of TRBM02.

Table 3: Desired Magnetic Field Performance

Specification (ppm)	Steering Magnet	Quadrupole Magnet	Bending Magnet
Stability	1000	500	100
Regulation	1000	500	100
Ripple	200	100	50

Practical Basis for Requirements

The actual MPS specifications are a compromise between what is desired and what is practical. If the desired specifications are so much more stringent than the actual measured values, how does the accelerator continue to run without massive beam spill? A critical assumption regarding ripple is that the beam is present at all times on the MPS's current ripple waveform. The observed current ripple waveforms measured at LANSCE are dominated by 60Hz line synchronized components. Beam pulses in the LANSCE accelerator are synchronized to zero crossings of the 60Hz power line. If "effective ripple" is defined as the variations in magnet current during the time the beam is actually present in the magnet, then the effective ripple at LANSCE may be an order of magnitude less than the measured ripple.

The measured ripple for Transition region bender magnet TRBM02 is shown in Figure 1, with dark blue highlights over a beam pulse operating at 60Hz, 620μs length with a standard 200μs delay from master timer T0. While ripple measured as peak to peak over the whole waveform is on the order of 8318 ppm, the effective ripple measured as the variation over the time of the beam pulse is on the order of 1122 ppm.

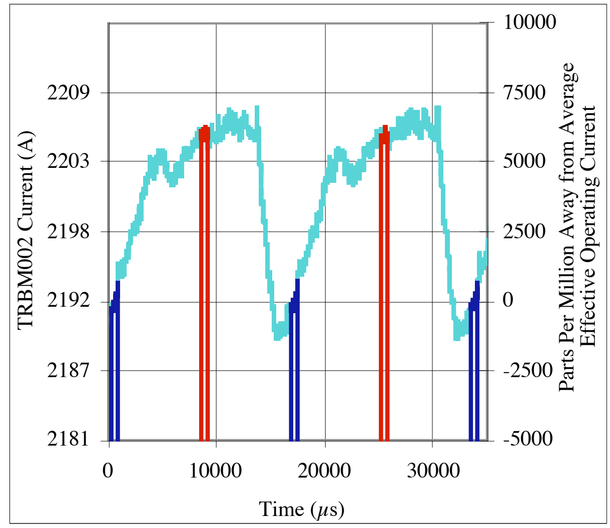

Figure 1: TRBM02 Current Ripple at 60 & 120Hz rep rate.

When the accelerator is operated at 120Hz, the effective ripple can increase substantially. Figure 1 also shows how increasing the repetition rate from 60 to 120Hz causes every other beam pulse (red and blue highlights) to occur at a different point on the ripple waveform, increasing the effective current ripple from 1122 to 6650 ppm.

One option to mitigate this effect is to delay the beam pulse such that the magnet current is roughly equal on successive beam pulses. Figure 2 shows how this can reduce the effective ripple from 6650 to 1583 ppm.

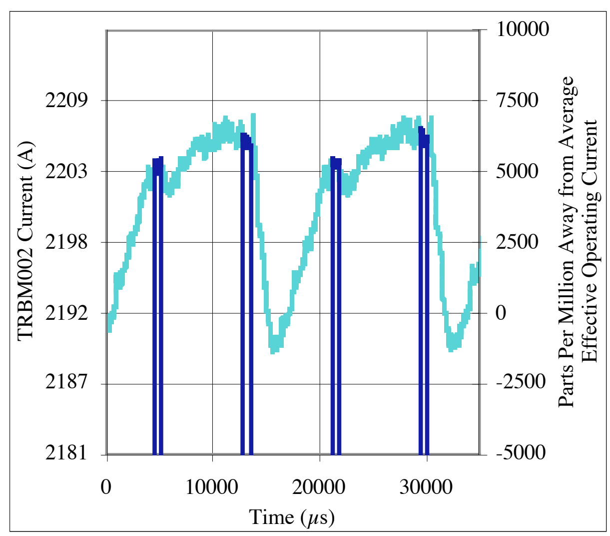

Figure 2: TRBM02 Current Ripple at 120Hz rep rate with delayed start of beam pulse.

HYSTERESIS EFFECTS

Hysteresis of TRBM02and TDBM01 Magnets

Magnet hysteresis introduces another factor into the determination of the MPS requirements. In the past, the maximum hysteresis of the TRBM magnets has been qualitatively estimated to be on the order of 0.5-0.9% of the maximum range of magnetic field variation.[1] Quantitative measurements taken recently on the TRBM02 magnet have shown that the maximum hysteresis error at the normal operating setpoint (86% of the maximum output current) is 2500 ppm, or 0.25%. This is significantly larger than the desired regulation error of 100 ppm. Operational constraints prevented the collection of a complete B/H curve for the TRBM02 magnet, so the complete curve was taken for the smaller Transport D Bender Magnet (TDBM01) in the LEBT.

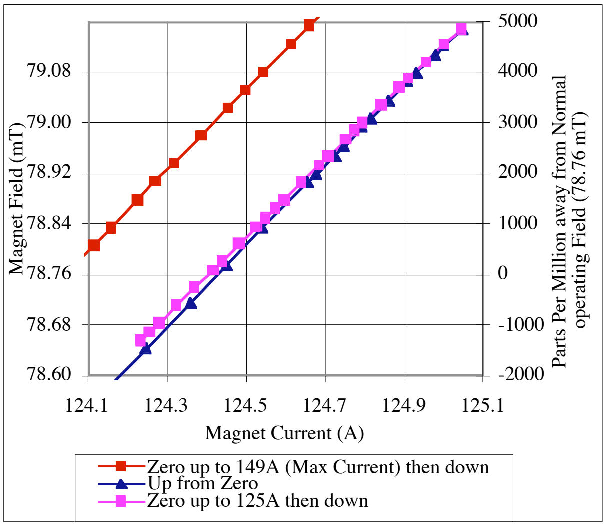

Figure 3: TDBM02 maximum hysteresis error at normal current.

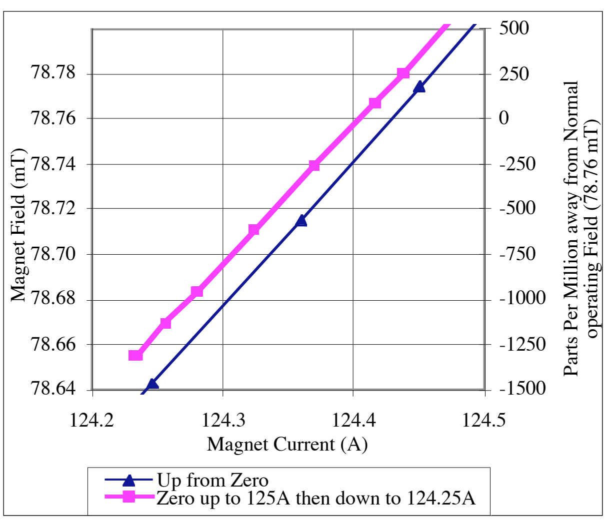

Figure 4: TDBM02 Hysteresis Error after a 0.5% variation up from and returning to normal current.

Figure 3 shows how the maximum hysteresis error for the TDBM01 magnet at its normal operating current is approximately 2500 ppm, which matches the value for the TRBM02 magnet at its normal operating current. It is assumed that the hysteresis errors over smaller current variations would be proportional for both magnets.

Figure 4 shows how the hysteresis error on the order of 200 ppm can result from simply adjusting the current up 0.5% and back down to its original setpoint. It is assumed that the TRBM01 magnet will exhibit a similar effect.

Hysteresis and Magnet Power Supply Ripple

As the magnet current varies up and down due to MPS current ripple, the magnet traces out a B/H subloop. When the magnet current ripple is dominated by 60Hz components, then this imposes a floor on the effective ripple when operating with a beam repetition rate of 120Hz. Even when the beam start time is perfectly adjusted to make the magnet currents equal on successive 120Hz beam pulses, the magnet alternates between being on upper and lower portions of the B/H subloop.

Measurements of the magnet hysteresis error on TRBM magnet in the test lab indicate that at normal operating currents the error is roughly a factor of 10 smaller than the variation in current. Therefore, a 8300 ppm peak to peak current ripple would produce a hysteresis error on the order of 830 ppm.

CONCLUSIONS

The requirements on MPS current stability, regulation and ripple are determined by the requirements on the magnetic fields in the beamline magnets in the accelerator. However, the requirements on ripple only apply when the beam is present in the magnet. If the ripple is dominated by 60Hz components, the accelerator beam pulse rep rate is 60Hz synchronized to the power line and the duty factor is relatively short, then the effective ripple during the beam pulse can be an order of magnitude lower than the measured MPS current ripple.

Errors as large as 200 ppm in reproducing a magnetic field have been shown to occur when the magnet current has an excursion as small as 0.5% up and back. If regulation and stability requirements are on the order of 100 ppm, then an independent measure of the magnetic field such as an NMR probe should be considered. When an NMR probe is added to the system, the MPS stability and regulation requirements can be relaxed as the probe can provide a closed loop feedback to the MPS to keep the magnetic field constant.

When the beam pulse is line synchronized and the magnet current ripple is dominated by 60Hz components and the beam rep rate is 120Hz synchronized to the power line, the hysteresis of the magnet will produce a lower limit on the ratio of the effective to actual magnet current ripple. The current ripple causes the magnet's field to travel a small B/H subloop. Even when the beam pulse delay is adjusted to provide the same current on successive 120Hz pulses, the magnet will alternate being on the upper and lower portions of the B/H subloop. This produces a hysteresis error floor that is estimated to be as high as 830 ppm in the LANSCE TRBM02 magnet.

REFERENCES

[1] R. McCrady, et al, "Mitigation Of Magnet Hysteresis Effects at LANSCE", LINAC 06, Knoxville, TN, August 2006.

