Some Test Results with Commercial Buck Converters

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Radiation Resistant DC- DC Power Conversion with Voltage Ratios > 10 capable of operating in High Magnetic Field for LHC Upgrade Detectors

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Abstract

Commercial power converters that have voltage ratios greater than ten and are capable of running near the LHC collision region would increase the efficiency of the power distribution system of the ATLAS Silicon Tracker high luminosity upgrade. The devices must operate in a high magnetic field (2T) and be radiation hard to ~50-100 Mrad and ~10^{15} N_{eq}/cm^2. These converters are to be mounted on the same multi-chip modules as the ASIC readout chips or in close vicinity without introducing any additional readout noise due to the high switching frequencies. Such devices will permit higher voltage power delivery to the tracker and thus increase overall power efficiency by limiting the ohmic losses in the stretch of cable (about 100 meters) between the tracker and the power sources.

I. Introduction

There is a clear need for a new system of power delivery to the upgraded Atlas Silicon Tracker for the SLHC. Conventional powering will result in an efficiency of power delivery to the detector of about 10% with existing cables whose size are limited in cross section due to space and mass constraints. A system featuring DC-DC converters with voltage ratios of ten will result in an estimated efficiency on the order of 70-80% with existing cables.

One approach to DC-DC conversion utilizes the buck regulator architecture. As DC-DC buck converters are commonly used in the commercial market, we have been surveying and testing currently available devices to understand the present state of the art.

Foremost of our *unique* requirements is operation in a high magnetic field. This necessitates the use of an air core inductor, which implies the need for high switching frequencies that lie in the readout ASIC's bandwidth. Additional noise introduced by the converter is thus one of the primary concerns. The radiation hardness of the devices, and the relatively high voltage ratios needed are also of primary concern.

In 2007, we had tested a number of devices that, although lacking the high voltage ratios required, have enabled us to learn a number of lessons. For example, the one device that we irradiated with gammas up to 100 Mrad showed no change in performance. Also, we have conducted noise tests with our own custom module utilizing current Atlas ABCD ASICs connected to a large silicon strip detector and mounted with a daughter buck regulator board. We found no noise increase due to switching noise on the power and ground. Magnetic/electrical pickup on the 8 cm silicon strips from the air-core inductor required shielding to reduce the noise to a satisfactory level.

Market forces are now driving the development of a new generation of converters with ratios greater than 10. We recently irradiated a number of these new devices. Here we present the results. Additionally, we have fabricated several small micro-H inductors that show promise in their initial testing, and results are shown.

Power Distribution Schemes and Efficiencies

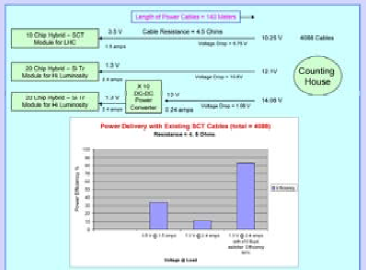


Figure I

Air Coils

Coil Spacing		100 KHz	1 MHz
Wide	L	1.21 µH	1.16 µH
	R	0.098 Ω	0.094 Ω
Near but not touching	L	1.80 µH	1.70 µH
	R	0.088 Ω	0.300 Ω
Pressed Together	L	2.37 µH	1.93 µH
	R	0.080 Ω	1.300 Ω

Spiral Coils: 3 Sizes
2 oz Copper on 3 mill FR4

Need for New methods of Power Distribution

Presently LHC inner detector electronics use DC power supplies located in the counting house that feed low voltage power over a long distance (30 m for CMS and 140 m for ATLAS detector). Here we focus on the powering of the silicon tracker for the high luminosity LHC that shall result in x10 higher luminosity and use x10 more detecting elements.
The "Power Delivery with Existing SCT Cables" plot illustrates the problem. At present 10.25 V power from the counting house is delivered by 4088 power cables each with a resistance of 4.5 Ω. The 10 chip ASIC readout chip hybrid Kapton PCB needs 1.5 amps @ 3.5 Volts. The bar graph shows the power delivery efficiency of ~33%. In an upgraded ASIC design with finer lithography and x2 more chips, the voltage drops to 1.3 V and with the same cables the power delivery efficiency drops to 10%. By inserting a DC-DC with x10 voltage converter on the 20 chip hybrid Kapton PCB, the efficiency climbs to over 80%.

Requirements & Challenges

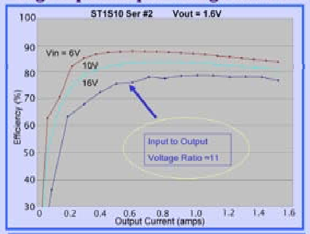
- Tolerate Hi Radiation ~ 100 Mrad
- Operate @ 2 Tesla or higher magnetic field.
- No Magnetic materials
- High efficiency
- Testing Newer COTS Devices
- Air core Coils – Solenoid, Toroid, Spirals etched on Kapton

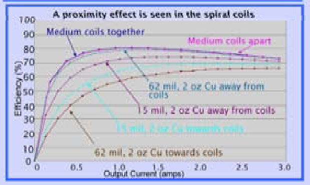
Selected Commercial Devices

Manufacturer	Evaluation Board @ Yale	Device	Type	Vin	Iout	Technology	Frequency MHz
ST	Yes	ST1510	Monolithic	18	3	BCD	0.9
TI	Yes	TPS62110	Monolithic	17	1.5	BCD 0.25 um	1
IR	Yes	IRDC 3822	MCC 3 Chips	21	4		0.6
Maxim	Yes	MAX 8654	Monolithic	12	8		1.2
Intersil	Yes	ISL8502	Monolithic	14	2.5	CMOS 0.6 um	1.2
Analog Devices	Yes	ADP21xx	Monolithic	5.5	2+2 amps	CMOS 0.35 um	1.2
Enpirion	Yes	EN 5360 Internal Inductor	Monolithic	5.5	6	CMOS 0.25 um	5
Enpirion	Yes	EQ 5382D	Monolithic	5.5	0.8	CMOS 0.25 um	4

1. New designs.
2. Finer lithography – prefer 0.25 µm CMOS.
3. High input/output voltage ratios. (ADP21xx is a low input voltage version (5.5 V) but a high input voltage version (20 V) will be available soon with the same technology.)
4. All devices fabricated on a single die except the Maxim device that has 3 chips including 2 external FET Switches.
5. Enpirion EN5360 had previously survived 100 Mrad of Co^{60} Gamma irradiation. EQ5382 part is made at a different foundry.
6. Evaluations PC Boards were purchased for our tests.
7. Standardized power connector (see photo "Evaluation PCBs) for interchangeability with our measurement system. Monitor input and output voltages at the Evaluation board and add resistive shunts near the output to monitor currents.

High Input/Output Voltage Ratio Converter

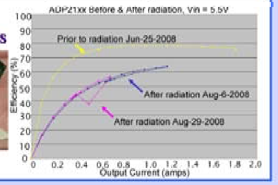


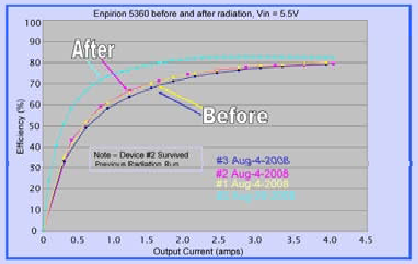


Radiation Damage

Device	Time in Seconds	Dose before Damage Seen (krad)	Observations Damage Mode
TPS 62110	720	40	Increasing input current
ISL 8502	730	40.6	Increasing input current
MAX 8654	850	47.2	Loss of output voltage regulation
ADP 21xx	1000	55.6	Loss of output voltage regulation
ST1510	2250	125	Loss of output voltage regulation
IR3822	2500	139	Increasing input current
EN5382	2000	111	Loss of output voltage regulation
EN5360 #3	864000	48000	MINIMAL DAMAGE
EN5360 #2	TESTED IN 2007	100000	MINIMAL DAMAGE

Evaluation PCBs





Enpirion:

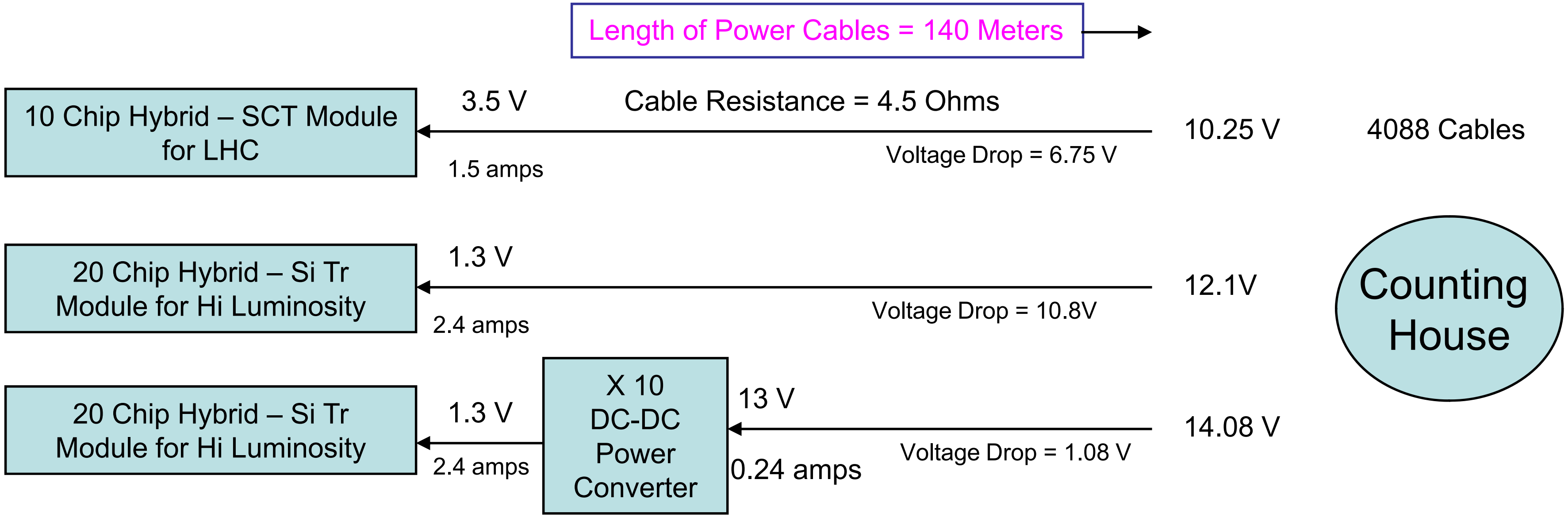
In our radiation testing Enpirion device EN5360 has outlasted all other irradiated devices from all manufacturers, while the similar EN5365 and EN5382 failed. The EN5360 was made by IHP Microelectronics foundry in Germany while successor devices are fabricated by Dongbu HiTek semiconductor in South Korea. Both are on 0.25 µm CMOS process, but some differences in the foundry processes and perhaps in the device circuit design make the EN5360 radiation hard. Recently Los Alamos National Laboratory irradiated an EN5360 and its successor EN5365 with heavy ions and protons for space satellite use. Their conclusion is that while both are suitable for their purposes, the EN5360 showed no effect up to their proton dosage limit while EN5365 failed.

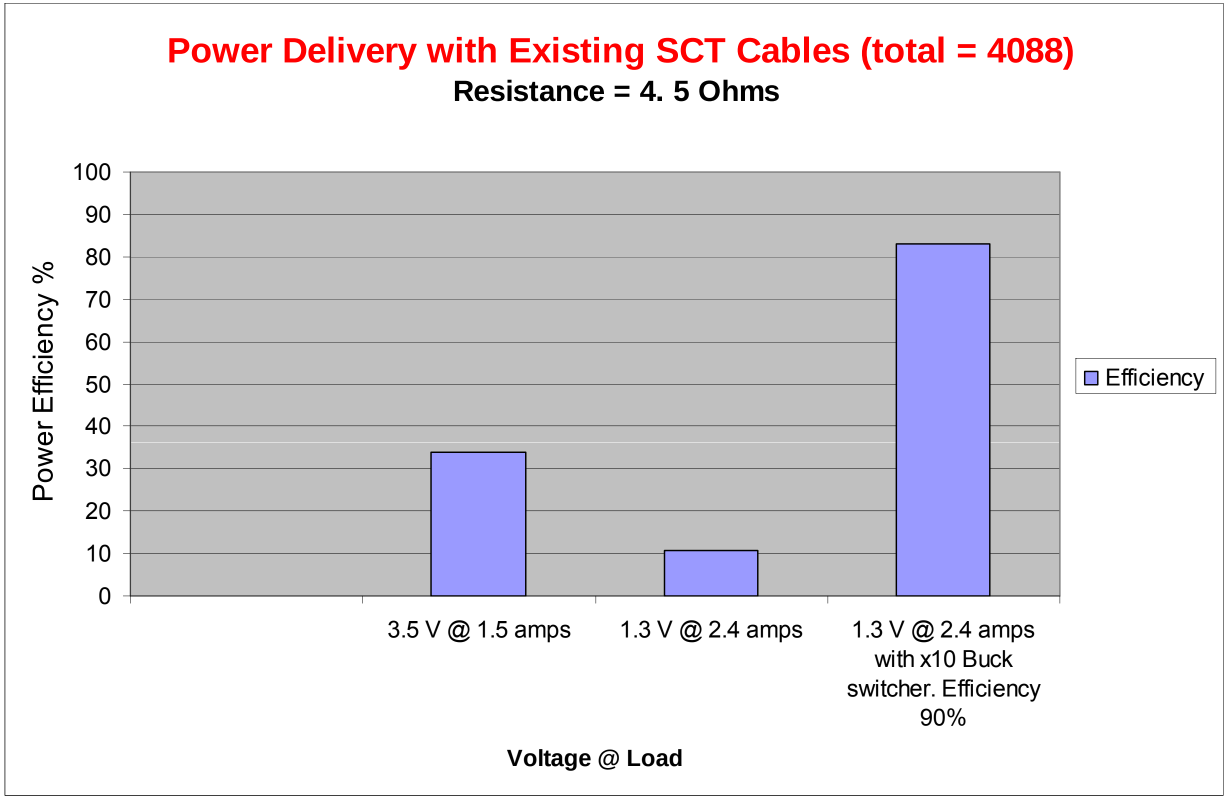
Conclusions/ Future Work

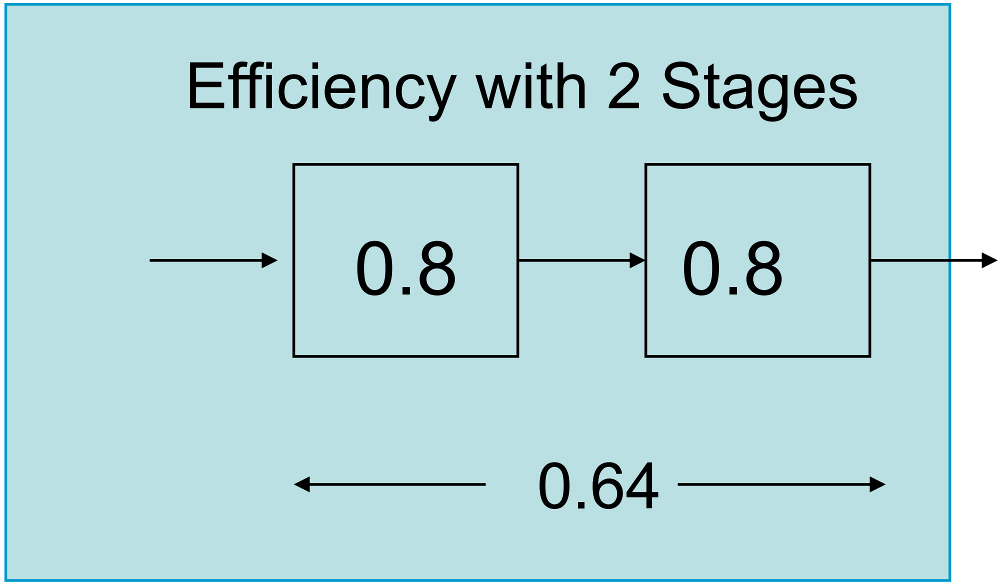
Enpirion EN5360 is a proof of principle that a commercial COTS device can be radiation hard. While we had cause to expect some next generation high voltage ratio 0.25 µm devices might similarly prove rad-hard, all of the devices we tested failed. We are attempting to understand differences in the IHP fabrication process that lead to a successful device. Additionally, as next generation devices come on the market we will use the infrastructure we developed to quickly evaluate these devices

References:

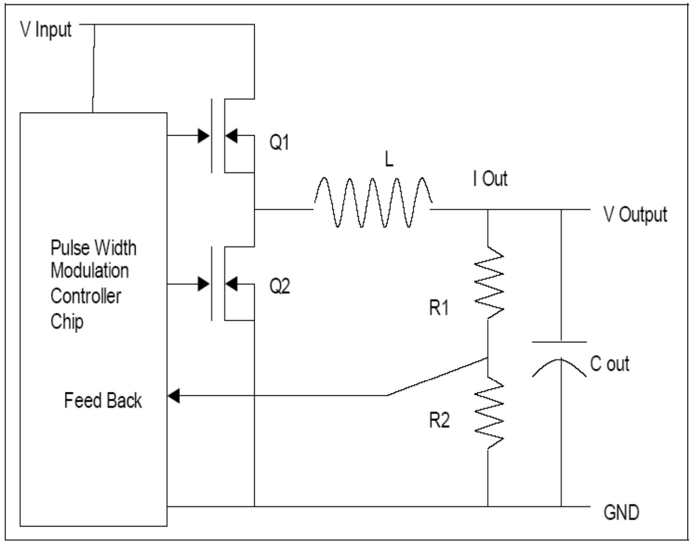
1. Topical Workshop on Electronics for Particle Physics, Sept 3 - 7, 2007, Prague, Czech Republic
2. Multi-Layer Folded High-Frequency Toroidal Inductor Windings, M. Nigam & C. Sullivan, IEEE APEC Conference, February 24-28, 2008, Austin, TX, USA
3. Lotfi, IEEE Trans on Magnetics, Vol.28, No 5, September 1992).
4. Bruce Carsten 'High Frequency Conductor Losses in Switchmode Magnetics' seminar www.bcarsten.com
5. Terman, F.E. Radio Engineers' Handbook, McGraw-Hill 1943


Length of Power Cables = 140 Meters
10 Chip Hybrid – SCT Module for LHC
3.5 V
Cable Resistance = 4.5 Ohms
10.25 V
4088 Cables
1.5 amps
Voltage Drop = 6.75 V
20 Chip Hybrid – Si Tr Module for Hi Luminosity
1.3 V
12.1V
Counting House
2.4 amps
Voltage Drop = 10.8V
20 Chip Hybrid – Si Tr Module for Hi Luminosity
1.3 V
2.4 amps
X 10 DC-DC Power Converter
13 V
0.24 amps
14.08 V
Voltage Drop = 1.08 V


Power Delivery with Existing SCT Cables (total = 4088)
Resistance = 4. 5 Ohms
Power Efficiency %
100
90
80
70
60
50
40
30
20
10
0
3.5 V @ 1.5 amps
1.3 V @ 2.4 amps
1.3 V @ 2.4 amps with x10 Buck switcher. Efficiency 90%
Voltage @ Load
Efficiency



Buck Converter

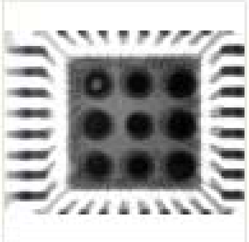


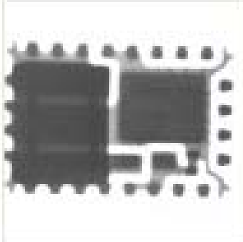
Controller operates @ 5 Volts with LDO from Vin
High Voltage is on Switches by Drain Extension, Deep Diffusion
0.25 um CMOS 12 V - Enpirion
0.25 um CMOS 20 V - ADI, ??

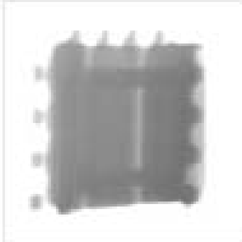
- High Vin / Vout Ratios ~10
- Minimum Ton ~85 nsec: Frequency ~ 1 MHz
- For Higher Ton, Lower Operating Frequency

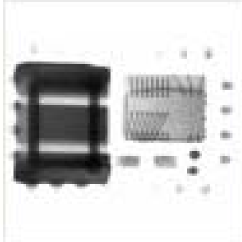
Table 1. Selected Commercial Devices

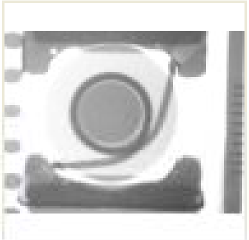
Manufacturer	Evaluation Board @ Yale	Device	Type	Vin	Iout	Technology	Frequency MHz
ST	Yes	ST1S10	Monolithic	18	3	BCD	0.9
TI	Yes	TPS62110	Monolithic	17	1.5	BCD 0.25 um	1
IR	Yes	IRDC 3822	MCC 3 Chips	21	4		0.6
Maxim	Yes	MAX 8654	Monolithic	12	8		1.2
Intersil	Yes	ISL8502	Monolithic	14	2.5	CMOS 0.6 um	1.2
Analog Devices	Yes	ADP21xx	Monolithic	5.5	2+2 amps	CMOS 0.35 um	1.2
Enpirion	Yes	EN 5360 Internal Inductor	Monolithic	5.5	6	CMOS 0.25 um	5
Enpirion	Yes	EQ 5382D	Monolithic	5.5	0.8	CMOS 0.25 um	4

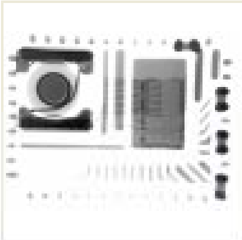

ADP2114.bmp

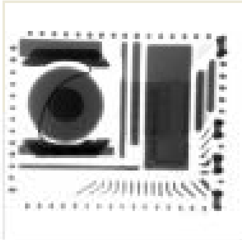

EN5322-1.bmp

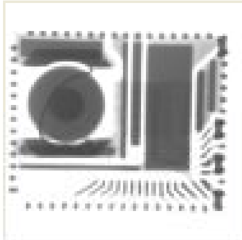

EN5322-2.bmp

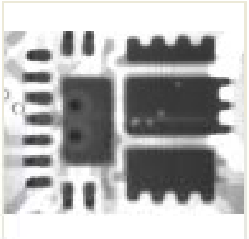

EN5322.bmp

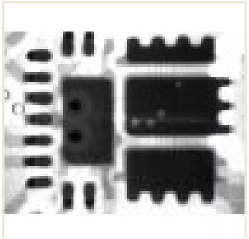

EN5335-1.bmp

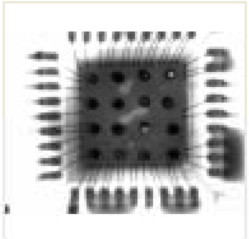

EN5335.bmp

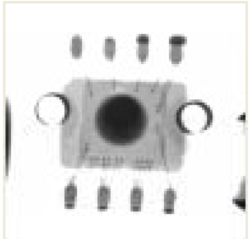

EN5365-1.bmp

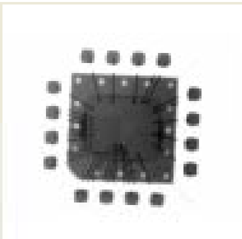

EN5365.bmp


IR3822-1.bmp


IR3822.bmp


MAX8654.bmp


ST1S10.bmp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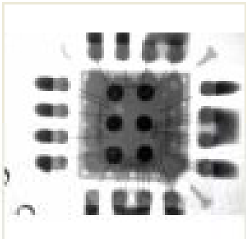
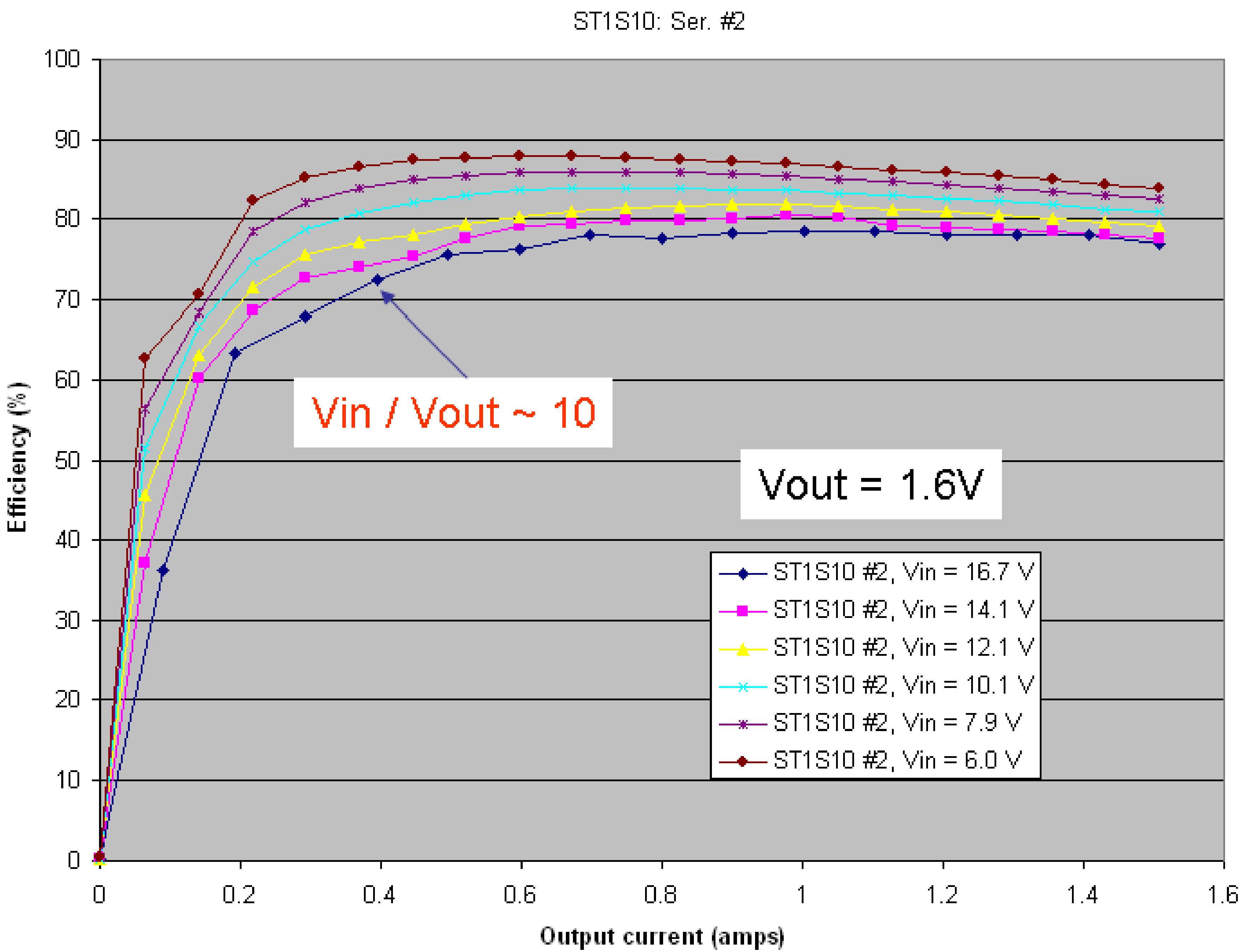
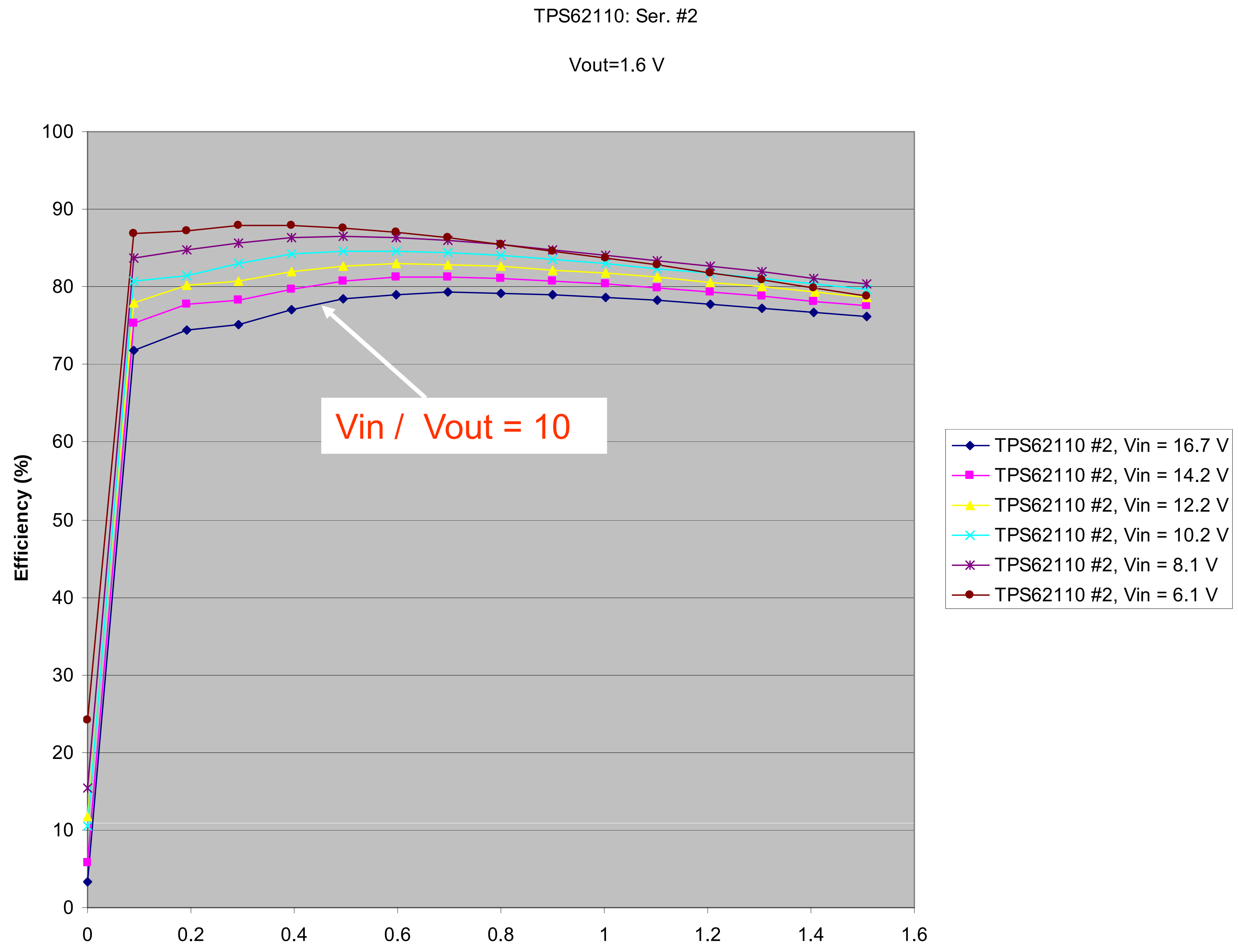
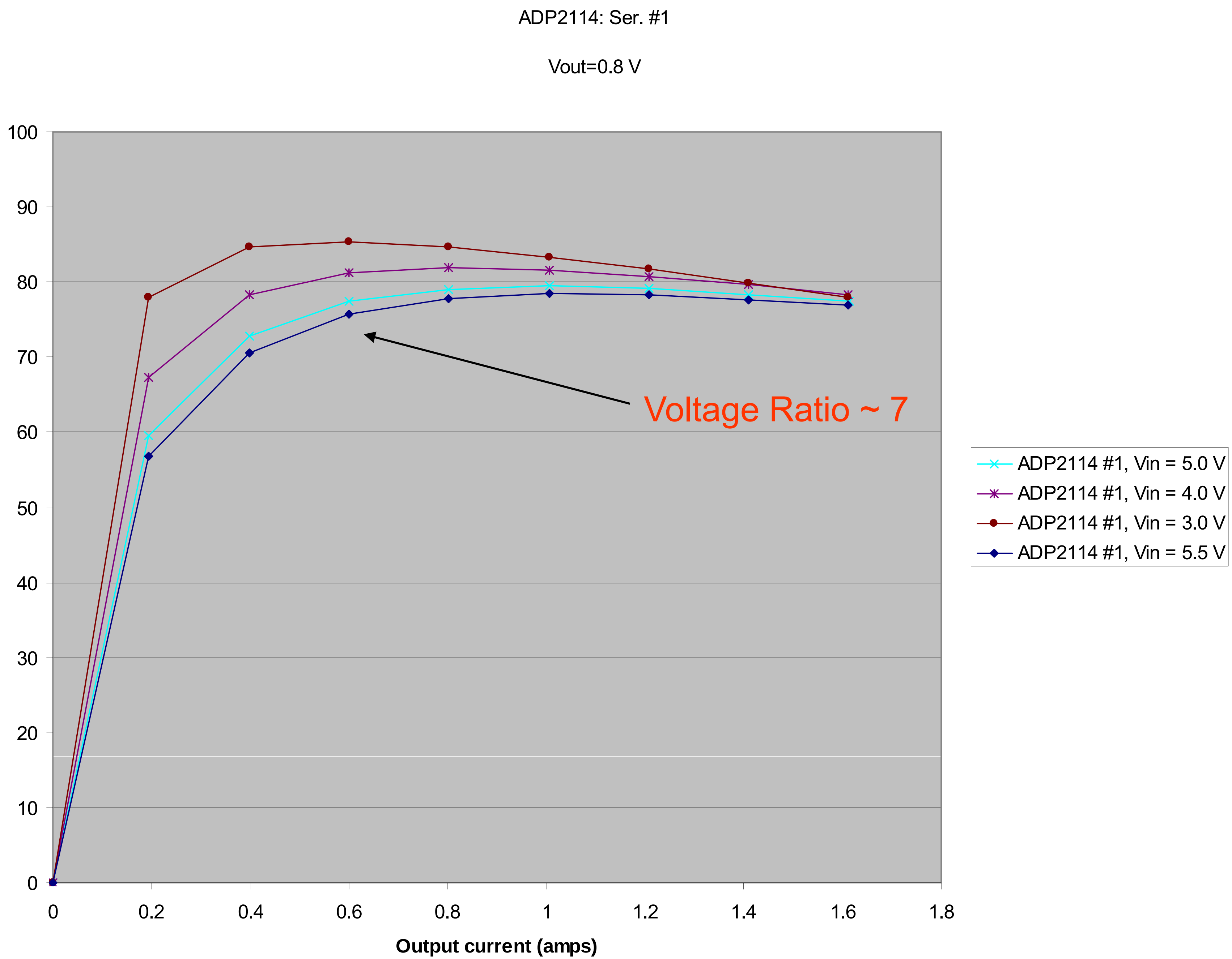

TPS6210i.bmp


ST1S10: Ser. #2
Efficiency (%)
Output current (amps)
Vin / Vout ~ 10
Vout = 1.6V
ST1S10 #2, Vin = 16.7 V
ST1S10 #2, Vin = 14.1 V
ST1S10 #2, Vin = 12.1 V
ST1S10 #2, Vin = 10.1 V
ST1S10 #2, Vin = 7.9 V
ST1S10 #2, Vin = 6.0 V


TPS62110: Ser. #2
Vout=1.6 V
Efficiency (%)
100
90
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Vin / Vout = 10
TPS62110 #2, Vin = 16.7 V
TPS62110 #2, Vin = 14.2 V
TPS62110 #2, Vin = 12.2 V
TPS62110 #2, Vin = 10.2 V
TPS62110 #2, Vin = 8.1 V
TPS62110 #2, Vin = 6.1 V


ADP2114: Ser. #1
Vout=0.8 V
100
90
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Output current (amps)
Voltage Ratio ~ 7
ADP2114 #1, Vin = 5.0 V
ADP2114 #1, Vin = 4.0 V
ADP2114 #1, Vin = 3.0 V
ADP2114 #1, Vin = 5.5 V

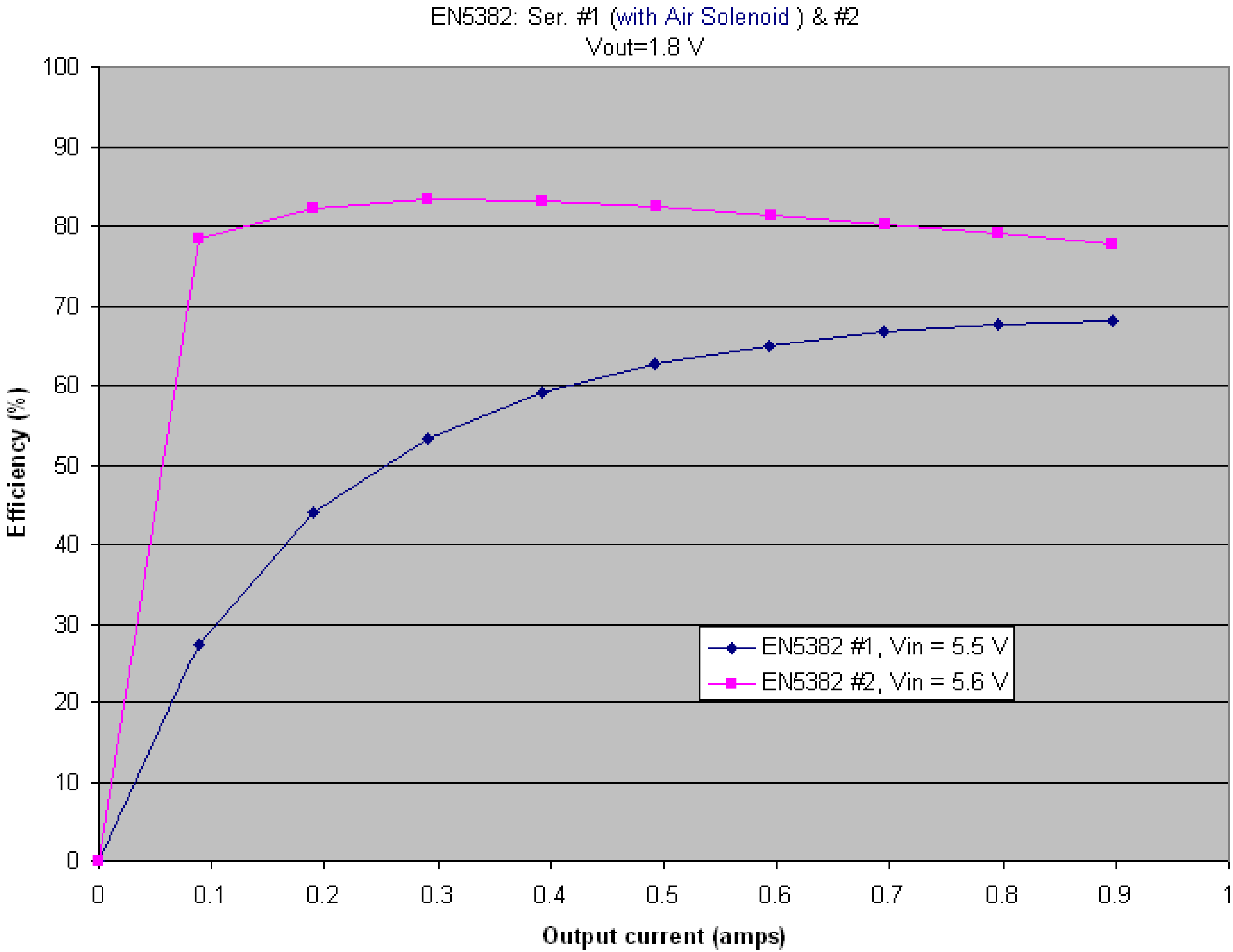
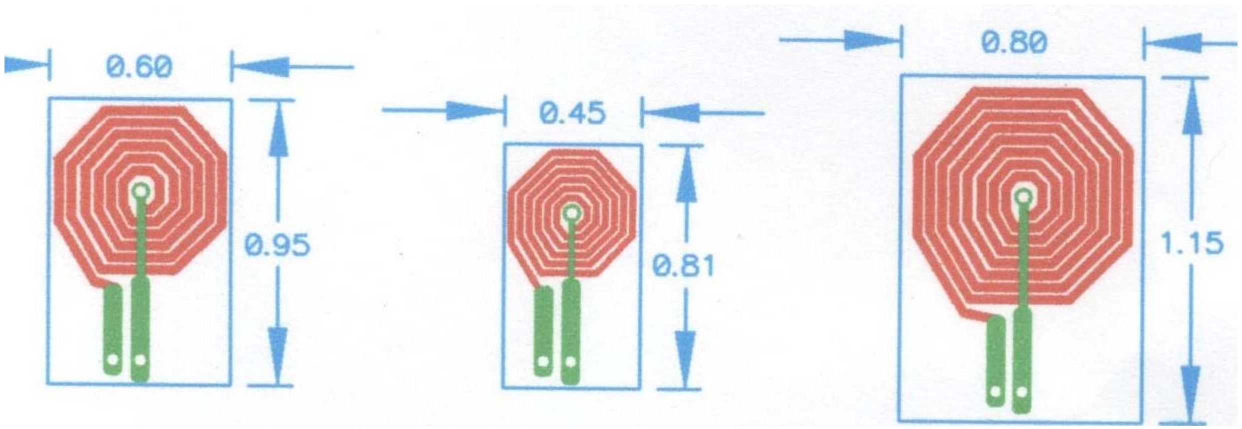
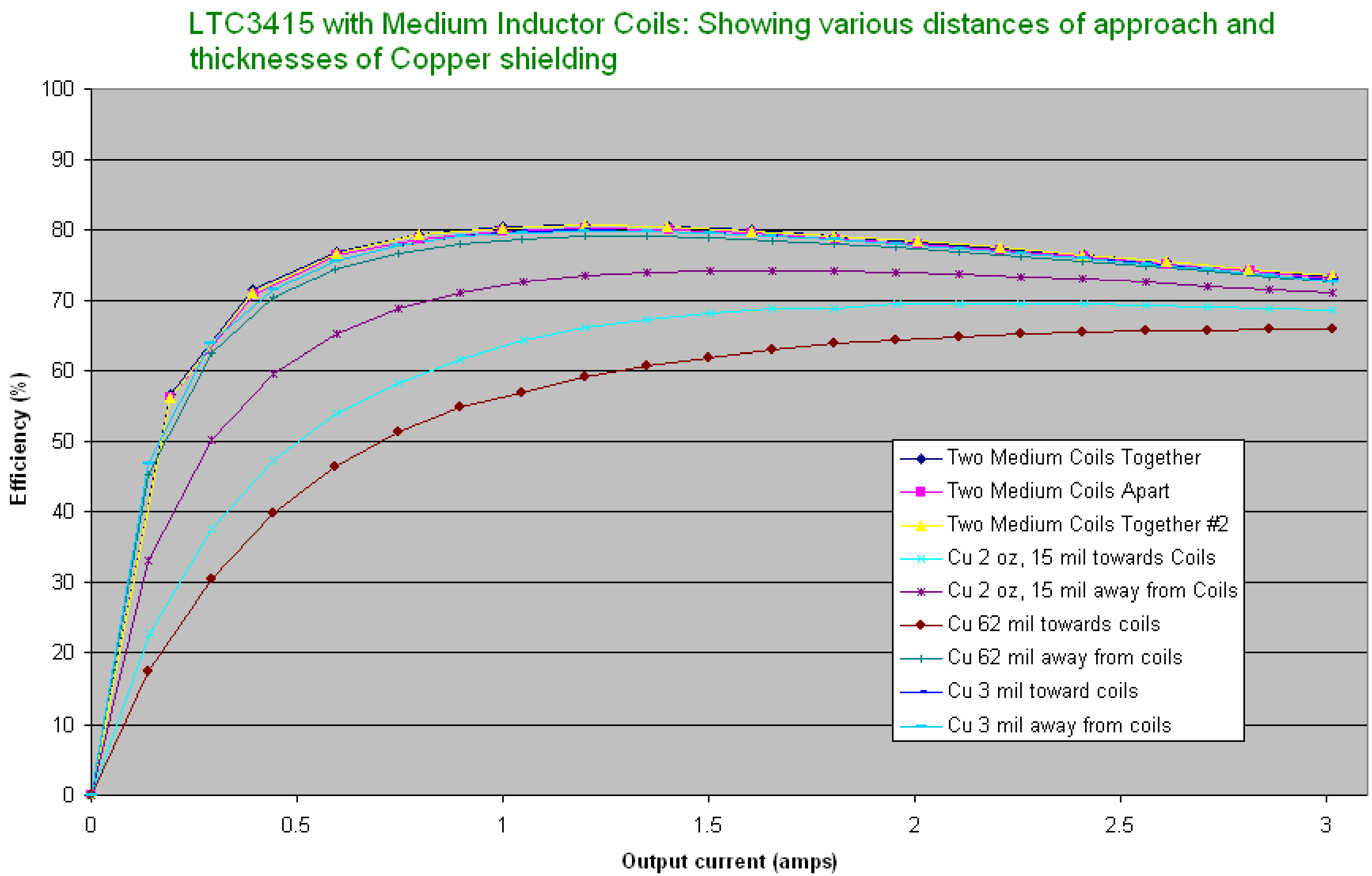


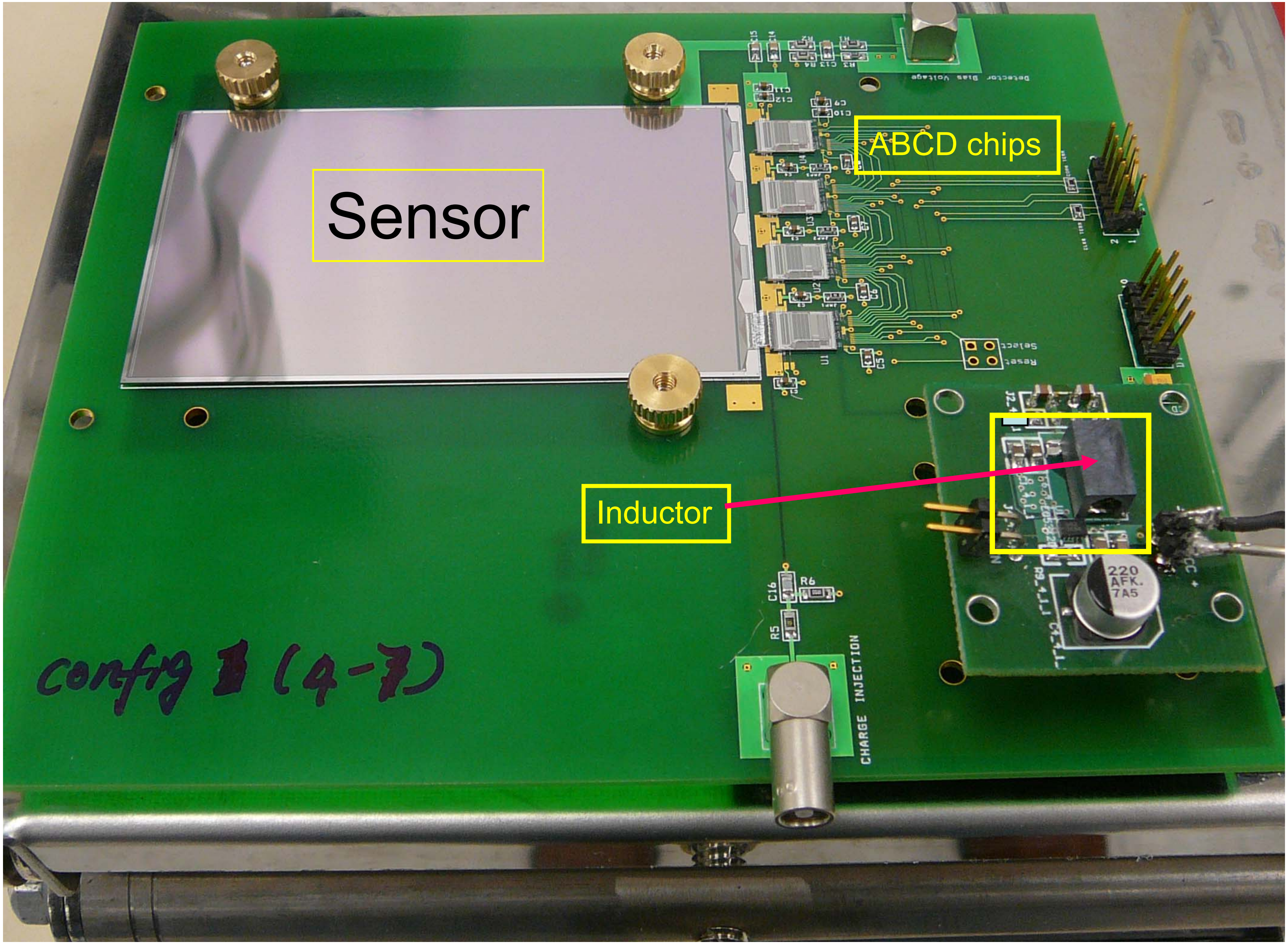
Figure III: Efficiency vs Output Current. #1 Has Ferrite Inductor. #2 Has Lower Inductance Air Coil.

Table II: Proximity Effect Measure of L and R vs. at frequency.

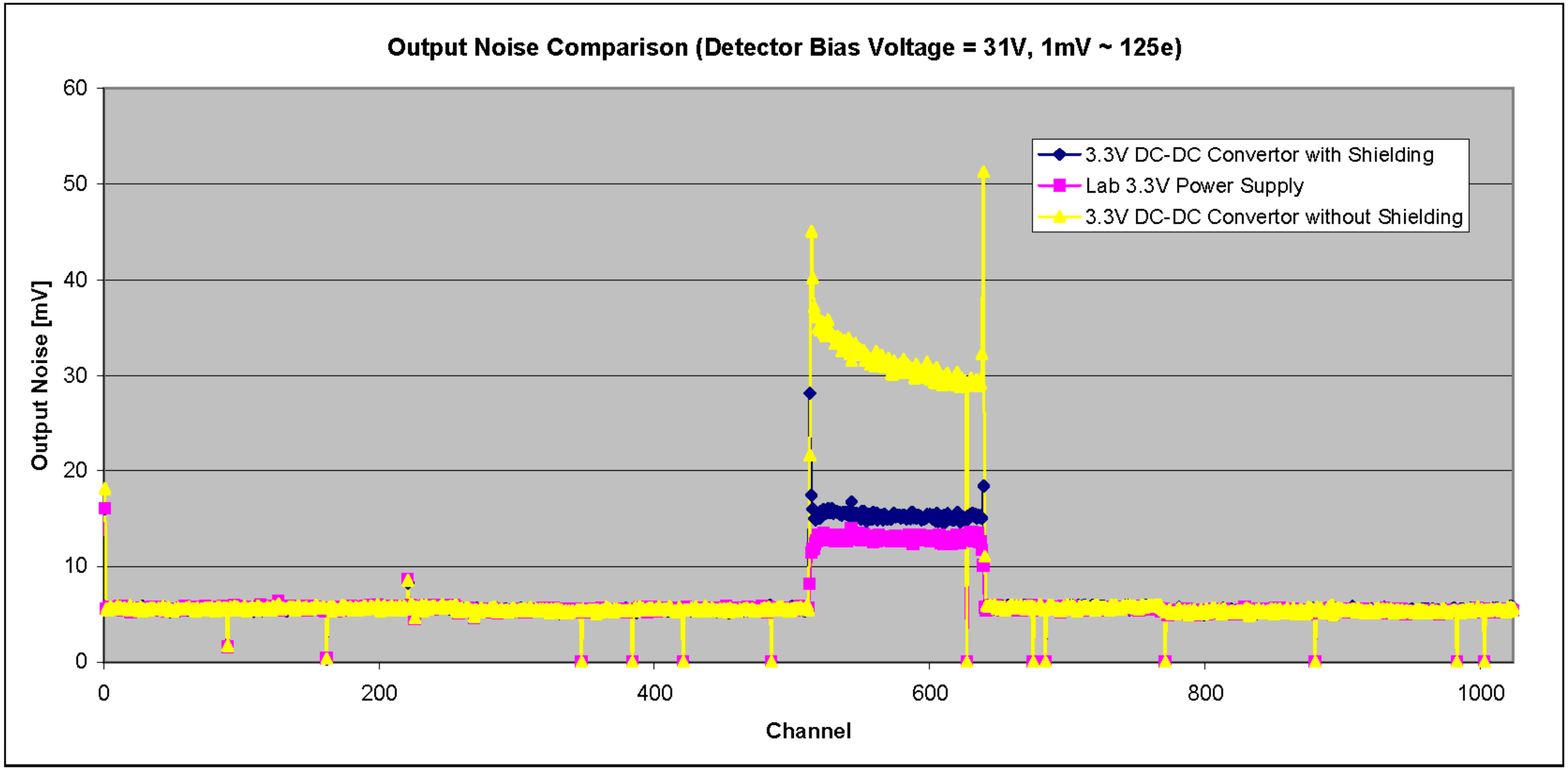
Coil Spacing		100 KHz	1 MHz
Wide	L	1.21 μH	1.16 μH
	R	0.098 Ω	0.094 Ω
Near but not touching	L	1.80 μH	1.70 μH
	R	0.088 Ω	0.300 Ω
Pressed Together	L	2.37 μH	1.93 μH
	R	0.080 Ω	1.300 Ω



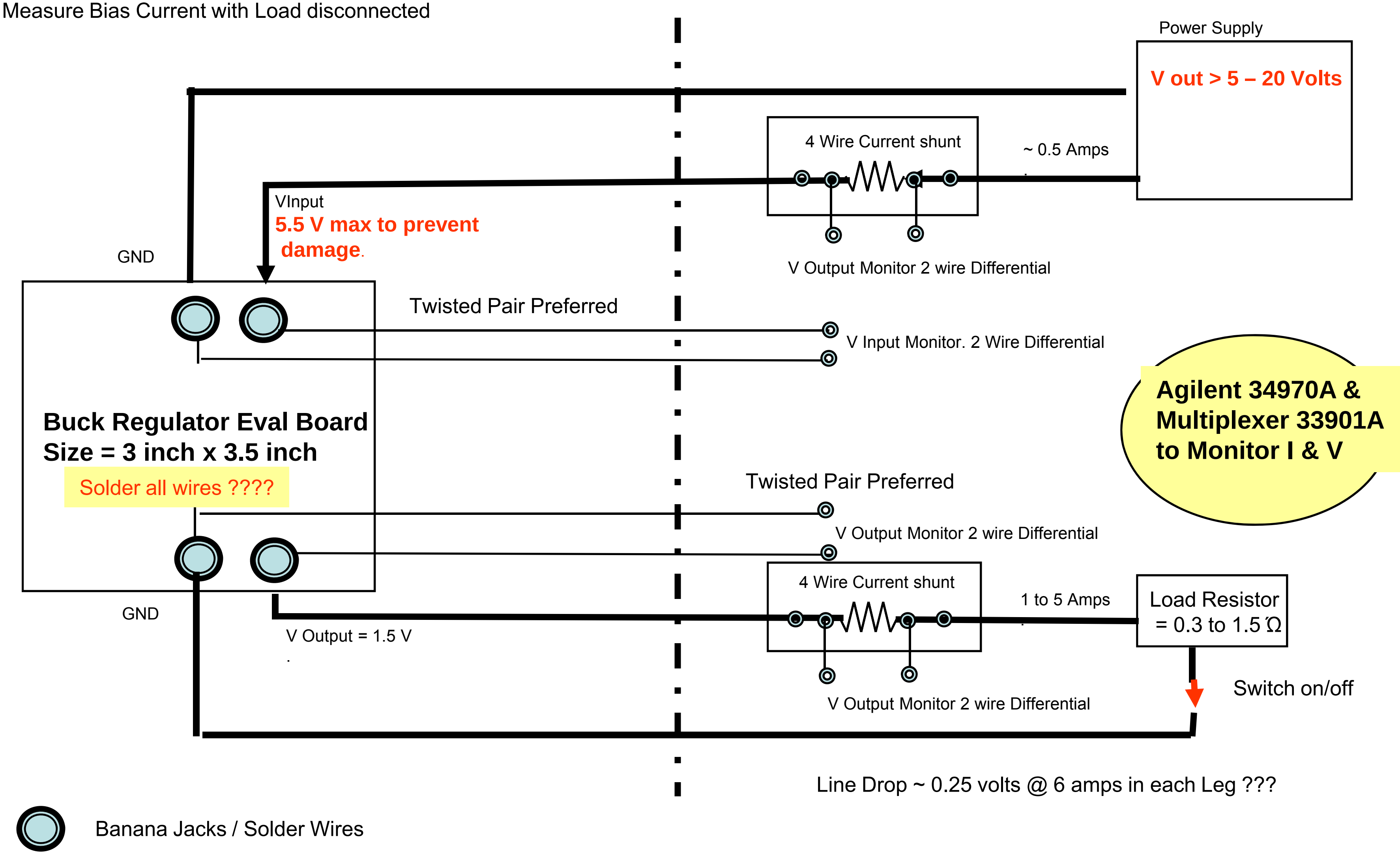

LTC3415 with Medium Inductor Coils: Showing various distances of approach and thicknesses of Copper shielding
Efficiency (%)
Output current (amps)
0
10
20
30
40
50
60
70
80
90
100
0
0.5
1
1.5
2
2.5
3
Two Medium Coils Together
Two Medium Coils Apart
Two Medium Coils Together #2
Cu 2 oz, 15 mil towards Coils
Cu 2 oz, 15 mil away from Coils
Cu 62 mil towards coils
Cu 62 mil away from coils
Cu 3 mil toward coils
Cu 3 mil away from coils



Sensor
ABCD chips
Inductor
config
CHARGE INJECTION
Detector Bias Voltage
Select
Reset
220
AFK.
7A5


Output Noise Comparison (Detector Bias Voltage = 31V, 1mV ~ 125e)
60
50
40
30
20
10
0
Output Noise [mV]
0
200
400
600
800
1000
Channel
3.3V DC-DC Convertor with Shielding
Lab 3.3V Power Supply
3.3V DC-DC Convertor without Shielding

DC-DC Converter Voltage ratio = 8/10
Load: Rated Current or maximum without cooling ~ 1 amp
Setup for 4 EVAL Boards
Measure Bias Current with Load disconnected



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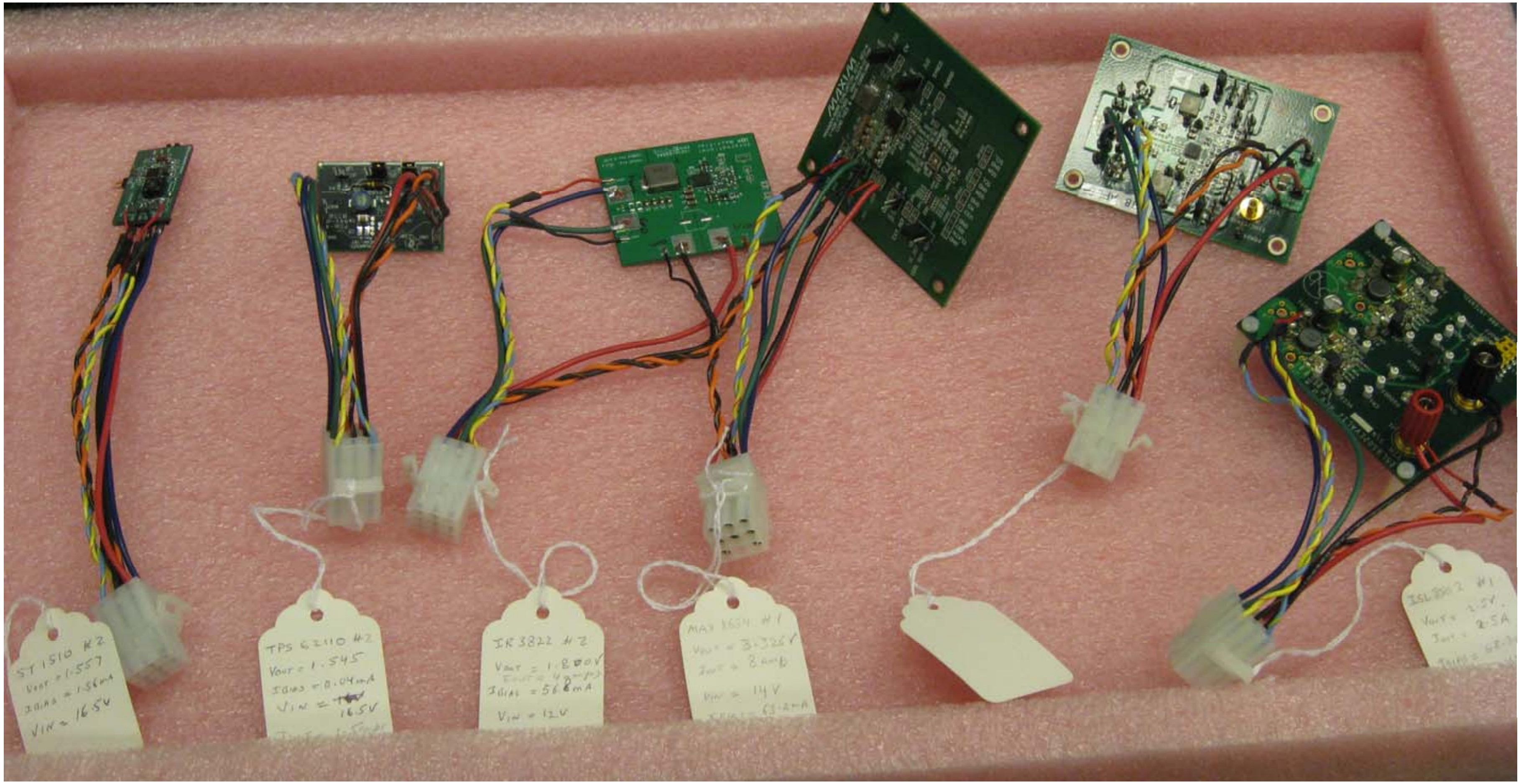
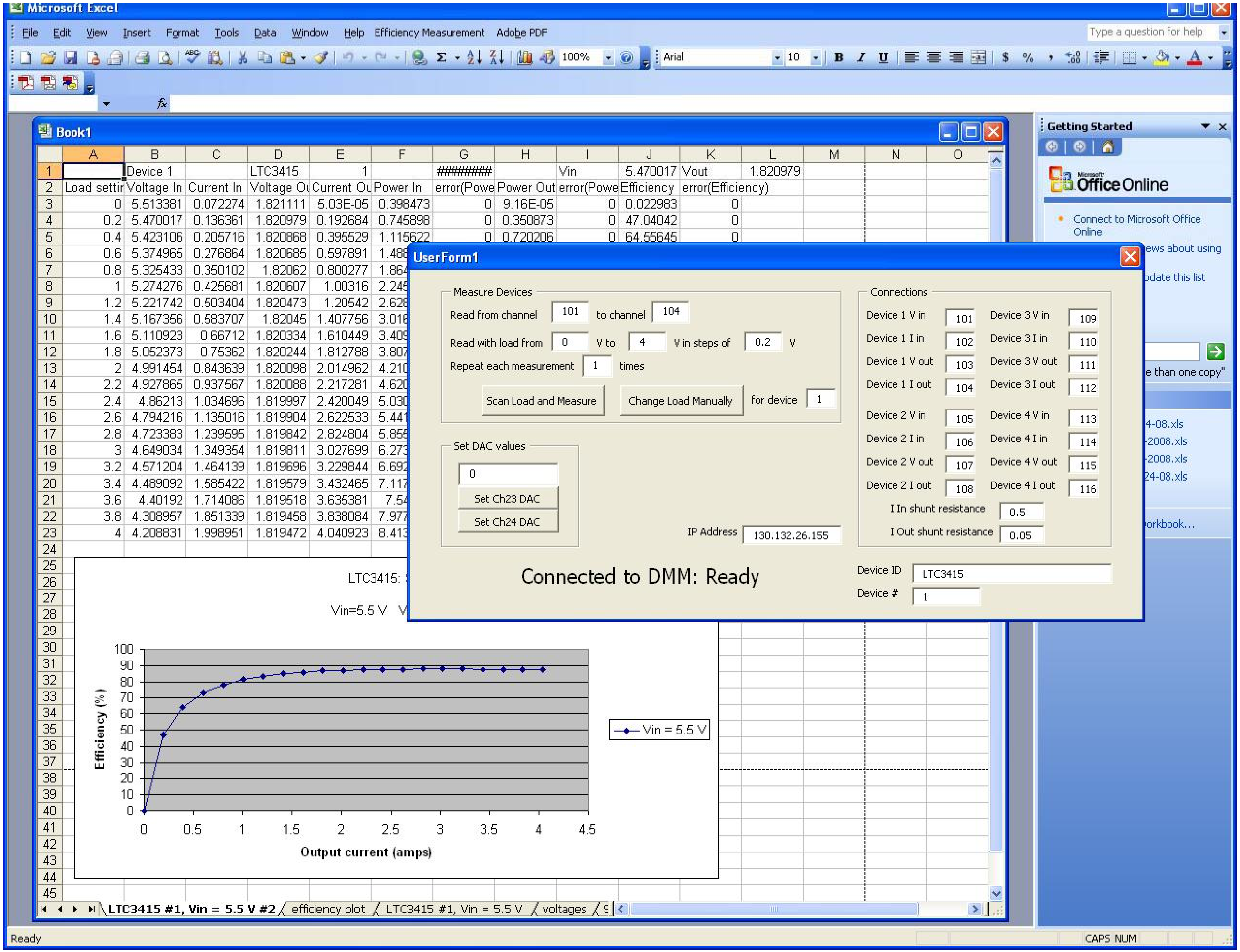
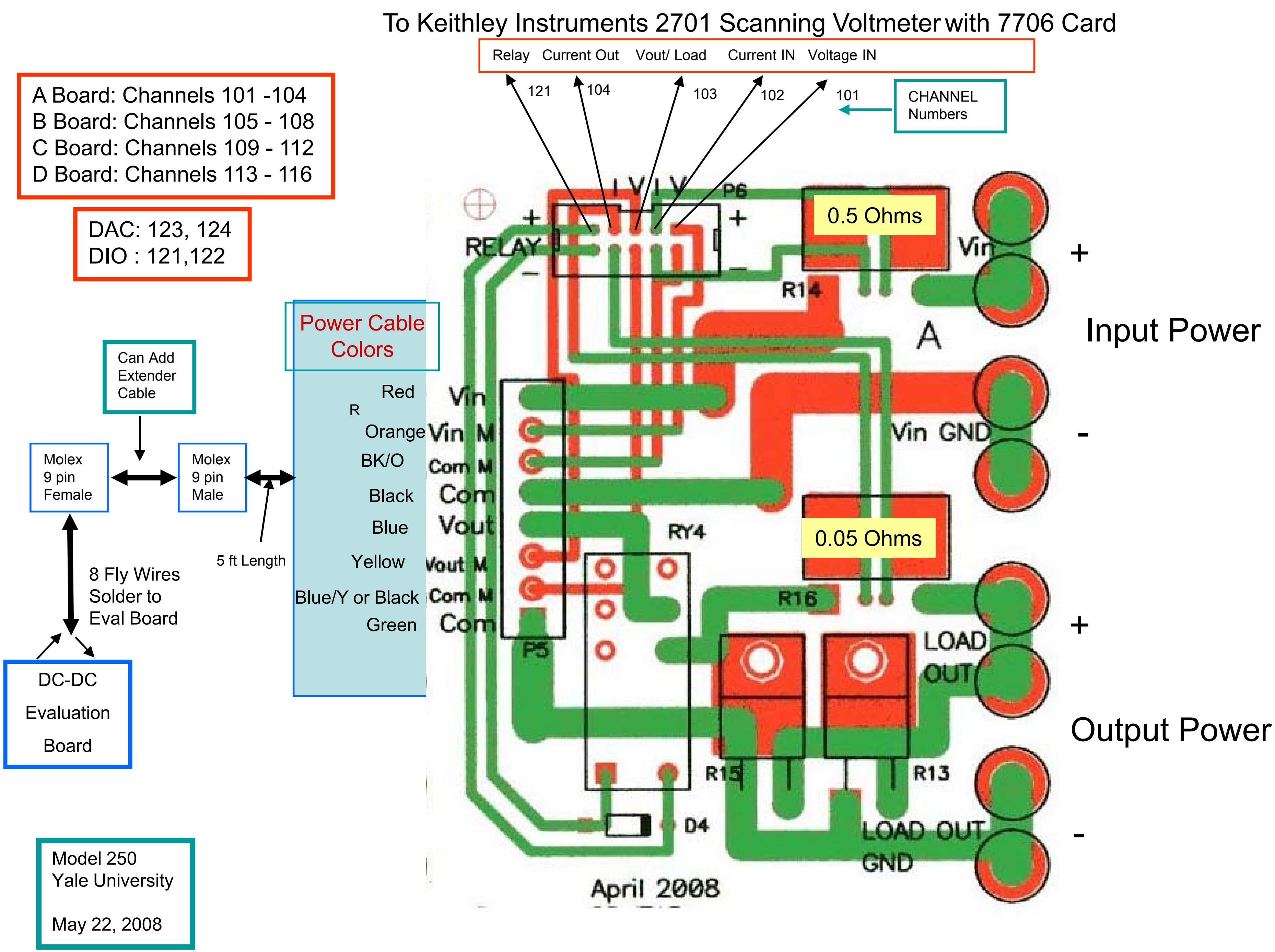
DC-DC Regulator Setup for Radiation Exposure

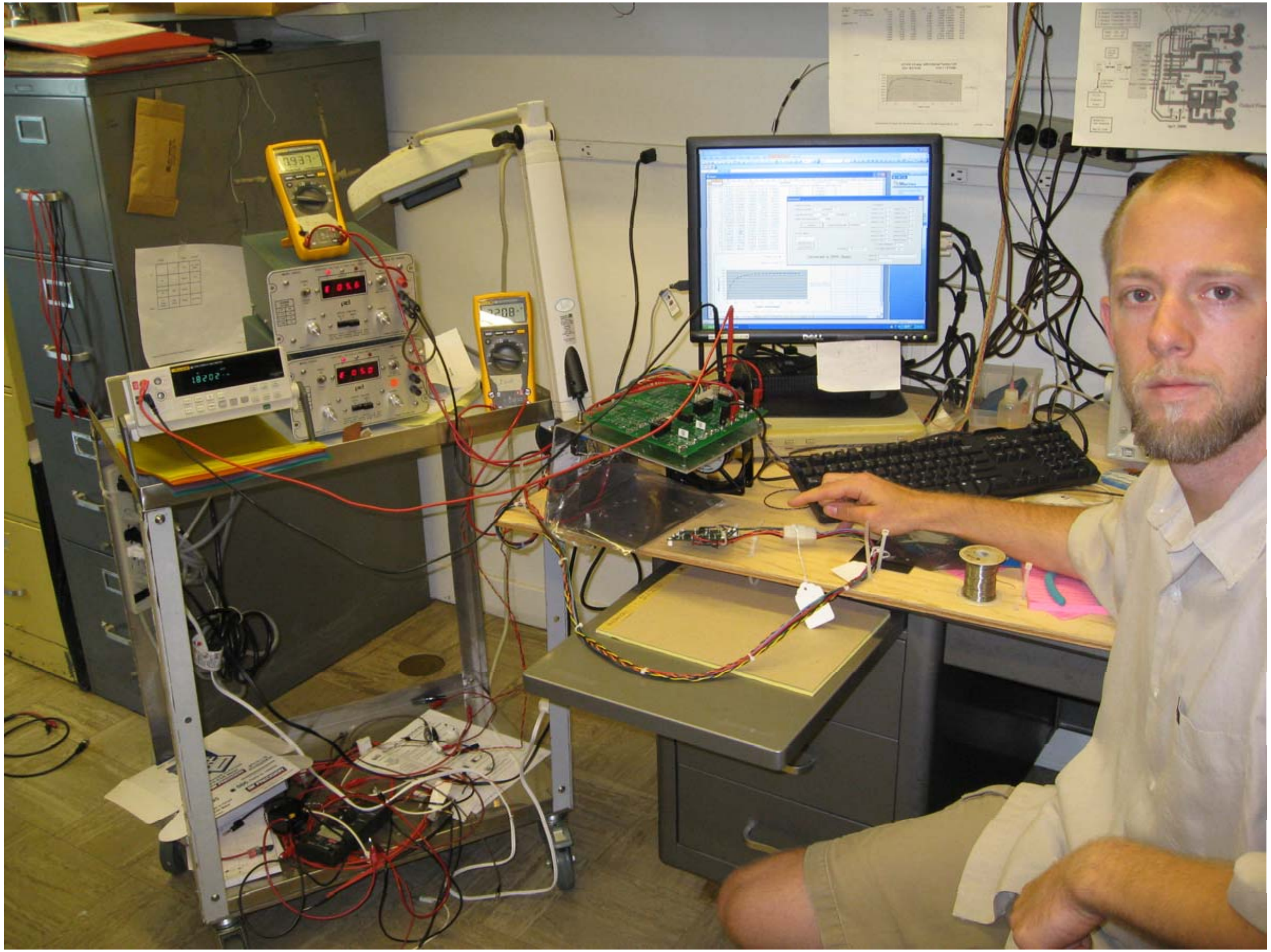
Fig 5 Evaluation
Boards




Microsoft Excel
File Edit View Insert Format Tools Data Window Help Efficiency Measurement Adobe PDF
Type a question for help
Book1
Device 1 LTC3415 1 ######## Vin 5.470017 Vout 1.820979
Load settir Voltage In Current In Voltage Ou Current Ou Power In error(Powe Power Out error(Powe Efficiency error(Efficiency)
0 5.513381 0.072274 1.821111 5.03E-05 0.398473 0 9.16E-05 0 0.022983 0
0.2 5.470017 0.136361 1.820979 0.192684 0.745898 0 0.350873 0 47.04042 0
0.4 5.423106 0.205716 1.820868 0.395529 1.115622 0 0.720206 0 64.55645 0
0.6 5.374965 0.276864 1.820685 0.597891
0.8 5.325433 0.350102 1.82062 0.800277
1 5.274276 0.425681 1.820607 1.00316
1.2 5.221742 0.503404 1.820473 1.20542
1.4 5.167356 0.583707 1.82045 1.407756
1.6 5.110923 0.66712 1.820334 1.610449
1.8 5.052373 0.75362 1.820244 1.812788
2 4.991454 0.843639 1.820098 2.014962
2.2 4.927865 0.937567 1.820088 2.217281
2.4 4.86213 1.034696 1.819997 2.420049
2.6 4.794216 1.135016 1.819904 2.622533
2.8 4.723383 1.239595 1.819842 2.824804
3 4.649034 1.349354 1.819811 3.027699
3.2 4.571204 1.464139 1.819696 3.229844
3.4 4.489092 1.585422 1.819579 3.432465
3.6 4.40192 1.714086 1.819518 3.635381
3.8 4.308957 1.851339 1.819458 3.838084
4 4.208831 1.998951 1.819472 4.040923
UserForm1
Measure Devices
Read from channel 101 to channel 104
Read with load from 0 V to 4 V in steps of 0.2 V
Repeat each measurement 1 times
Scan Load and Measure
Change Load Manually
for device 1
Set DAC values
0
Set Ch23 DAC
Set Ch24 DAC
IP Address 130.132.26.155
Connected to DMM: Ready
Connections
Device 1 V in 101
Device 1 I in 102
Device 1 V out 103
Device 1 I out 104
Device 2 V in 105
Device 2 I in 106
Device 2 V out 107
Device 2 I out 108
Device 3 V in 109
Device 3 I in 110
Device 3 V out 111
Device 3 I out 112
Device 4 V in 113
Device 4 I in 114
Device 4 V out 115
Device 4 I out 116
I In shunt resistance 0.5
I Out shunt resistance 0.05
Device ID LTC3415
Device # 1
Vin=5.5 V
Efficiency (%)
Output current (amps)
Vin = 5.5 V
LTC3415 #1, Vin = 5.5 V #2 / efficiency plot / LTC3415 #1, Vin = 5.5 V / voltages
Getting Started
Office Online
Connect to Microsoft Office Online
Ready
CAPS NUM



To Keithley Instruments 2701 Scanning Voltmeter with 7706 Card
Relay Current Out Vout/ Load Current IN Voltage IN
121
104
103
102
101
CHANNEL Numbers
A Board: Channels 101 -104
B Board: Channels 105 - 108
C Board: Channels 109 - 112
D Board: Channels 113 - 116
DAC: 123, 124
DIO : 121,122
Power Cable Colors
Red
R
Orange
BK/O
Black
Blue
Yellow
Blue/Y or Black
Green
Can Add Extender Cable
Molex 9 pin Female
Molex 9 pin Male
5 ft Length
8 Fly Wires Solder to Eval Board
DC-DC Evaluation Board
Model 250
Yale University
May 22, 2008
I V I V
P6
RELAY
+
-
0.5 Ohms
R14
Vin
A
Input Power
Vin
Vin M
Com M
Com
Vout
Vout M
Com M
Com
Vin GND
RY4
0.05 Ohms
R16
P5
LOAD OUT
Output Power
R15
R13
D4
LOAD OUT GND
April 2008

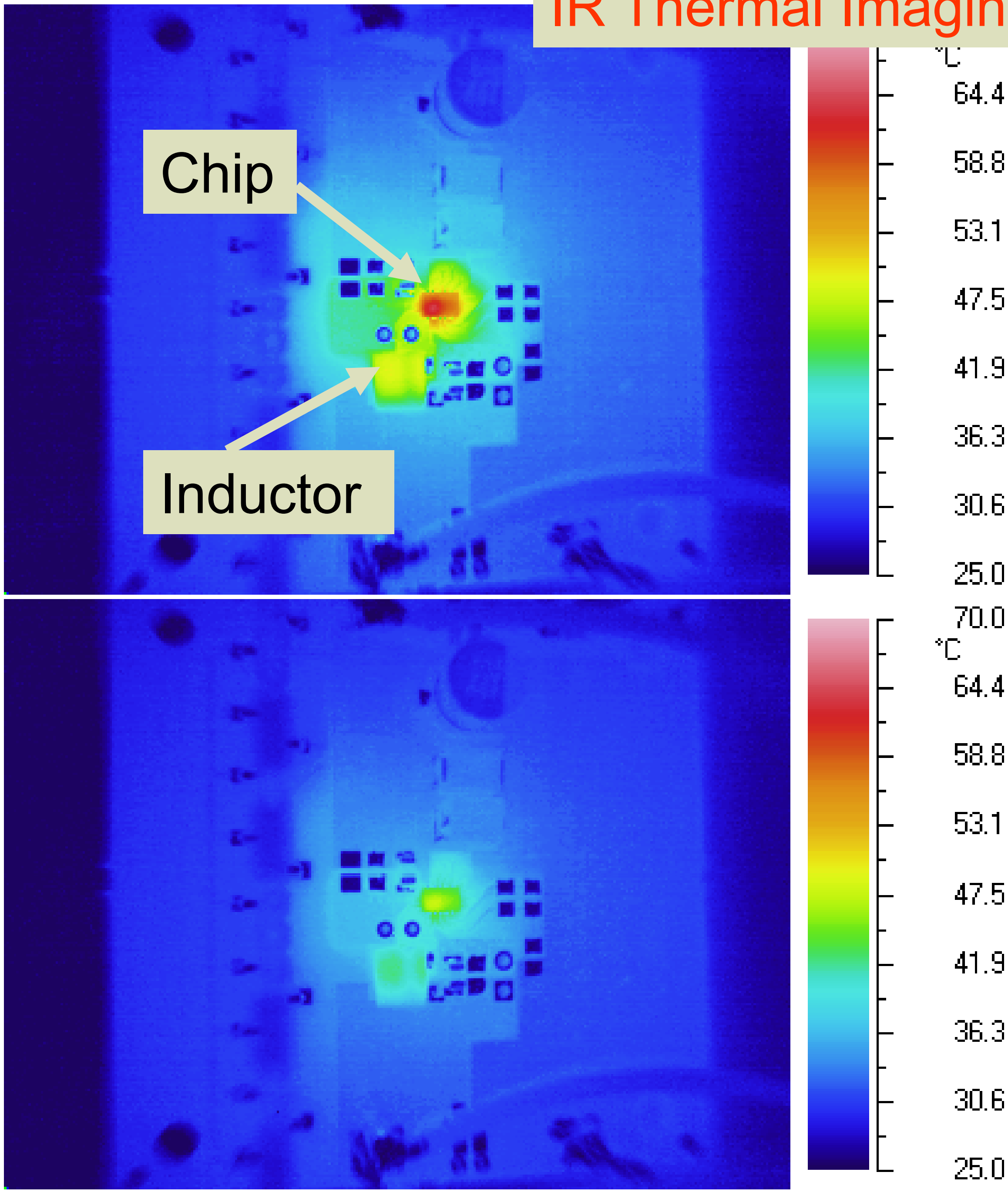


Irradiation Results

Device	Time in Seconds	Dose before Damage Seen (krads)	Observations Damage Mode
TPS 62110	720	40	Increasing input current
ISL 8502	730	40.6	Increasing input current
MAX 8654	850	47.2	Loss of output voltage regulation
ADP 21xx	1000	55.6	Loss of output voltage regulation
ST1510	2250	125	Loss of output voltage regulation
IR3822	2500	139	Increasing input current
EN5382	2000	111	Loss of output voltage regulation
EN5360 #3	864000	48,000	MINIMAL DAMAGE
EN5360 #2	TESTED IN 2007	100,000	MINIMAL DAMAGE

IR Thermal Imaging Camera

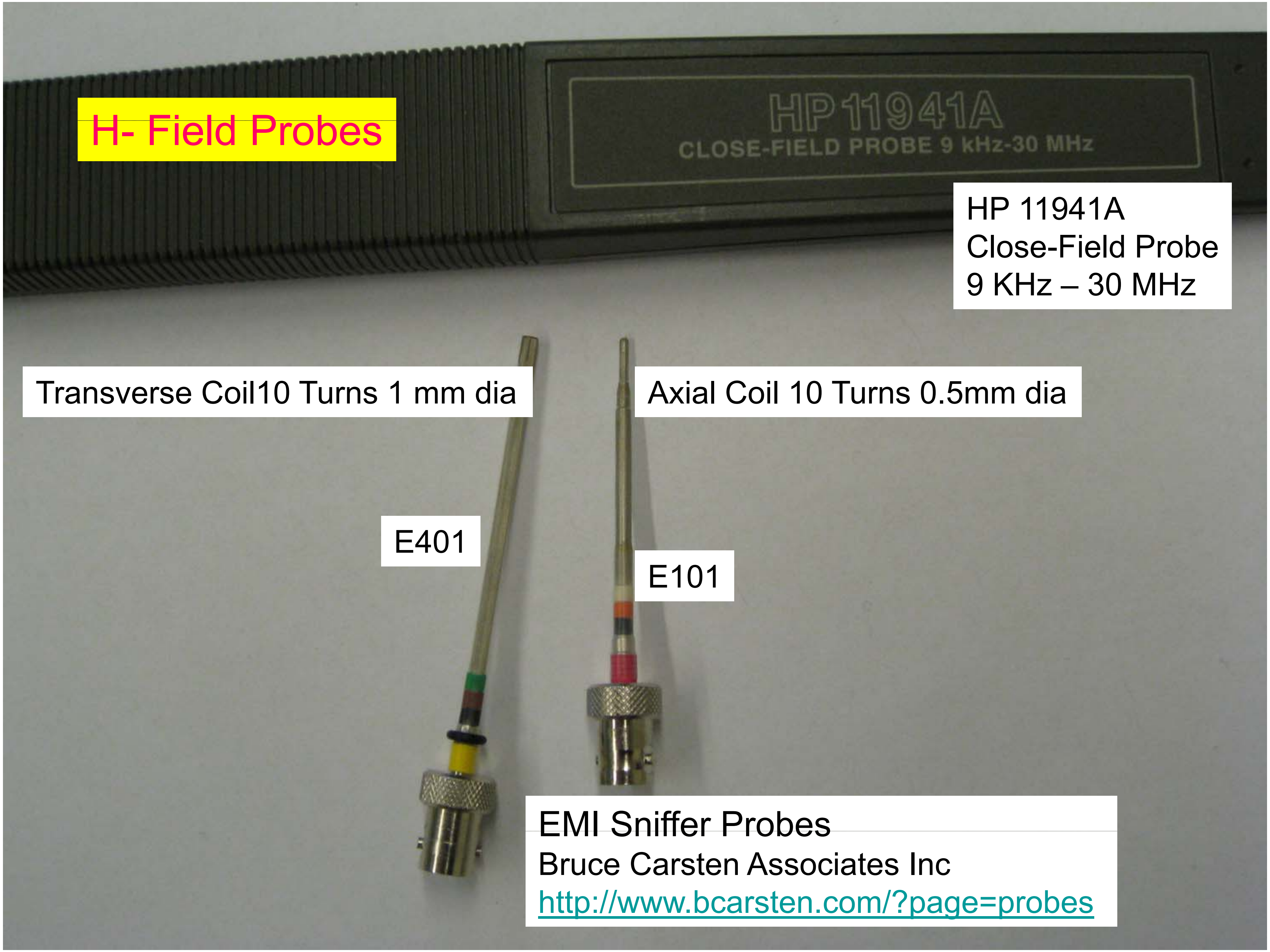
EN5382 Thermals



Load = 1 amp

No Load

H- Field Probes



HP 11941A
Close-Field Probe
9 KHz – 30 MHz

Transverse Coil10 Turns 1 mm dia

Axial Coil 10 Turns 0.5mm dia

E401

E101

EMI Sniffer Probes
Bruce Carsten Associates Inc
http://www.bcarsten.com/?page=probes

Some Power Supply Developments

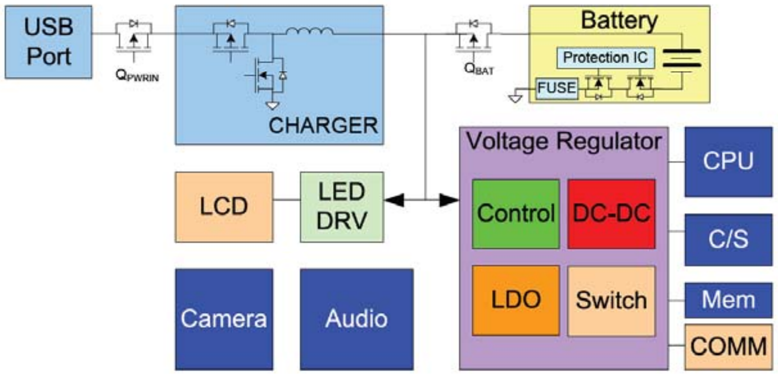
What can we learn?

Size190 mm x 80 mm
Screen 12 cms

Multimedia Internet Device

- Web Browsing
- Touch Screen
- WiFi, Bluetooth, Tri & Quad Band
- HSDPA- World wide Roaming
- ATOM CPU 1.3 GHz 45nm Dual-core
- 1.8 inch 60GB Hard Drive. 32GB SSD
- SD Card Slot, SIM Card
- 1.3 MP Webcam. Stereo Speakers
- HD Mobil TV while Moving
- 1 Kg

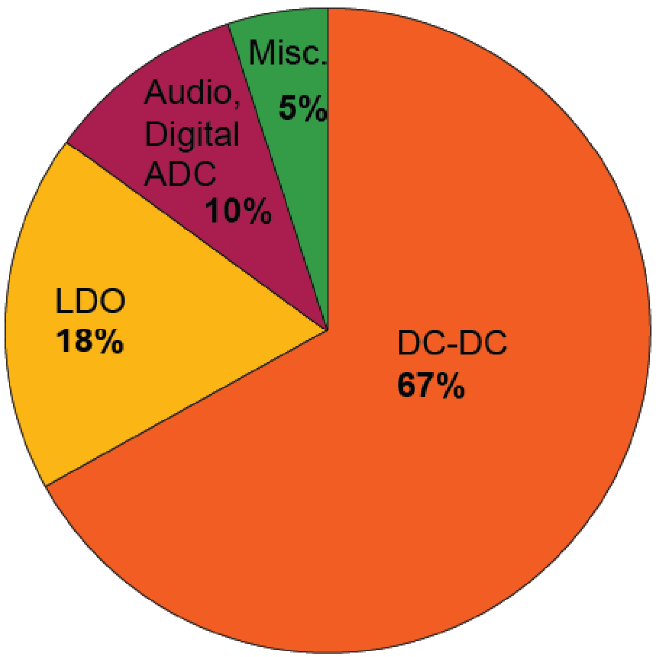
Overall Block Diagram



Power System is efficiently designed to allow long battery life, low-standby power and quick wake-up call

- **25 Voltage Rails !!!**
- 15 Inductors- Buck
- Back Lighting LEDs
- 17 % of PCB Area

Intel Developer FORUM



DC-DC Convertors on Silicon Conference

International Workshop on Power Supply On Chip

September 22nd - 24th, 2008
Cork, Ireland

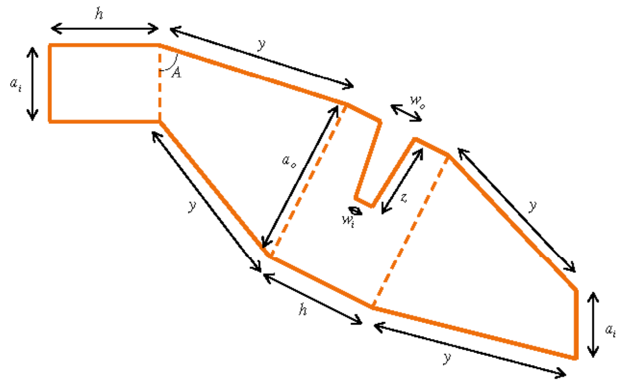
DC-DC convertors on silicon:
next generation technology for emerging business opportunities

In recent years, power supply miniaturisation and reliability concerns are being increasingly addressed by semiconductor companies through their ability to deliver advanced processing and functional integration in the form of system-in-package (SiP) and system-on-chip (SoC) platforms. This proliferation of functionally-integrated hardware solutions can be seen as an inflection point in the power supply industry which is seeing a dramatic move away from traditional power supply manufacturing (with a focus on the assembly of power supply modules or bricks from discrete components) to an increasing emphasis on power supply products deriving directly from semiconductor and microelectronics products and technologies.

A major challenge to the further miniaturisation of DC-DC converters is the inability to integrate passive components on silicon due to their relatively large size at today's operating frequencies of 0.5 to 5 MHz. Increasing the switching frequencies into the 10's of MHz region offers the potential for the reduction of passive component values to the point where, with the right technology, their size becomes compatible with silicon device dimensions. Currently, significant R&D activity is evident in both academia and industry into advances in semiconductor, magnetic, capacitor and packaging materials and technologies that will deliver products operating at multiMHz frequencies. The ultimate target is to develop new miniaturised product formats that can be referred to as power supply-in-package (PSiP) and power supply-on-chip (PwrSoC).

This concept of integrated power solutions presents a significant disruptive opportunity in power management solutions and warrants an international forum for its discussion and for the elucidation of the key challenges that lie ahead.

Photograph of prototype.



Dimensions of one turn of the winding

Fig. 2. Six-turn folded-foil toroidal winding layout.

Six-turn folded-foil toroidal winding layout.

Multi-Layer Folded High-Frequency Toroidal Inductor Windings

M.Nigam & C. Sullivan, IEEE APEC Conference, February 24-28, 2008, Austin, TX, USA

What's Next

- Why are Enpirion chips (IHP Foundry) Rad Hard ?
- Combination of Foundry & Circuit Design
- Discuss with IHP, Chip Designers
- Test newer Commercial Chips
- Interested companies IHP, National, ADI
- Other Interested Groups to Join our Collaboration

Betreff: FW: DC-DC Buck converter for Harsh Environment

Dear Dr. Dhawan,

Thank you for the information.
The different results obtained for the two ICs look interesting. May be we should try to learn more about the root cause together.
For technology and design information we would give you access to the design kit. For this purpose you need to visit our web site. The topic MPW and Prototyping will guide you to a NDA template. Please fill out this template and follow the given guidelines. After receiving your signed NDA we will provide you with the access data.
The data within the design kit are technology related. If we would need to get more information about potential differences in the IC design we would need to involve Enpirion.

Best regards

Bernd

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