How to Deliver Oodles and Oodles of Current to HEP Detectors in High Radiation and Magnetic Fields?

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Yale University

BNL: Instrumentation Division Seminar

April 07, 2010

1 Oodle = 10,000 amps

Agenda

- How we got into this Power Supply mess
- Type of Converters
- Coil Development
- Proximity Effect
- Plug in cards
- Noise Test with Detectors
- Magnetic Field
- Radiation Effect > Thin Oxide
- Radiation Test Results
- GaN Wide band Gap materials
- Industry Developments
- Did we find a commercial part for sLHC ?
- Market Trends Single Chip
- Conclusions
- *Rad Resistant PS & Li Nitrogen*

Collaborators:
Yale University: Keith Baker
Brookhaven National Laboratory: Hucheng Chen, James Kierstead, Francesco Lanni, David Lynn, Sergio Rescia,

CMS ECAL: 5 Oodles (50 Kamps) .

Power Supply output = 315 KW
Power loss in Leads to SM = 100 KW
Power loss in Regulator Card = 90 KW
Power Delivered @ 2.5 V = 125 KW

Power Supply
6.3 V

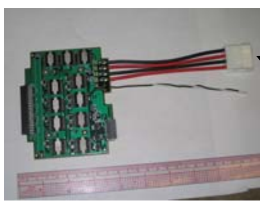
64 Amps

30 m

# of Power Supplies ~ 700
# of ST LDO Chips = 35 K LHC Radiation Hard made by ST Microelectronics
# of LVR Cards = 3.1 K.

Yale: Designed, built, burn-in and Tested.

SM: Super Module



4.3 V

Junction Box

2x16 mm^2 (AWG 6)

1 to 3 m

Vdrop = 2V
Pd = 128 W

50 mm^2 (AWG 00)

2.5V
64 amps
160 W

4 LVR Boards

Power Delivery Efficiency = 40%
NOT INCLUDED
1. Power Supply efficiency
2. Water cooling
3. Removal of Waste heat
4. Air Conditioning

What can we do?

- Is there a better way to distribute power ?
- High Radiation
- Magnetic Field 4 T
- Load ~1 V Oodles of current
- Feed High Voltage and Convert - *like AC power transmission*
- Commercial Technologies – *No Custom ASIC Chips*
- Learn from Semiconductor Industry
- Use Company Evaluation Boards for

First Heard about Intel's Air Coil Work in 4Q 2005 @ IDF

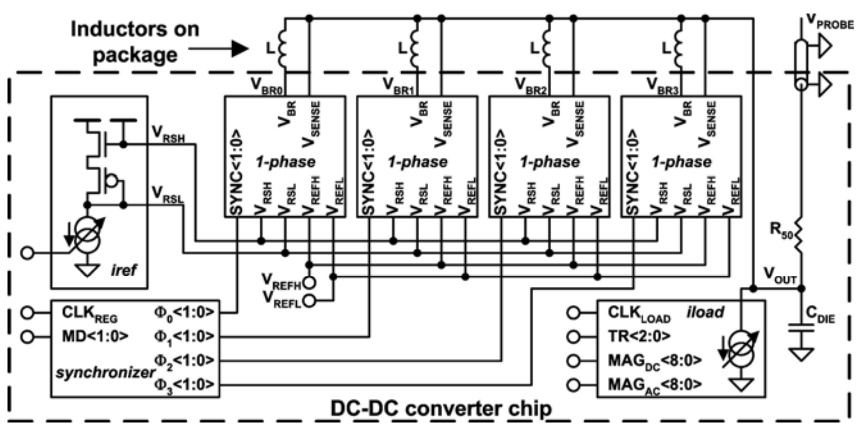
IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 40, NO. 4, APRIL 2005

A 233-MHz 80%–87% Efficient Four-Phase DC–DC Converter Utilizing Air-Core Inductors on Package

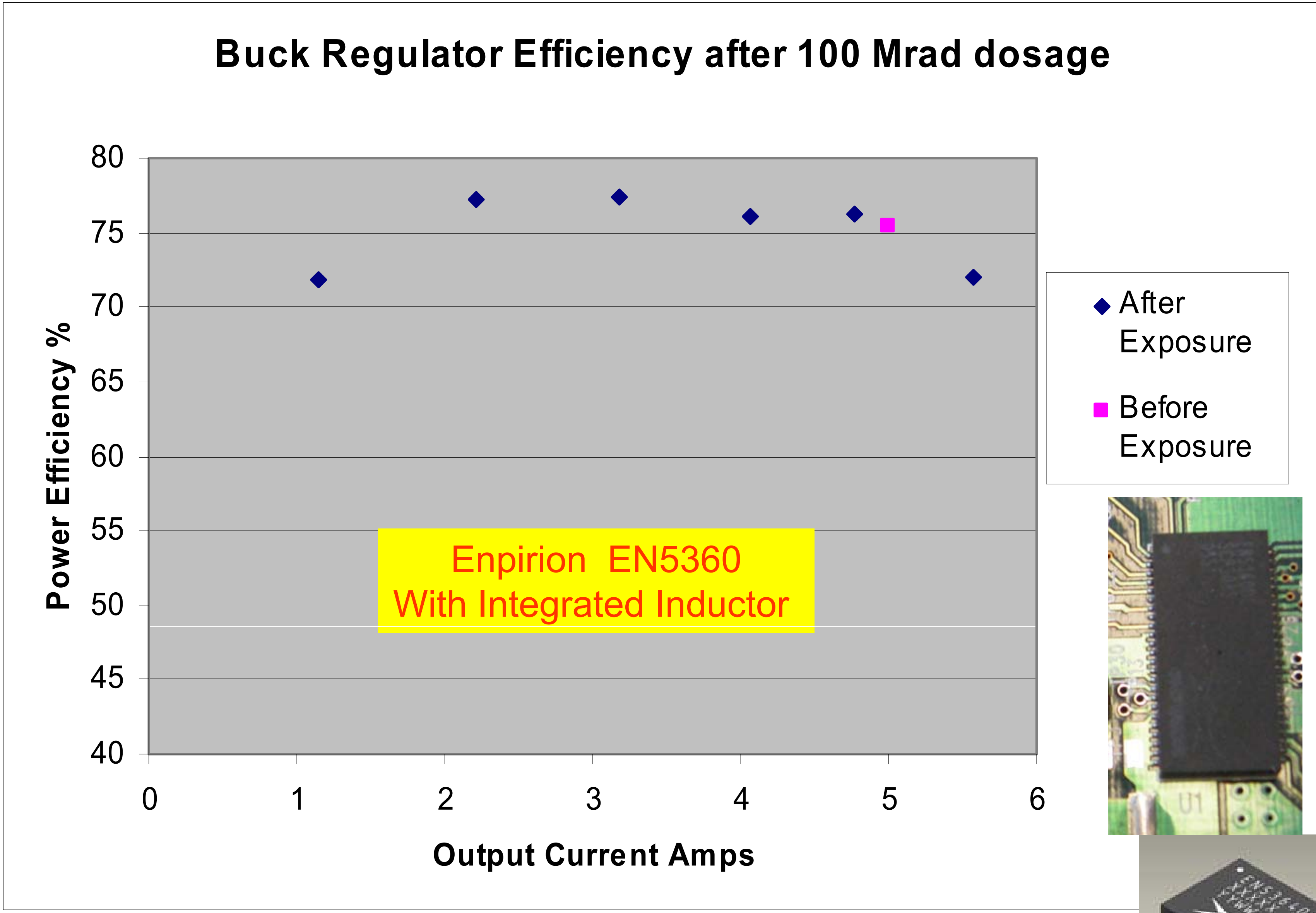
Peter Hazucha, *Member, IEEE*, Gerhard Schrom, Jaehong Hahn, Bradley A. Bloechel, *Associate Member, IEEE*, Paul Hack, Gregory E. Dermer, *Member, IEEE*, Siva Narendra, *Member, IEEE*, Donald Gardner, *Member, IEEE*, Tanay Karnik, *Senior Member, IEEE*, Vivek De, *Member, IEEE*, and Shekhar Borkar, *Member, IEEE*

Circuit Research, Intel Laboratories, Intel Corporation, Hillsboro, OR 97124

Flat Inductors on the Chip.

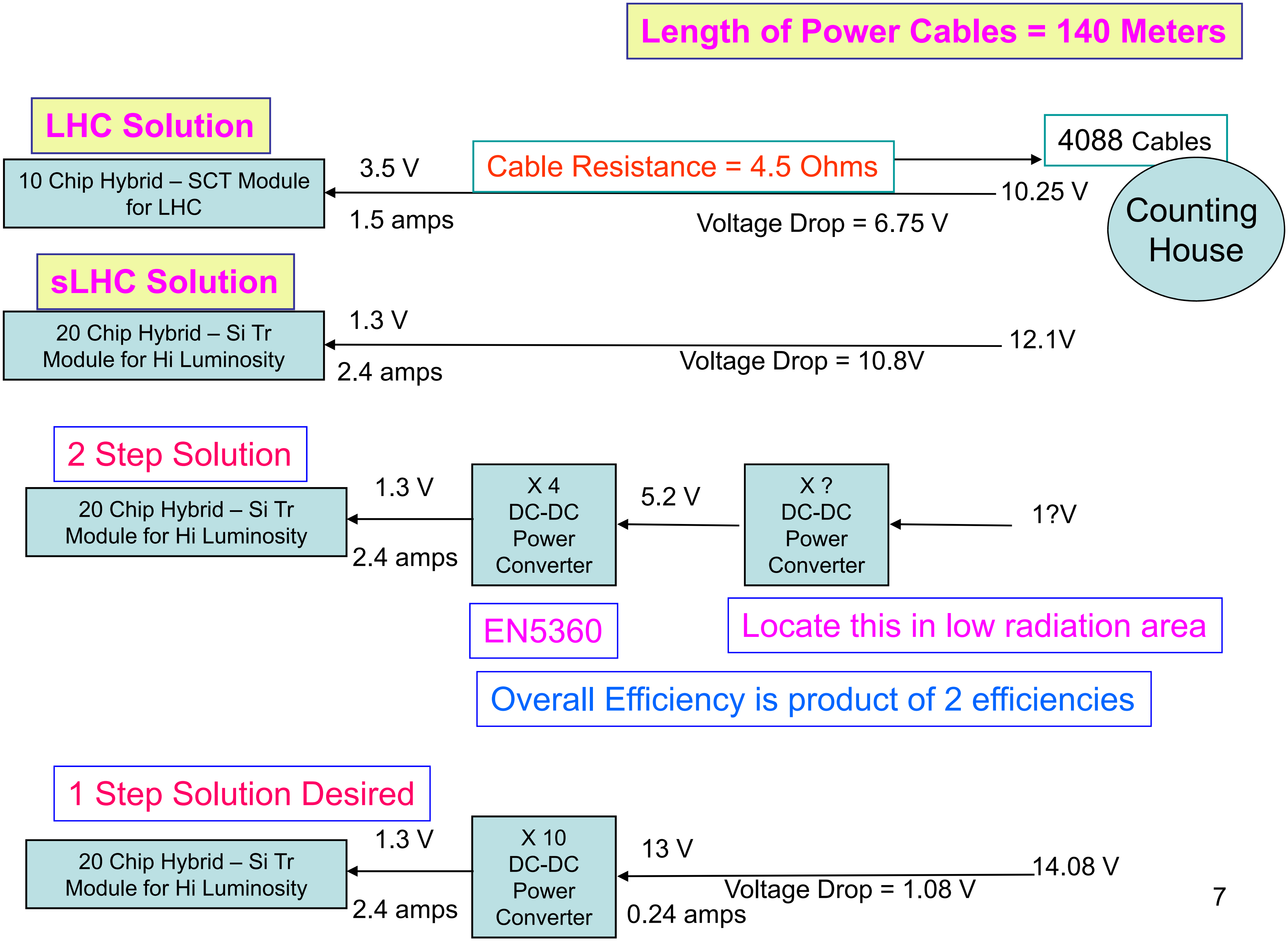


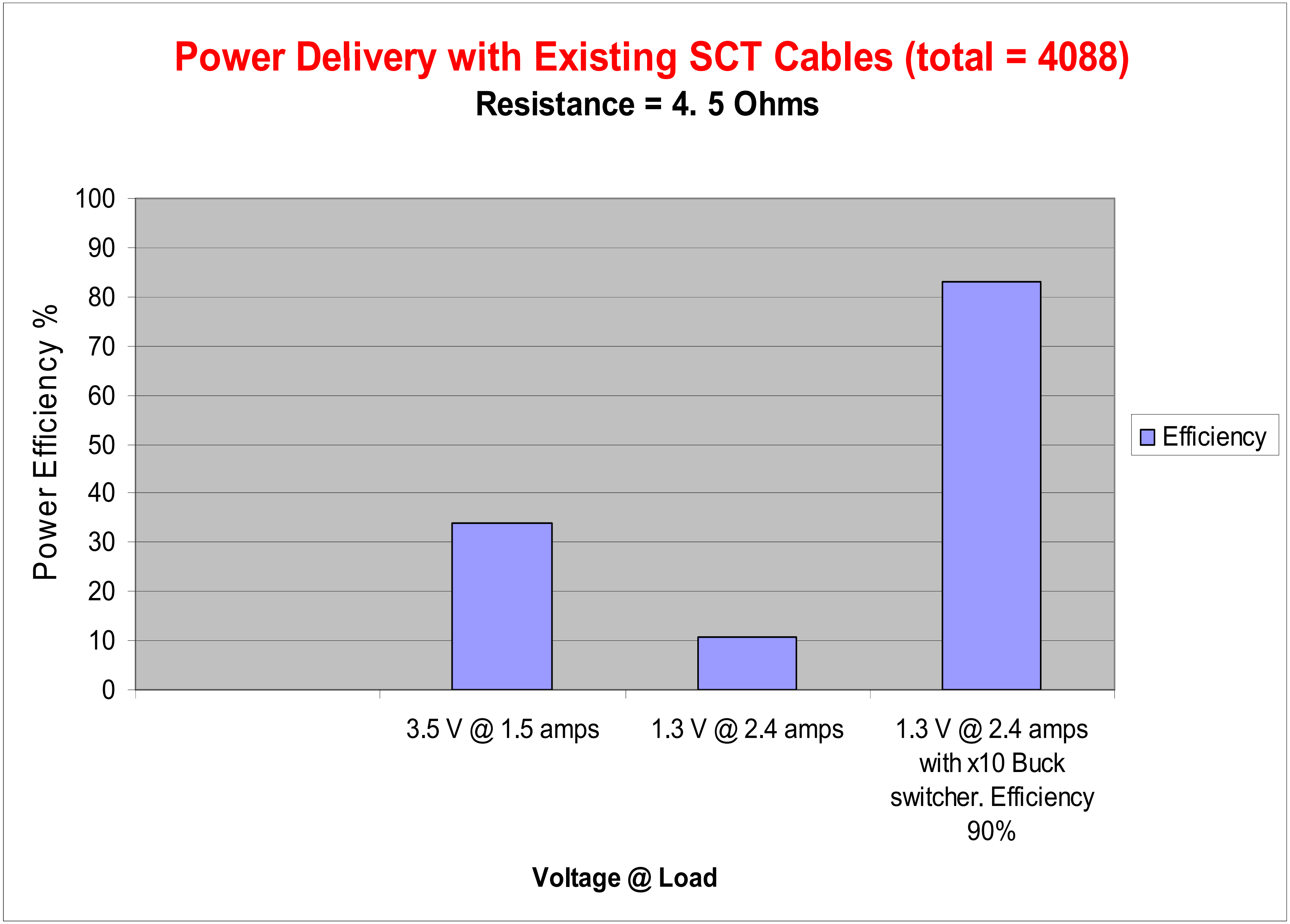
Block diagram of a high-frequency four-phase interleaved dc–dc converter.



Found out at Power Technology conference 0.25 μm Lithography

- Irradiated Stopped on St. Valentines Day 2007
- We reported @ TWEPP 2008 - IHP was foundry for EN5360


Length of Power Cables = 140 Meters
LHC Solution
10 Chip Hybrid – SCT Module for LHC
3.5 V
1.5 amps
Cable Resistance = 4.5 Ohms
4088 Cables
10.25 V
Voltage Drop = 6.75 V
Counting House
sLHC Solution
20 Chip Hybrid – Si Tr Module for Hi Luminosity
1.3 V
2.4 amps
12.1V
Voltage Drop = 10.8V
2 Step Solution
20 Chip Hybrid – Si Tr Module for Hi Luminosity
1.3 V
2.4 amps
X 4 DC-DC Power Converter
5.2 V
X ? DC-DC Power Converter
1?V
EN5360
Locate this in low radiation area
Overall Efficiency is product of 2 efficiencies
1 Step Solution Desired
20 Chip Hybrid – Si Tr Module for Hi Luminosity
1.3 V
2.4 amps
X 10 DC-DC Power Converter
13 V
14.08 V
Voltage Drop = 1.08 V
0.24 amps



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
Efficiency
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

Type of High to Low Voltage Converters without transformers

❖ Charge pumps

- Normally limited to integral fractions of input voltage
- Losses proportional to switch losses
- Can provide negative voltage

❖ Buck Converter – Used in consumer & Industrial Electronics

- Needs an ASIC, Inductor and Capacitors
- Cannot provide a negative voltage
- Topology allows for more flexibility in output voltage than charge pump
- Much more common use in commercial applications

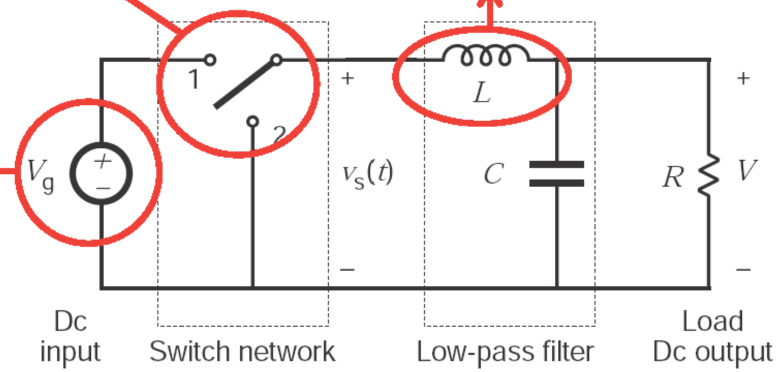
9

Synchronous Buck Converter

f_s = 1-5MHz
⇒ switching noise

HV-tolerant semi-conductor technology needed
→ radiation-hardness

Ferrites saturate for B > ~2T
⇒ air-core inductor needed



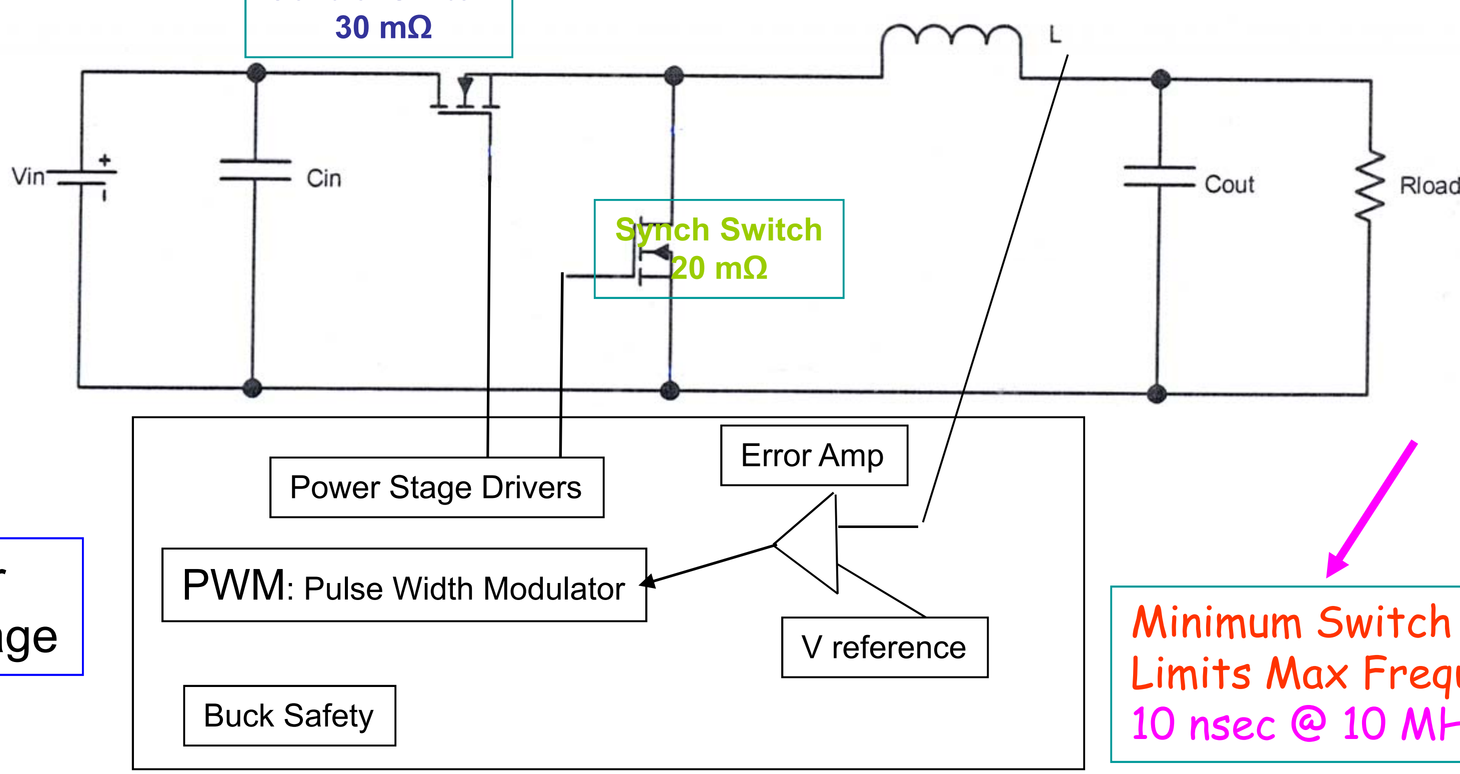
- bulky
- radiates

- Efficiency
- Material budget
- Space constraints

Synchronous Buck Converter

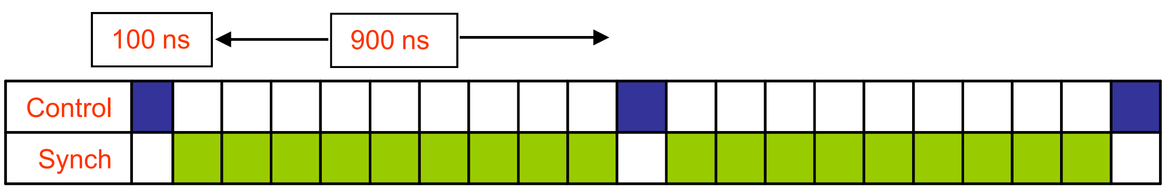
Power Stage - High Volts

Controller Low Voltage



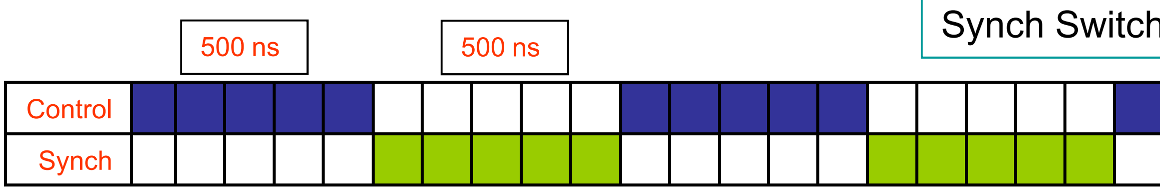
Minimum Switch ON Time
Limits Max Frequency
10 nsec @ 10 MHz

Vout = 11%

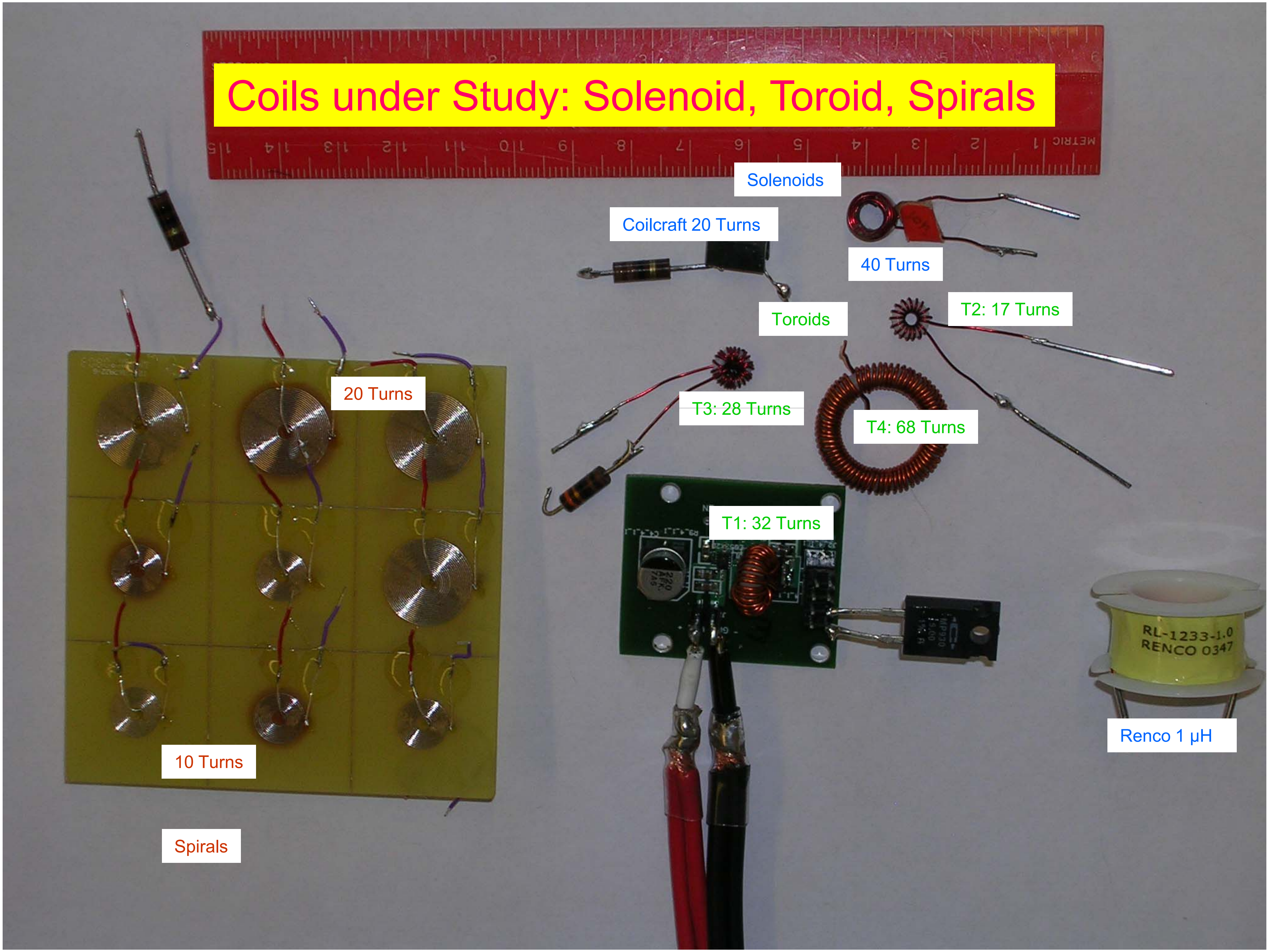


Control Switch: Switching Loss > I^2
Synch Switch: Rds Loss Significant

Vout = 50%



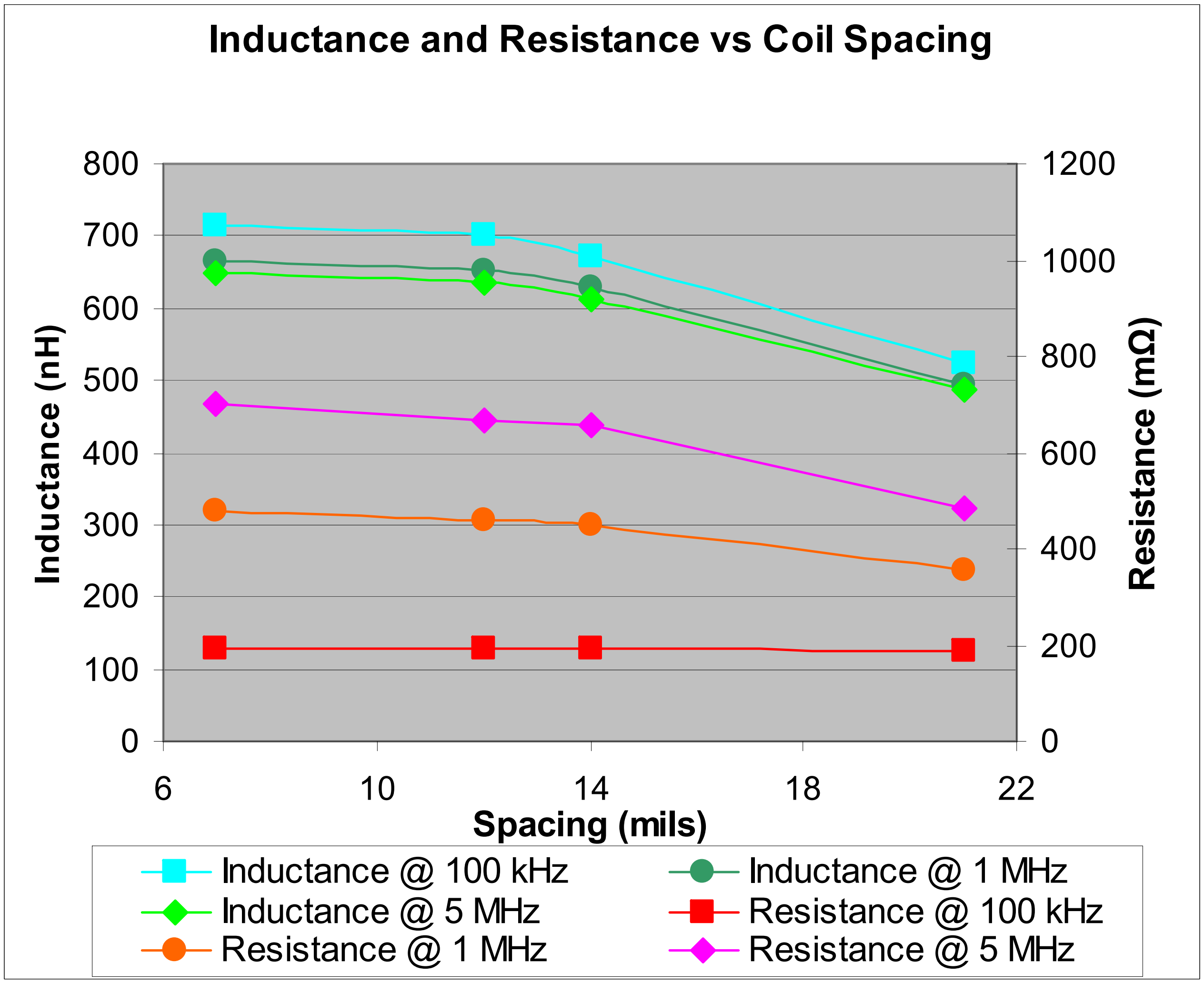
Coils under Study: Solenoid, Toroid, Spirals

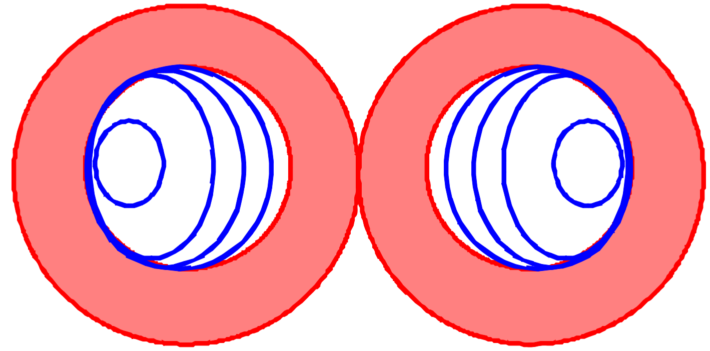


Proximity Effect

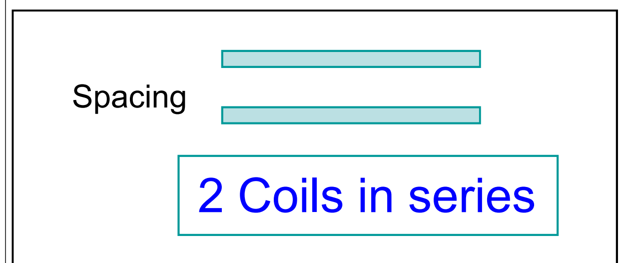
2 oz copper for coils

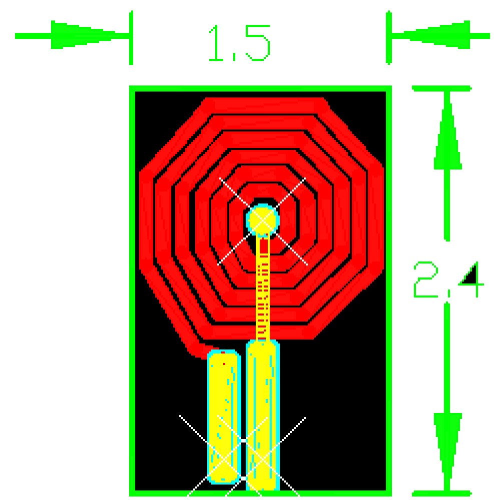
2 coils in series for larger L





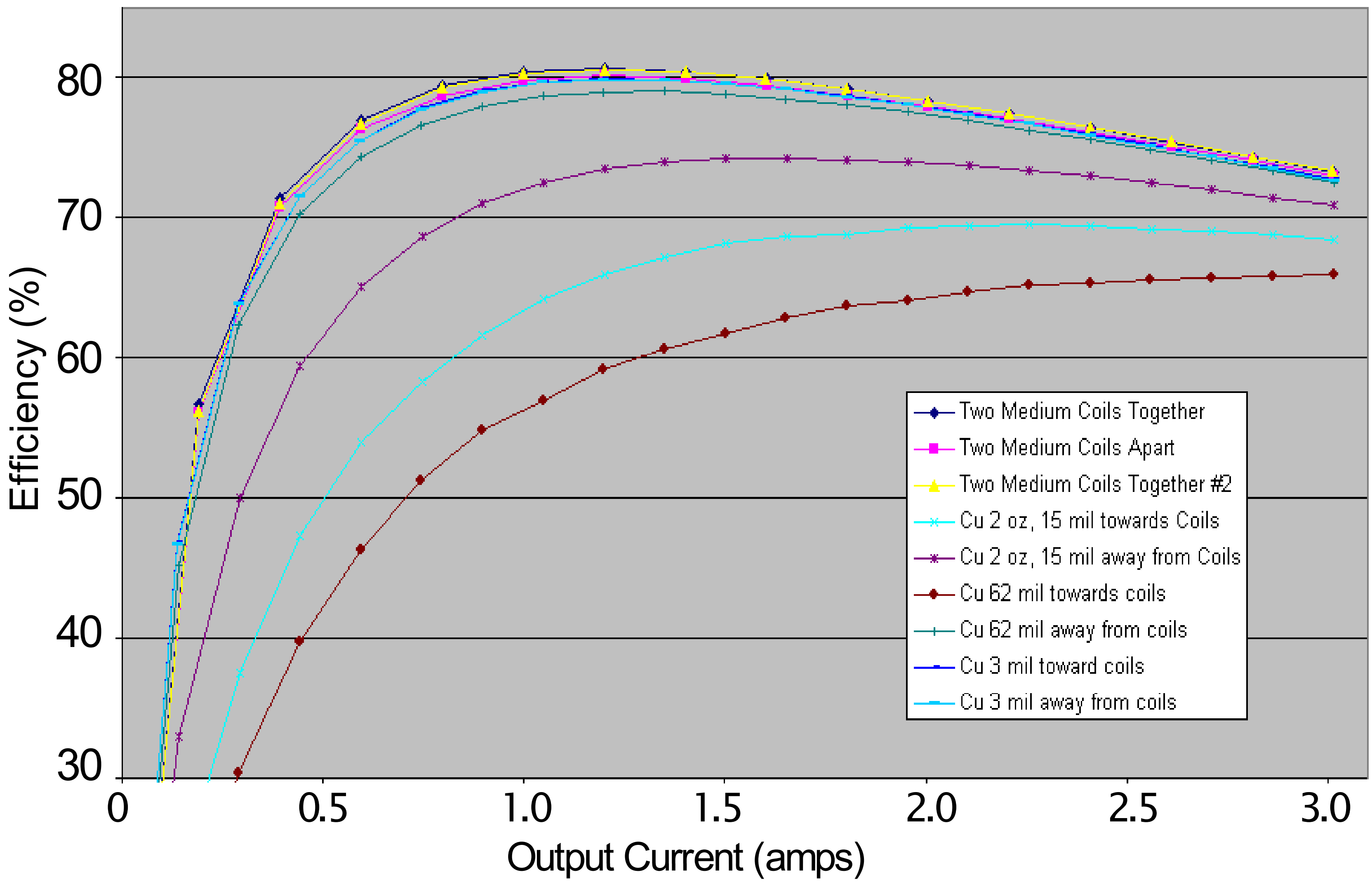
Current Distribution in Neighboring Conductors





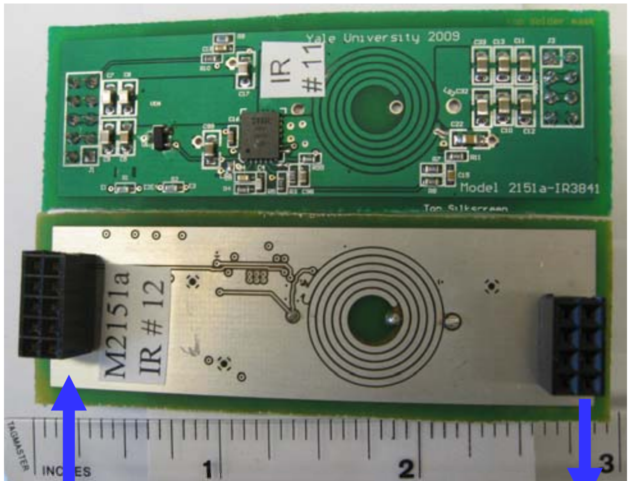
cms

A proximity effect is seen in the spiral coils



2 spiral Coils in series- Squeezing together lowers efficiency !

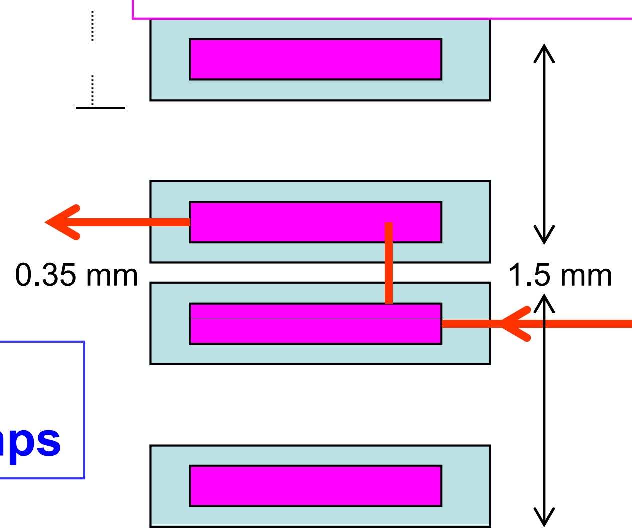
Plug In Card with Shielded Buck Inductor

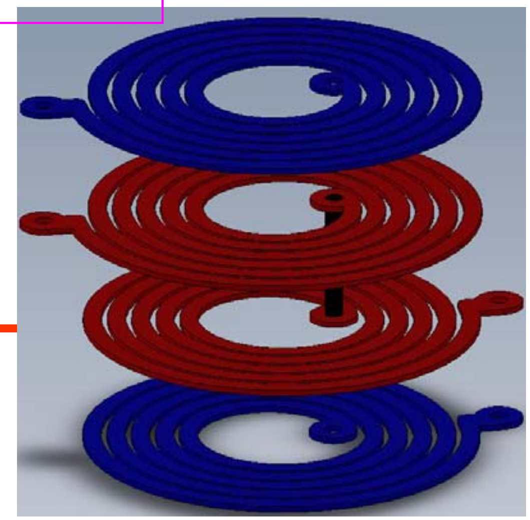


12 V

2.5 V
@ 6 amps

Coupled Air Core Inductor Connected in Series



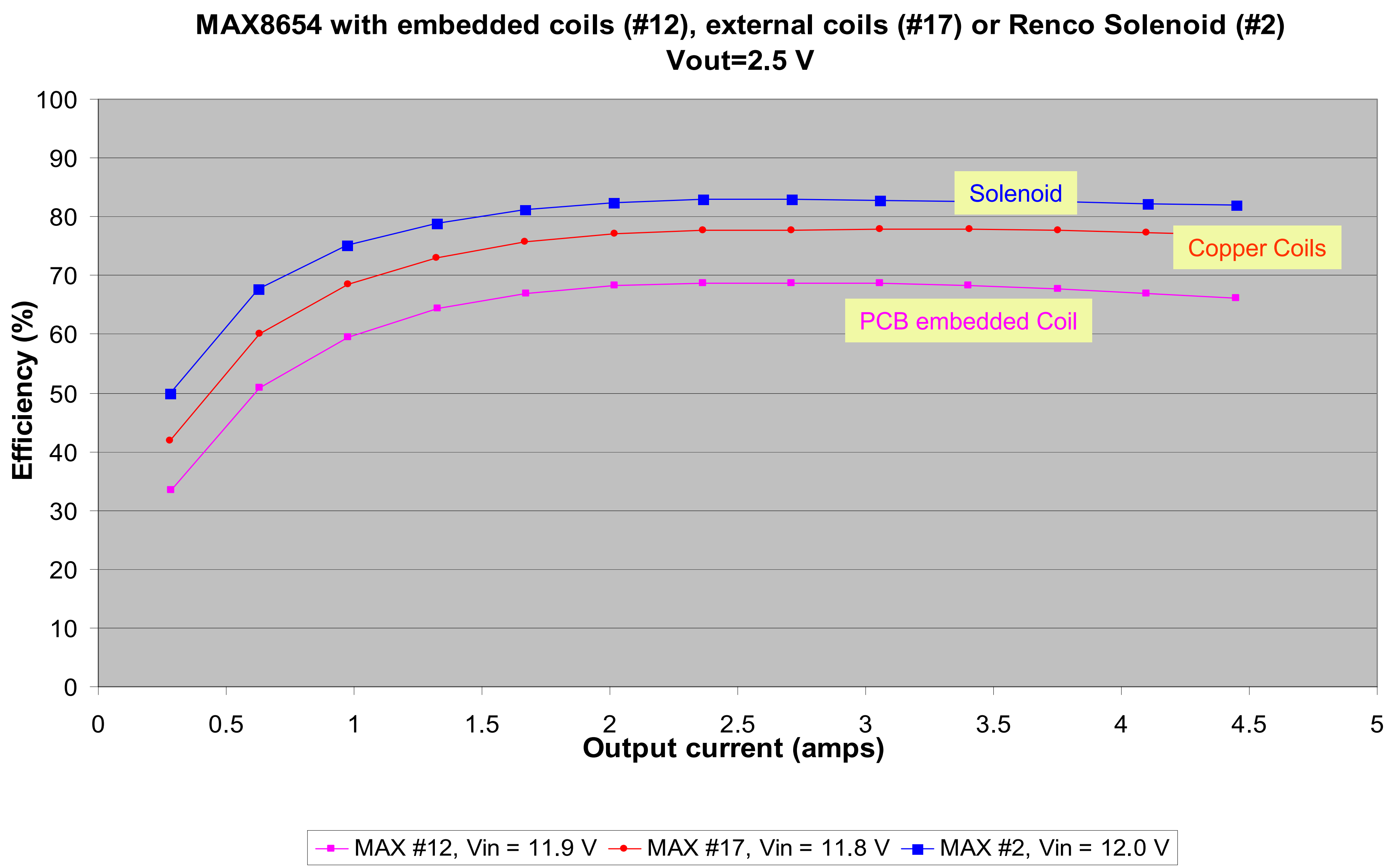


Different Versions

- Converter Chips
  - Max8654 monolithic
  - IR8341 3 die MCM
- Coils
  - Embedded 3oz cu
  - Solenoid 15 mΩ
  - Spiral Etched 0.25mm

Spiral Coils Resistance in mΩ

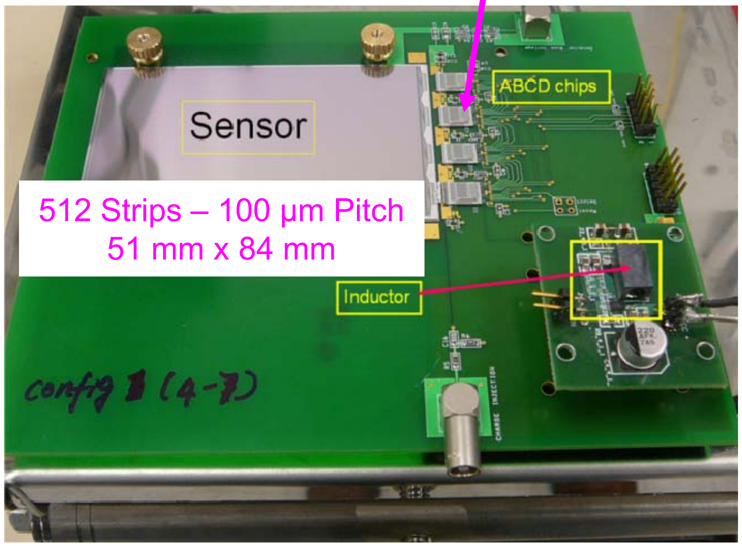
	Top	Bottom
3 Oz PCB	57	46
0.25 mm Cu Foil	19.4	17

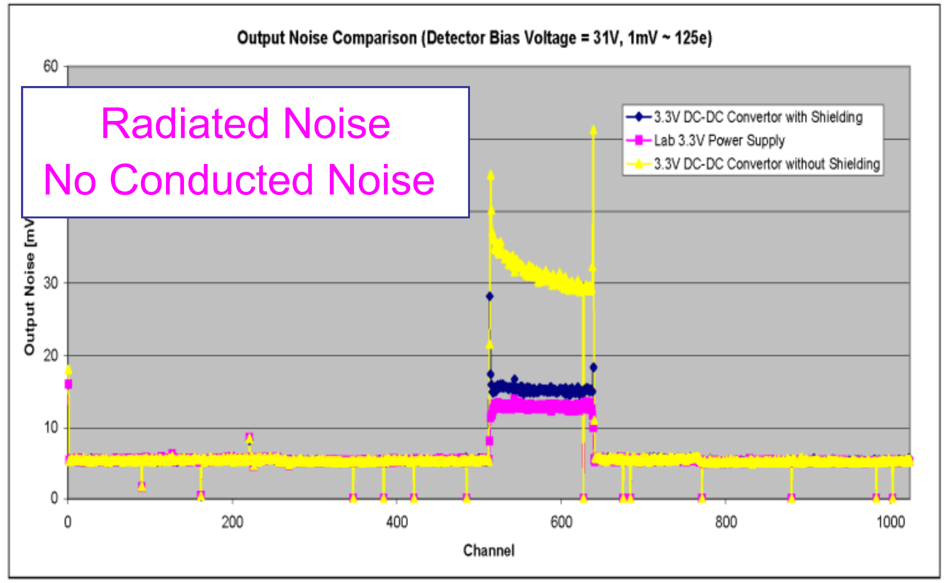

MAX8654 with embedded coils (#12), external coils (#17) or Renco Solenoid (#2)
Vout=2.5 V
Efficiency (%)
Output current (amps)
Solenoid
Copper Coils
PCB embedded Coil
MAX #12, Vin = 11.9 V
MAX #17, Vin = 11.8 V
MAX #2, Vin = 12.0 V

Noise Tests with Silicon Sensors

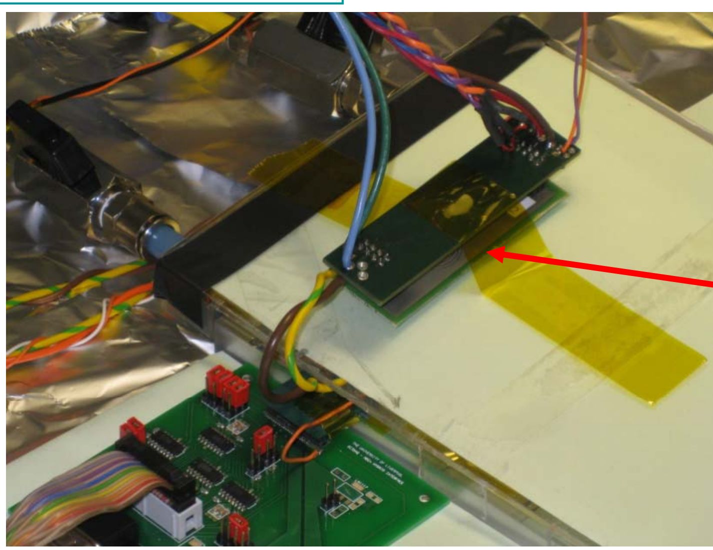
Test @ BNL

Only One Chip Bonded





Test @ Liverpool



Plug in Card
1 cm from Coil
facing Sensor

20 µm Al foil
shielding

Coil Type	Power	Input Noise electrons rms
Solenoid	DC - DC	881
Solenoid	Linear	885
Spiral Coil	DC - DC	666
Spiral Coil	Linear	664

DC-DC with Air Coil

Magnetic Field Effect

7 Tesla Field Chemistry Department Super Conducting Magnet in Persistence Mode

Effect:

Vout = 3.545 Outside

Vout = 3.546 Edge of magnet

Vout = 3.549 Center of magnet

Change= Increased Vout 1 part in 900 at 7T

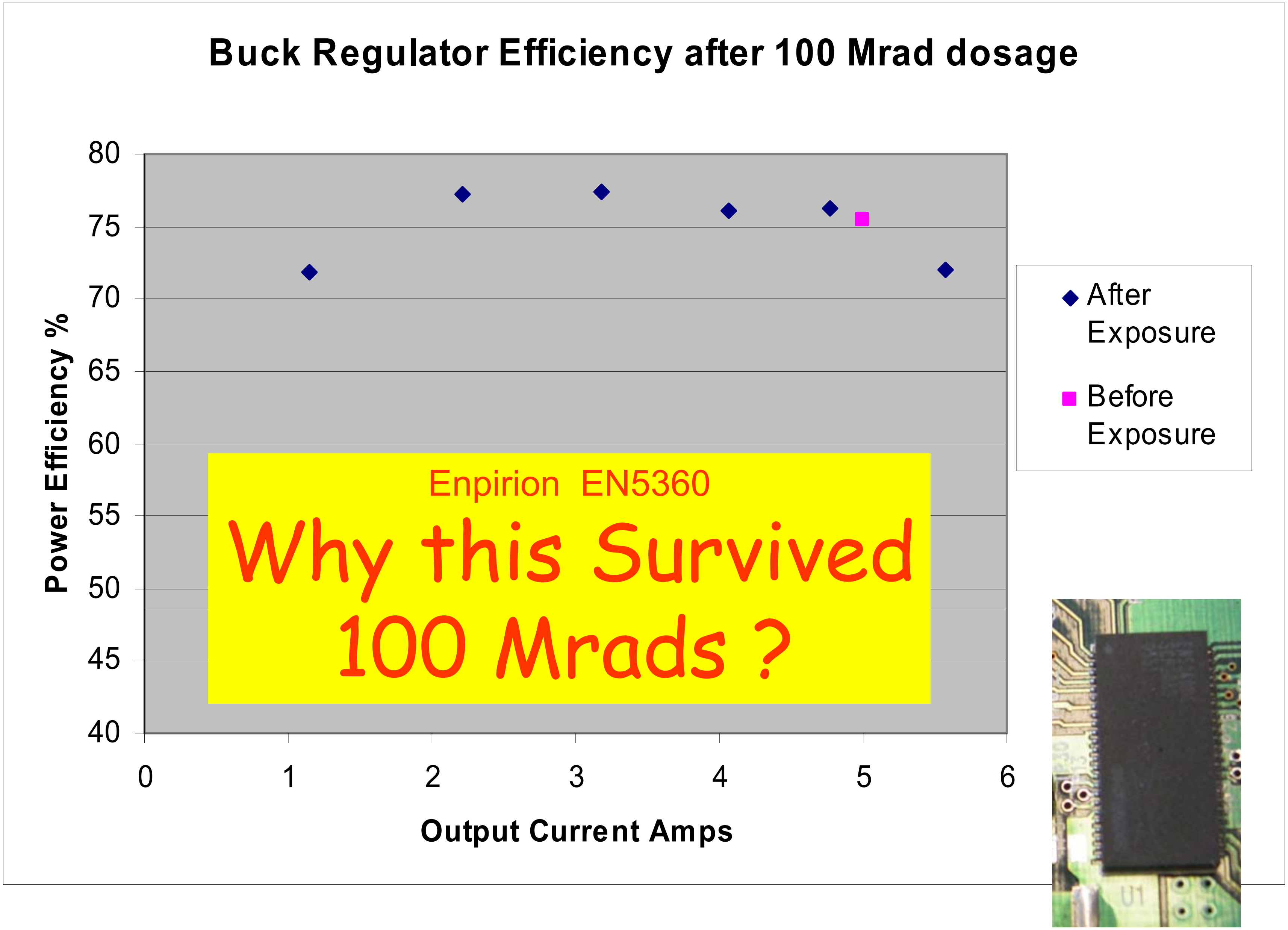
Ionizing Radiation Results – Commercial Converters

Dose rate= 0.2 Mrad/hr

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 Tested in 2008	48000	MINIMAL DAMAGE
EN5360 #2	Tested in 2007	100000	MINIMAL DAMAGE

5 nm Oxide DC-DC

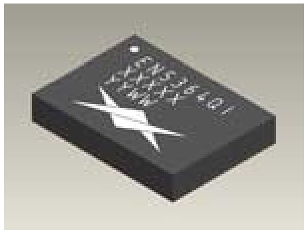
Many more tested but similar failure-
Thin oxide converters survive > 200 Krads


Buck Regulator Efficiency after 100 Mrad dosage
80
75
70
65
60
55
50
45
40
Power Efficiency %
0
1
2
3
4
5
6
Output Current Amps
After Exposure
Before Exposure
Enpirion EN5360
Why this Survived 100 Mrads ?
U1

What Makes it Rad Resistant ?

Empirical Evidence: Deep submicron

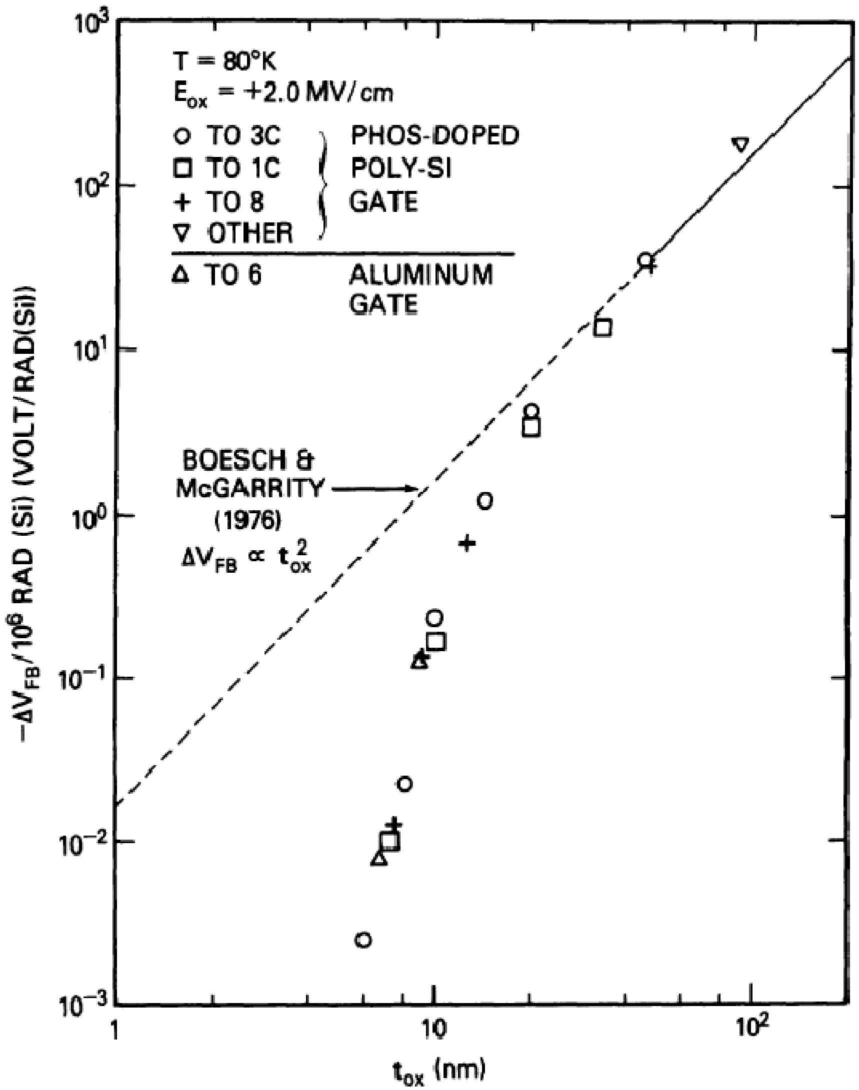
But why?



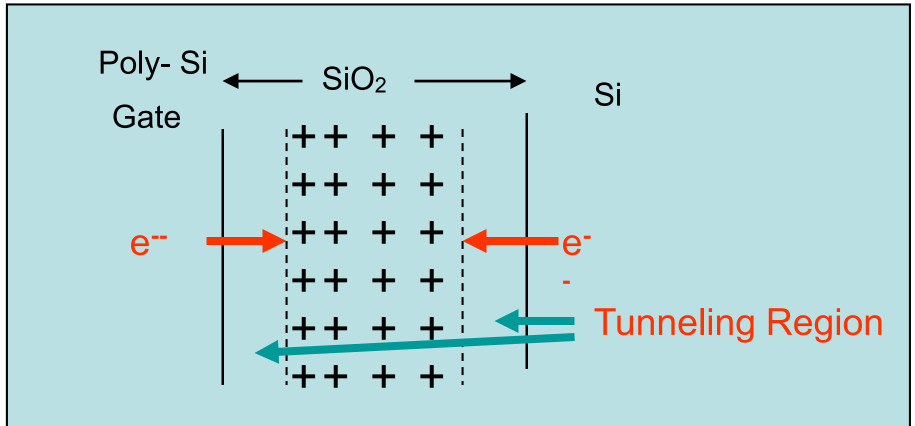
What Makes it Rad Resistant ?

We say thin Gate Oxide is a necessary Condition

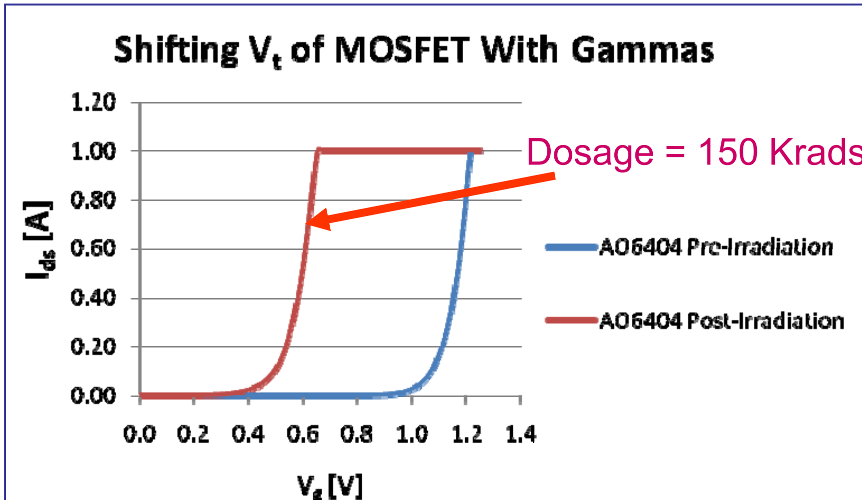
Threshold Shift vs Gate Oxide Thickness



Sachs et. al. IEEE Trans. Nuclear Science NS-31, 1249 (1984)



Hole removal process by tunneling in thin-oxide MOS Structures



Book. Timothy R Oldham "Ionizing Radiation Effects in MOS Oxides" 1999 World Scientific

IBM Foundry Oxide Thickness			
Lithography	Process	Operating	Oxide
	Name	Voltage	Thickness
			nm
0.25 µm	6SF	2.5	5
		3.3	7
0.13 µm	8RF	1.2 & 1.5	2.2
		2.2 & 3.3	5.2

CERN ASICs

Mantra: Deep sub micron is more rad hard

Why ?

Can We Have
High Radiation Tolerance & Higher Voltage Together ???

Controller : Low Voltage

High Voltage: Switches –

LDMOS, Drain Extension, Deep Diffusion etc

>> 20 Volts HEMT GaN on Silicon, Silicon Carbide, Sapphire

LDMOS Structure
Laterally Diffused
Drain Extension

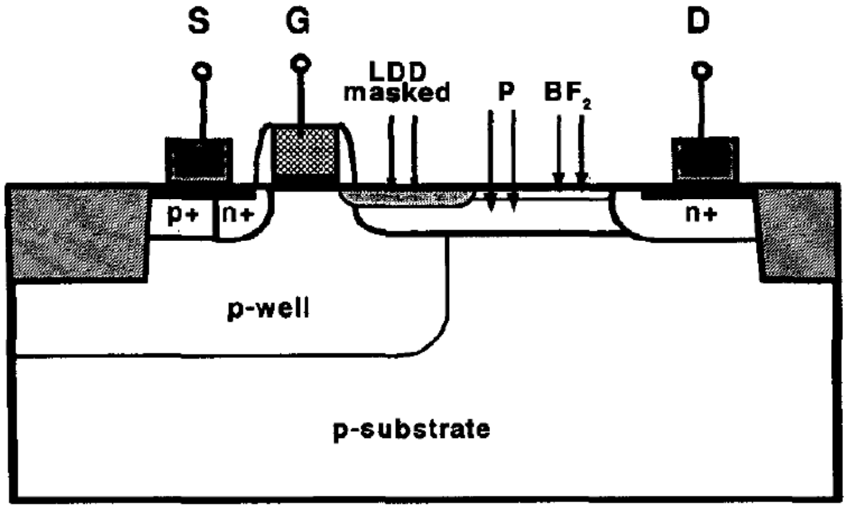


Fig.1: Schematic cross-section of the RF-LDMOS transistor.

High Voltage / high Frequency
Main market. Cellular base stations

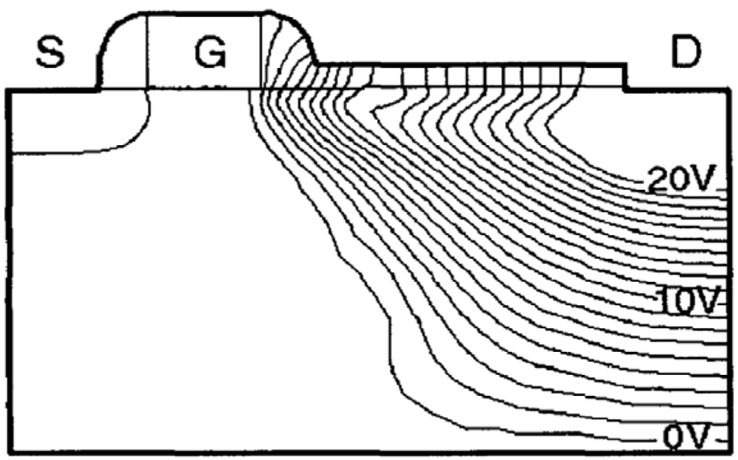


Fig.3a: Potential distribution at the highest operating voltage (20V) with $V_G = 0V$ (LDMOS 3 from Table 1).

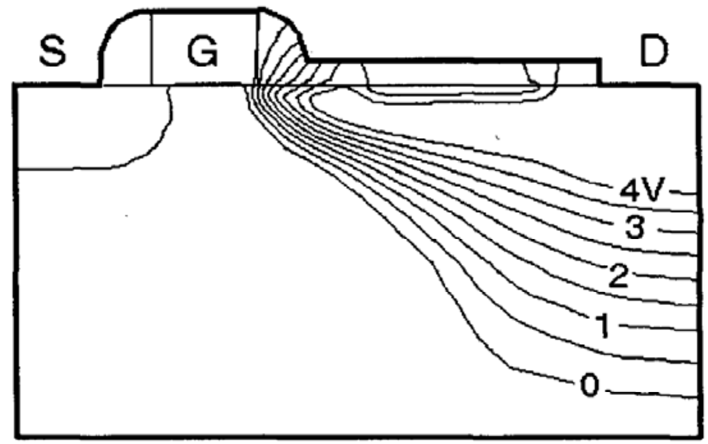


Fig.3b: Potential distribution at the lowest operating voltage (4V) with $V_G = 0V$ (LDMOS 3 from Table 1).

High performance RF LDMOS transistors with 5 nm gate oxide in a 0.25 µm SiGe:C BiCMOS technology: IHP Microelectronics
Electron Devices Meeting, 2001. IEDM Technical Digest. International
2-5 Dec. 2001 Page(s):40.4.1 - 40.4.4

Thin Oxide Devices (non IBM)

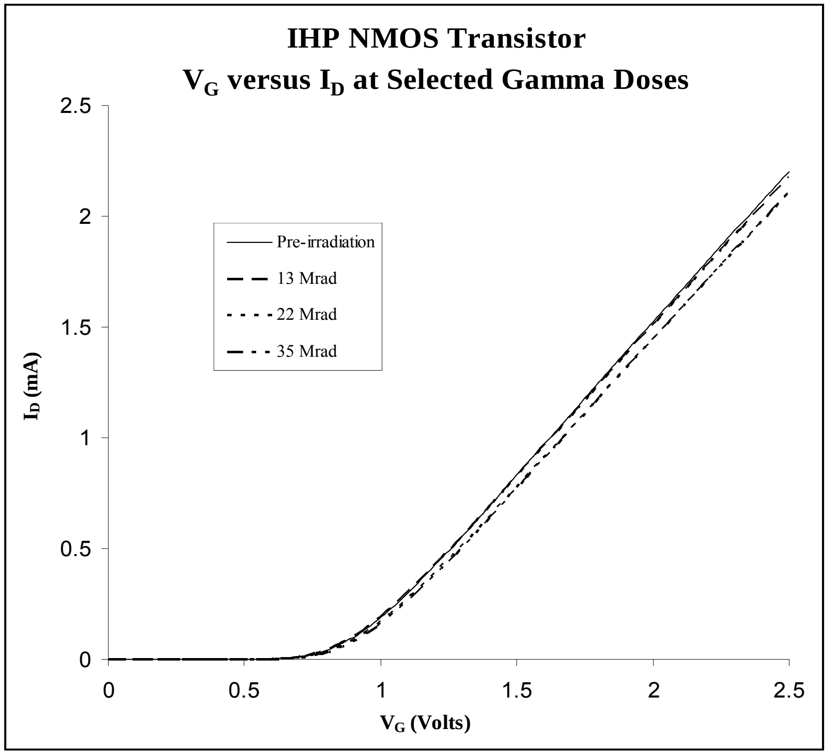
Company	Device	Process	Foundry	Oxide	Dose before	Observation
		Name/ Number	Name	nm	Damage seen	Damage Mode
IHP	ASIC custom	SG25V GOD **12 V**	IHP, Germany	5		Minimal Damage
XySemi	FET 2 amps	HVMOS20080720 **12 V**	China	7		Minimal Damage
XySemi	XP2201	HVMOS20080720 **15 V**	China	12 / 7		1Q2010
Enpirion	EN5365	CMOS 0.25 µm	Dongbu HiTek, Korea	5	64 Krads	
Enpirion	EN5382	CMOS 0.25 µm	Dongbu HiTek, Korea	5	111 Krads	
Enpirion	EN5360 #2	SG25V (IHP)	IHP, Germany	5	100 Mrads	Minimal Damage
Enpirion	EN5360 #3	SG25V (IHP)	IHP, Germany	5	48 Mrads	Minimal Damage

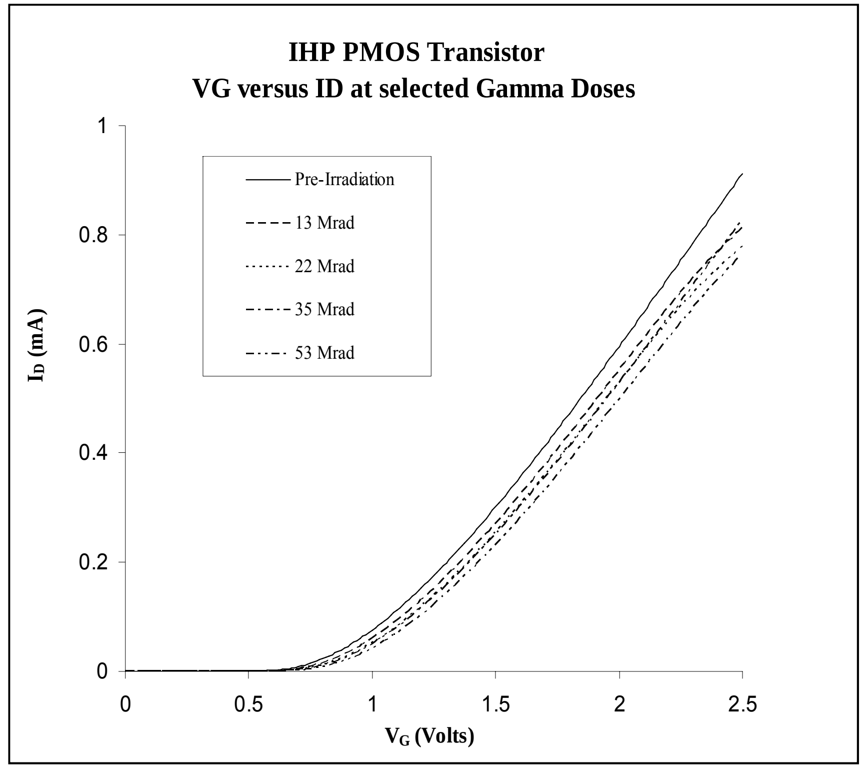
Necessary condition for Radiation Hardness - Thin Gate Oxide

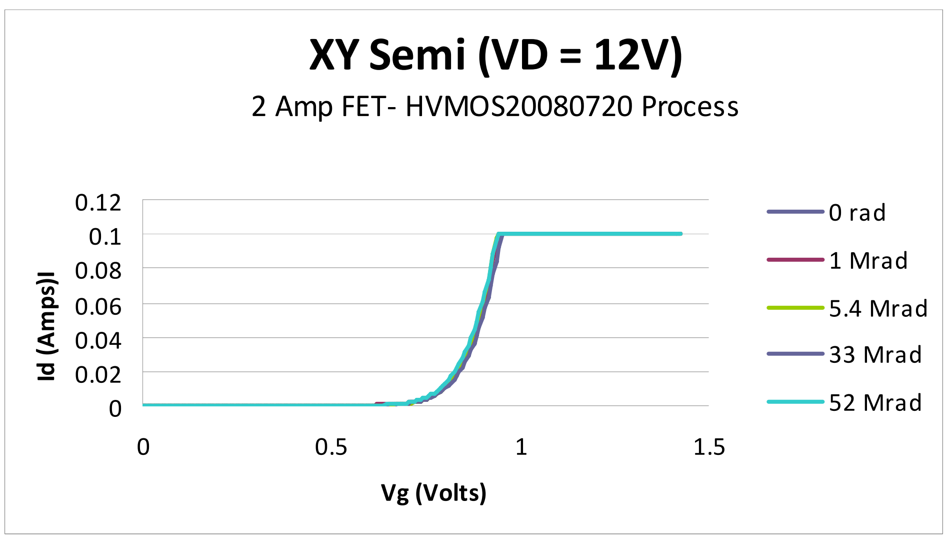
But not sufficient

IHP: Epi free, High resistivity substrate, Higher voltage, lower noise devices

Dongbu: Epi process on substrate, lower voltage due to hot carriers in gate oxide


IHP NMOS Transistor
V_G versus I_D at Selected Gamma Doses
Pre-irradiation
13 Mrad
22 Mrad
35 Mrad
I_D (mA)
V_G (Volts)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5

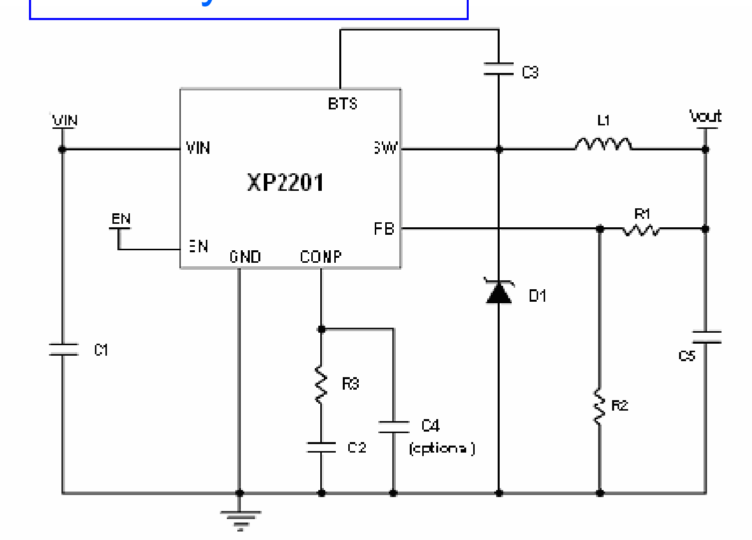

IHP PMOS Transistor
VG versus ID at selected Gamma Doses
Pre-Irradiation
13 Mrad
22 Mrad
35 Mrad
53 Mrad
I_D (mA)
V_G (Volts)
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5


XY Semi (VD = 12V)
2 Amp FET- HVMOS20080720 Process
0 rad
1 Mrad
5.4 Mrad
33 Mrad
52 Mrad
Id (Amps)I
Vg (Volts)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5

XP2201 - 20V 2A STEP-DOWN DC to DC CONVERTER

General Description

Non- Synchronous

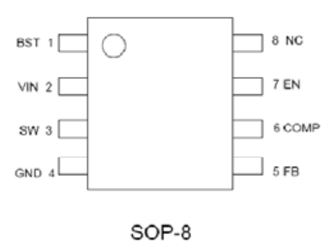


Replacement for LHC4913:
LHC Radiation Hard LDO
Made by ST Microelectronics

Use with Ferrite Coil

Features

- 2A Output Current
- Up to 95% Efficiency
- 4.5V to 20V Input Range
- Adjustable Output Voltage
- Fixed 400KHz Frequency
- Integrated 0.2Ω Switch
- 20uA Shutdown Supply Current
- Internal Soft Start
- Cycle-by-Cycle Over Current Protection
- Thermal Shutdown
- Programmable Under Voltage Lockout
- Operating Temperature: -40°C to +85°C
- Available in an 8-Pin SO Package



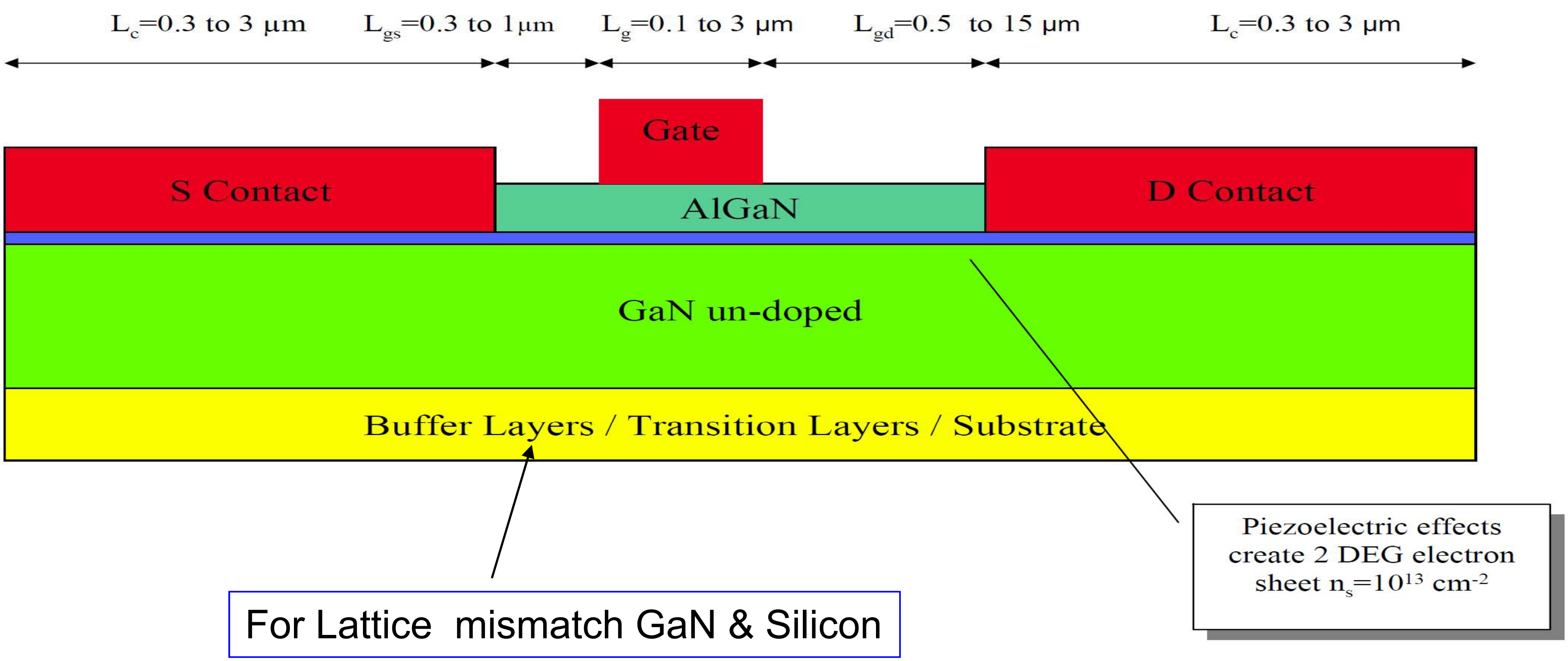
Engineering Samples
1Q2010

GaN HEMTs Why of Interest?

- High voltage and current rating
- Very high switching frequency (> 1 GHz range)
- Depletion mode are radiation Hard (details follow), Enhancement mode devices not yet available. Yes – one brand

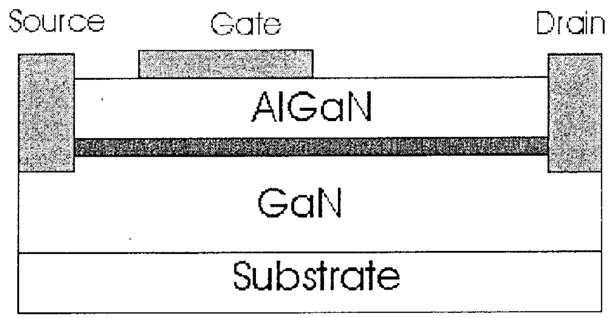
30

GaN for Power Switching

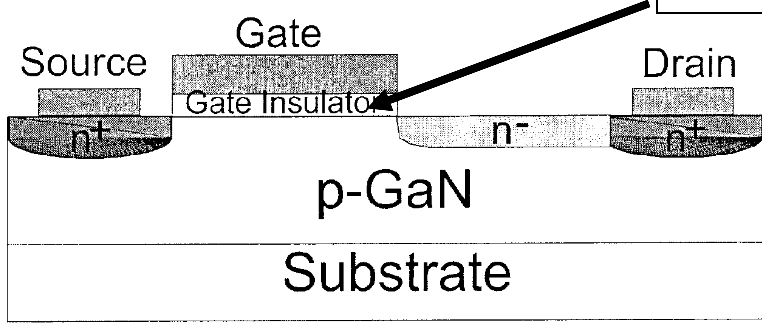


No Gate Oxide
High Dielectric strength
High Thermal conductivity

GaN HEMT



GaN MOSFET



- Low on-resistance due to high Channel mobility (1500 $cm^2/V\text{-}s$) and sheet electron density ($1\times10^{13}cm^{-2}$)
- High gate leakage current (reduced by hybrid MOS-HEMT structure)
- Small conduction band offset between AlGaN and GaN

- Inversion-mode, normally-off operation
- Blocking voltage controlled by dopants incorporated by epi-growth or ion-implantation
- Low gate leakage current

Depletion Mode
Normally ON

Enhancement Mode
Normally OFF

Gallium Nitride Devices under Tests

RF GaN 20 Volts & 0.1 amp

- ❖ 8 pieces: Nitronex NPT 25015: GaN on Silicon
- ✓ Done Gamma, Proton & Neutrons
- ✓ 65 volts Oct 2009

- ❖ 2 pieces: CREE CGH40010F: GaN on siC

- ❖ 6 pieces: Eudyna EGNB010MK: GaN on siC
- ✓ Done Neutrons

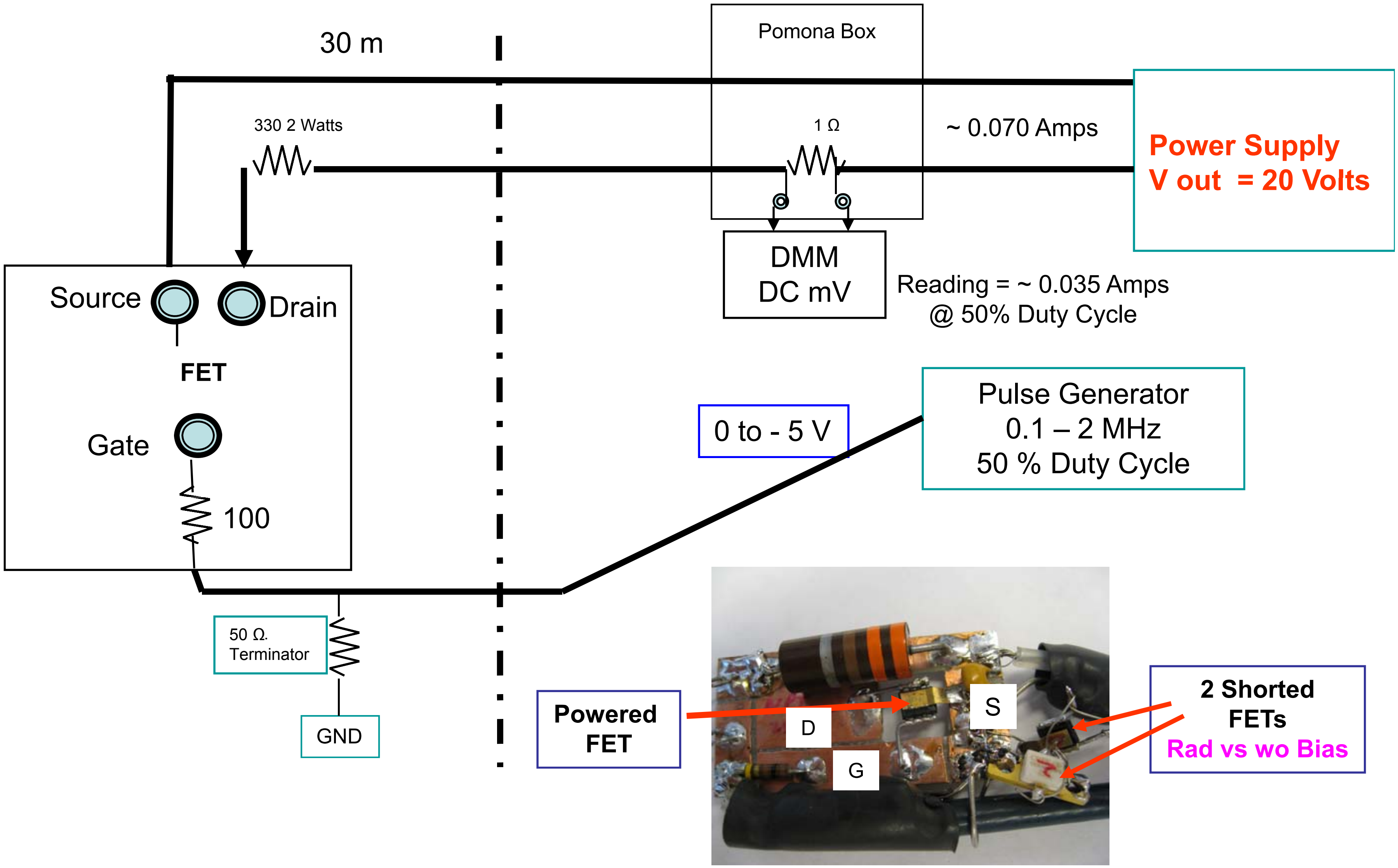
Switch GaN

- ❖ International Rectifier GaN on Silicon
  Under NDA

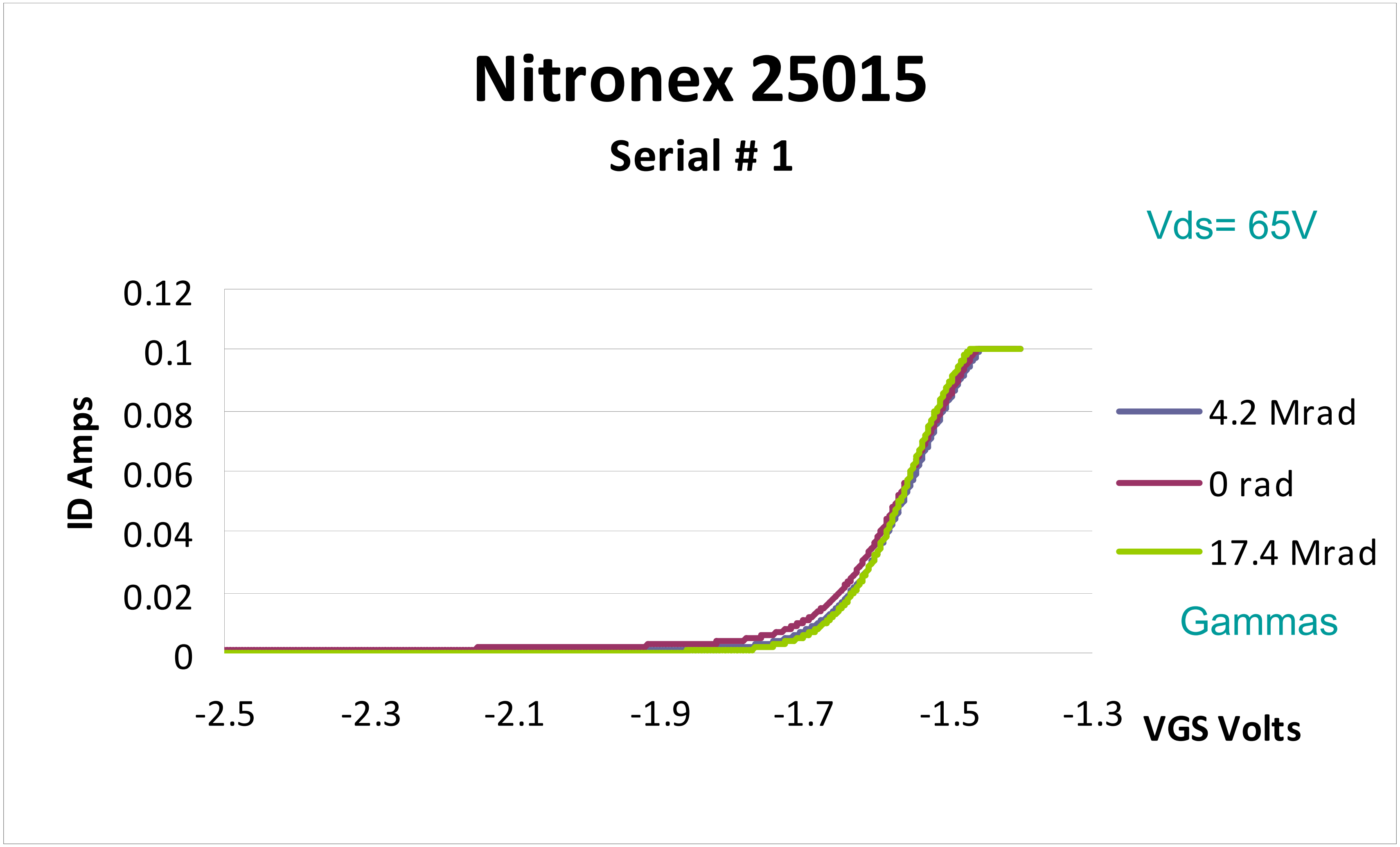
Gamma: @ BNL
Protons: @ Lansce
Neutrons: @ U of Mass Lowell

Plan to Expose same device to Gamma, Protons & Neutrons
Online Monitoring

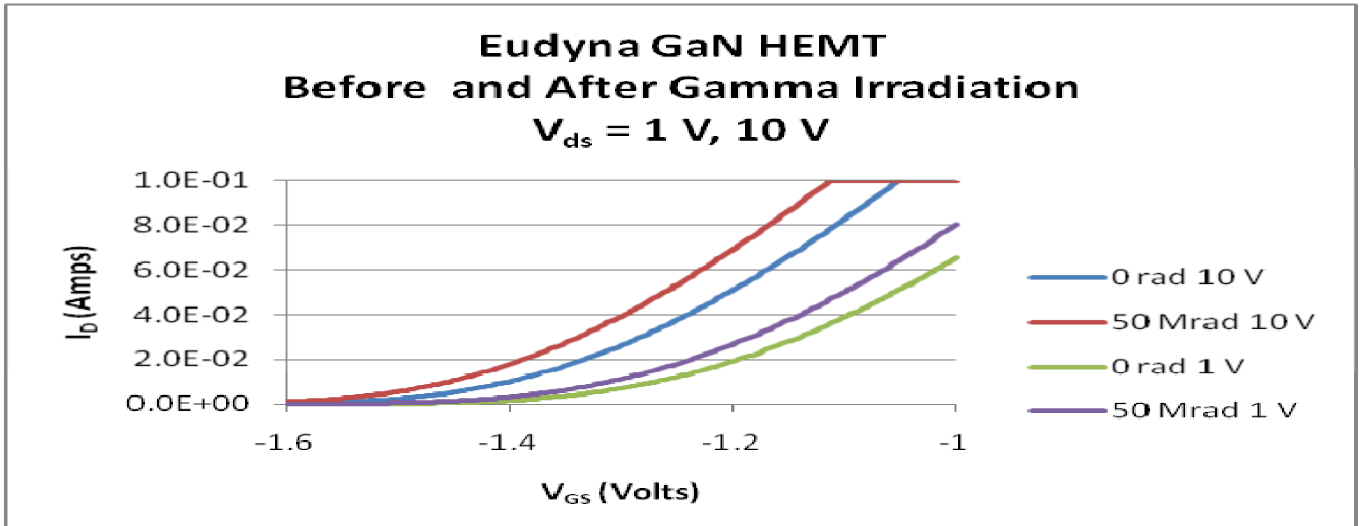
Bias during Radiation
Max operating V & I Limit Power by duty cycle



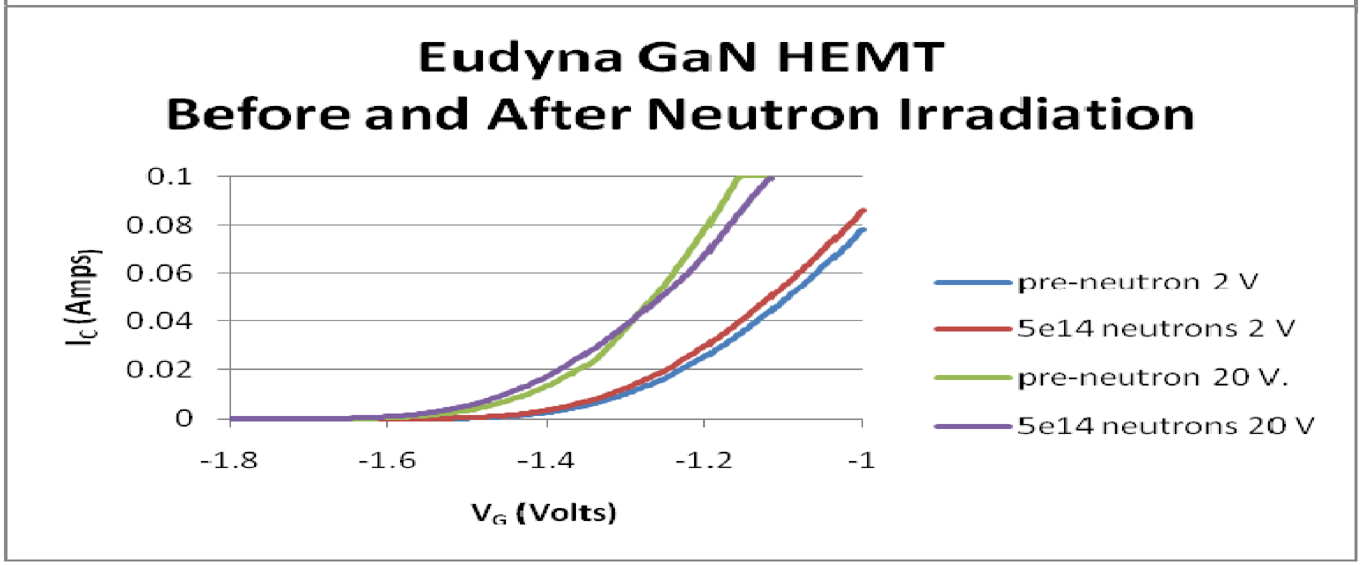
FET Setup for Proton Radiation Exposure



200 Mrads of Protons had no effect – switching 20 V 0.1 Amp
Parts still activated after 7 months



Our next IEEE TNS Paper shall summarize work to date



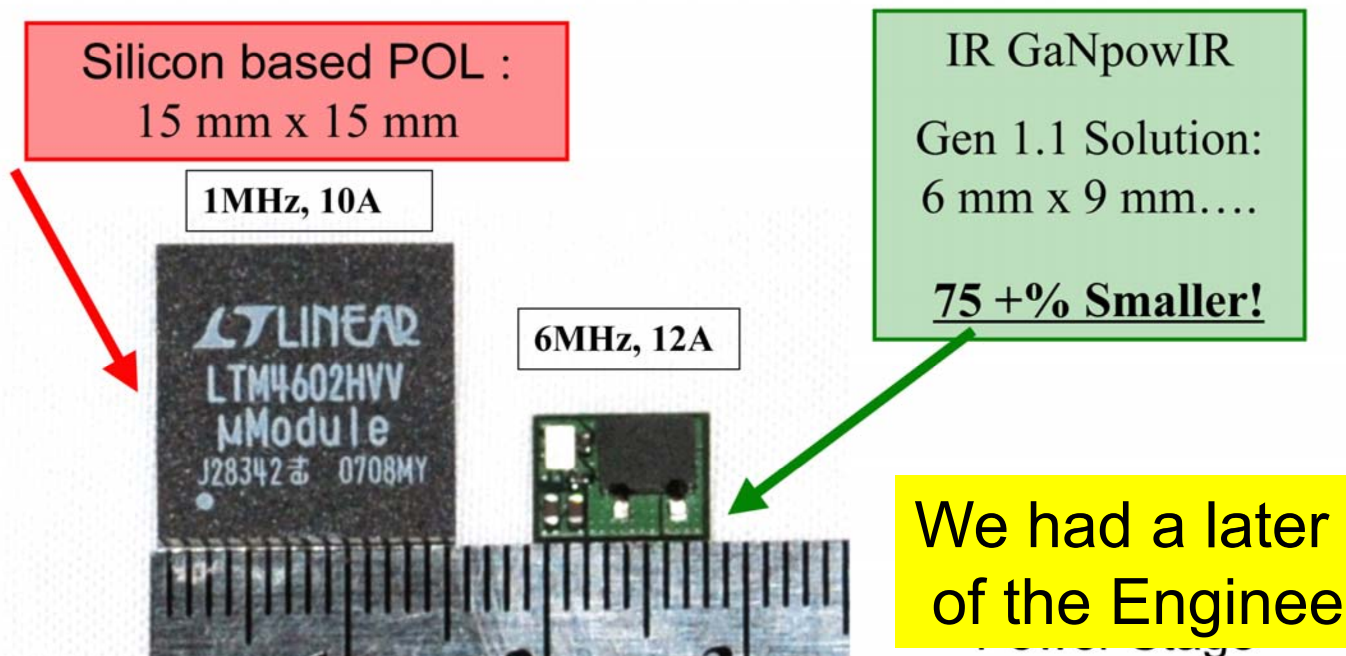
Proton Test

Proton Fluence =1 x 1015p/cm2 over a period of about 24 hours.

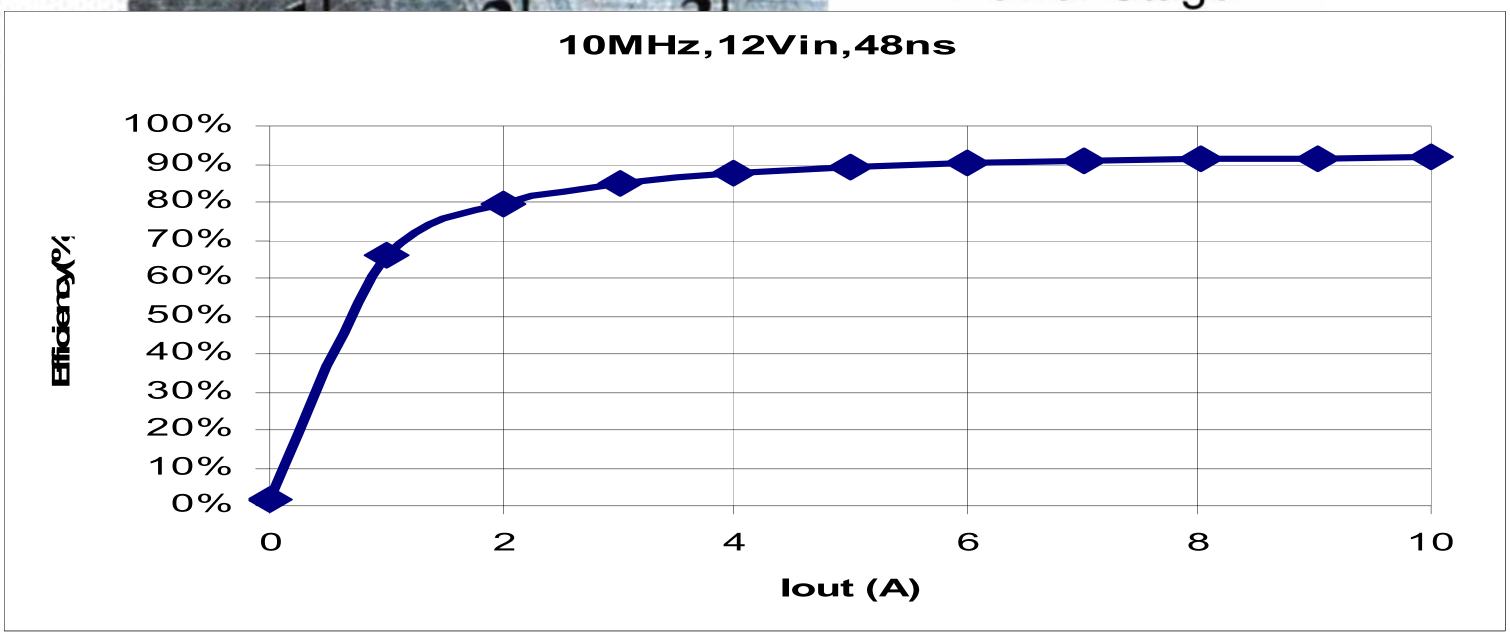
Biased = 65 volts switching @ 1MHz

Average current = 65 mA limited by Load resistor . No change in current.

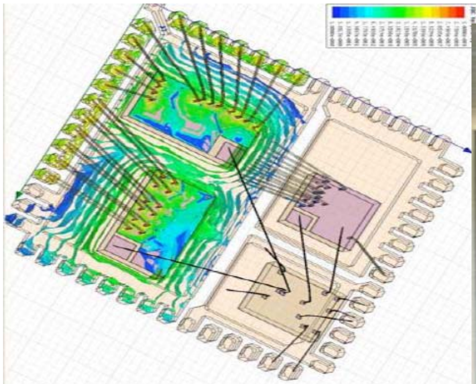
6 times Higher Frequency over Si Solution with similar efficiency !



We had a later version of the Engineering sample

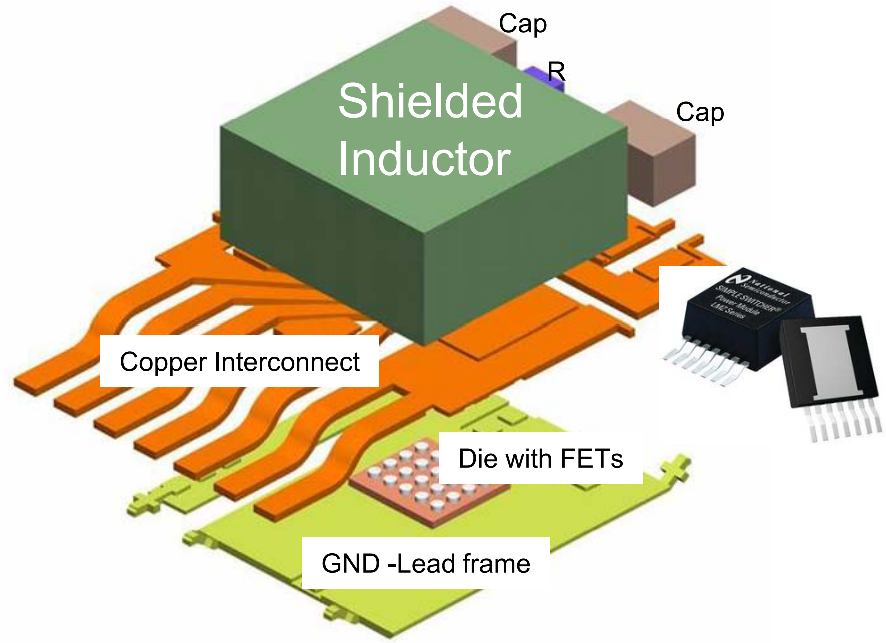


PSOC: Power Supply On a Chip

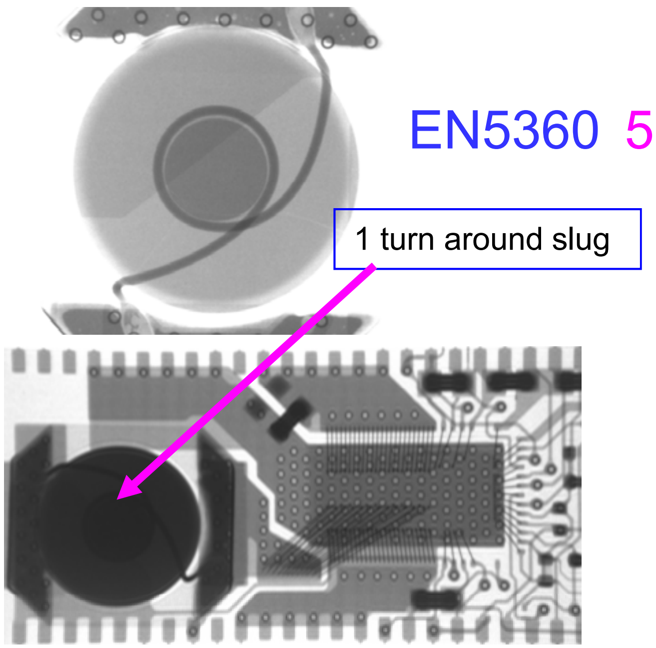


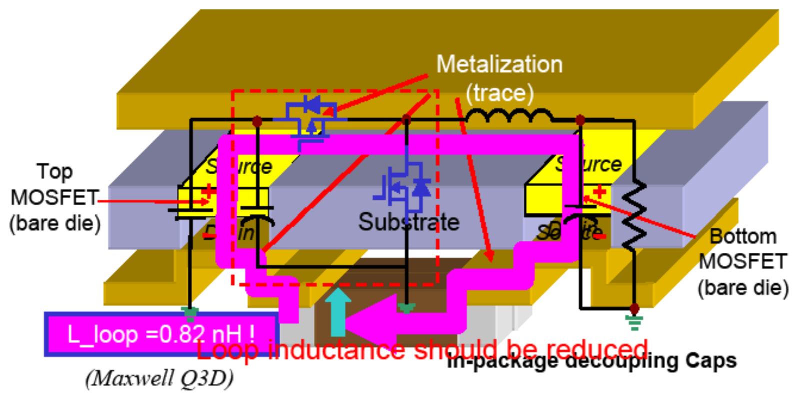
FAN5009 8 x 8 mm MCM
12 V > 1.2 V = 88.5% @ 30 A

National: LMZ Package 10 x14 x5 mm 20/42 V > 1.2V 5 A



EN5360 5 MHz





❖ Embedding the flipped devices allows for smallest loop inductance and for layering of components on top and bottom

PSOC: Power Supply On Chip

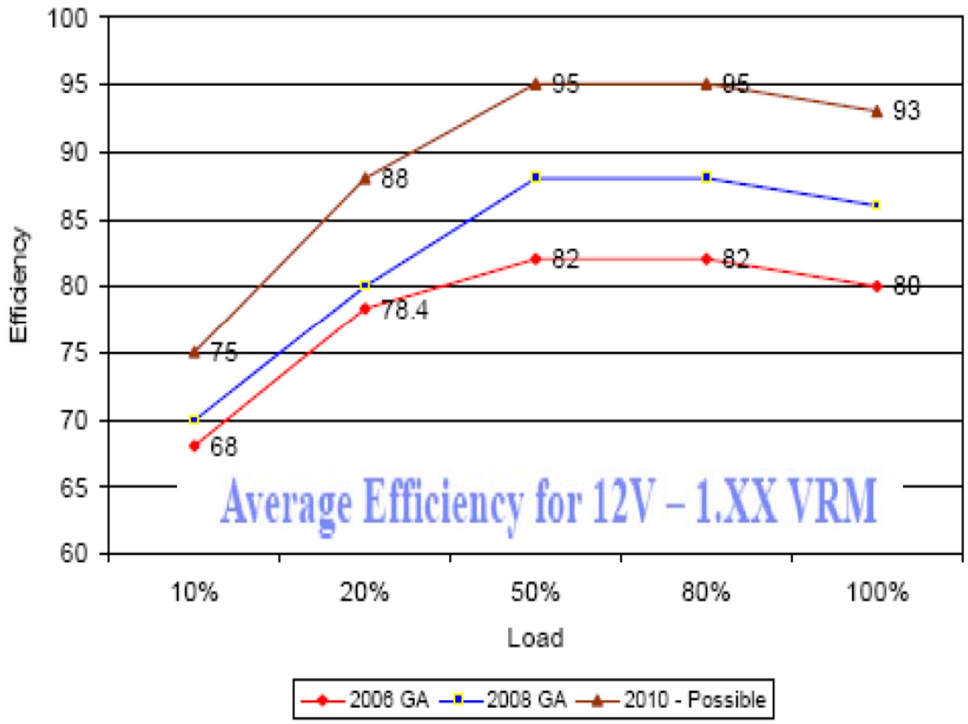
PSMA: Road Maps
Power Supply Manufacturer Association
Yale University is member

What is happening outside HEP ?

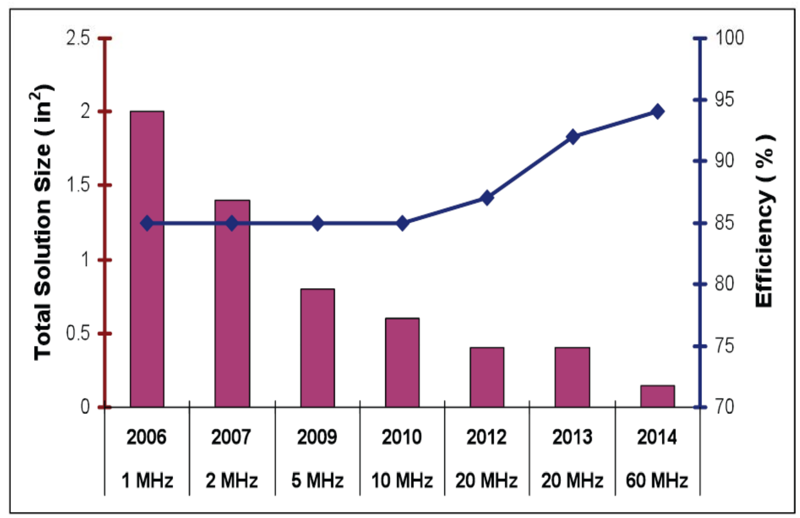
Server Power System Distribution from IBM

1. **AC Distribution - 208/230/115V**
   - Servers, Blade Servers, Workstations
2. **12V DC Distribution**
   - Blade Server Chassis, Low end and Midrange Servers, Workstations
3. **48V Distribution in a Rack**
   - High End Server Applications
4. **350V DC Distribution in a Server Rack or a Rectifier Cabinet**
   - Main Frame Servers

International Workshop on Power Supply On Chip
Sept 22nd - 24, 2008
Cork, Ireland



Potential LV DC-DC Power Stage Roadmap
Optimized Performance – Without tradeoff



12Vin, 1.2Vout, 100A **Based on Circuit Simulation**

Is there a Commercial product available ?

Yes = It is the EN5360

- Satellite folks are using it now
- sLHC Levels – 100 Mrads
- Use for voltage ratio = 4
- Work at Super LHC levels for Tracker
- 5.5 V in > 1.3 out
- Enpirion is still supplying these to a very large customer
- IHP foundry will make it for many years.
- Can purchase in Die form for use with Air coil

For Purchasing EN5360:
Steve Robb (908) 894 -6083 srobb@enpirion.com
Tom Howell (908) 894-6029 thowell@enpirion.com

Some Random Remarks

- Learned from commercial devices, companies & power conferences
- Can get high radiation tolerance & higher voltage simultaneously
- High frequency > smaller air coil > less material
- Goal: ~20 MHz buck, MEM on Chip *size 9 mm x 9mm*
- Power SOC: MEMs air core inductor on chip
- Will study feasibility of 48 / 300V converters
- Irradiations:
  - Important to run @ max operating V & I.
  - Limit power dissipation by switching duty cycle
  - Use online monitoring during irradiation for faster results

- Yale Plug Cards can be loaned for evaluation
- Collaborators are Welcome

Conclusions

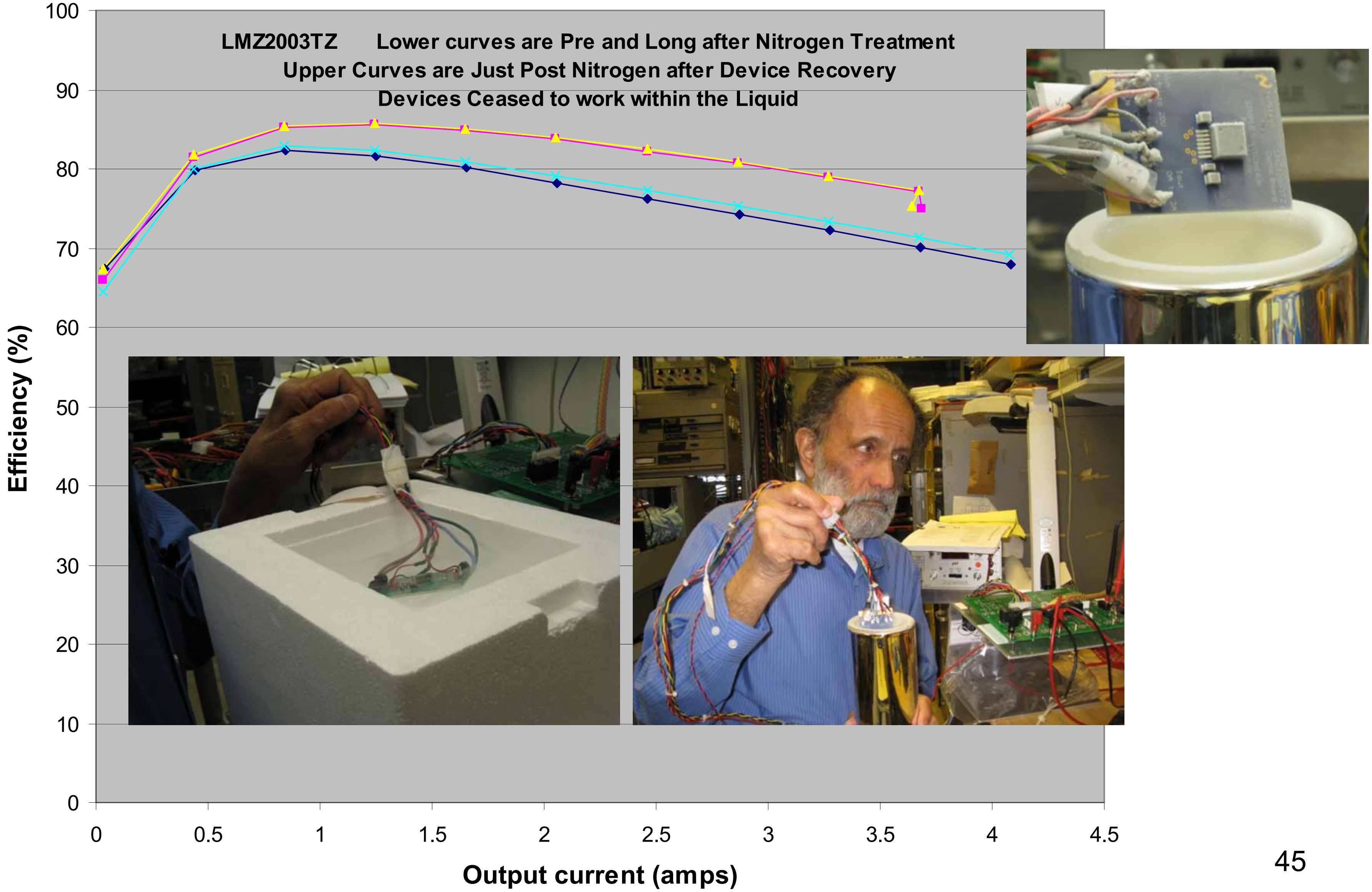
- The power distribution needs of HEP detectors require new solutions/technologies to meet power and environmental requirements.
- DC/DC (Buck) Converters are potential solutions for these needs.
- The environment requires that these converters operate in high radiation environments and high magnetic fields at high switching frequencies in a small size/mass package.
- Target technologies for the switches are radiation hard GaN and 0.25 μm LDMOS. High frequency controllers driving small sized nonmagnetic/air core inductors are also required.
- Many of these components have been tested and now need integration to produce a working prototype. This is the next step in our R&D program.


Working on Power Supply
Is not Glamorous
Top of the World is Cool but lonely !
Let us keep it cool with highly efficient PS
More Details: www.Yale.edu/FASTCAMAC click on DC-DC

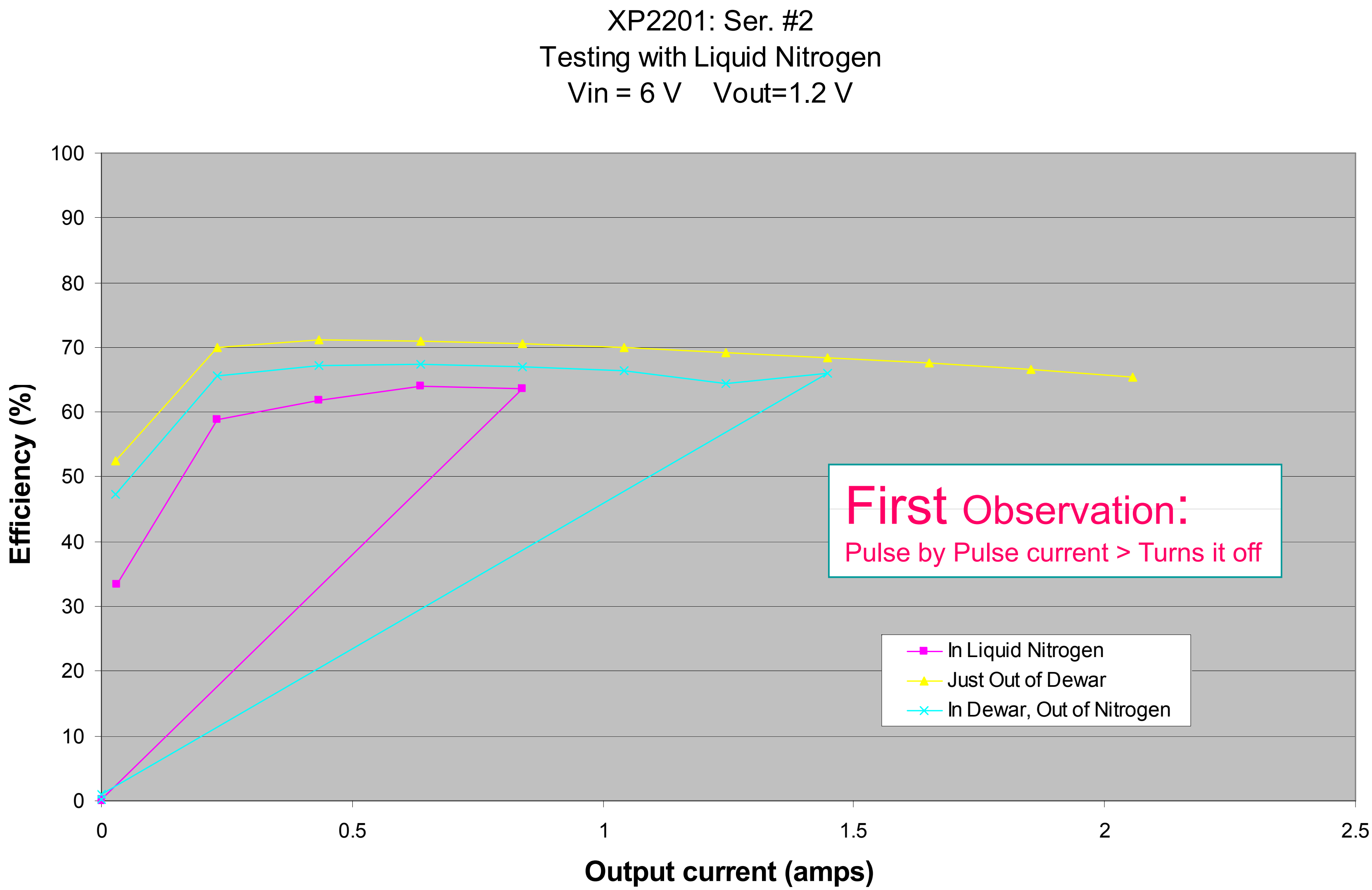
Radiation Resistant Power Supplies with GaN ?

- Materials Journey Se .. Ge…Si…GaN
- Why Gallium Nitride. Better FOM = $R_{DS(ON)}$ X Q_G
- Enable new Capabilities ?
- High Electron Mobility
- High Frequency – 10 GHz
- X10 higher dielectric strength
- Higher Thermal Conductivity
- Majority Carrier Device – No reverse recovery
- Cost ?
- Is it easy to use? Learning curve
- End of the Silicon near?
- DC-DC Converters 48V- 1V, 400V- 48V Radiation ?
- Development 600V,1200,5000V

Can Commercial Converters Operate in Li Nitrogen ?

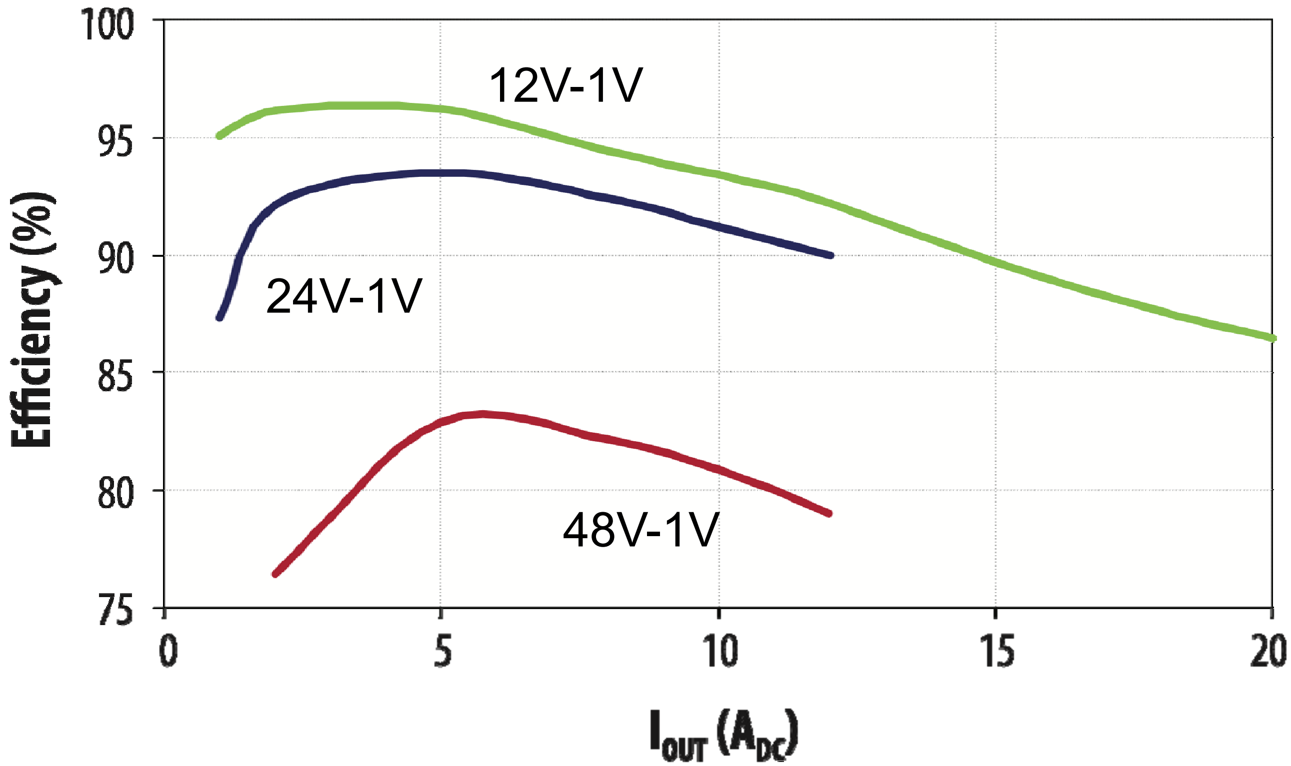


Can Commercial Converters Operate in Li Nitrogen ?



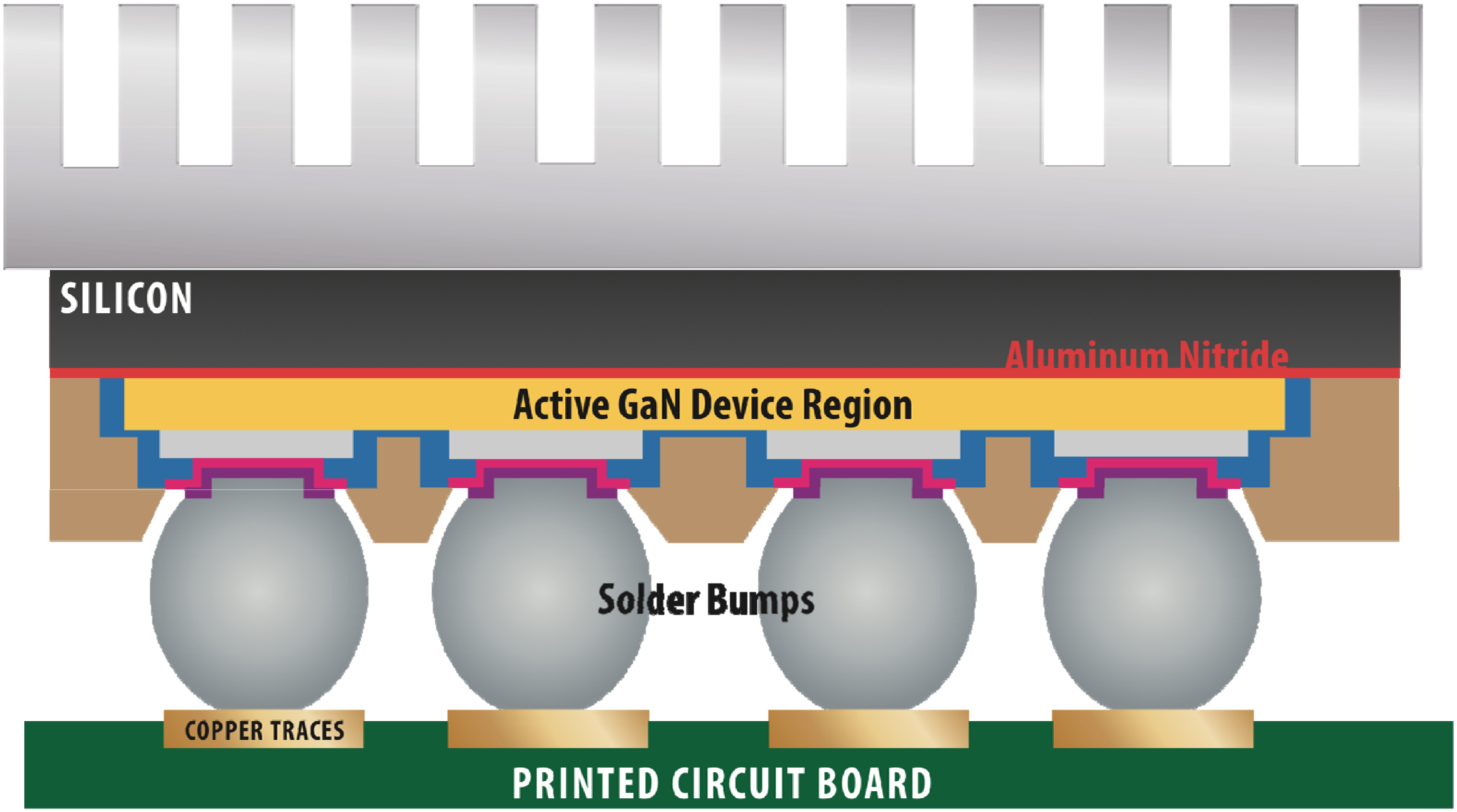
Converter Efficiency

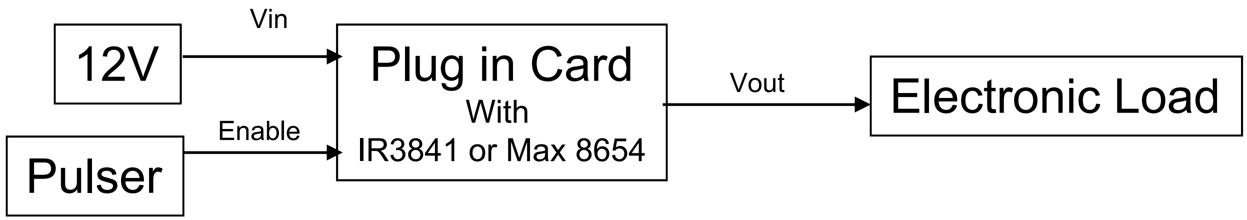
EPC1001 at 250 kHz

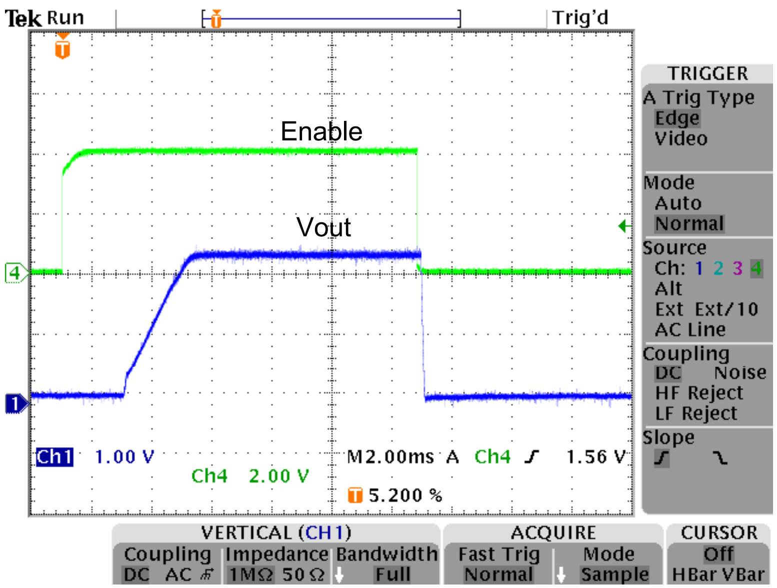


Reduction of light load efficiency and high conversion voltage efficiency is mostly due to the limitations of the commercial driver IC

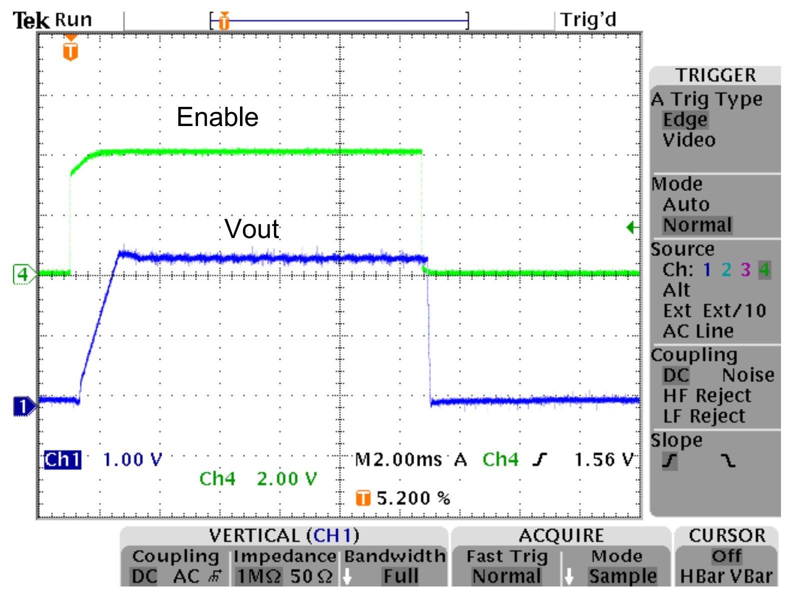
Flip Chip Assembly





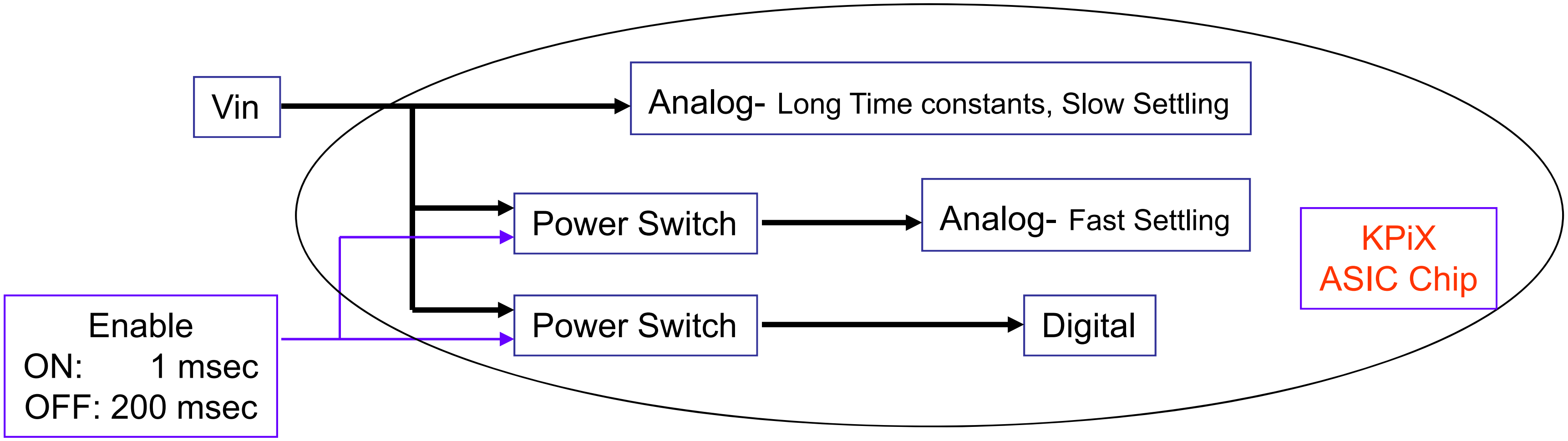


IR8431 with 3 amp Load
Vin= 12 V
Vout = 2.5 V
Load = 3 amps (Electronic)



MAX8654
Vin= 12 V
Vout = 2.5 V
Load = 3 amps (Electronic)

DC-DC Converter pulsing from ON/OFF Pin



Simulation with a National Semiconductor Buck Converter

- ~ 1 MHz
- Load 3 amps Type R, Electronic, CMOS ASIC
- Vin > 12 V
- Vout = 1.2 / 2.5 V
- Settling Time on/off, Voltage/ Current Loop?, Caps, Stability, Ripple/Noise

Circuit for simulation of converter settling times