TRIM POWER SUPPLIES FOR THE DUKE BOOSTER AND STORAGE RING*

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Abstract

The on-going Duke storage ring upgrades and the development of a new booster synchrotron injector require more than 100 units of high performance unipolar and bipolar trim power supplies in the current range of –15 A to +15 A. However, most of the trim power supplies on the market do not deliver two critical performance features simultaneously: a high current stability and a low current noise. An in-house trim power supply development program has been put in force to design, fabricate, and test low cost linear power supplies with current stability about 100 ppm and current ripples less than 100 ppm in a broad band. A set of unipolar power supplies (0-12 A) have been designed, fabricated and successfully tested. Since August, 2004 they have been used in storage ring operation with excellent performance. The prototype of bipolar power supplies (±15 A) has been designed and tested as well. The main design principles and the performance results of both unipolar and bipolar supplies have been presented in this paper.

INTRODUCTION

A number of upgrades are underway at Duke FELLab. Among those are following:

- booster synchrotron injector [1];
- OK-5 FEL Wigglers installation [2];
- north Straight Section (NSS) upgrade;
- south Straight Section (SS) and Arcs upgrade.

Table 1 presents trim magnets and quads required for these upgrades. A number of trim magnets demand more than usual high DC current stability that relates to specific operation of the Duke FEL storage ring. Dedicated FEL storage rings require exceptionally high stability, reproducibility and low noise for orbit trim power supplies as compared to other light sources. The Duke storage ring in particularly has additional requirements: the FEL based high intensity γ-source requires highly accurate control of the collision point between the electrons and FEL photons.

We have tested a number of available, on-the-market power supplies. Some of them have high level of DC performance but unacceptable noise or dynamic behavior. Some power supplies, especially based on a linear regulator, have a good transient response and low noise but are not capable of keeping the DC current within a required stability. That was a reason to design and fabricate trim power supplies in-house.

POWER SUPPLY CONFIGURATION

Resistance of the magnets presented in the Table 1 doesn't include resistance of wires from the power supply to the magnet. Taking into account possible length of the DC cables the total resistance of the power supply, the load is not less than 0.5 Ohm. Since the maximum required output voltage is 15V, it is possible to use a linear regulator. The maximum possible dissipated power on the regulating device is:

$$P_{diss}=V^2/(4\cdot R),$$

<-where R is total load resistance and V is raw power supply voltage. In our case the dissipated power is limited

Table 1. On the table: *DI/I* – pick-to-pick stability and reproducibility; DI_{AC} – AC ripples (pick-to-pick); LTB - linac-to-booster transport line; BTR - booster-to-ring transport line; SS - straight section; NSS - north straight section.

Project	N	Magnet type	L mH	R mΩ	τ sec	I_{max}, A	U_{max}, V	$\Delta I/I^a$ ppm	$\Delta I_{AC}{}^b$ mA
Booster	8	QF Y trim	9	540	0.016	12	±12	200	1
	8	QD Y trim	8	540	0.015	12	±12	200	1
	4	Inj/Extr X trim	26	400	0.065	15	±10	200	1
	4	LTB/BTR Quads	12	720	0.017	6	+5	500	4
NSS	8	X trim	50	400	0.125	15	±10	100	1
	8	Y trim	50	400	0.125	15	±10	100	1
OK-5	12	X trim	44	400	0.11	15	±10	100	1
	12	Y trim	26	400	0.065	15	±10	200	2
	8	Octupoles	9	320	0.028	12	±6	200	2
ARCs&SS	24	Skew Quads	---	200	---	15	±15	500	5

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to 110 Watts. Power MOSFET transistors mounted on a water-cooled heat-sink are capable of providing low-cost and reliable current regulating.

Six unipolar power supplies built in-house for the Duke FEL storage ring have been employed for more than one year with good performance. This experience has inspired us to design and produce a set of bipolar devices. Fig. 1 shows the block diagram of the multi-channel power supply.

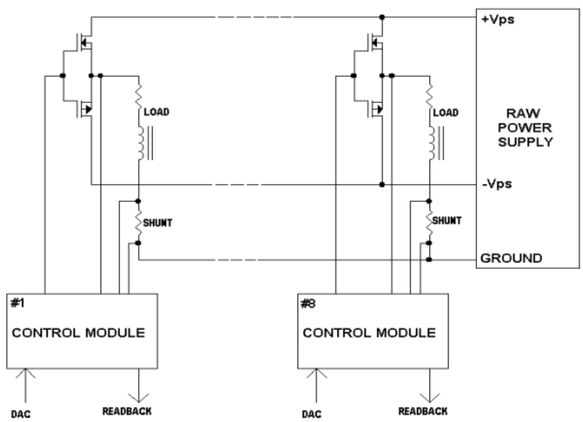

Figure 1: Trim power supply block diagram.

Every transistor on the block diagram in fact presents two HEXFET Power MOSFETs from International Rectifier wired in parallel to obtain reliable operation over the full current range and mounted on a water-cooled plate.

Each channel has an individual control module. A shunt connected in series with the load is located inside the module close to the low-offset and low-drift amplifier with a gain G=61.7 to insure a low noise voltage for the current feedback. A shunt amplifier has a gain trim that allows identical calibration for each power supply. This ensures that module replacement doesn't change the calibration. With the shunt separated from the transistor stage, it doesn't experience additional heat and has an improved thermal condition. All electronics within the module are supplied through an individual DC-DC converter to prevent the interference between channels caused by a common power supply.

Every current regulator also has a local voltage feedback loop. Relative to the current feedback, the voltage feedback is fast and able to eliminate ripples of output current caused by the noise from the raw power supply and also to improve the linearity of the MOSFET amplifier crossing the zero current. The current regulator is a proportional-integral type.

Each control module contains an input differential amplifier for reference voltage, a buffer follower for read-back and two interlock inputs: one to protect transistors against overheating and another for the magnet protection.

Eight control modules are brought together in one crate. The crate also contains an additional module to distribute the eight reference voltages and the eight read-back signals.

SHUNT ISSUES

The choice of resistance of the shunt is a compromise between a low power dissipation to obtain good resistance stability and a large enough voltage on the shunt. We have tested three types of precision resistors: RTO-Z-B, A-H both from Isabellenhutte Hensler GmbH KG, Germany [3] and FHR4-4618 from POWERTRON, GmbH, Germany [4]. The last two have the same design and very similar electrical specifications. RTO-Z-B shunts with ±50 ppm temperature coefficient have been installed in our in-house built unipolar 12 A power supplies. They have been mounted on a water-cooled plate with a good thermal stability of DI water. Fig. 2 shows a difference between the measured current and its linear fit. According to manufacturer specifications and our measurements, A-H and FHR shunts have ±10 and ±15 ppm temperature coefficient, respectively, and meet our requirements for the most part. POWERTRON 0.01 Ohm resistors with a 0.1% tolerance have been chosen. Maximal power dissipation for 15A current is only 2.25 W. We provide an aluminum heat-sink for the shunt and forced air cooling common for whole crate to reduce any nonlinearity caused by the shunt's self-heating.

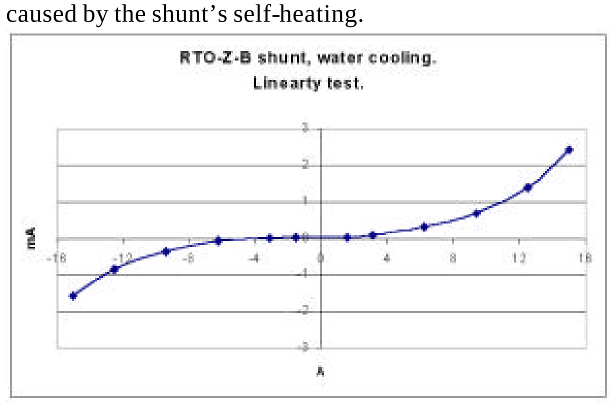

Figure 2: Unipolar 12A power supply nonlinearity.

TEST RESULTS

The prototype bipolar ±15A power supply has been produced and tested. The Duke FELLab standard measurement procedure described in [5] was applied.

Stability Test.

A Danfysik Ultrastab 860R current transducer (DCCT) was used to measure the DC current. The stability test covers several levels of current: 0A, ±3.25A, ±6.5A, ±10.8A and ±15A. Each measurement cycle takes about 2000 sec. Fig. 3 shows the typical DC performance of a prototype power supply. The current deviation during measuring cycle was less than 30 ppm for the worst case (0.3 mA for DC current at -10.8 A). This test relates to the short-term stability only. The real storage ring operation requires good DC performance at least during one shift, or period of 8 to 24 hours, and it is quite possible that extra efforts will be necessary to maintain temperature conditions inside trim power supplies to obtain this level of stability.

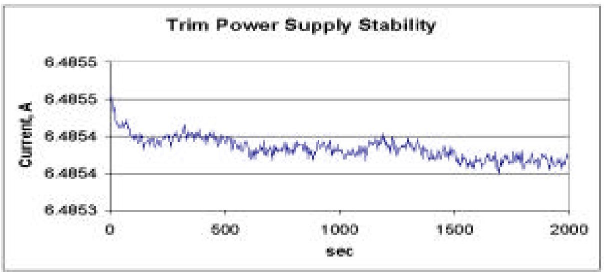

Figure 3: Bipolar trim power supply test.

Linearity Test

The nonzero value of a shunt's thermal coefficient of resistance is a reason of nonlinearity. In fact, the result of a linearity test mostly depends on shunt cooling conditions and the particular parameters of the shunt. We define the nonlinearity of a power supply as a difference between measured current and its linear fit. Fig. 4 demonstrates good stability of shunt resistance over the overall range of current: its maximum deviation doesn't exceed 0.4 mA for 12 A (33 ppm).

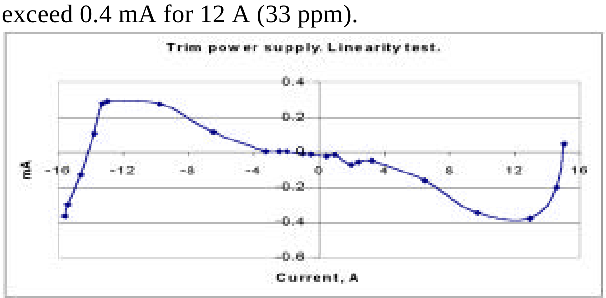

Figure 4: Difference between measured current and its linear fit.

Reproducibility

The reproducibility is calculated from a series of repeated slow step-function runs as the difference current for the same control setting.

It is clear that initial temperature conditions of the shunt primary determine the stability of the power supply. Due to this factor, reproducibility calculated for the beginning of runs was 70 ppm while the final current had a 20 ppm deviation.

Noise measurements

Unfortunately, a direct measurement of the current noise from the DCCT was not possible. The DCCT with an additional amplifier have a noise comparable to that of the power supply. Fig. 5 presents the output voltage of the error amplifier inside the current feedback loop scaled to the output current.

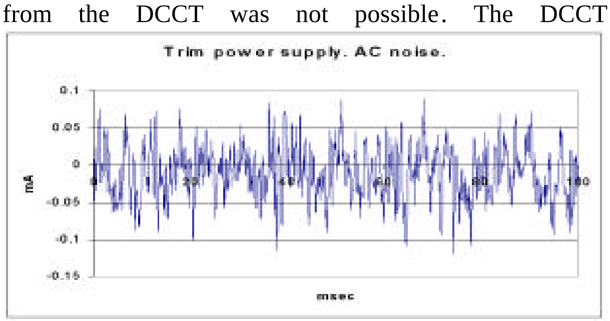

Figure 5: Trim power supply noise measured in the pass band 1Hz – 1kHz.

Transient response

Besides the DC and AC performance, the dynamic behavior of the power supply is critical for reliable operation with energy ramping. A linear transistor regulator usually doesn't have any problem with dynamic performance. Properly adjusted frequency compensation in the current feedback loop ensures good ramping. For this reason, each control module has a removable daughter board with frequency compensation circuitry. Results of the step response test are shown in Fig. 6. Obviously, the frequency compensation was not adjusted carefully and a small overshoot took place.

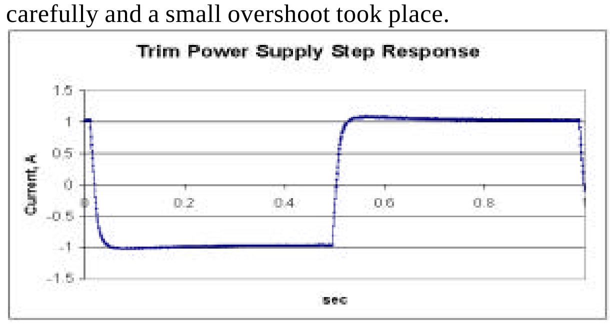

Figure 6: Bipolar power supply step response, crossing zero current.

CONCLUSION

The positive experience of an employment of unipolar 12 A trim power supplies and results of comprehensive tests of a bipolar prototype ensure that main design principles are correct. Now the fabrication of new bipolar ±15 A trim power supplies has been launched.

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