Power Delivery for Future Experiments

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Richard Sumner - *CMCAMAC LLC*

Instrumentation Frontier Community Meeting (CPAD)
9 – 11 January, 2013. Argonne National Laboratory, Argonne, IL

Agenda

- ❖Examples of systems running @ LHC
- ❖Losses & Efficiency
- ❖Is there a better way?
- ❖2D Inductors – Air Core / Coreless
- ❖Radiation Tolerance / Testing / Noise
- ❖Wide Band gap
- ❖Notes on our Direction of our Work
- ❖SiD (LCRD) Powering – It has paid rent to Yale
- ❖Commercial Power World
- ❖Toroid vs. 2D Inductor Noise Comparison
- ❖Carbon Fiber for shielding
- ❖ Summary

CMS ECAL Powering @ LHC Running Now

CMS ECAL 2.5 v @ 50,000 AMPS

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

# of Power Supplies ~ 700
# of ST LDO Chips = 35 K LHC Radiation Hard made by ST Microelectronics
# of LVR Cards = 3,100
Yale: Designed, built, burn-in and Tested.

Power Supply
6.3 V

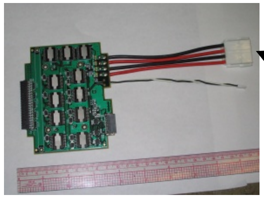
64 Amps

30 m

Vdrop = 2V
Pd = 128 W

50 mm^2 (AWG 00)

SM: Super Module



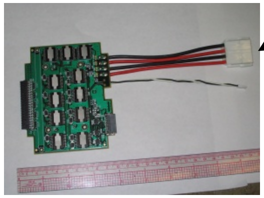
4.3 V

Junction Box

2x16 mm^2 (AWG 6)

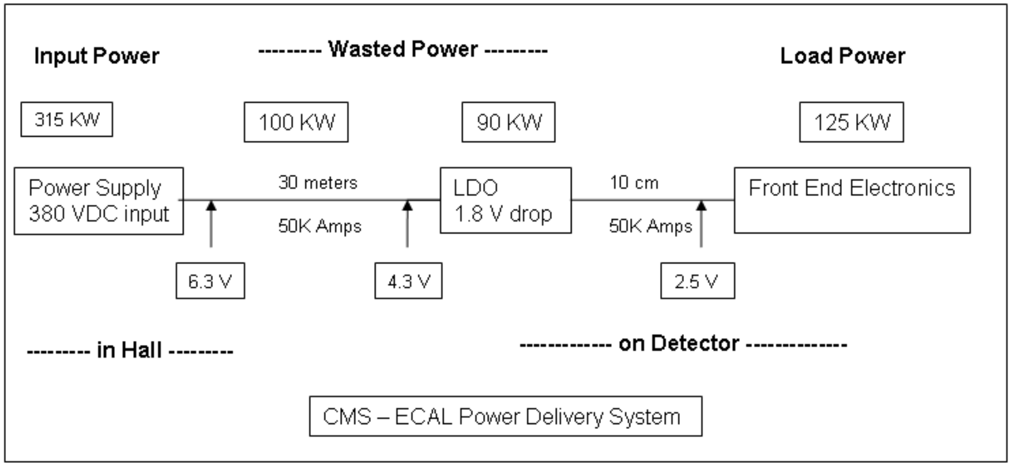
1 to 3 m

2.5V
64 amps
160 W



4 LVR Boards

Power Chain Efficiency for CMS ECAL



Input Power

--------- Wasted Power ---------

Load Power

315 KW

100 KW

90 KW

125 KW

Power Supply
380 VDC input

30 meters

50K Amps

LDO
1.8 V drop

10 cm

50K Amps

Front End Electronics

6.3 V

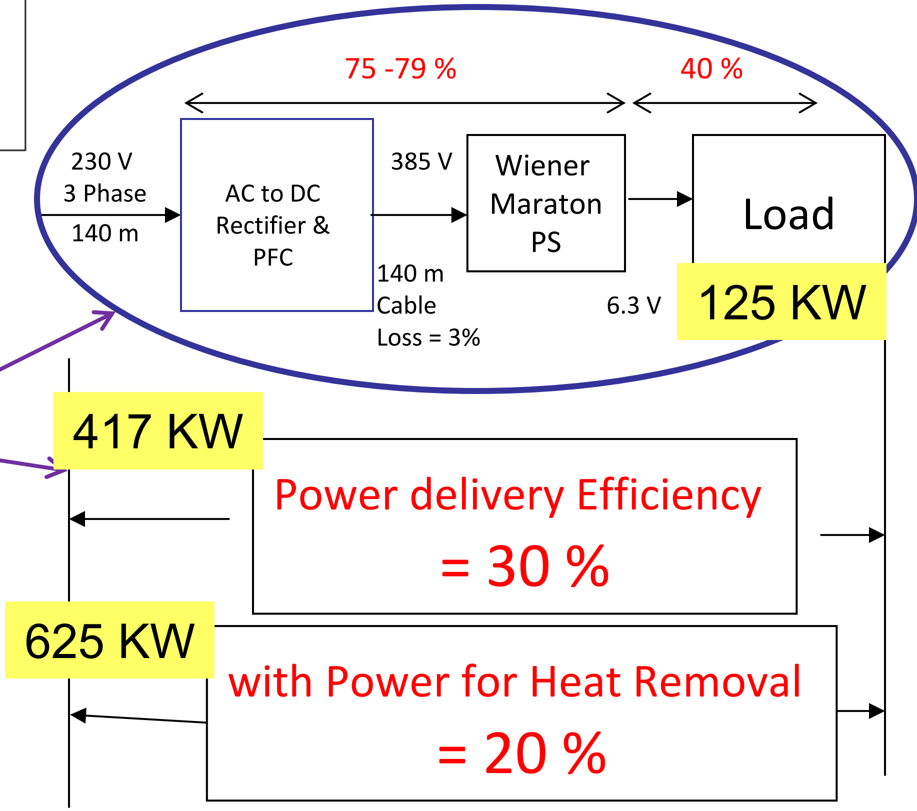
4.3 V

2.5 V

--------- in Hall ---------

------------- on Detector --------------

CMS – ECAL Power Delivery System



75 -79 %

40 %

230 V
3 Phase
140 m

AC to DC
Rectifier &
PFC

385 V

140 m
Cable
Loss = 3%

Wiener
Maraton
PS

6.3 V

Load

125 KW

417 KW

Power delivery Efficiency
= 30 %

625 KW

with Power for Heat Removal
= 20 %

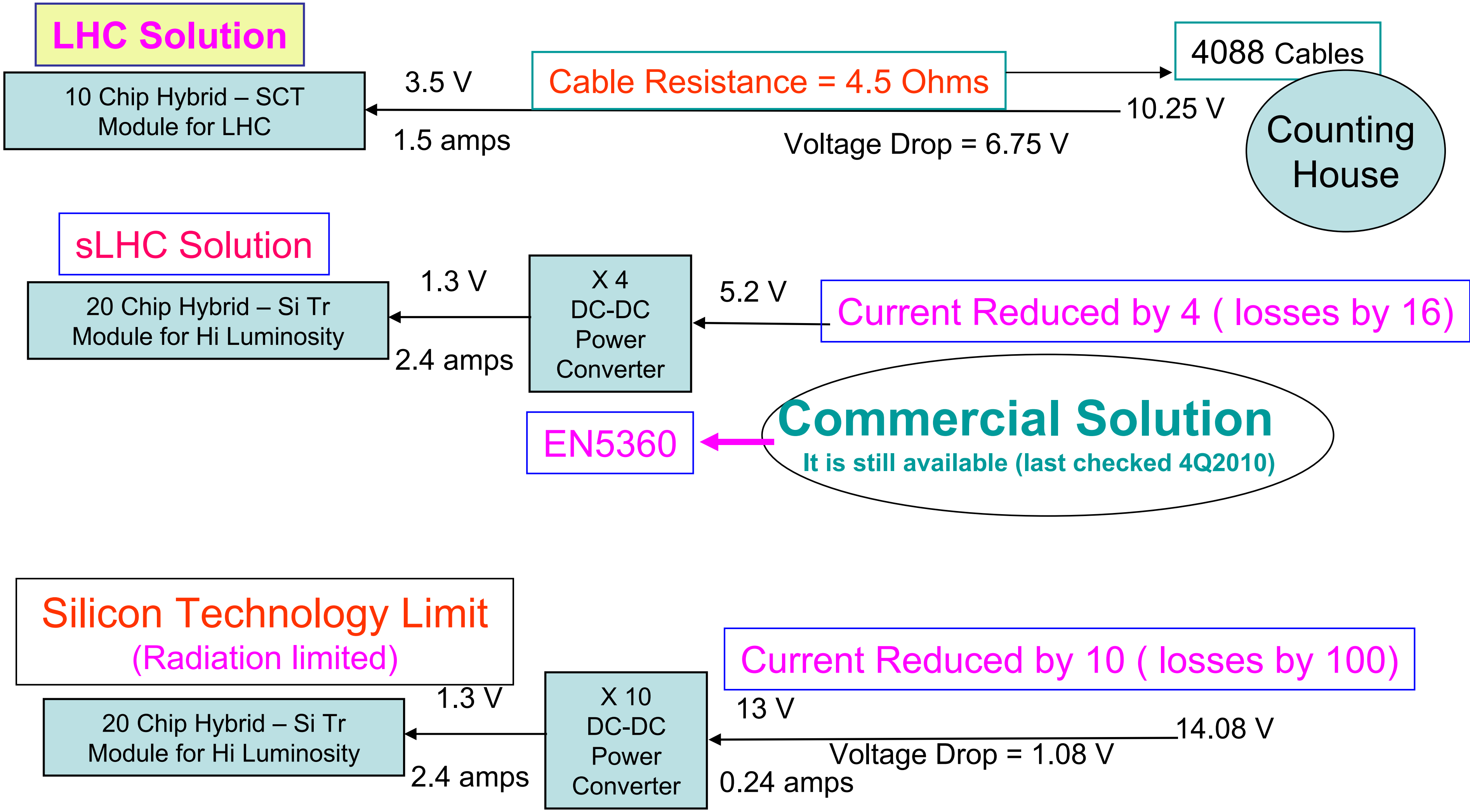
Represents the efficiency of power delivery to a physics detector, e.g. ECal

It takes 2 watts of power to remove 1 watt of heat load

Is there a better way to distribute power ?

- Radiation & Magnetic fields depend on location of the sub-system
- High Radiation 1 Mrad -100 Mrads
- Magnetic Field Up to 4 T
- Load ~1 V Tens of Kilo- Amps
- Feed High Voltage and Convert - *like AC power transmission*
- Commercial Technologies – *No Custom ASIC Chips*
- Learn from Semiconductor Industry LDMOS, Thin Gate Oxide

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

X 4 DC-DC Power Converter

5.2 V

Current Reduced by 4 (losses by 16)

Commercial Solution

It is still available (last checked 4Q2010)

EN5360

Silicon Technology Limit

(Radiation limited)

20 Chip Hybrid – Si Tr Module for Hi Luminosity

1.3 V

2.4 amps

X 10 DC-DC Power Converter

Current Reduced by 10 (losses by 100)

13 V

14.08 V

Voltage Drop = 1.08 V

0.24 amps

\> X 40 with Gallium Nitride Transistors

Why we need Air Core Inductor for Buck converters ?

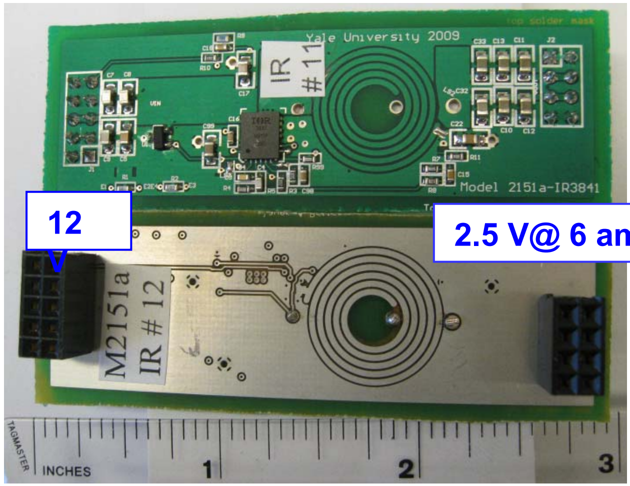
1. Run in 4 Tesla field. Any magnetic material in the field will move when magnet is turned on.
2. Some detectors exposed to radiation environments 1 -100 Mega Rads
3. Low mass: So interacting protons don't create secondary particle noise

1. Two spirals in close proximity - Magnetic field storage vs distance
2. How can we reduce leakage flux?
3.

This is for Coil Design engineers

Plug In Card with Shielded Buck Inductor

Coupled Air Core Inductor Connected in Series

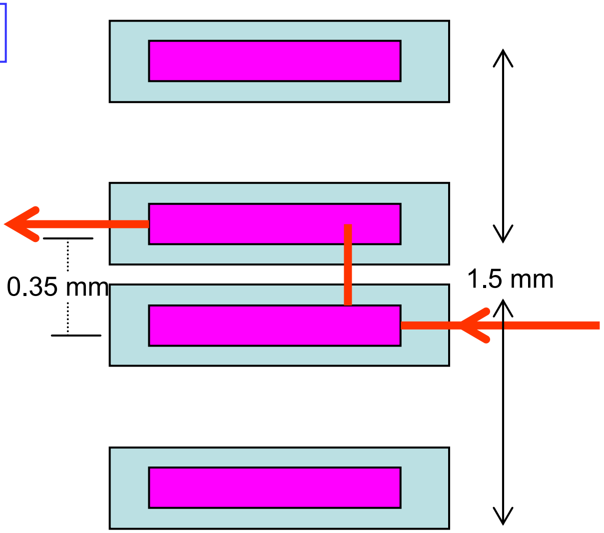


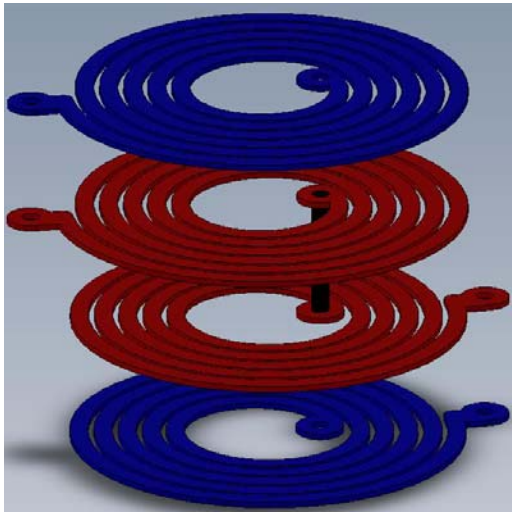
12

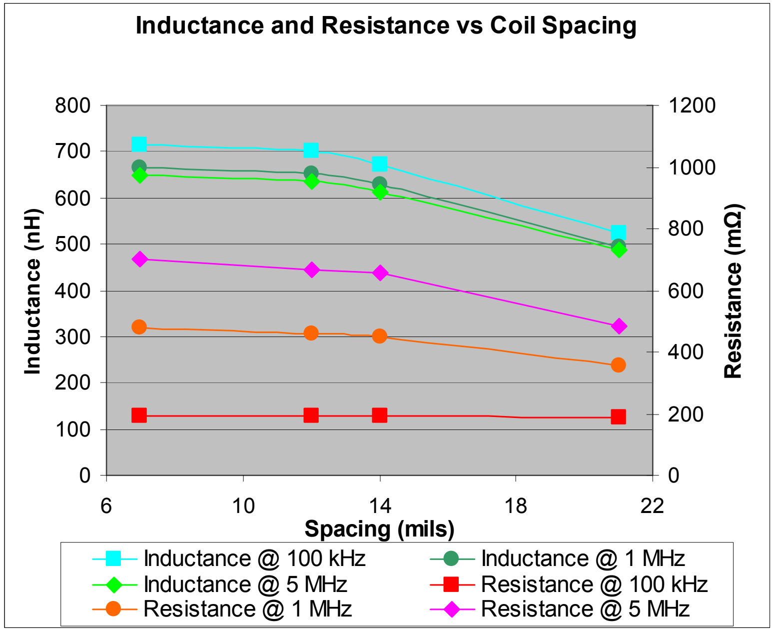
2.5 V@ 6 amps

Different Versions

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

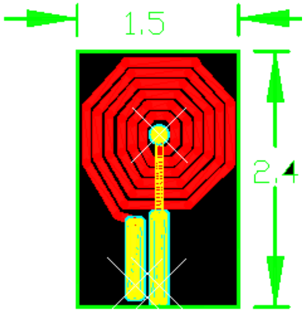






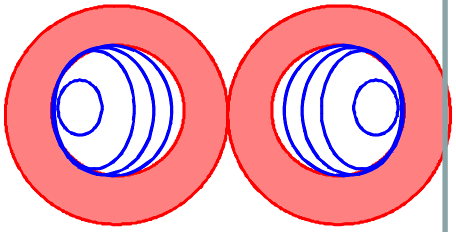
2 oz copper for coil on thin Laminate

2 coils in series for larger L



cms

Proximity Effect



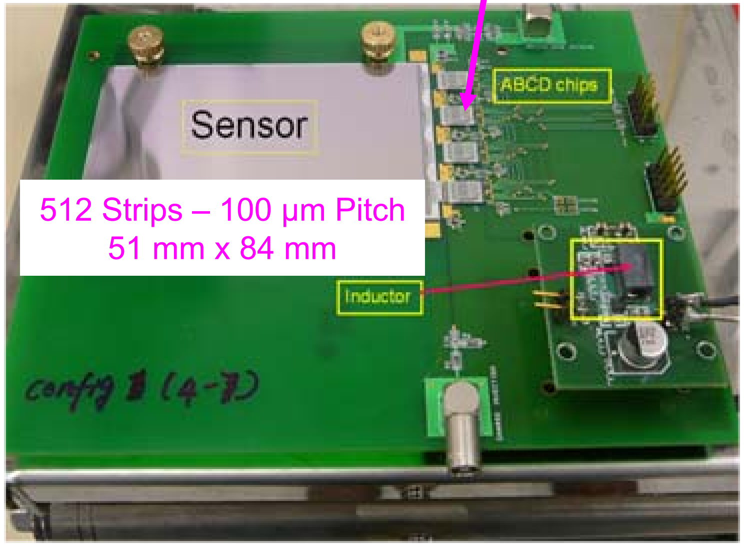
Current Distribution in Neighboring Conductors

Summer 2009

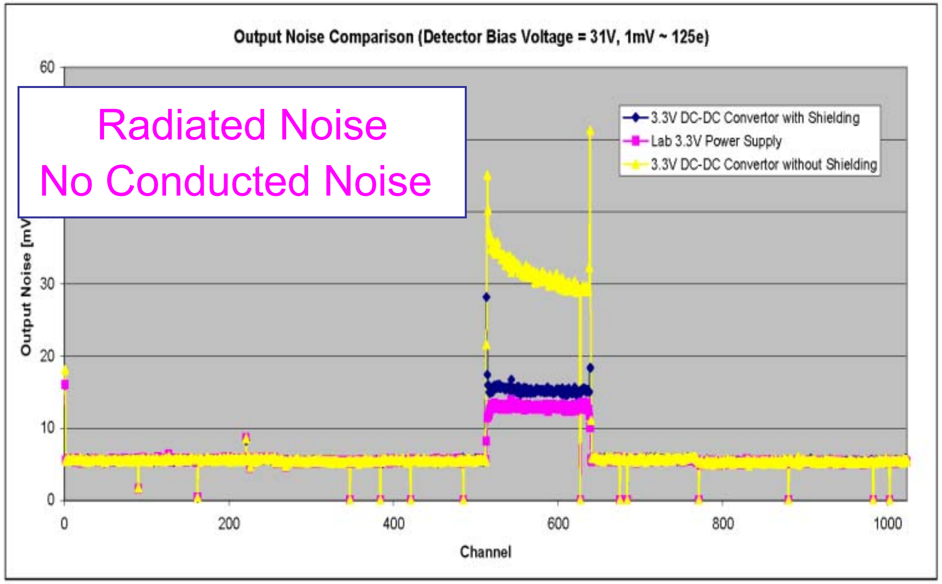
Noise Tests with Silicon Sensors

Test @ BNL

Only One Chip Bonded

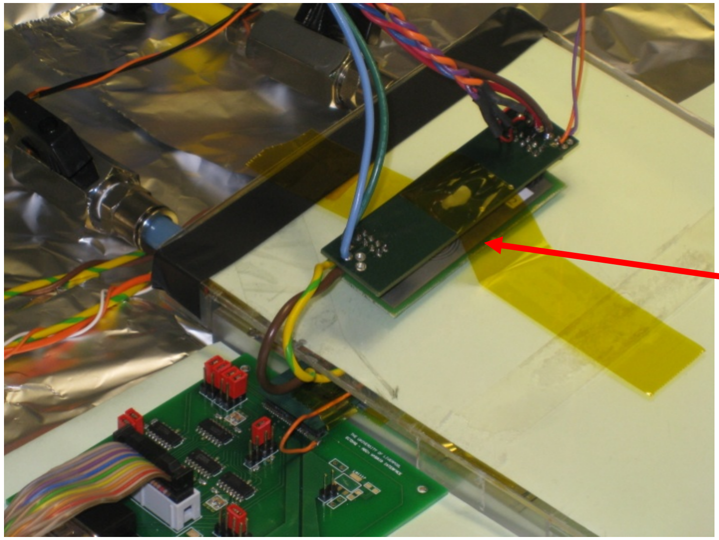


512 Strips – 100 μm Pitch
51 mm x 84 mm



Radiated Noise
No Conducted Noise

Test @ Liverpool in September 2009

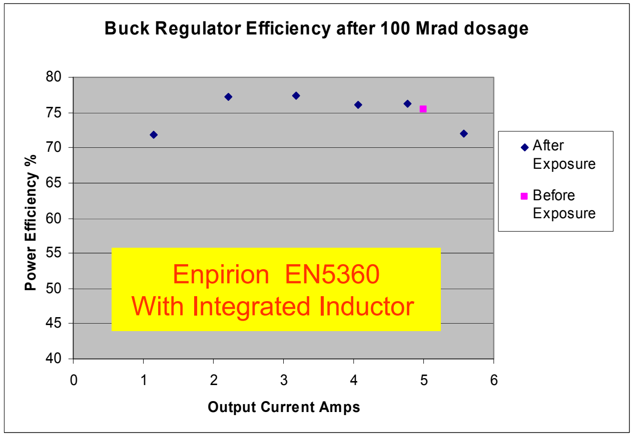


Plug in Card
1 cm from Coil
facing Sensor

20 μm Al foil
shielding

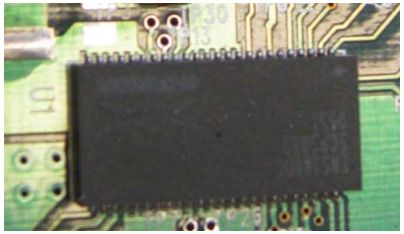
Coil Type	Analog Power to FE	Input Noise electrons rms
Solenoid	DC - DC	881
Solenoid	Linear	885
Spiral Coil	DC - DC	666
	Linear	664

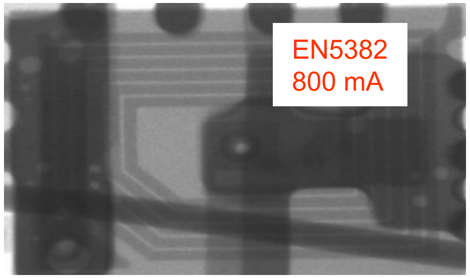
DC-DC POWER CONVERTER INTEGRATION



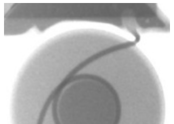
Found out at Power Technology conference 0.25 µm Lithography

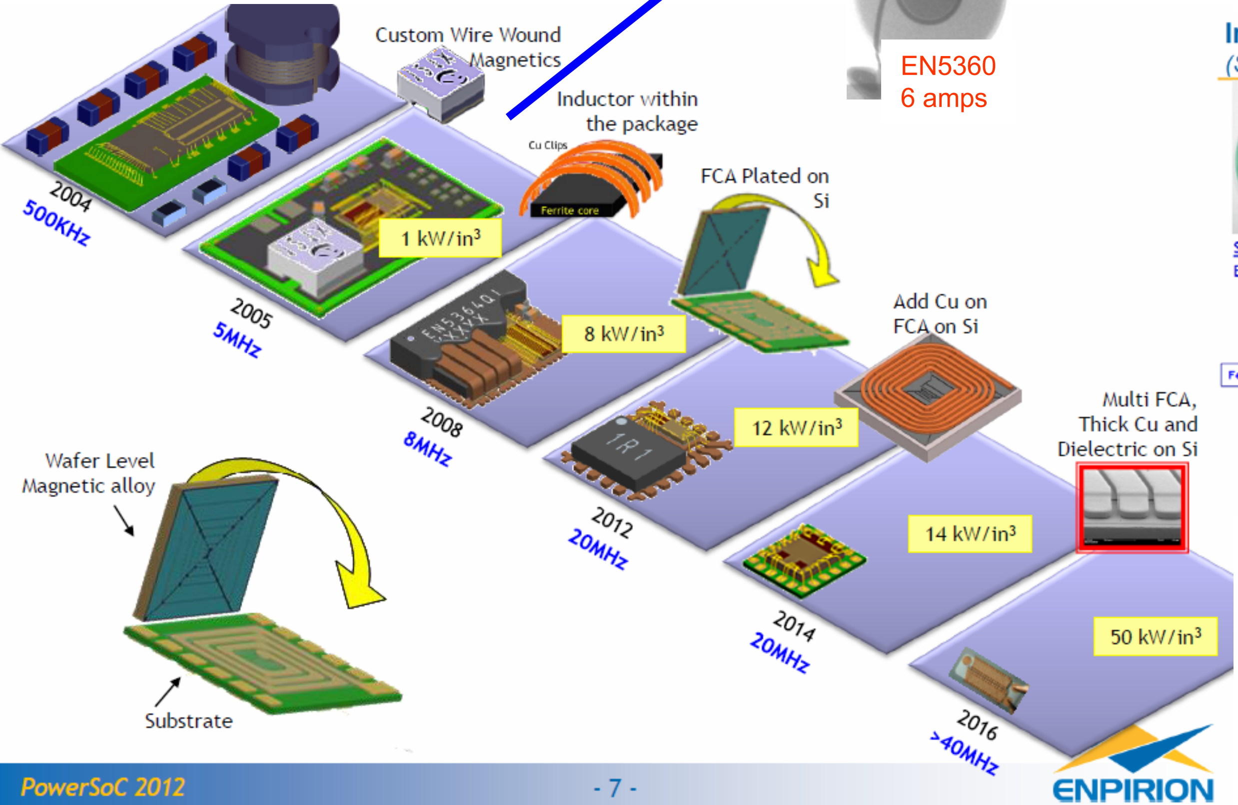
- Irradiated Stopped on St. Valentines Day 2007
- We reported @ TWEPP 2008 - IHP was foundry for EN5360





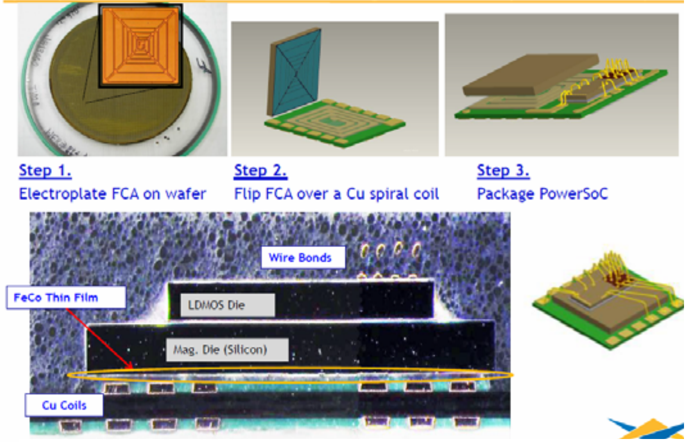
AWG30 (10 mil wire)





Introduction of Wafer Level Magnetic

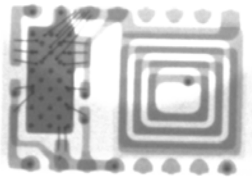
(Simple but effective inductor design at mature process cost)



Step 1. Electroplate FCA on wafer

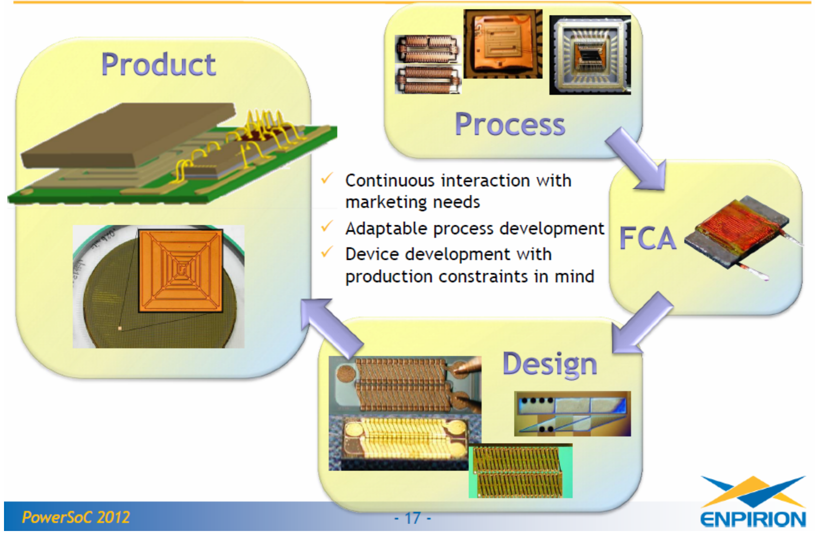
Step 2. Flip FCA over a Cu spiral coil

Step 3. Package PowerSoC



Price ??

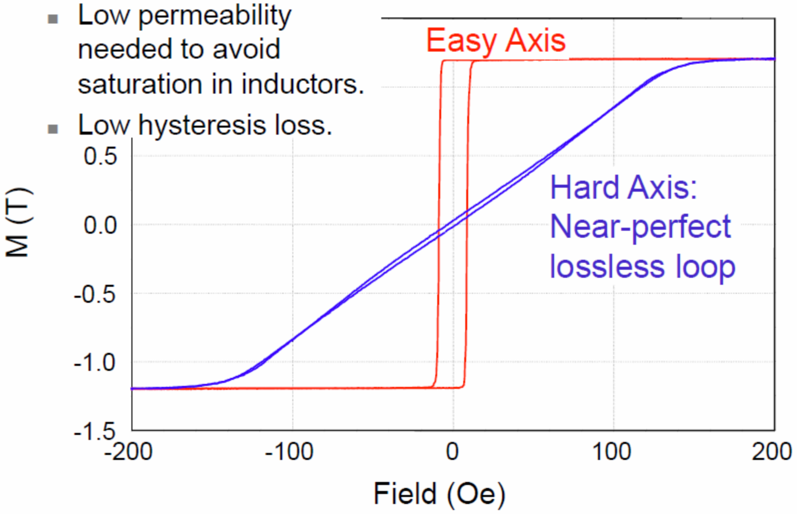
DESIGN ITERATIONS and DEVELOPMENT
(Quest For Optimum Micro-Inductor Application)



- ✓ Continuous interaction with marketing needs
- ✓ Adaptable process development
- ✓ Device development with production constraints in mind

Magnetic anisotropy

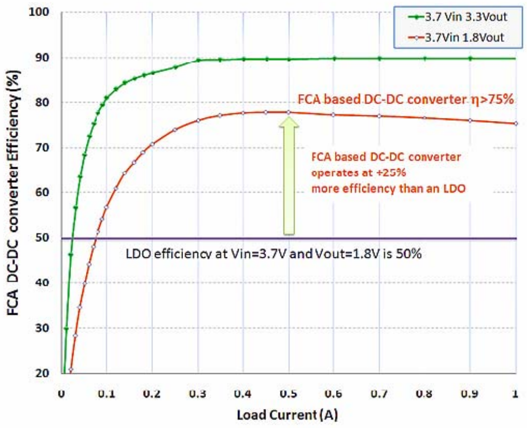
- Hard axis loop provides:
  - Low permeability needed to avoid saturation in inductors.
  - Low hysteresis loss.

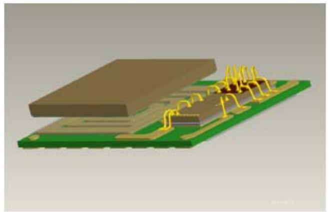


power.thayer.dartmouth.e

FCA in Enpirion’s first PwrSoC product

- Enpirion implement FCA in its first PwrSoC product
- FCA offered +25% improvement in efficiency over existing solutions





LDO Replacement by DC-DC Buck Converter

Price 97 cents quantity 1
Distributor Future Electronics

Proceedings of the 2012 24th International Symposium on Power Semiconductor Devices and ICs
3-7 June 2012 - Bruges, Belgium

12 V – 1 V, 1 amp Converter @ > 25 MHz

Over 20V off-state breakdown voltage with low leakage

- 4A, 6A, 9A, 15A in production, 20A and 40V product in develop.

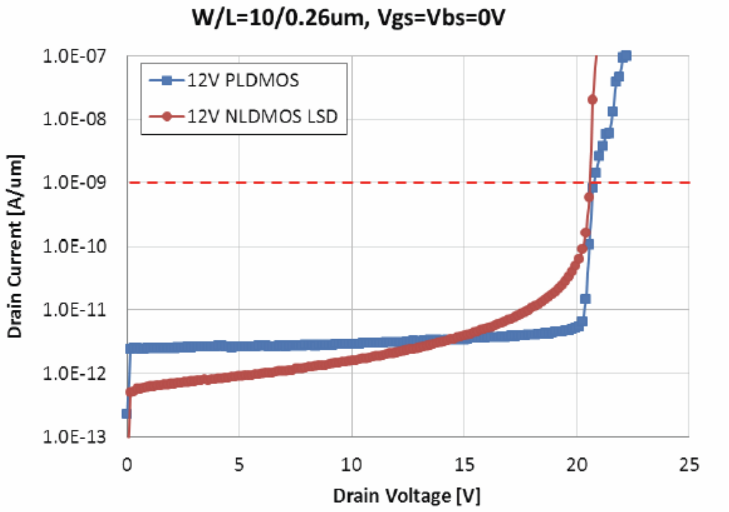
Ft and Fmax characteristics according to Vgs at Vds=6V

- Ft,max/Fmax = 37.2GHz/66.9GHz for 12V RF NLDMOS LSD
- Ft,max/Fmax = 12.9GHz/38.4GHz for 12V RF PLDMOS

Dongbu HiTek
0.18 μm platform for Power Management

Implementation of Low Vgs (1.8V) 12V RF-LDMOS
for High-Frequency DC-DC Converter Applications

Abstract—a 12V low Vgs (1.8V) RF-N/PLDMOS have been successfully implemented on the 0.18 μm analog CMOS process without thermal budget addition. N- and P-ch LDMOS needs additional body and drift implants, respectively. A short channel length and a small overlap of gate-to-drain were accomplished by the optimization of implant conditions for the source halo and the drift region which is followed by the gate formation with 30 Å gate oxide. Cut-off frequency 37.2GHz and 12.9GHz each for NLDMOS and PLDMOS were achieved with breakdown voltage of 20V. The long-term wafer level HCI test result showed Idlin shift under 10% after 150Ksec stress at Vds=12V and Vgs=1.8V.



OFF State Breakdown Voltage

High-Frequency LDMOS in 0.18 μm BCD Technology for Power Supply-On-Chip
The 3rd International Workshop on Power Supply on Chip (PowerSoC2012)
November 16-18, 2012, San Francisco, CA, USA

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

Higher radiation tolerance needs thin oxide
while higher voltage needs thicker oxide – Contradiction ?

Mixed signal power designs from TI, TSMC, IBM etc - 0.18 μm & 0.13 μm
Automobile Market. Voltage ratings 10 - 80 Volts
Deep sub-micron but thick oxide

Controller : Low Voltage

High Voltage: Switches – some candidates HV & Thin oxide

RF Process LDMOS, Drain Extension, Deep Diffusion etc

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

LDMOS Structure

Laterally Diffused
Drain Extension

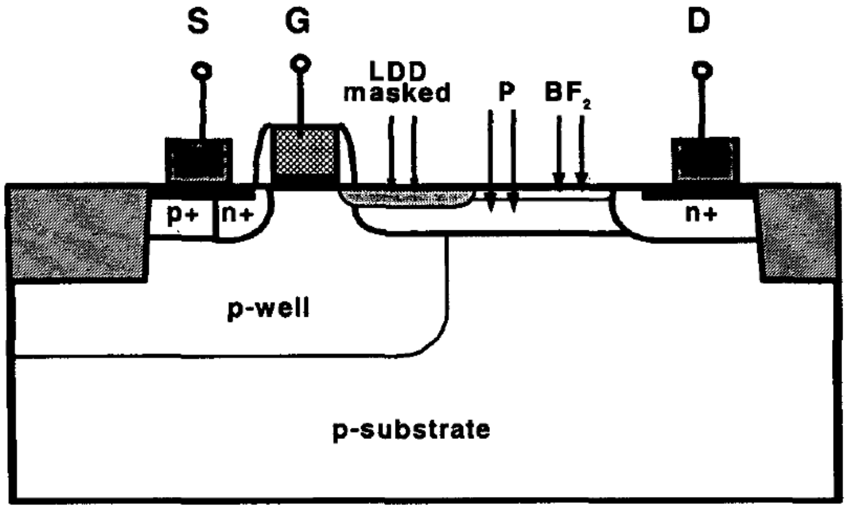


Fig.1: Schematic cross-section of the RF-LDMOS transistor.

High Voltage / high Frequency
Main market. Cellular base stations

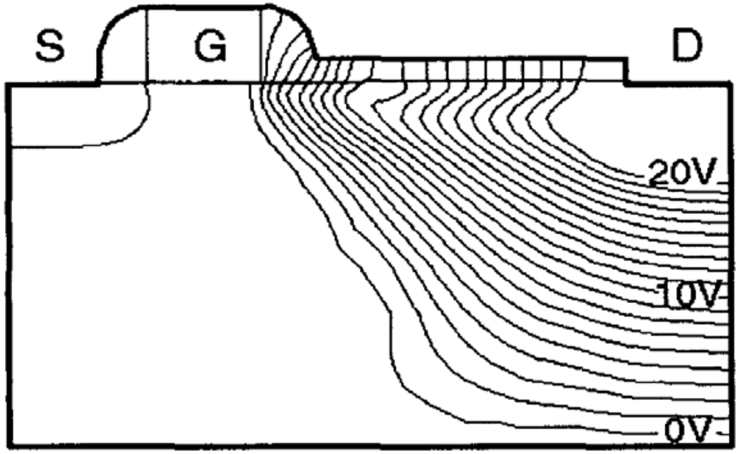


Fig.3a: Potential distribution at the highest operating voltage (20V) with $V_G = 0V$ (LDMOS 3 from Table 1).

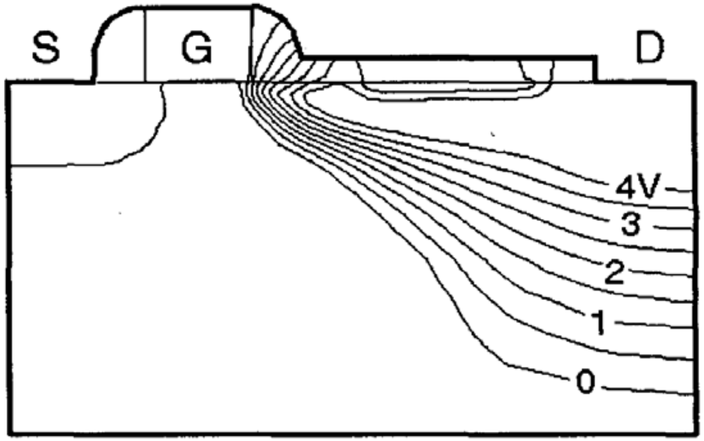
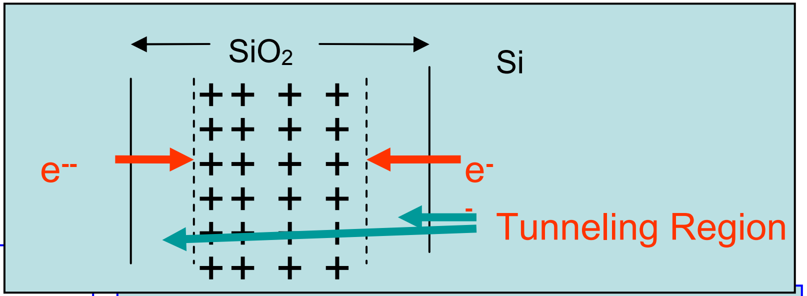


Fig.3b: Potential distribution at the lowest operating voltage (4V) with $V_G = 0V$ (LDMOS 3 from Table 1).

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

Radiation Tolerance: Thin Gate Oxide & LDMOS Structure

IBM 6SF 0.25 µm Process. Many LHC Custom ASICs. Tox= 5 nm (2.5V). 7 nm (3.3V). Radiation Hard for LHC Logic Circuits



Hole removal process by tunneling in thin-oxide MOS Structures
Sachs et. al. IEEE Trans. Nuclear Science NS-31, 1249 (1984)
Book. Timothy R Oldham
"Ionizing Radiation Effects in MOS Oxides" 1999 World Scientific

Following are Drain extension / LDMOS Structures

IHP Microelectronics Fab Only – no standard products
2005 EN5360. First 5 V 5 MHz converter. 0.25 µm 5 nm Gate Oxide.100 Mrads
2007 Increased LDMOS Vin operating to >12 volts

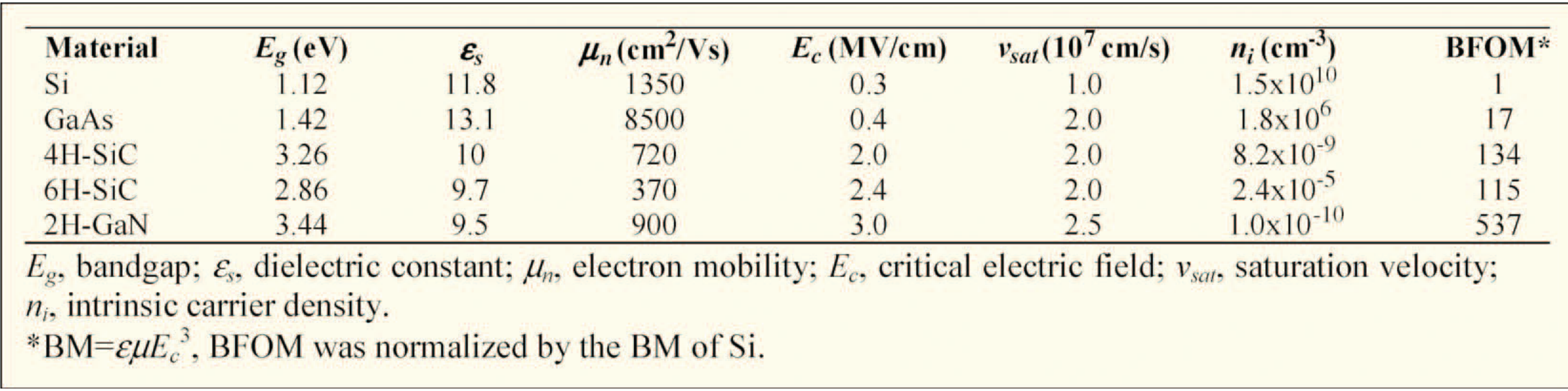
Dongbu HiTek
Lower cost version of EN5360 – ***NOT*** Radiation Hard
Implementation of Low Vgs (1.8V) 12V RF-LDMOS for High-Frequency DC-DC Converter Applications, ISPSD 2012 June 2012, Bruges, Belgium
12 > 1 V converter 25 MHz Converter
Gate Oxide = 3 nm   Breakdown Voltage is 20 Volts

Texas Instruments
High Voltage (up to 20V) Devices Implementation in 0.13 µm BiCMOS Process Technology for **System-On-Chip (SOC) Design. ISPSD 2006, Naples, It**
20 Volt devices in 0.13 µm BiCMOS Process
2012 80 V Power Transistors (2 amps) in 0.18 µm Process with Gate oxide 12 nm
LBC8 (180nm, 20-60V) and **LBC9** (130nm, 20V).   7 nm Gate Oxide for 20 volts

2009 XySemi Inc,
Founder Designed original EN5360
2 amp Power FET Transistor. 7 nm Gate Oxide. Process HVMOS20080720. Radiation Tested to 52 Mrads

2010 National Semiconductor LM2864 20V/4 amps Process PVIP25 11.8 nm 1 Mrads

Electrical Properties of Wide Bandgap Semiconductors Compared With Si and GaAs



Material	E_g (eV)	ε_s	μ_n (cm^2/Vs)	E_c (MV/cm)	v_{sat} (10^7 cm/s)	n_i (cm^{-3})	BFOM*
Si	1.12	11.8	1350	0.3	1.0	$1.5\text{x}10^{10}$	1
GaAs	1.42	13.1	8500	0.4	2.0	$1.8\text{x}10^{6}$	17
4H-SiC	3.26	10	720	2.0	2.0	$8.2\text{x}10^{-9}$	134
6H-SiC	2.86	9.7	370	2.4	2.0	$2.4\text{x}10^{-5}$	115
2H-GaN	3.44	9.5	900	3.0	2.5	$1.0\text{x}10^{-10}$	537

E_g, bandgap; ε_s, dielectric constant; μ_n, electron mobility; E_c, critical electric field; v_{sat}, saturation velocity; n_i, intrinsic carrier density.

*$BM=\varepsilon\mu E_c^3$, BFOM was normalized by the BM of Si.

Nariaki Ikeda et al. GaN Power Transistors on Si Substrates for Switching Applications. Proceedings of the IEEE, Vol. 98, No. 7, July 2010
B. J. Baliga, BPower semiconductor device figure of merit for high-frequency applications IEEE Electron Device Lett., vol. 10, p. 455, Oct. 1989.

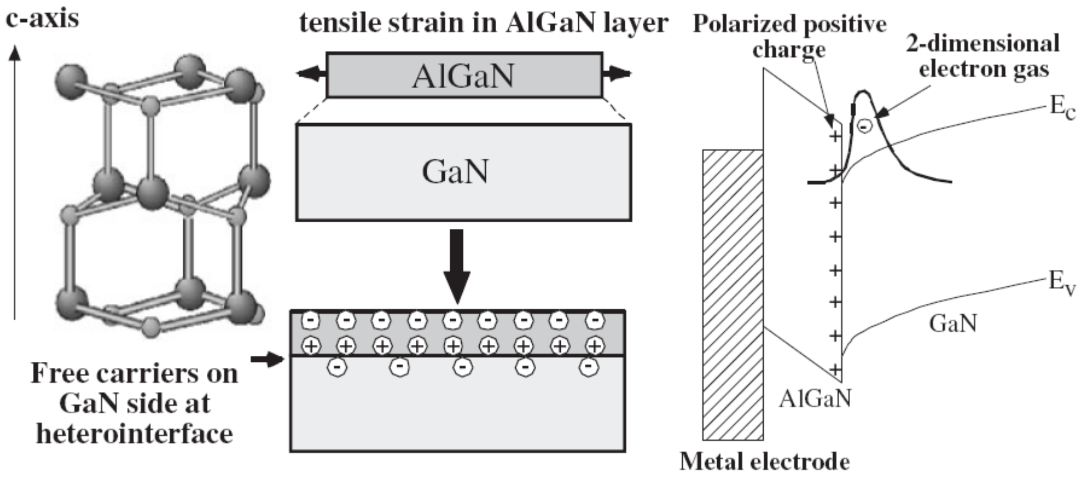


Fig. 6. AlGaN/GaN heterostructure and its band diagram. When the AlGaN layer is under tensile strain, free carriers are accumulated at the heterointerface owing to the piezoelectric effect caused by the strain, and a spontaneous polarization effect.

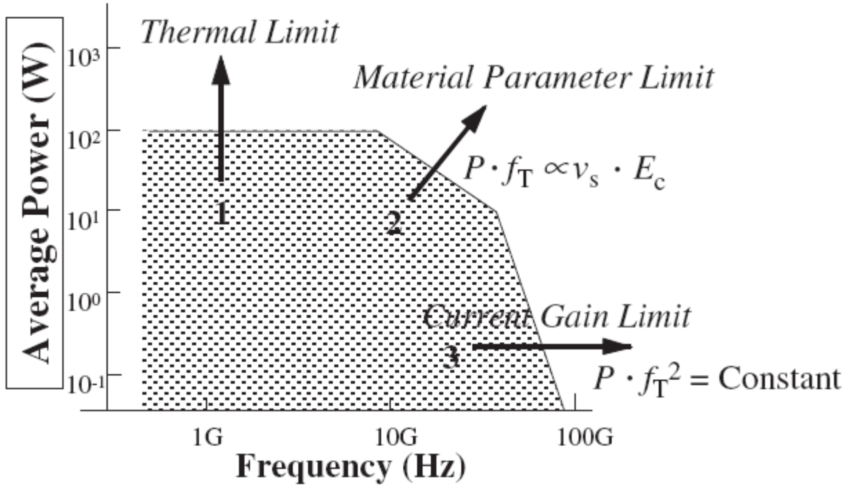


Fig. 7. Restrictions of HF devices in terms of output power and frequency. The limiting factors for HF device operation are thermal restriction, material property restriction and current gain restriction, for the respective regions shown in the figure.

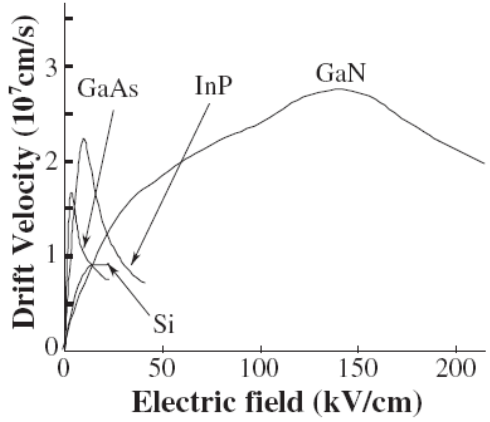


Fig. 8. Dependence of drift velocity of semiconductors on electric field. GaAs and InP have high mobilities (slope of drift velocity–electric field relation in the low-electric-field region); however, their drift velocities decrease in the high-electric-field region. On the other hand, GaN shows high drift velocity in the high-electric-field region.

H. Okumura. Present Status and Future of Widegap Semiconductor High-Power Devices, Jpn. J. Appl. Vol. 45. No. 10A (2006)

Gallium Nitride Devices Tests 2009

RF GaN 20 Volts & 0.1 amp

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

48V Converter ?

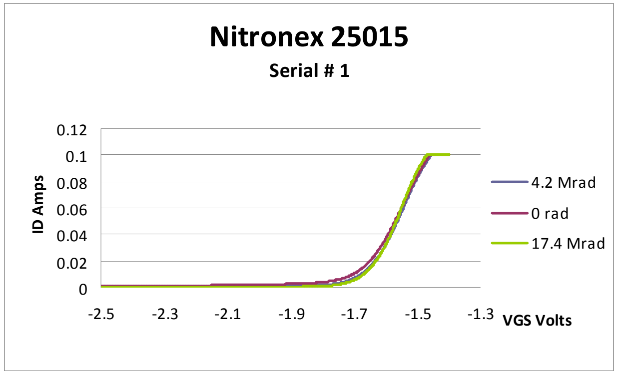
- ❖ 2 pieces: CREE CGH40010F: GaN on siC

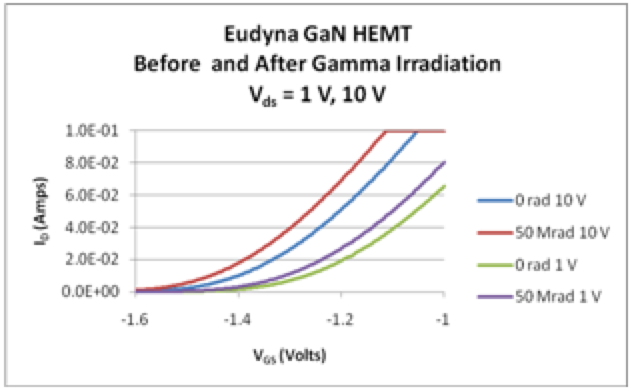
- ❖ 6 pieces: Eudyna EGNB010MK: GaN on siC
- ✓ Done Neutrons

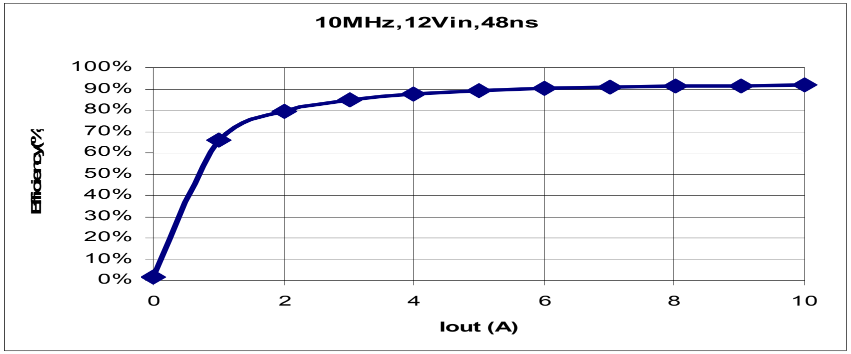
Switch GaN

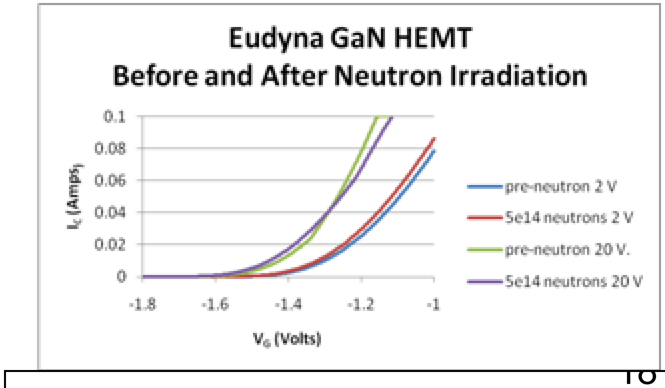
- ❖ International Rectifier GaN on Silicon

_*Good efficiency to >12 MHz* Driver limited





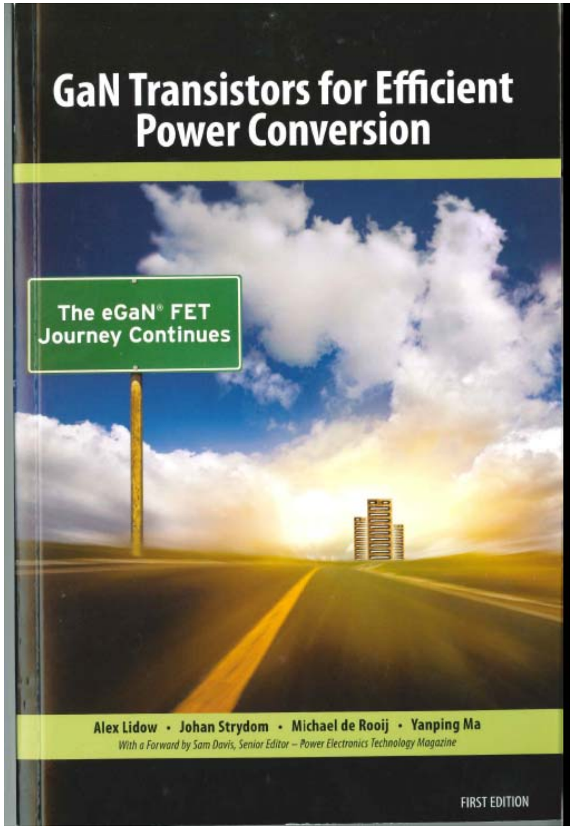




Gamma: @ BNL
Protons: @ Lansce
Neutrons: @ U of Mass Lowell

Oscillations in SPA @ >>1 GHz

Design Guide for Enhancement Mode (Normally Off) FETs
Includes radiation testing by Yale and others



GaN Transistors for Efficient Power Conversion

The eGaN® FET Journey Continues

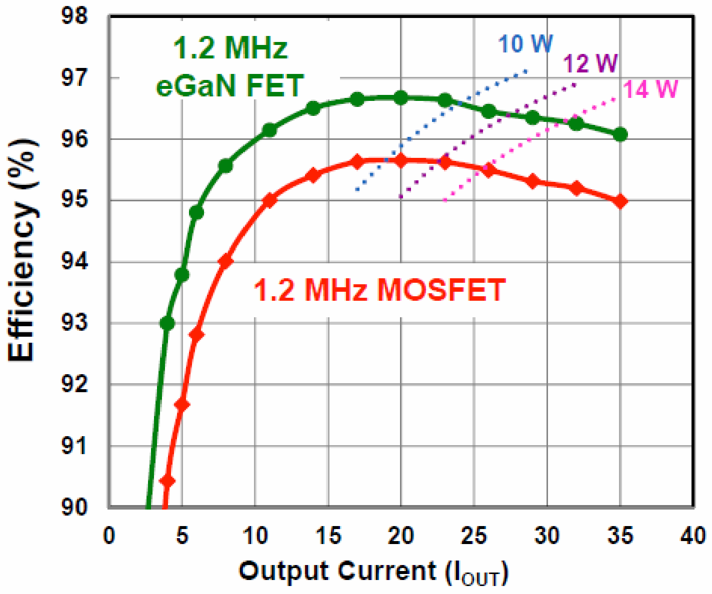
Alex Lidow • Johan Strydom • Michael de Rooij • Yanping Ma

With a Forward by Sam Davis, Senior Editor – Power Electronics Technology Magazine

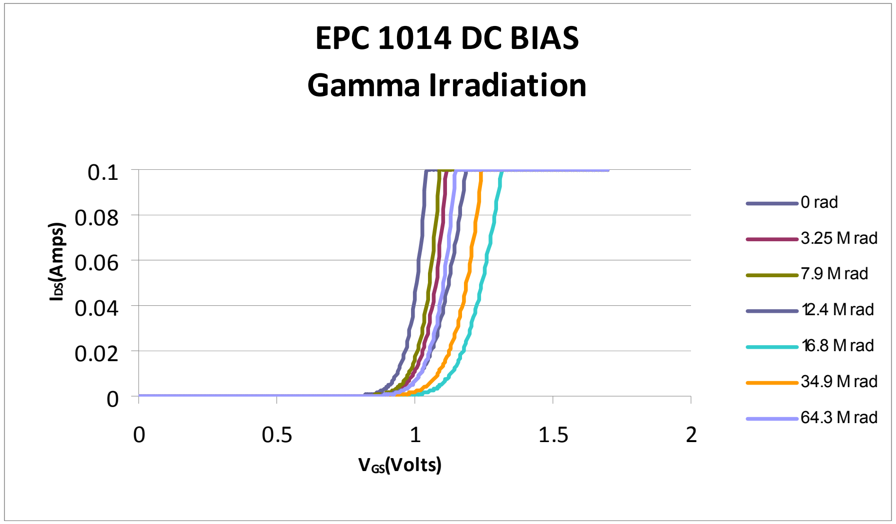
FIRST EDITION

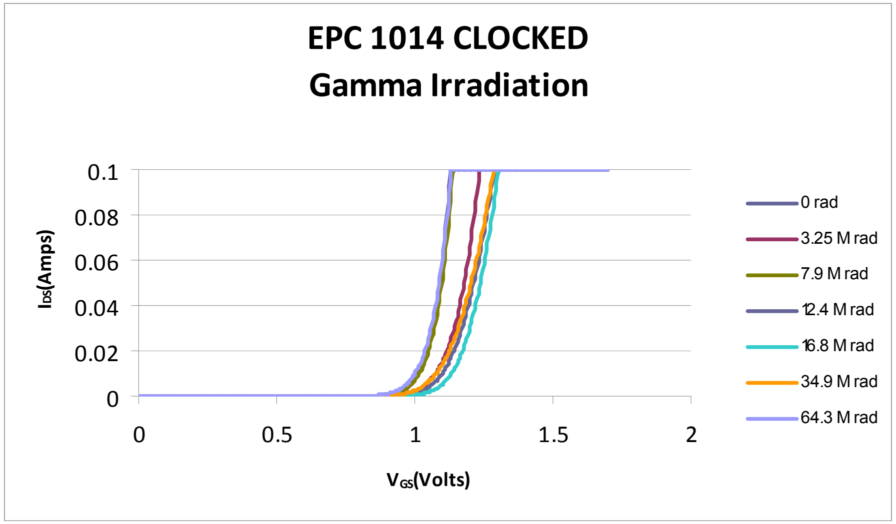
This shows reducing waste heat (improved Efficiency)
Can get more output current for the same cooling capacity

Efficiency Comparison



F_S = 1.2 MHz, V_{IN} = 48 V, and V_{OUT} = 12 V





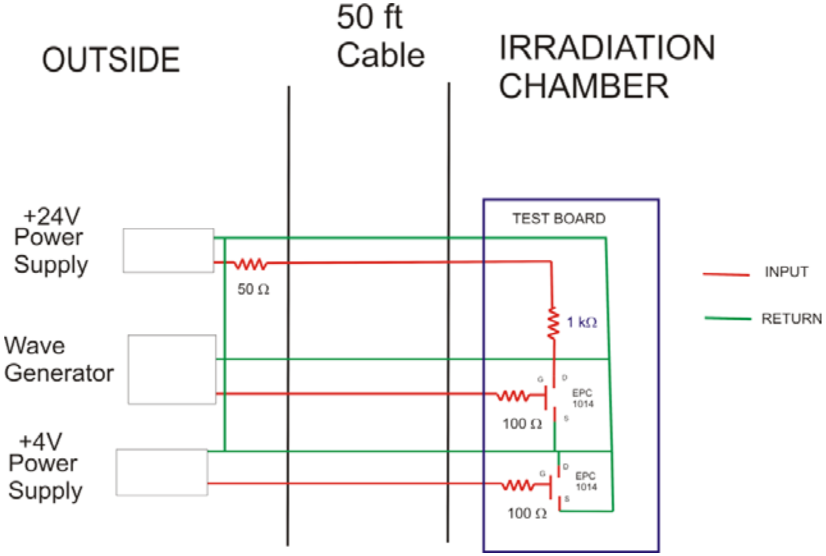
During Gamma Irradiation DC BIAS 4 VOLTS, VDS = 0
Fluence rate= 5 mega M rad/day

Enhancement Mode GaN FETs

Proton Irradiation

The run went well, we left your board in the beam until it reached approximately 1x10^15 p/cm^2 (800 MeVp). The initial measurement ov voltage across the 50 ohm resistor was 0.645V, and the final measurement was 0.643V. Readings were taken after every entry to remove samples from the blue room (7 times) and they were always between 0.643V - 0.645V. I'm sure Leo Bitteker has your shipping information but you may want to send him a reminder in a couple

of weeks.



Gamma Irradiation done @ BNL Gamma Facility *James Kierstead July 2010*
Proton Irradiation @ LANSCE, Los Alamos National Lab. *August 2010*

Converter Notes

- Learned from commercial Devices, Companies & Power conferences
- Can get high Radiation Tolerance & Higher Voltage
- High Frequency > Smaller Air coil > Less Material
- Goal: ~20 MHz Buck, 1 amp *size 9 mm x 9mm*
- Power SOC: MEMs Air Core Inductor on Chip
- Study Feasibility 48 / 300V Converters
- Irradiation: Run @ Max operating V & I.
  - Limit Power Dissipation by Switching duty cycle
  - ~ 20 device – almost all failed
- Online Monitoring during irradiation for faster results

Circa 2010

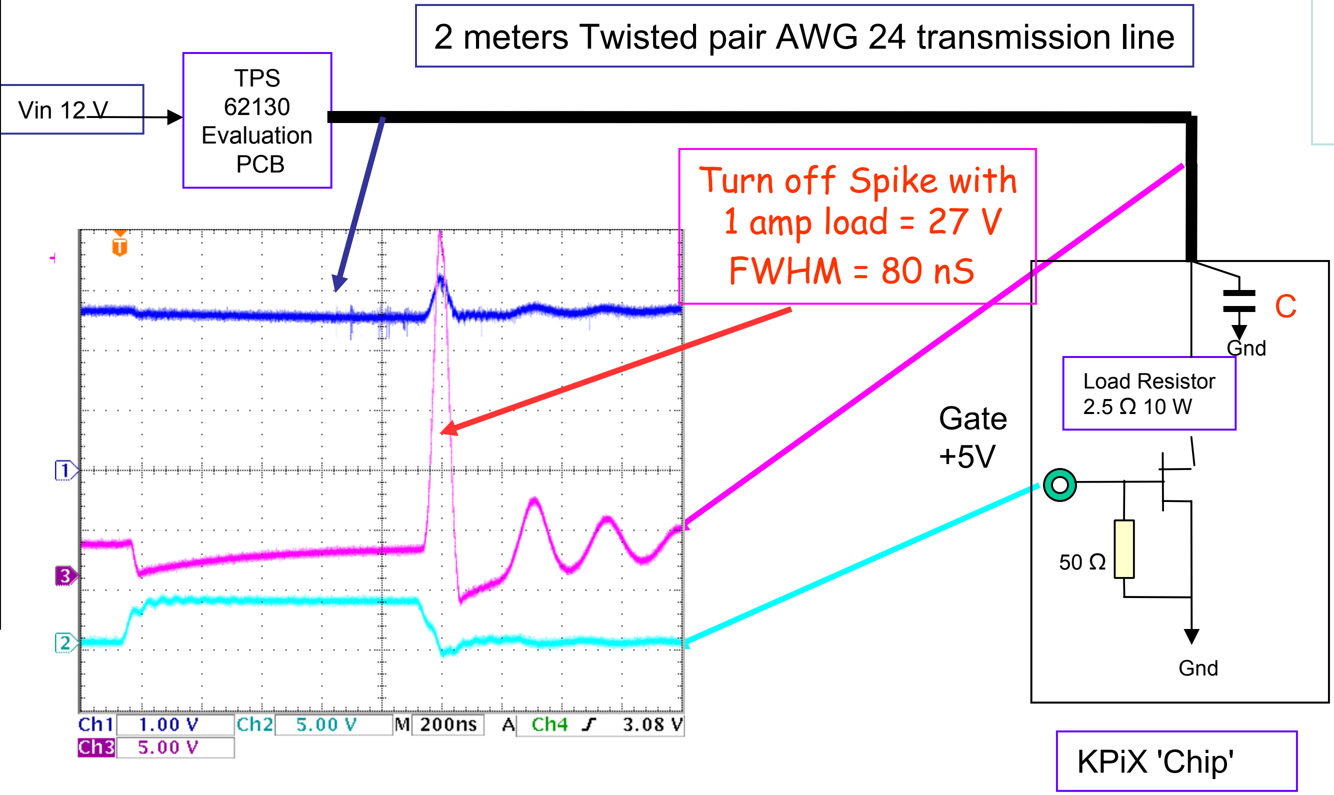
SiD

Power Transmission Issues for SiD:

- Want large conversion ratio to reduce Cu and thermal losses.
- Need to operate in high magnetic field: air core inductors
- Need to control V=LdI/dt resulting from power modulation
- Must not bother sub-fC signals to KPiX!

Turn Off Spike

- Damage IC if >20% of VCC
- Decreased with Lower Cable Z
- Engineer KpiX current turnoff



2 meters Twisted pair AWG 24 transmission line

Vin 12 V

TPS
62130
Evaluation
PCB

Turn off Spike with
1 amp load = 27 V
FWHM = 80 nS

C

Gnd

Load Resistor
2.5 Ω 10 W

Gate
+5V

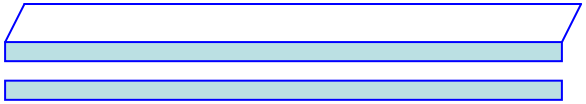
50 Ω

Gnd

KPiX 'Chip'

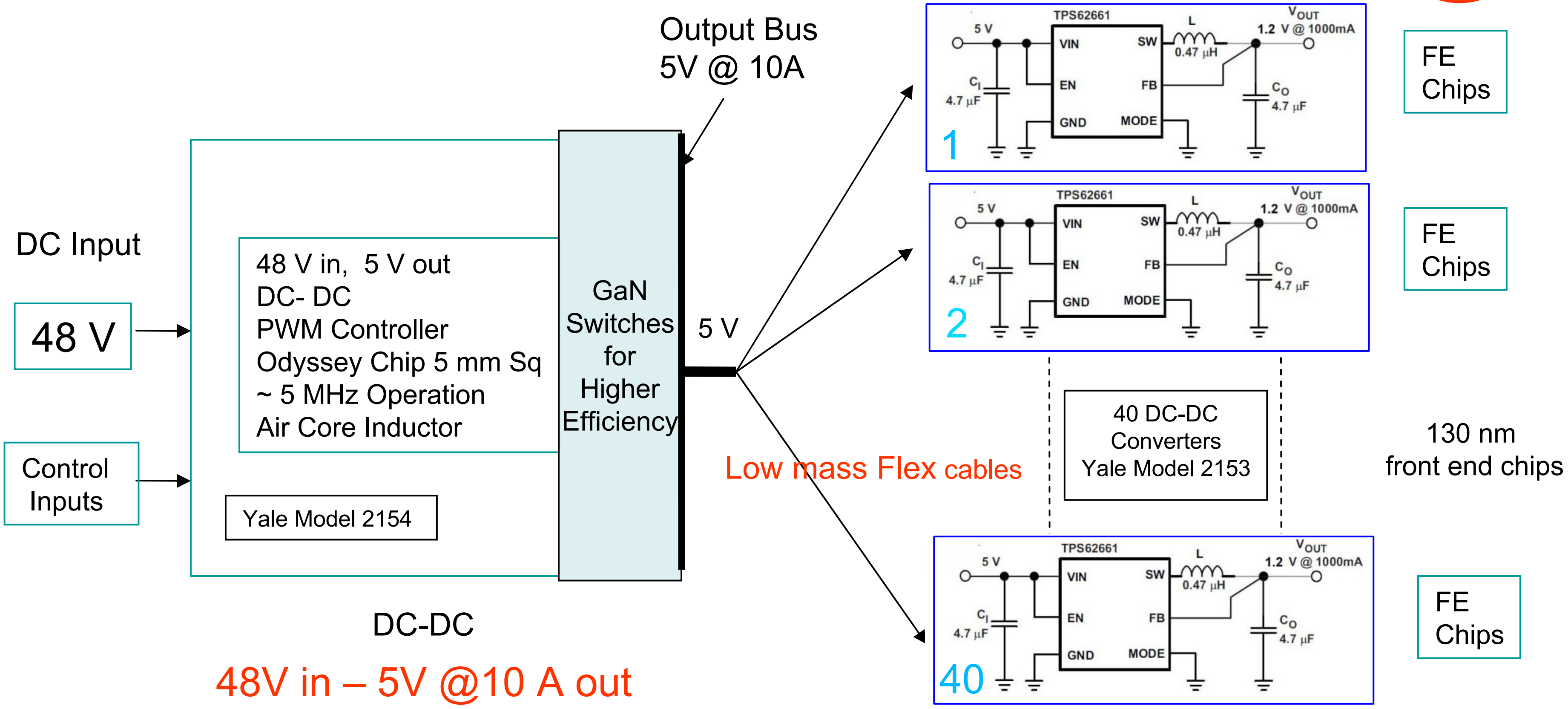
Waveforms when 1 amp flowing thru 130 Ohms twisted pair is interrupted /switched off.
27 Volt spike appears across KPiX chip. Not yet tested with real KPiX.

Cu Microstrip Line
t = 9, w = 90 mils
Enamel insulation~ 0.2 mils



Two Stage DC-DC Power Conversion & Distribution

SiD



DC Input

48 V

Control Inputs

48 V in, 5 V out
DC- DC
PWM Controller
Odyssey Chip 5 mm Sq
~ 5 MHz Operation
Air Core Inductor

Yale Model 2154

GaN Switches for Higher Efficiency

Output Bus
5V @ 10A

5 V

Low mass Flex cables

40 DC-DC Converters
Yale Model 2153

FE Chips

FE Chips

FE Chips

130 nm
front end chips

DC-DC

48V in – 5V @10 A out

Fewer of these modules
further from the detector/sensors

DC-DC

5V in – 1.2V @1 A out

Many of these modules
close to the detector/sensors
Low mass chip scale package
small Air Core Inductor.
Test 6, 9 and 20 MHz
Converters

Status

Model 2153: Prototype for coil configurations under Test
Model 2153: Odyssey Chip Eval Board under NDA

Proposed **Power Switching** Tests in 7T Magnet at Yale University for SiD

- KPiX chip with & without Pulse power. Needs DAQ & Software experts to run it.
- Current leads tests – vibration, movement, tilting.

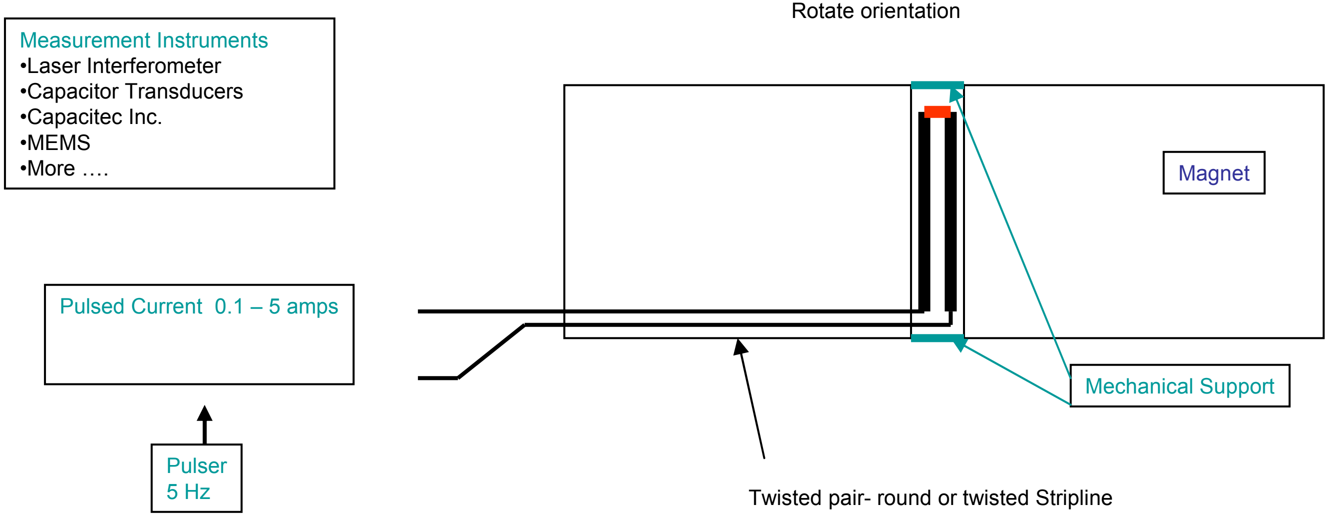
SiD

7T Magnets	Warm Bore cms	Length cms	Orientation	Access
# 1	8.9	150 ??	Vertical	Top
# 2	16	105	Horizontal	One end
# 3	16	105	Horizontal	One end

Bruker 7T, 20 cm bore

Test set up in 7 Tesla Magnet

Conductors under Test
Thin material: Kapton, Cu
Rotate orientation



Measurement Instruments
- Laser Interferometer
- Capacitor Transducers
- Capacitec Inc.
- MEMS
- More ….

Pulsed Current 0.1 – 5 amps

Pulser
5 Hz

Magnet

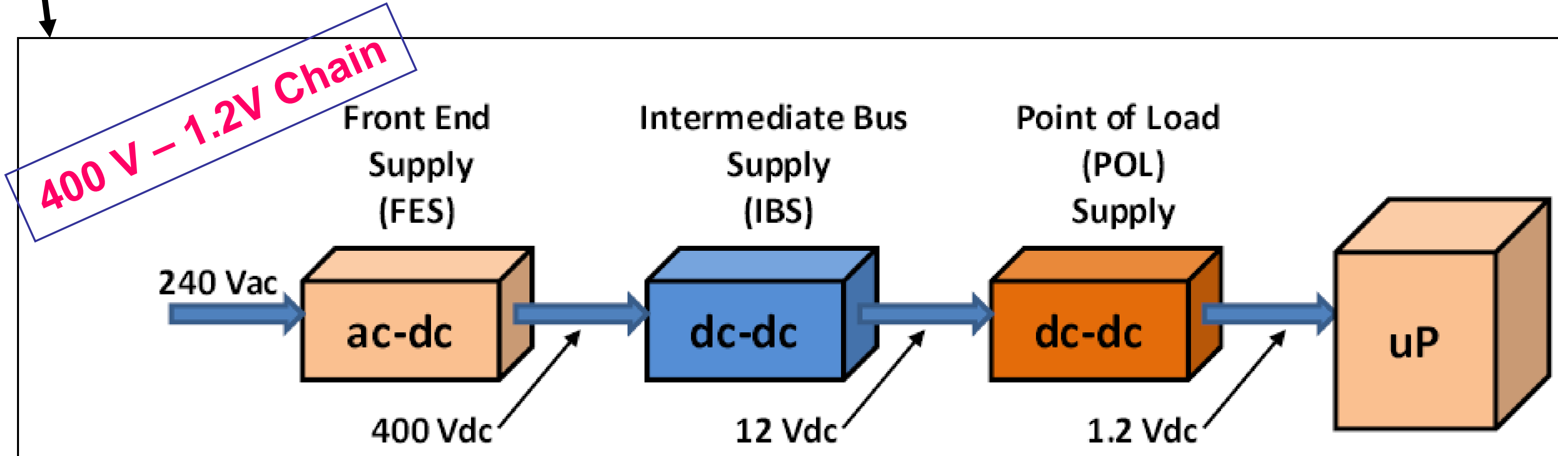
Mechanical Support

Twisted pair- round or twisted Stripline

Satish Dhawan
Yale University Jan 09, 2011

GaN High Efficiency Power Switching Applications

- ❖ Data Center: Efficiency sensitive / More CPU power in same vault
  400 V DC (+/-200 V) Power distribution: 12 V – 1 V converters.
  - IEC SMB SG4, IEC TC64, ETSI EE, The Green Grid -Power sub working group
- ❖ AC Line > DC power converters 600V 5 - 20 amps. Low vampire power
- ❖ Electric Vehicles 600 /900 V 100 kwatts
- ❖ Railways 8 KV SiC FETs, SiC diodes



400 V – 1.2V Chain

Front End Supply (FES)

Intermediate Bus Supply (IBS)

Point of Load (POL) Supply

240 Vac

ac-dc

dc-dc

dc-dc

uP

400 Vdc

12 Vdc

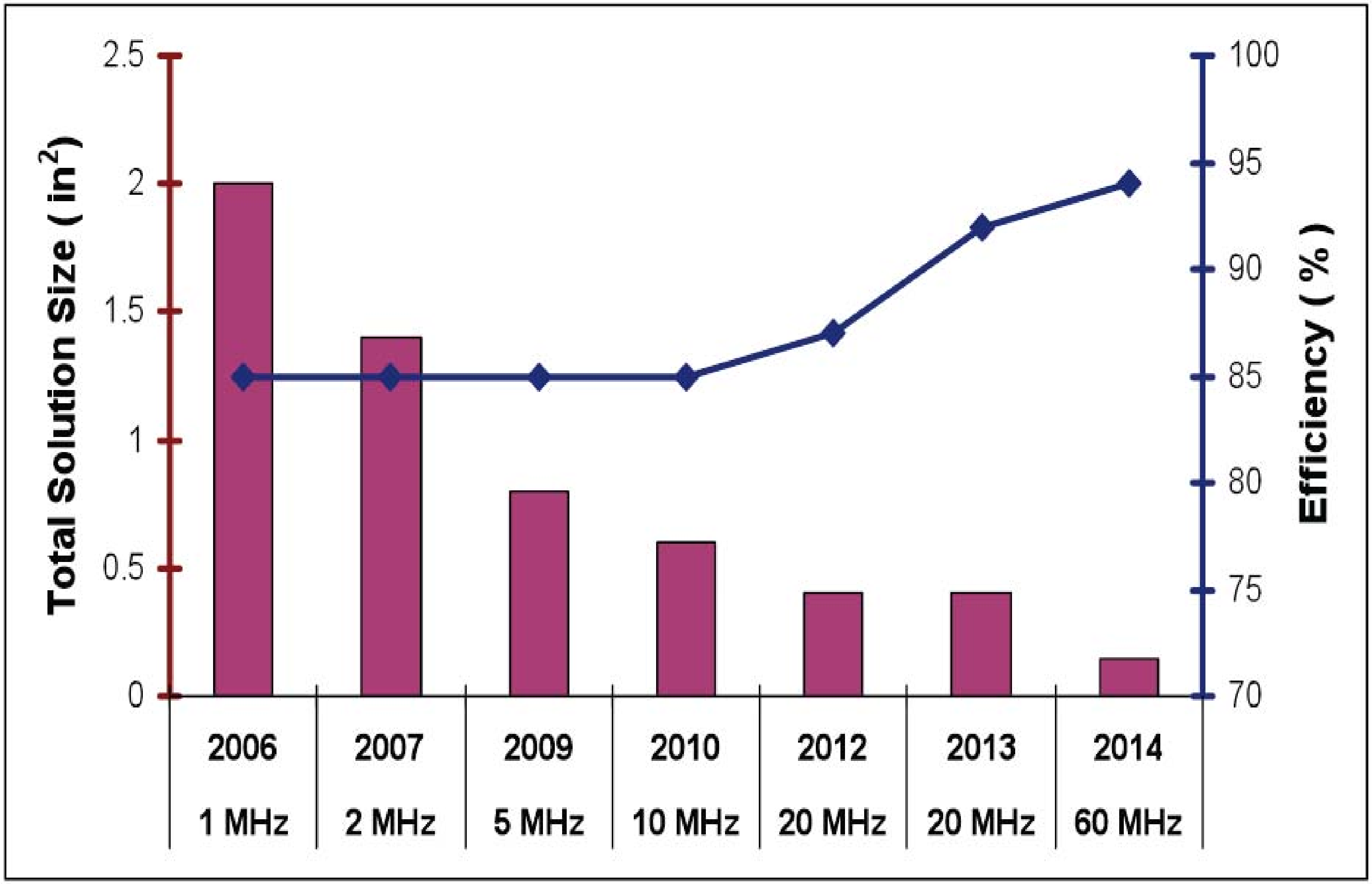
1.2 Vdc

	FES	IBS	POL	Plug-to-Processor
Recent	93%	95%	88%	78%
Best Immediate	95%	98%	90%	84%
	IBM Challenge			***90%***
Needed	98%	98%	94%	***90%***

Arnold Alderman: Bodos Power Systems April 2010. Randy Malik IBM Digital Forum 2007

Potential LV DC-DC Power Stage Roadmap

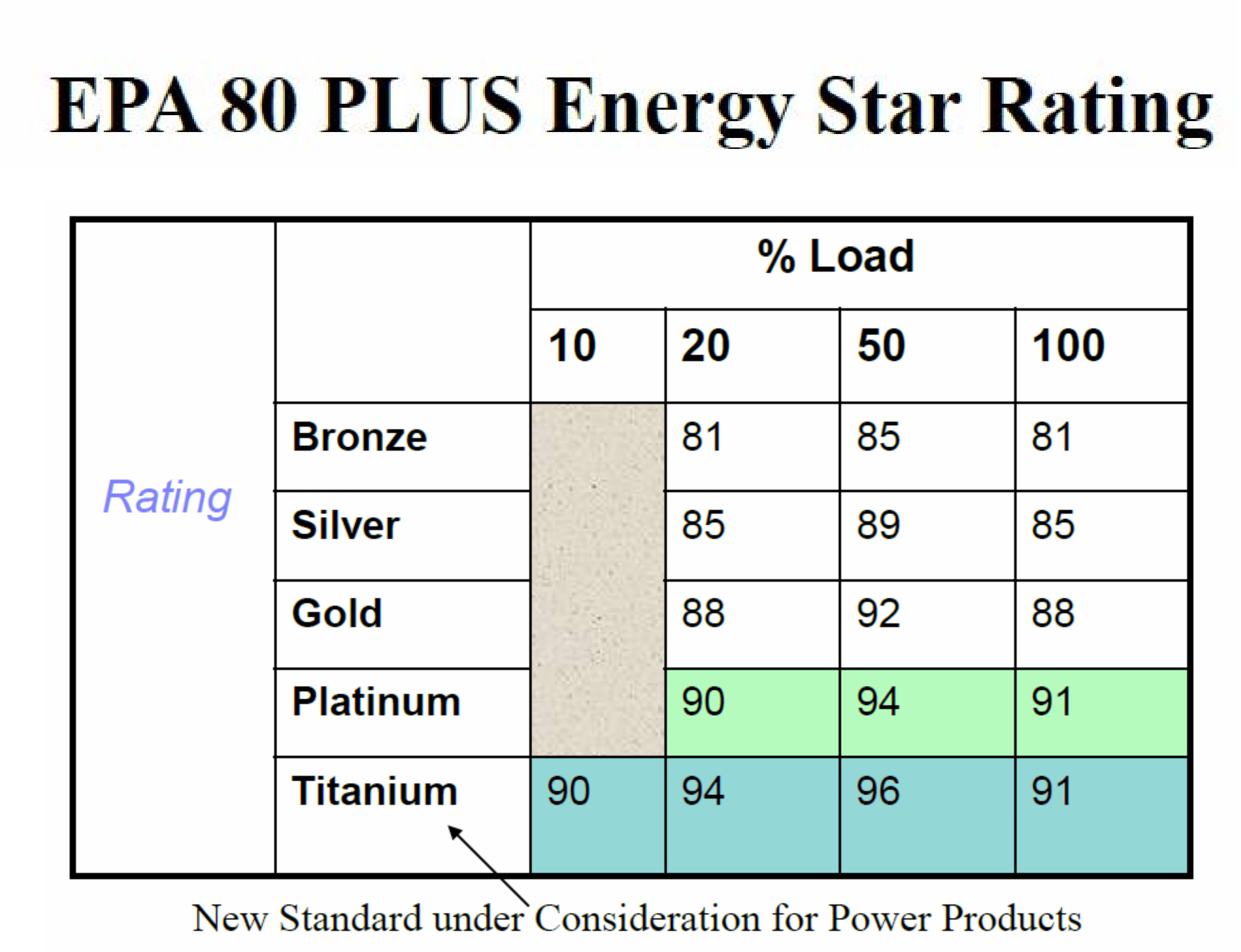
Optimized Performance – Without tradeoff



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

For high frequency Integrate a GaN Driver into Power Stage !

High Voltage Distribution Bus- IBM

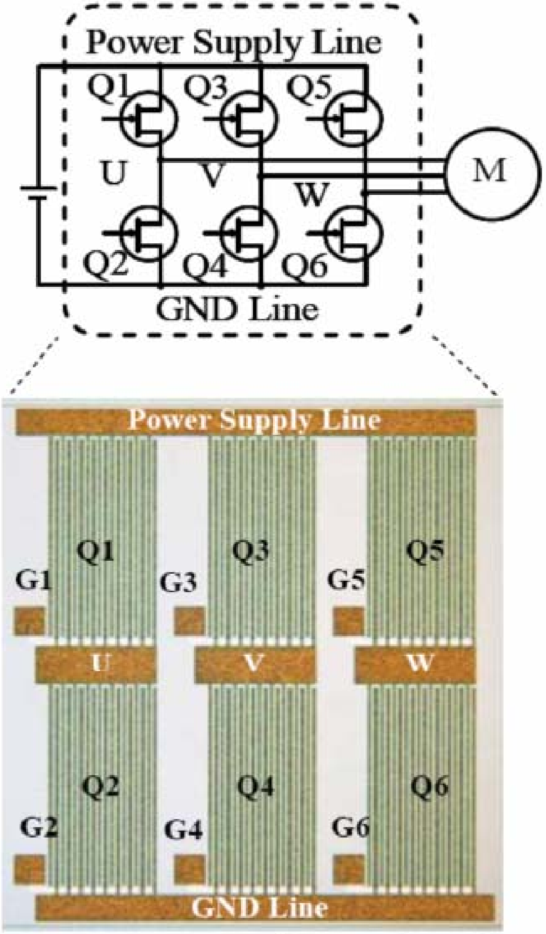


EPA 80 PLUS Energy Star Rating

		% Load			
		10	**20**	**50**	**100**
Rating	**Bronze**		81	85	81
	Silver		85	89	85
	Gold		88	92	88
	Platinum		90	94	91
	Titanium	90	94	96	91

New Standard under Consideration for Power Products

Panasonic Integrated GaN Inverter for small Motors, Air Conditioners, Refrigerators



.8 Circuit diagram and chip photograph of fabricated GaN monolithic inverter IC using GITs on Si.

GaN Power Switching Devices

Masahiro Ishida*, Yasuhiro Uemoto**, Tetsuzo Ueda*, Tsuyoshi Tanaka*, and Daisuke Ueda***

*Semiconductor Device Research Center, Semiconductor Company, Panasonic Corporation,
1 Kotari-yakemachi, Nagaokakyo-shi, Kyoto 617-8520, Japan

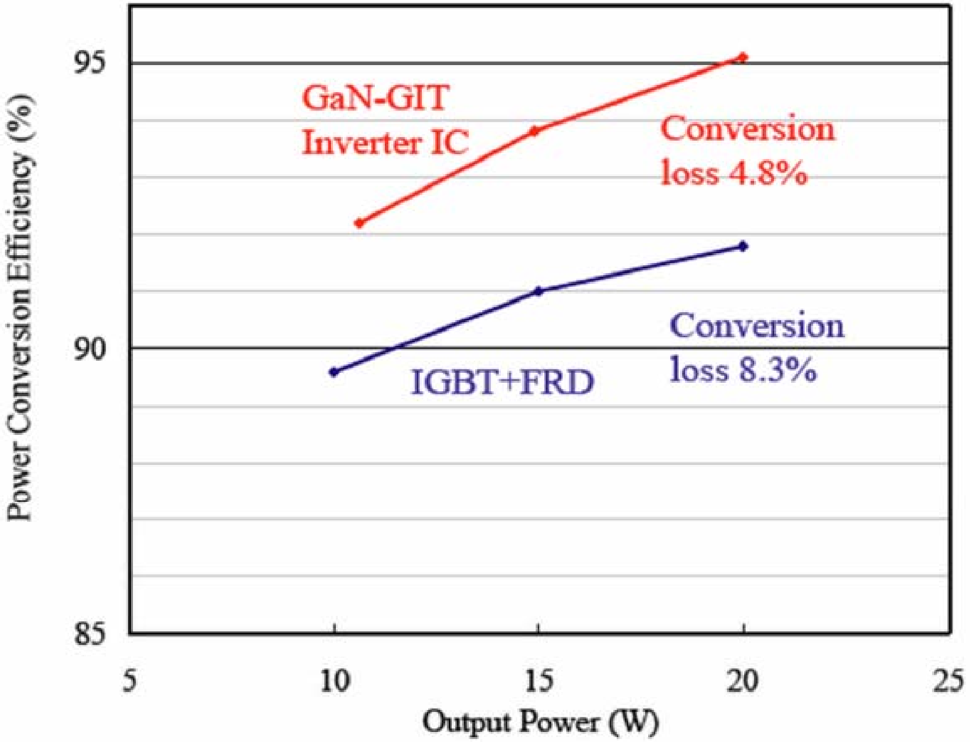
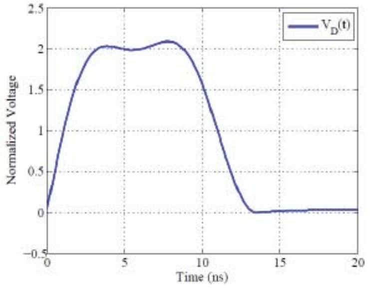


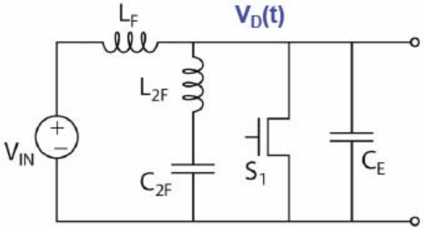
Fig.10 Power conversion efficiency of GaN monolithic inverter and that by conventional Si-IGBTs with FRDs at various output power of the motor.

Switching Frequency Solutions

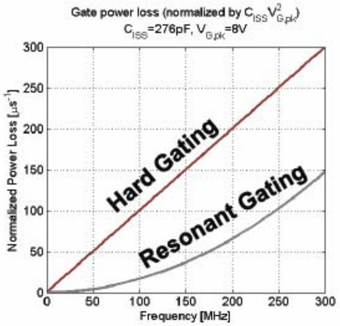
- Minimize frequency dependent device loss, switch fast enough to change or eliminate magnetic materials

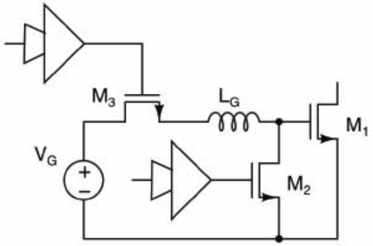
- ZVS Soft switching



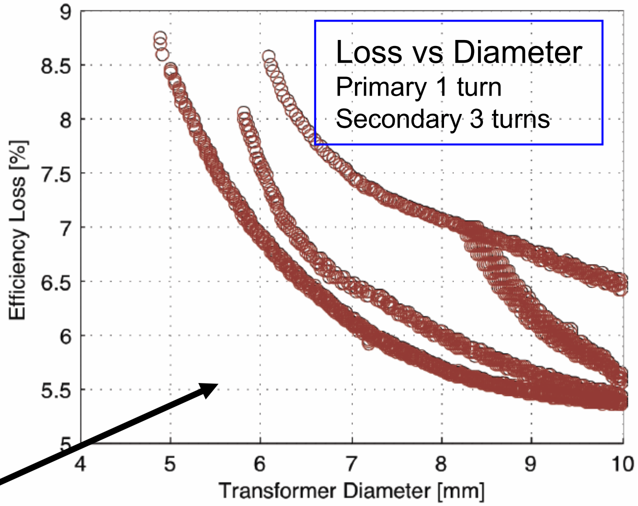


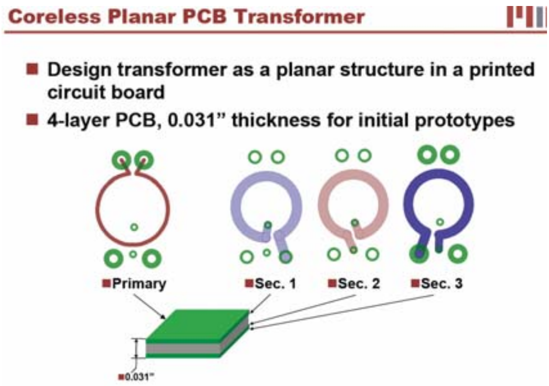
- Resonant gating





- Coreless magnetics in package or substrate





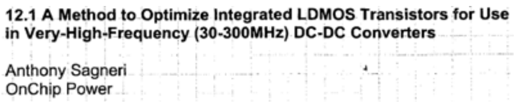
Coreless Planar PCB Transformer

- Design transformer as a planar structure in a printed circuit board
- 4-layer PCB, 0.031" thickness for initial prototypes

Higher frequency into the VHF range offers miniaturization, integration, bandwidth

- ☐ Must overcome switching, gating and magnetics losses
- ☐ Must *manage and apply* parasitics

☐ Converter examples at 10's of Volts and Watts

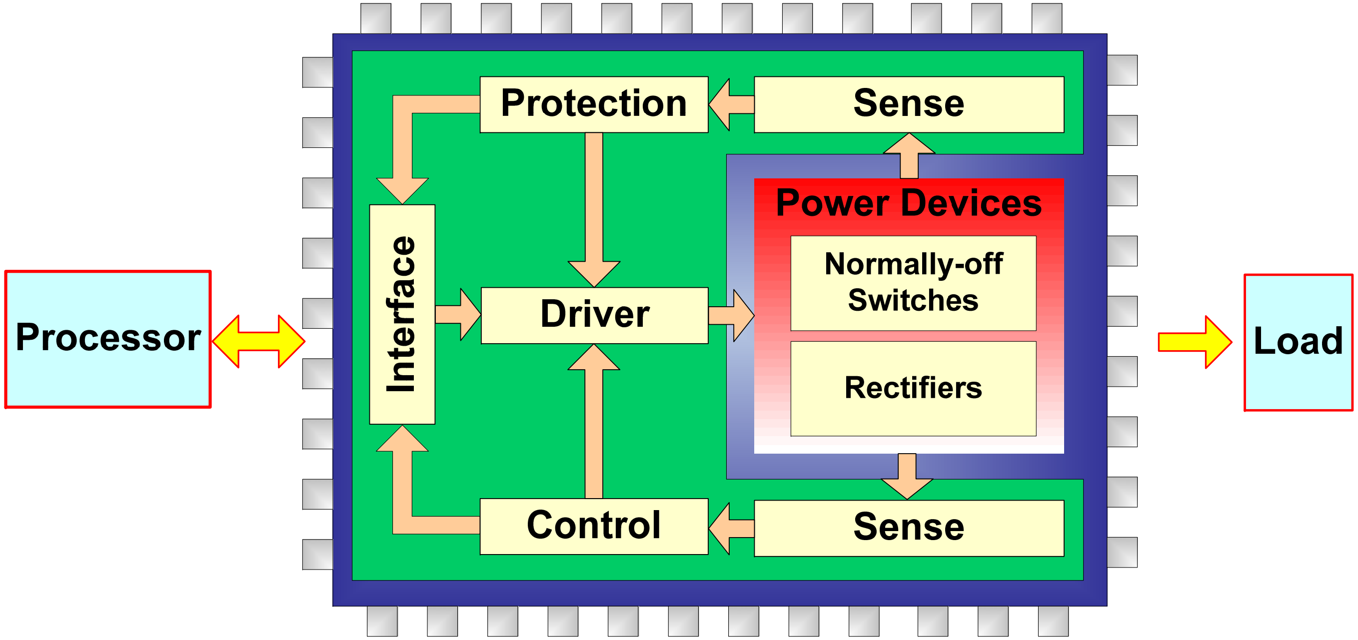


12.1 A Method to Optimize Integrated LDMOS Transistors for Use in Very-High-Frequency (30-300MHz) DC-DC Converters

Anthony Sagneri
OnChip Power

Design of Miniaturized, Isolated dc-dc Cnoverters Operating at Radio Frequencies, David J. Perreault, MIT
Antohny Sagneri OnChip Power Corporation PowerSoC 2012 Confernce

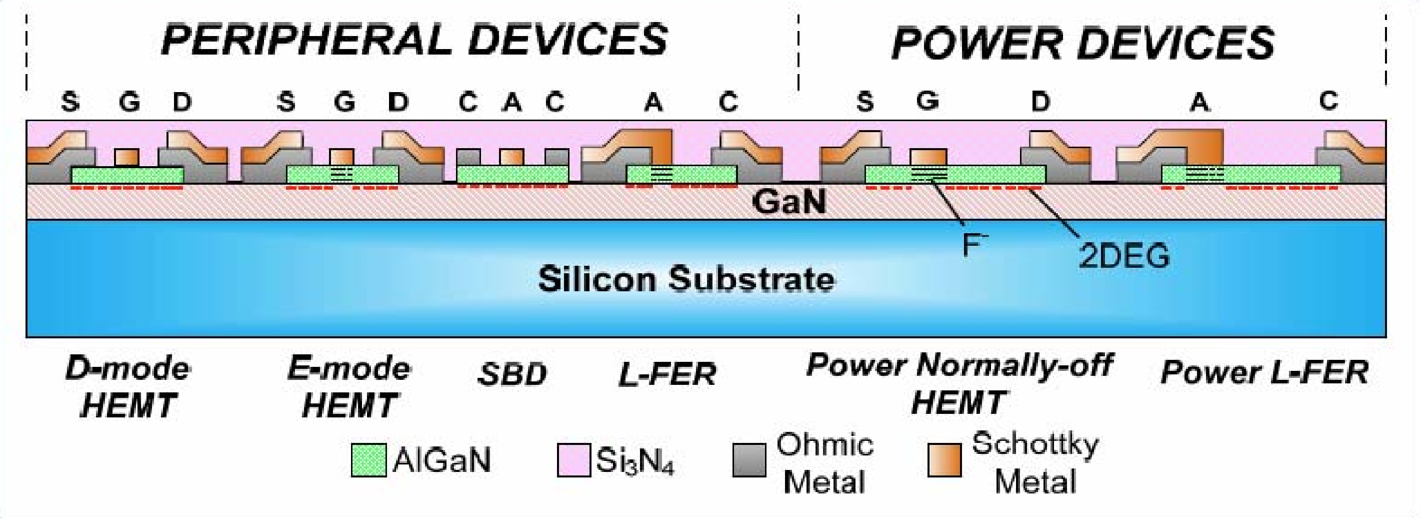
Implementation of GaN power modules



- **Multi-chip modules:** GaN(power)+Si CMOS (peripheral circuits)
  → quick design turn-around, development is underway
  → *operating temperature limit set by Si*
- **All-GaN single-chip solution**: long development time for GaN digital/analog ICs, wide temperature range

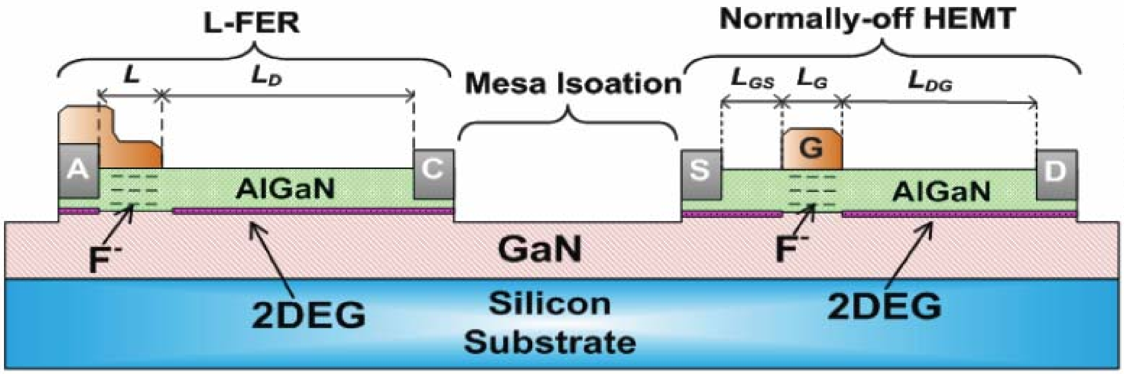
30

GaN Smart Power Technology Platform

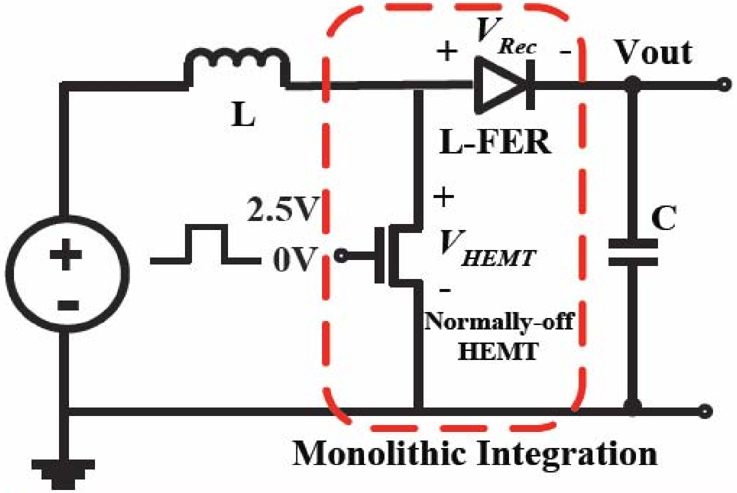


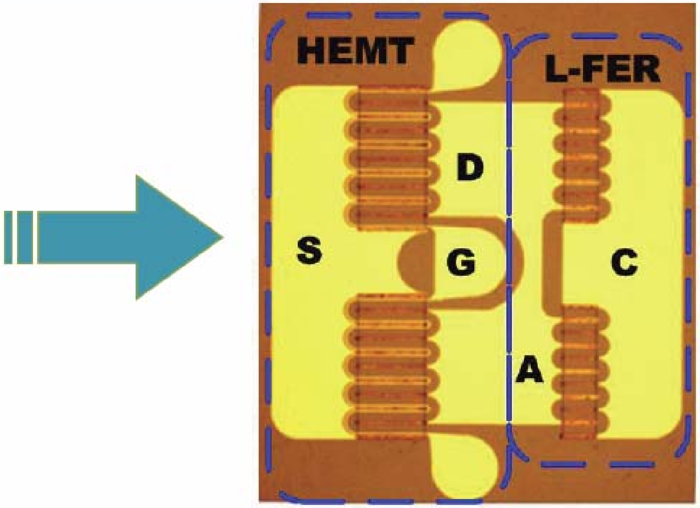
Power Devices	Smart Part	
❖ Normally-off HEMT ❖ Lateral Field-Effect Rectifier (L-FER)	Digital: Direct-coupled FET logic (DCFL)	Analog: Sensing & Protection

Monolithic integration of HEMT and L-FER



W. Chen, et al., *APL, 2008*, *IEEE EDL* 2009
W. Chen, et al., *IEDM 2008*.





L-FER: Lateral Field Effect Rectifier

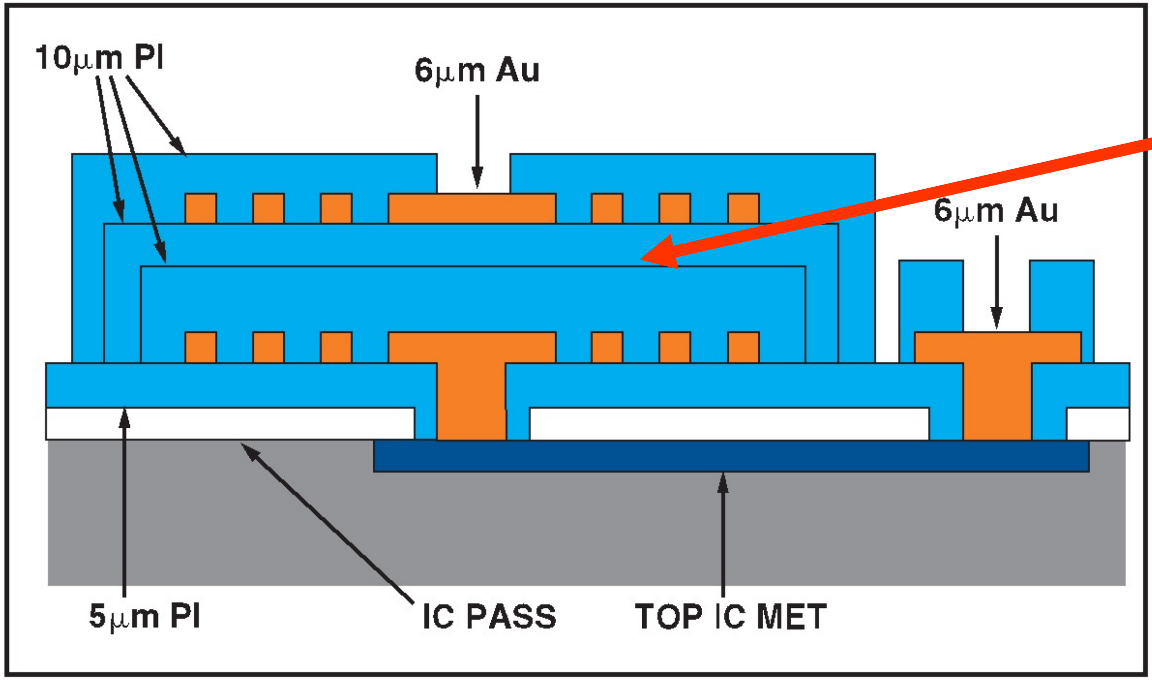


Figure 2. Cross section of iCoupler transformer coil.

Intra coil Insulation

Polyimide (Kapton)

Q @300 MHz

Top Coil = 20

Bottom Coil = 15

Technology CMOS

0.35 µm & 0.6 µm

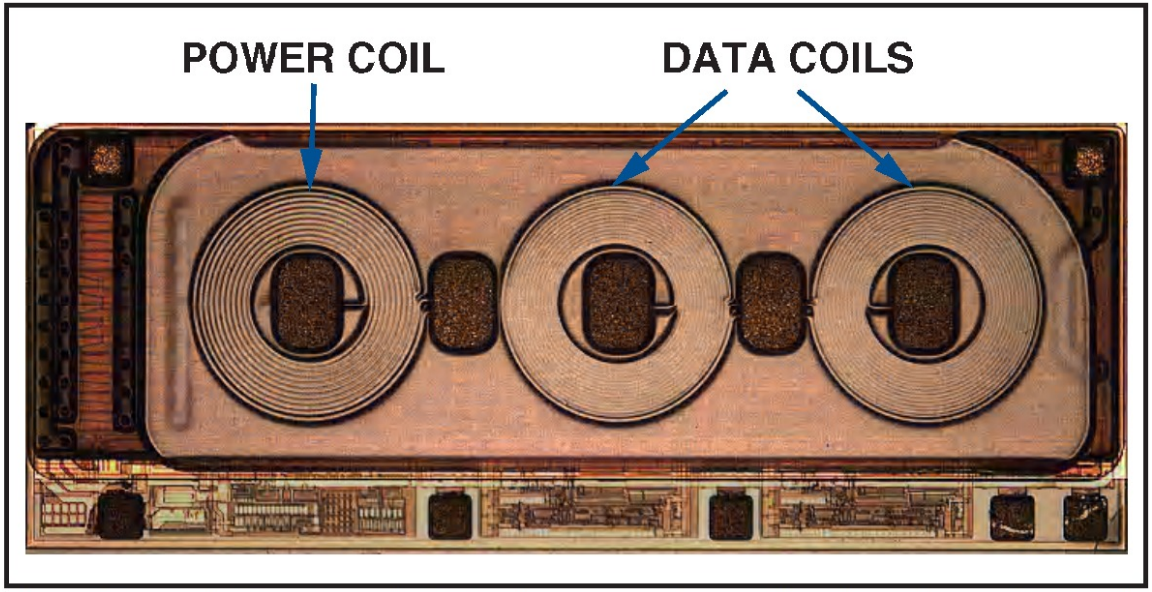
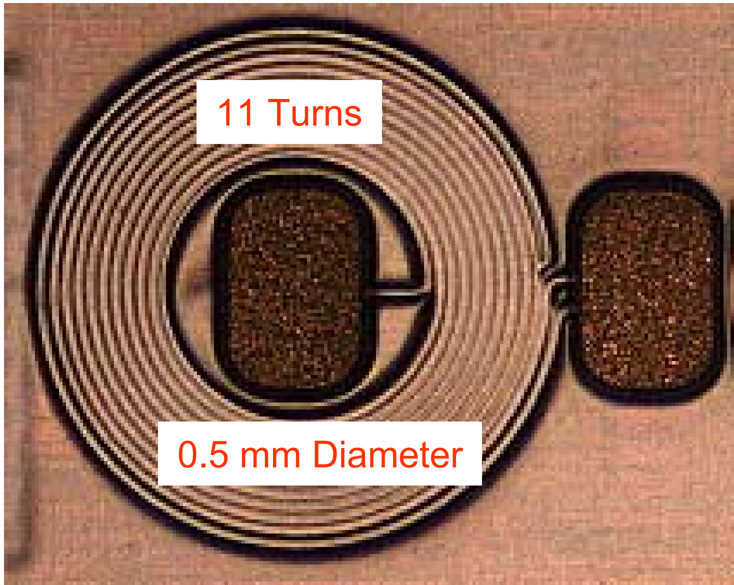
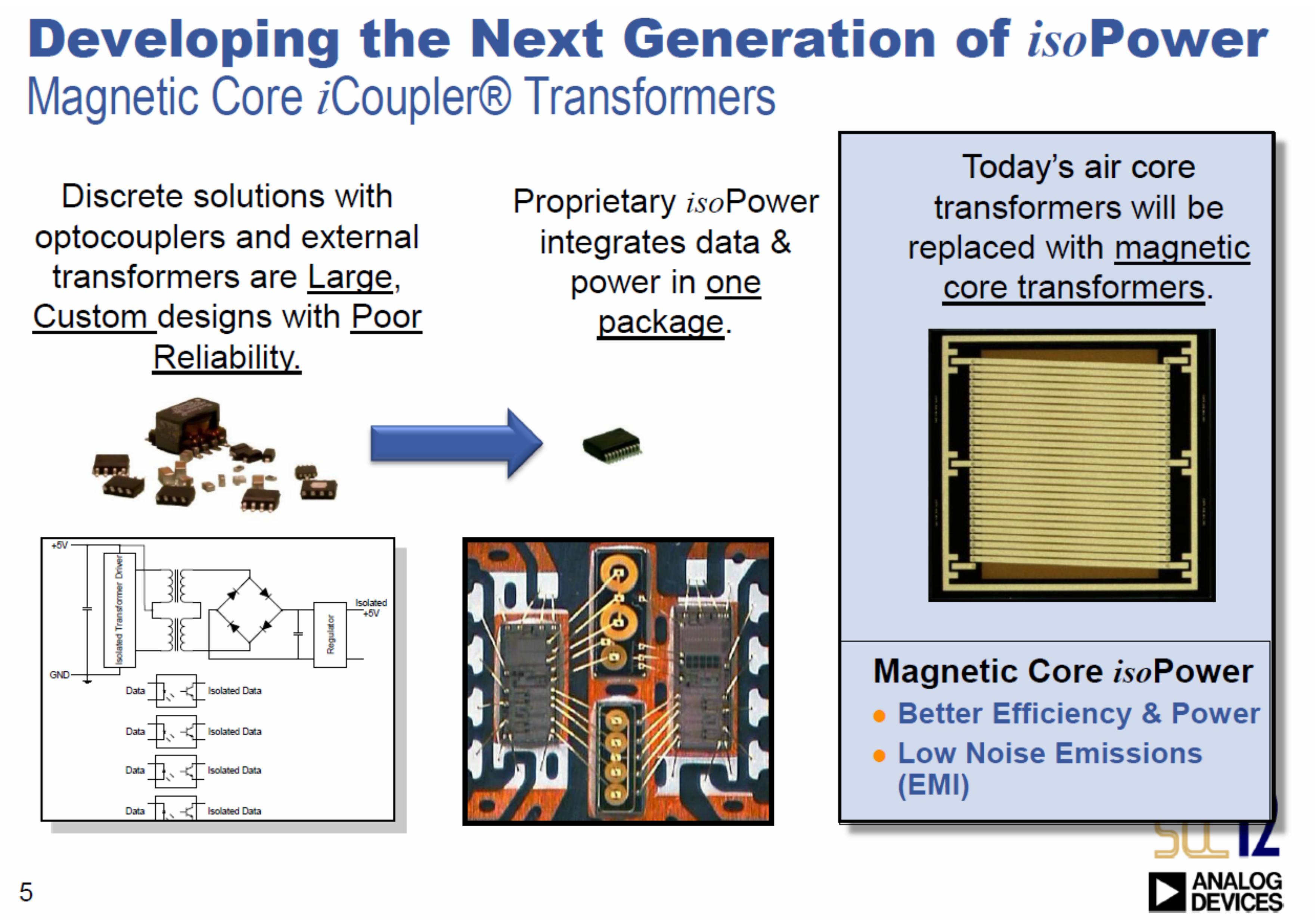


Figure 3. Photograph of transformer die showing the power transformer coil and the two data transformer coils.


11 Turns

0.5 mm Diameter



Developing the Next Generation of *iso*Power

Magnetic Core *i*Coupler® Transformers

Discrete solutions with optocouplers and external transformers are Large, Custom designs with Poor Reliability.

Proprietary *iso*Power integrates data & power in one package.

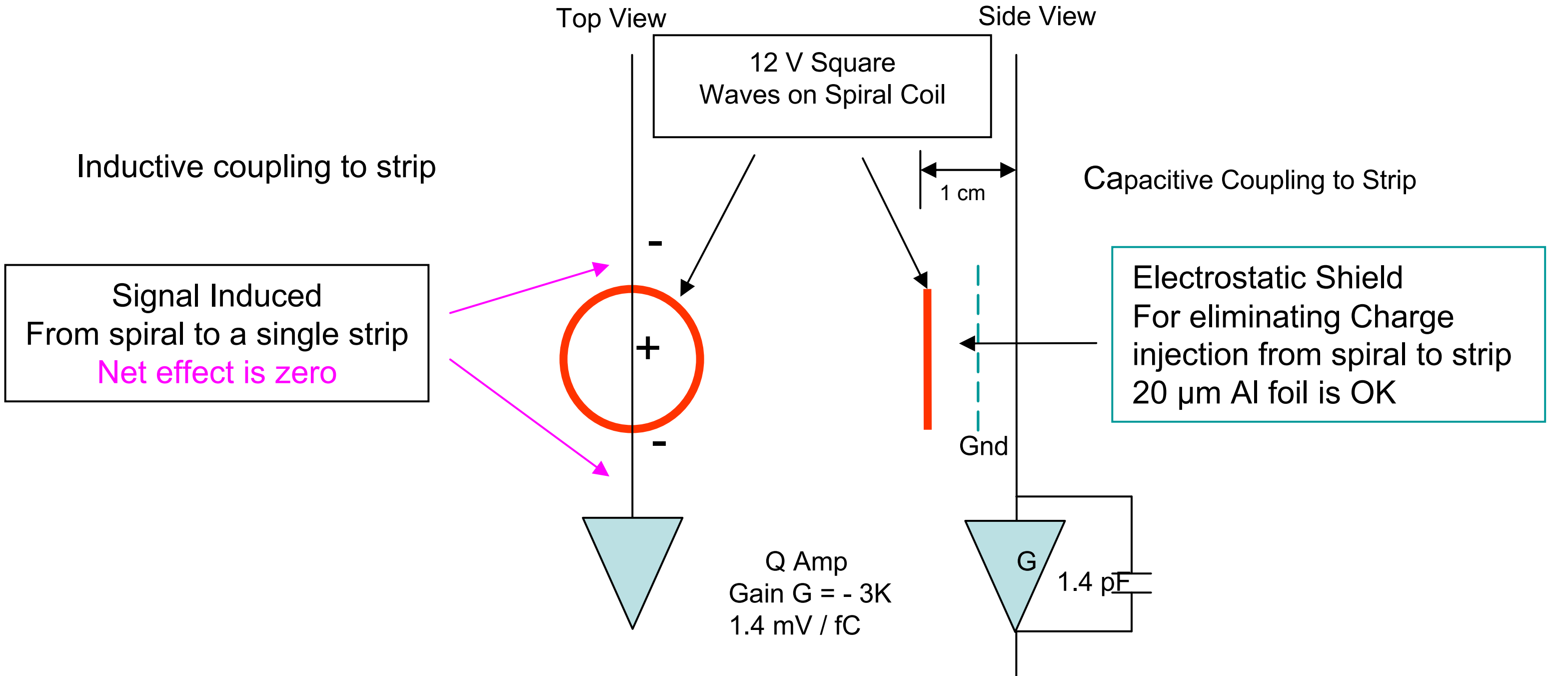
Today's air core transformers will be replaced with magnetic core transformers.

Magnetic Core *iso*Power

- **Better Efficiency & Power**
- **Low Noise Emissions (EMI)**

Magnetic Electroplating : Power output increase **0.5 to 1 Watt**

Why an Electrostatic Shield ?



Top View

Side View

12 V Square
Waves on Spiral Coil

Inductive coupling to strip

Signal Induced
From spiral to a single strip
Net effect is zero

Capacitive Coupling to Strip

Electrostatic Shield
For eliminating Charge
injection from spiral to strip
20 µm Al foil is OK

Q Amp
Gain G = - 3K
1.4 mV / fC

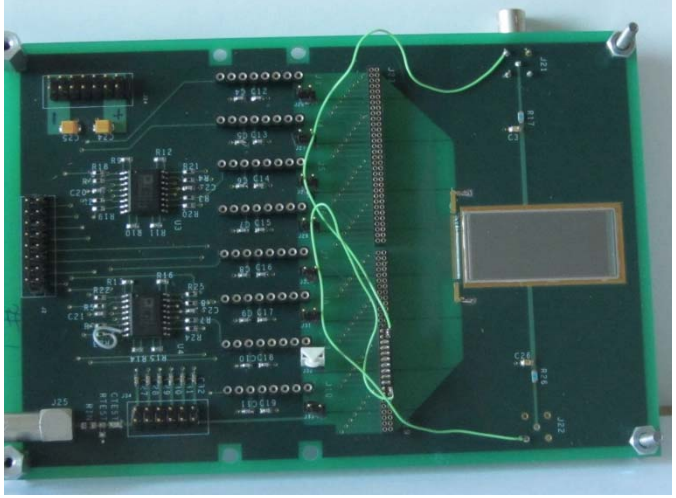
Why do we need electrostatic Shield ?

Parallel Plate Capacitance in pF = 0.225 x A x K / Distance

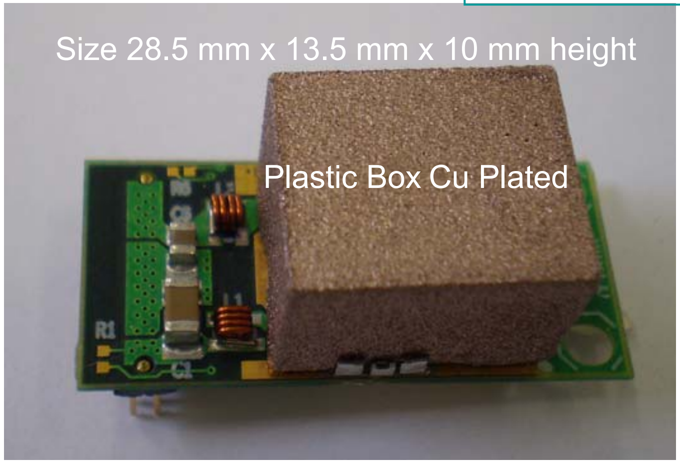
	Inches	C in femto farads
Area =	1	
Distance =	0.4	500
GLAST = .5 x 1.3	0.6	
per strip= 0.6 /48	0.0125	6.25

1 volt swing on spiral coil will inject Q= 6 femto Coulombs

Charge from one minimum ionizing particle (1 mip) = 7 femto Coulombs



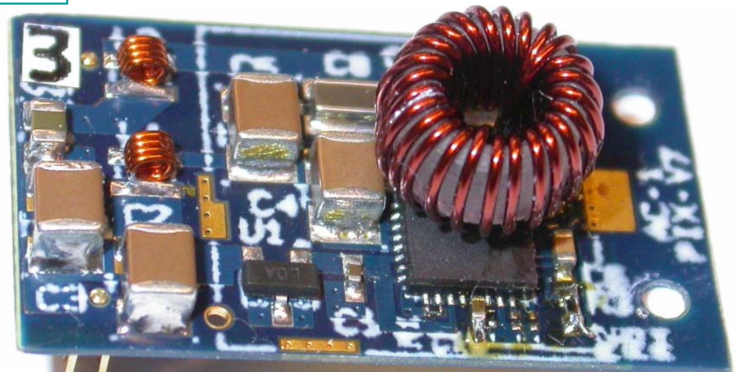
Converters with Toroid



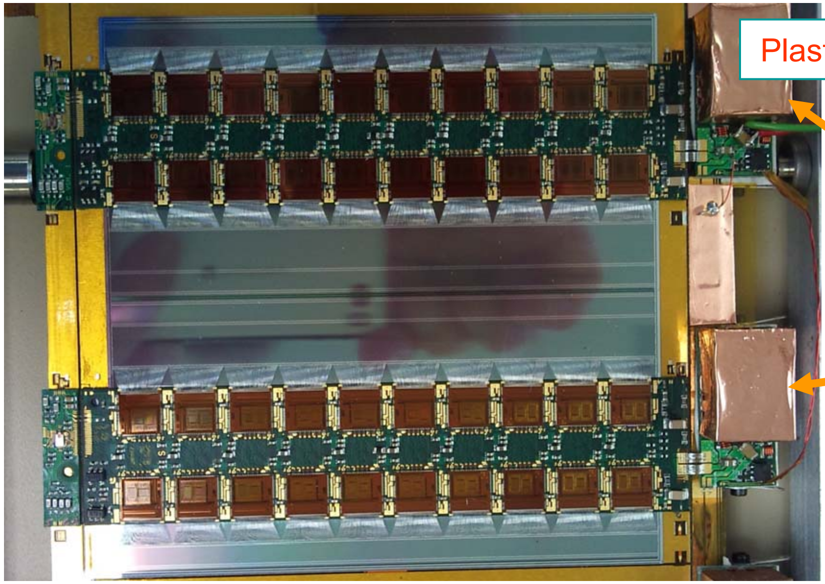
Size 28.5 mm x 13.5 mm x 10 mm height

Plastic Box Cu Plated

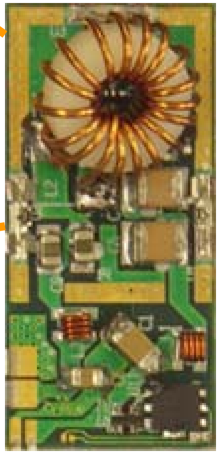
F. Faccio: Development of DCDC converters @ CERN
http://project-dcdc.web.cern.ch/project-DCDC/public/Documents/SM01C%20Datasheet.pdf



Katja Klein: DC-DC Converter Development for the CMS Pixel Upgrade
https://indico.cern.ch/conferenceDisplay.py?confId=127662



Plastic Box with Cu Tape for Shielding



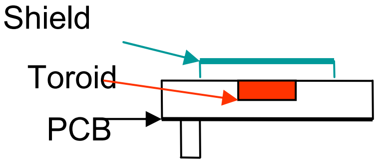
Air Core Toroid: OD = 10 mm, ID = 4 mm

thickness = 4 mm, # of turns = 20

ATLAS Stavelet Update: Upgrade- Peter Phillips

Form Factor Comparison Toroid vs 2D Inductor Spirals

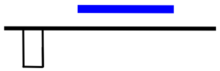
CERN (2012)



28 x 14 mm

Thickness = 9 mm

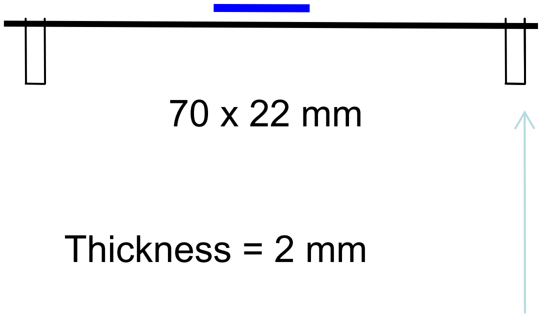
Yale Proposed (2012)



26 x 12 mm

Thickness = 1.6 mm

Yale Model 2151 (2009)



70 x 22 mm

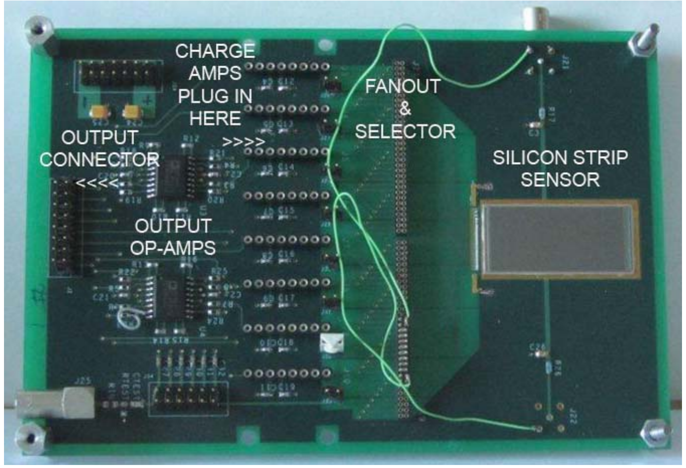
Thickness = 2 mm

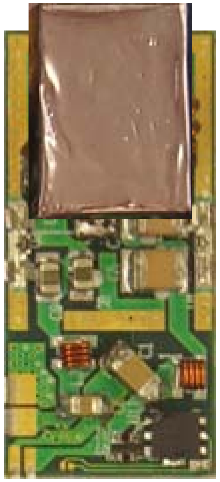
Thickness excludes power connector

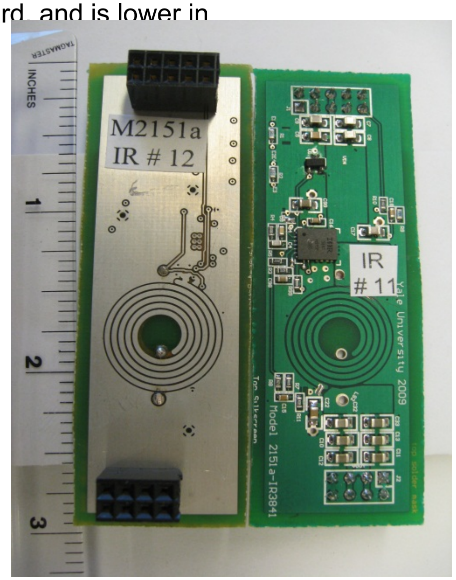
Noise Toroid with shield vs unshielded 2D Inductor

We have used a working 64 channel baby GLAST Silicon strip detector in the lab to measure noise pickup from DC-DC converters. This test board was designed by David Lynn at BNL. The detector strip pitch is 228 µm, size is 15 mm x 35 mm, with substrate thickness of 410 µm. The strips are wire bonded on the PCB and fanned out to high density connectors where 8 channels can be selected for readout by 8 charge sensitive preamps (Cremat CR110, gain 1.4 V/pC) followed by a 10x voltage gain op-amp output driver. In this setup a minimum ionizing particle signal is estimated to be about 32 mv.
The analog output signals are measured with an oscilloscope. The advantage of this analog readout instead of the digital readout used at Liverpool is that with the oscilloscope we can easily see the switching frequency noise, even when buried in other noise sources. In addition, the waveform can be Fourier analyzed to accurately measure the noise at the DC-DC switching frequency and its harmonics.

In the tests at Yale the DC-DC was placed in the same plane as the Silicon strip detector and about 1 - 2 cm from the end of the detector [fig. 7]. We have measured noise with a sample of the CERN type DC-DC with a shielded toroidal inductor [ref. 5] and a Yale designed DC-DC with an unshielded flat spiral inductor. The noise from the toroid DC-DC was about 4 mv p-p without the copper shield, and about 1 mv p-p with the shield. The Yale DC-DC also measured 1 mv p-p noise. The Yale DC-DC has about the same footprint as the toroid DC-DC excluding the power connectors, but is much thinner, barely thicker than the pc board, and is lower in mass.



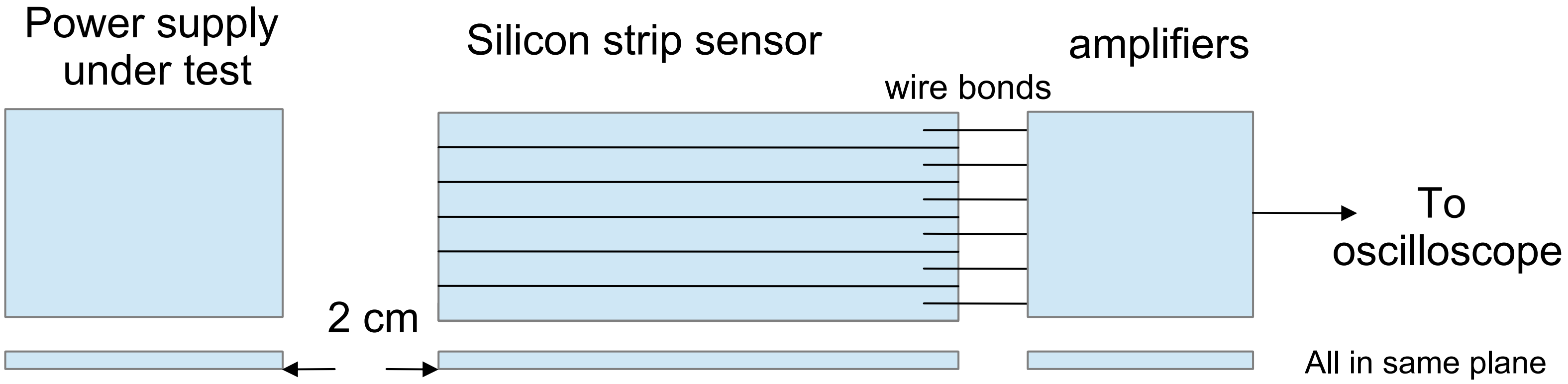




Test Board designed by David Lynn (BNL)
Built by Chris Musso (NYU)
with GLAST Silicon Strip Detector & Analog Readout

Ref: Design and properties of the GLAST flight silicon micro-strip sensors. T. Ohsugi et al., GLAST Collaboration Nucl. Inst. & Meth. A 541(2005) 29-39

Radiated Noise test with silicon sensor at Yale



Power supply under test

Silicon strip sensor

wire bonds

amplifiers

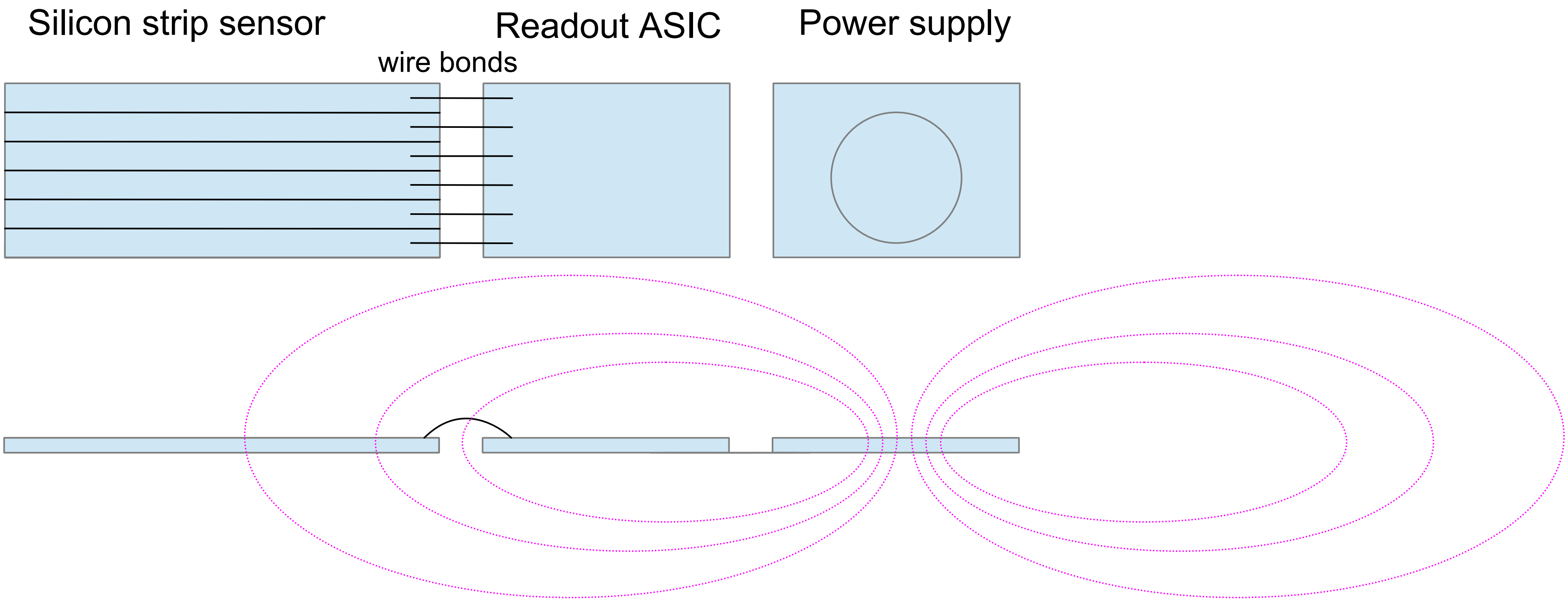
To oscilloscope

2 cm

All in same plane

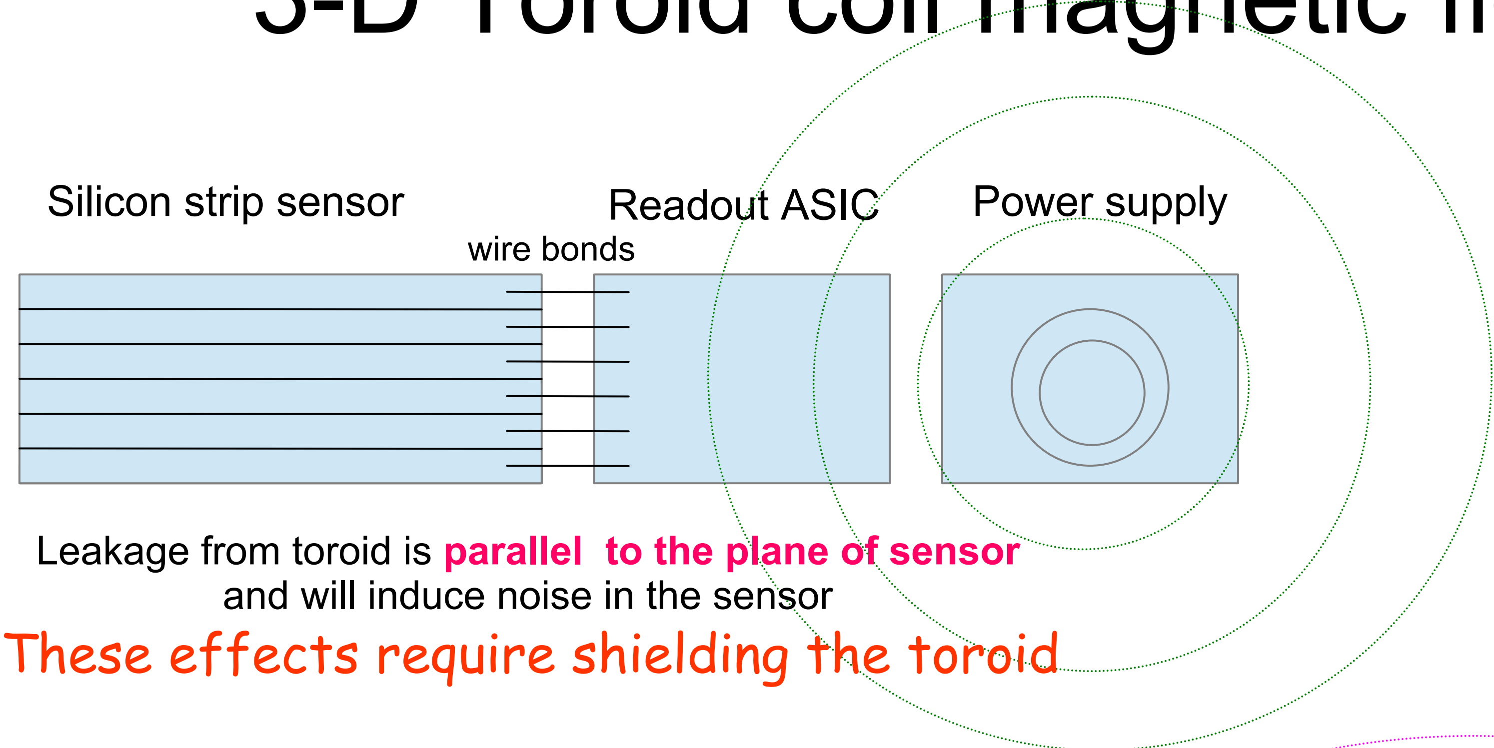
	Noise measured with oscilloscope
Power supply with unshielded 3-D toriodal inductor	4 mv peak to peak
Power supply with shielded 3-D toriodal inductor	1 mv peak to peak
Power supply with unshielded 2-D flat spiral inductor	1 mv peak to peak

2-D flat coil magnetic field



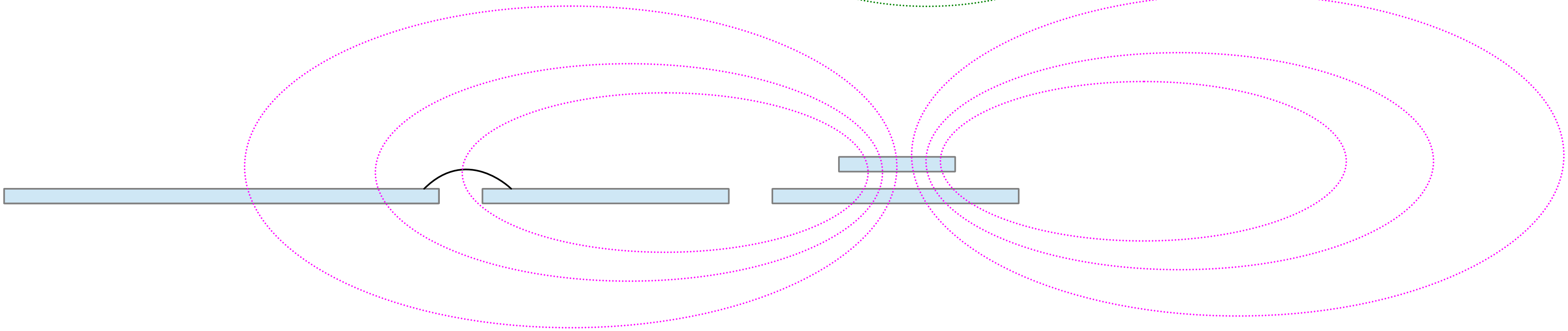
Magnetic field lines passing through sensor and wire bonds are **perpendicular to the plane** and will not induce noise in the sensor or in the wire bonds.

3-D Toroid coil magnetic field



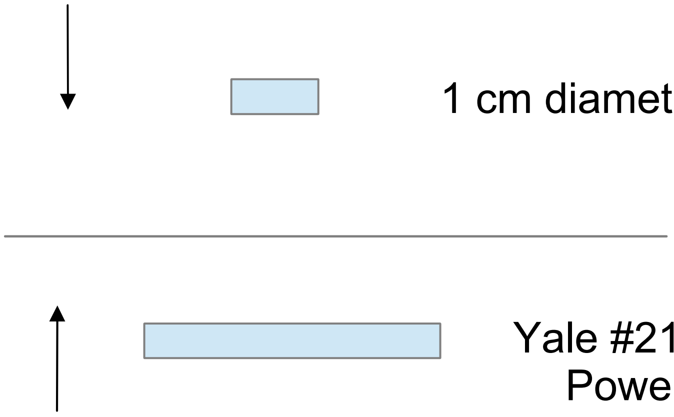
Leakage from toroid is **parallel to the plane of sensor**
and will induce noise in the sensor

These effects require shielding the toroid



The single turn effect of the toroid produces the same field as the flat spiral
But it is **not perpendicular** to the plane as it crosses the sensor
since the toroid is above the plane

Carbon Fiber shielding tests



1 cm diameter magnetic field probe (to oscilloscope)

Carbon fiber sheet under test

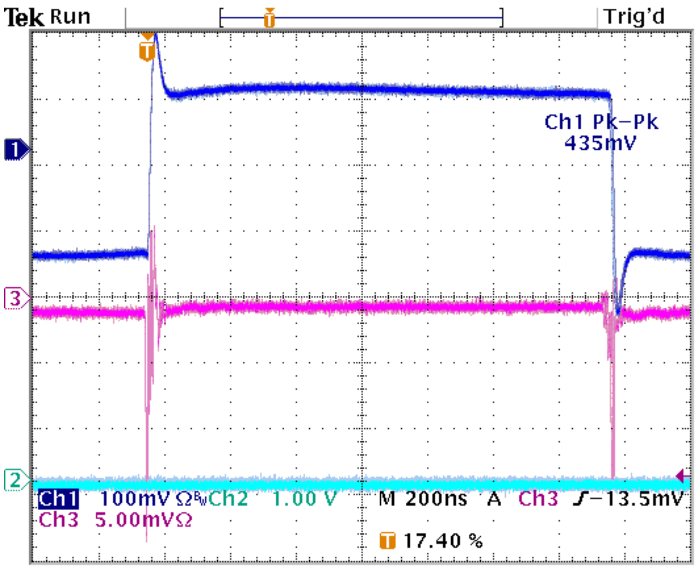
Yale #2151 flat coil
Power supply

About 1 inch

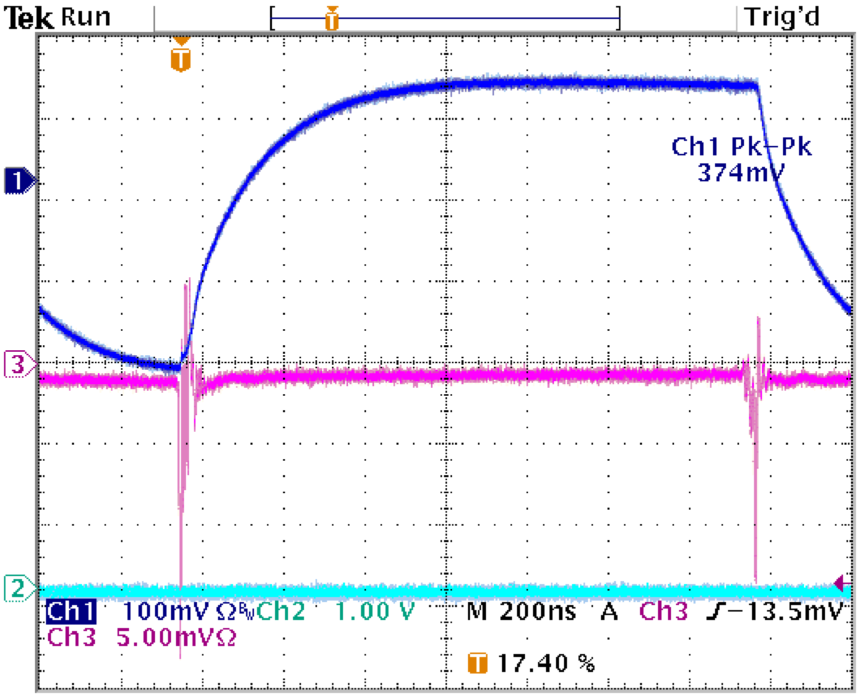
Result with no carbon fiber sheet

Switching frequency less than 500 Khz

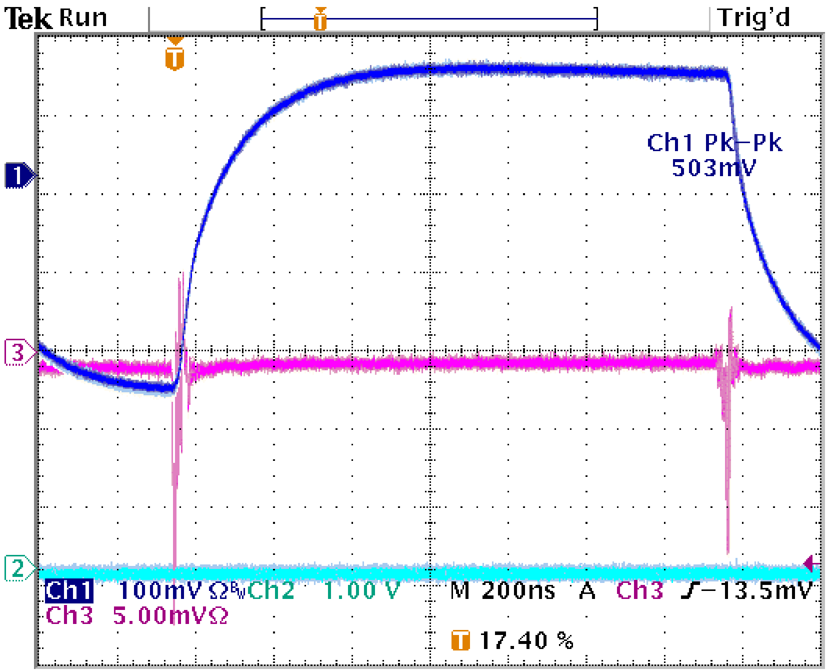
Blue trace is probe
Red trace is scope trigger



Carbon Fiber shielding tests



6 layer carbon fiber sample from Fermilab
Rise time about 200 nS



3 layer carbon fiber sample from LBL
Rise time about 100 nS

Al foil results in complete shielding (not shown, very dull picture).
Both Carbon fiber sheets shield only high frequencies components.

Can be used as an EMI Shield ?

Summary

- Reduce Power Losses to deliver more Power
- Look out for Commercial Converters with Thin Gate Oxide
- GaN for High frequency & Efficiency. Future with integrated GaN Driver
- 2D inductors are superior
- Powering detectors : Standard ~400 DC > Isolated 48 V into detector
- Carbon Fiber for shielding is promising

Working on Physics Power Supply Is not considered a Cool thing to do!

Thanks for your Attention

Top of the World is Cool but lonely !
Let us keep it cool with highly efficient PS

More Details: http://shaktipower.sites.yale.edu Click on Recent seminars/

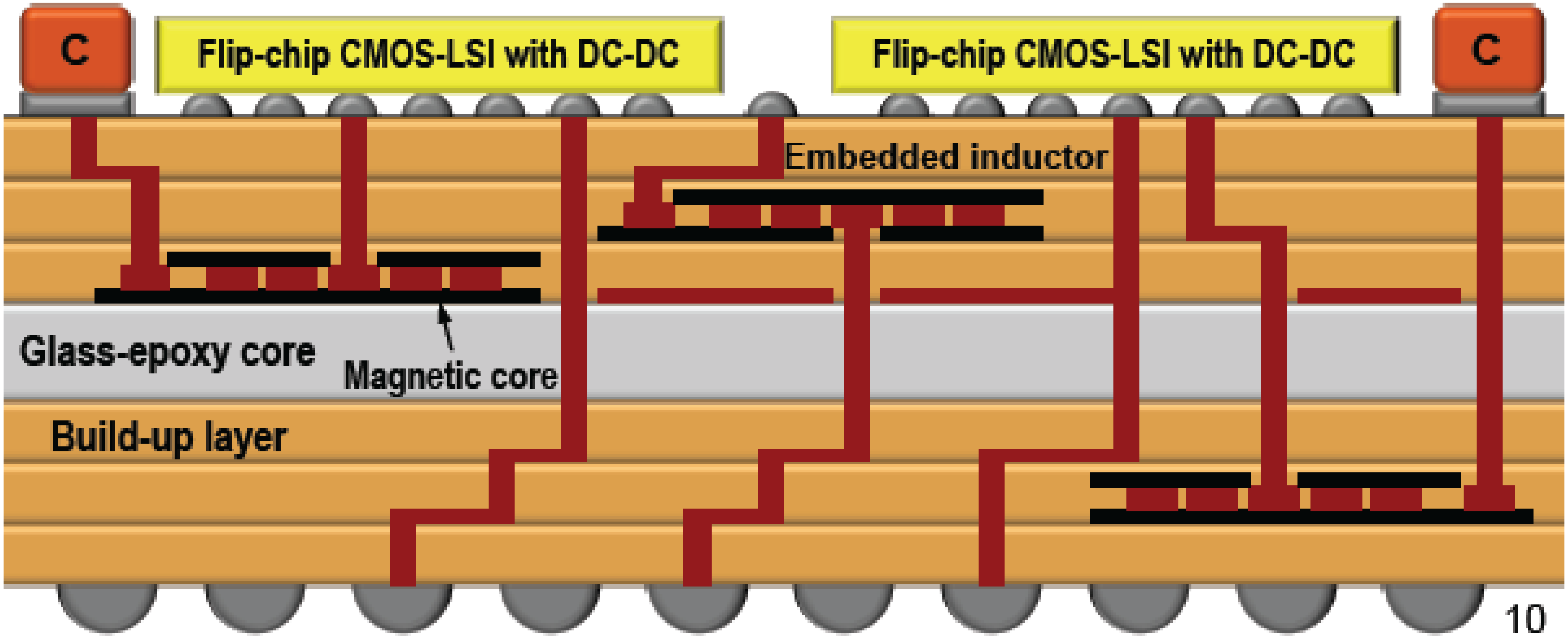
Back up Slides

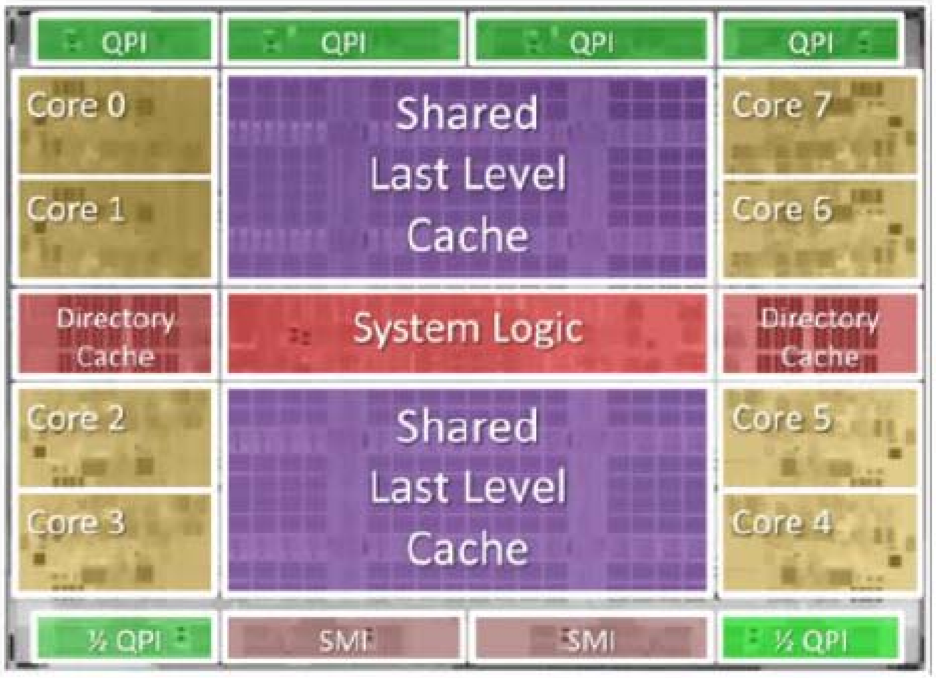
□ Objective ; Package-level power grid (PLPG)

Power magnetics embedded in package

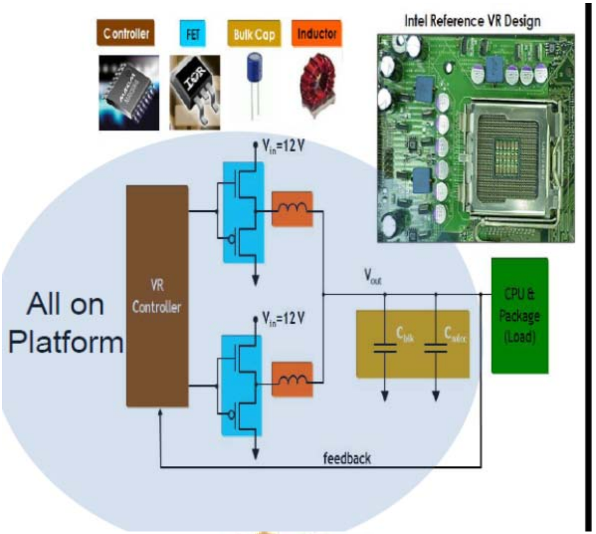
Embedded power inductor in package

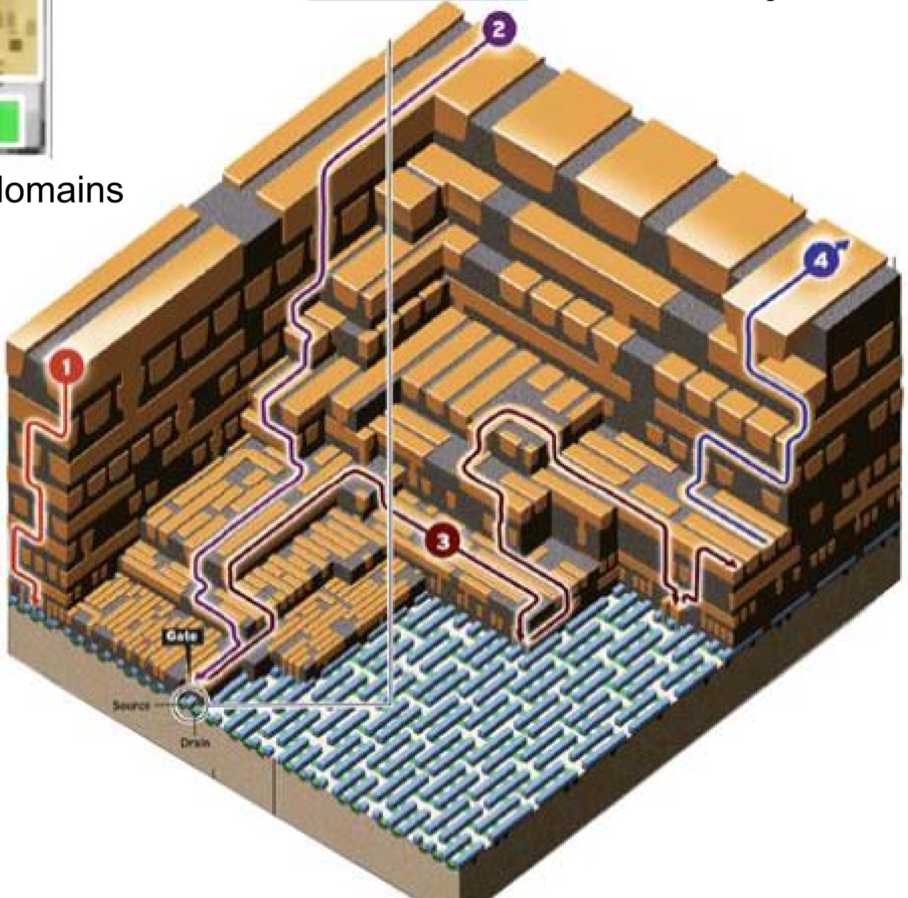
Low cost, Low profile ; tens micron height, Small near-EMI ; magnetic core





8 Core Intel PSN IPF Microprocessor with 10+ Voltage domains



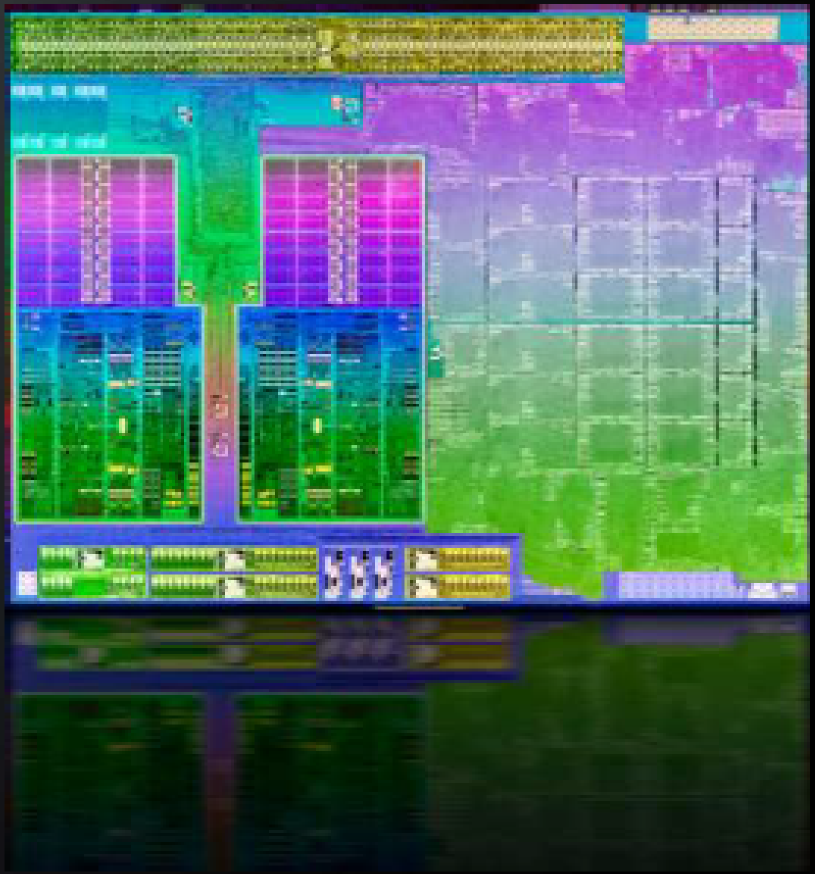


Creation of test benches & tools to project and understand impact of degraded power delivery in **pre-Si**

Era of Intelligent Power Delivery
Mandy Pant & Bill Bowhill
PWRSoC 2012

HIGH PERFORMANCE APU "TRINITY"

- "Piledriver" Cores
  - Quad CPU Core with total of 4MB L2
- 2nd-Gen AMD Radeon™ with DirectX® 11 support
  - 384 Radeon™ Cores 2.0
- HD Media Accelerator
  - Accelerates and improves HD playback
  - Accelerates media conversion
- Enhanced Display Support
  - 3 Simultaneous DisplayPort 1.2 or HDMI/DVI links
  - Up to 4 display heads with display multi-streaming



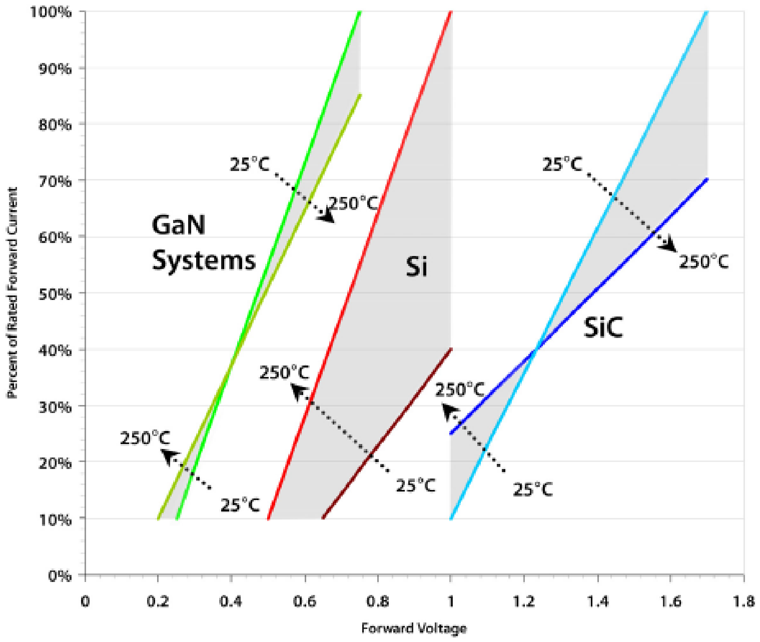
	Nominal Voltage (V)	TDC (A)	Max Load Step (A)
VDD	Variable	50	42
VDDNB	Variable	29	37
VDDIO	1.5	3.2	-
VDDR	1.2	3.5	-
VDDP	1.2	4	-
VDDA	2.5	0.75	-

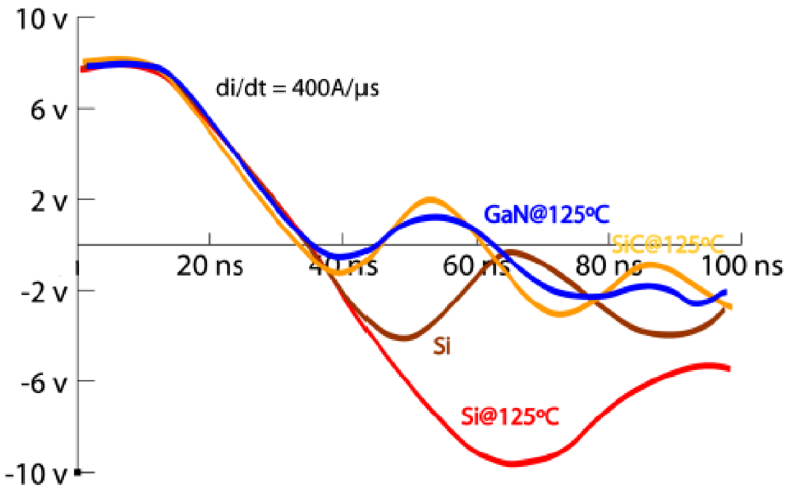
← 6 voltage rails

Line → Power factor correction PFC → Switched Mode Power Supply SMPS → Point of Load conversion PoL →

87% | 85% | 89%

Typical conversion efficiency today





- Ultra Low Voltage Drop
- Temperature Stable

- Zero charge storage
- Temperature Stable

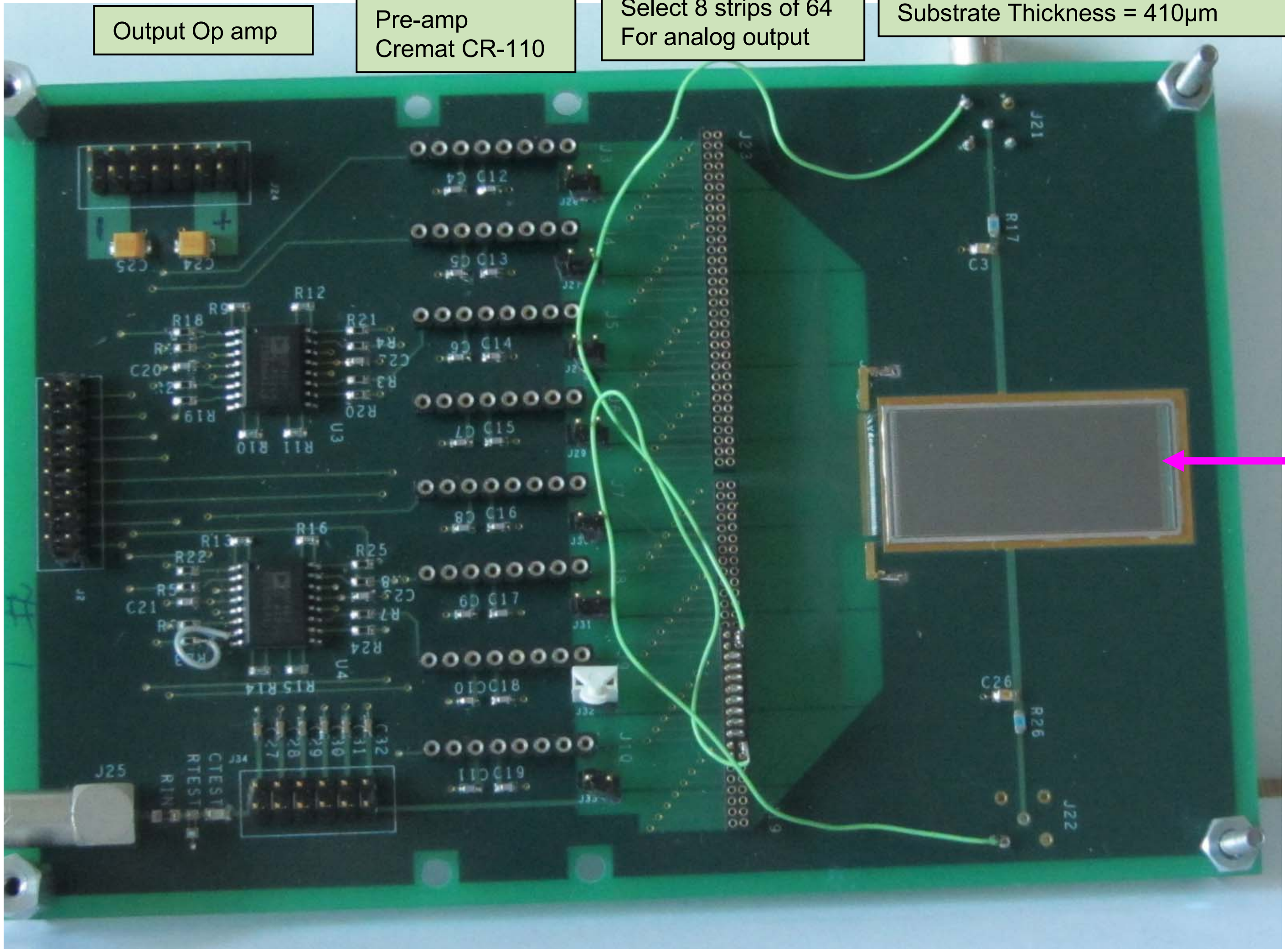
Test Silicon Strip Detector

Output Op amp

Charge
Sensitive
Pre-amp
Cremat CR-110

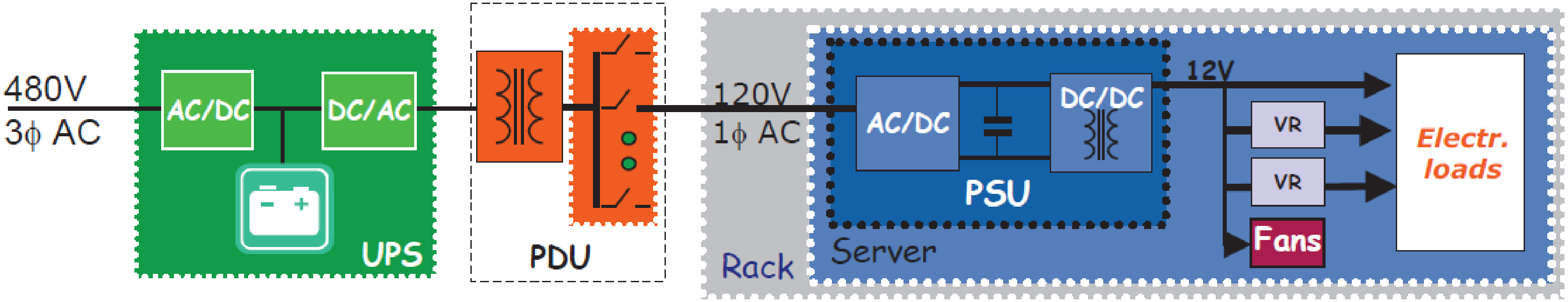
Switch Matrix
Select 8 strips of 64
For analog output

GLAST Sensor [Nucl & Instr Meth A 541 (2005) 29-39]
64 strips- 228 µm pitch
Size 15mm x 35mm
Substrate Thickness = 410µm

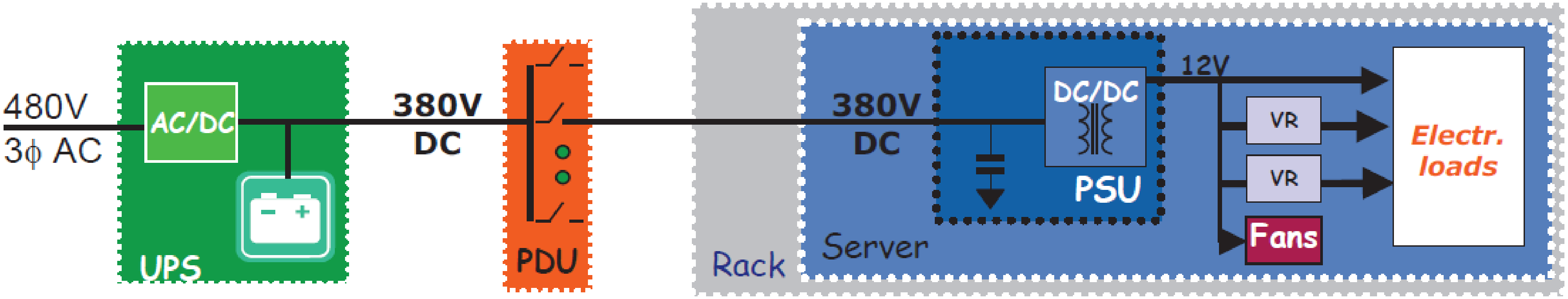


64 Parallel Al Strips
Length = 35 mm
Width = 56µm
Pitch = 228 µm

Efficiency Improvement with DC 380 Volts

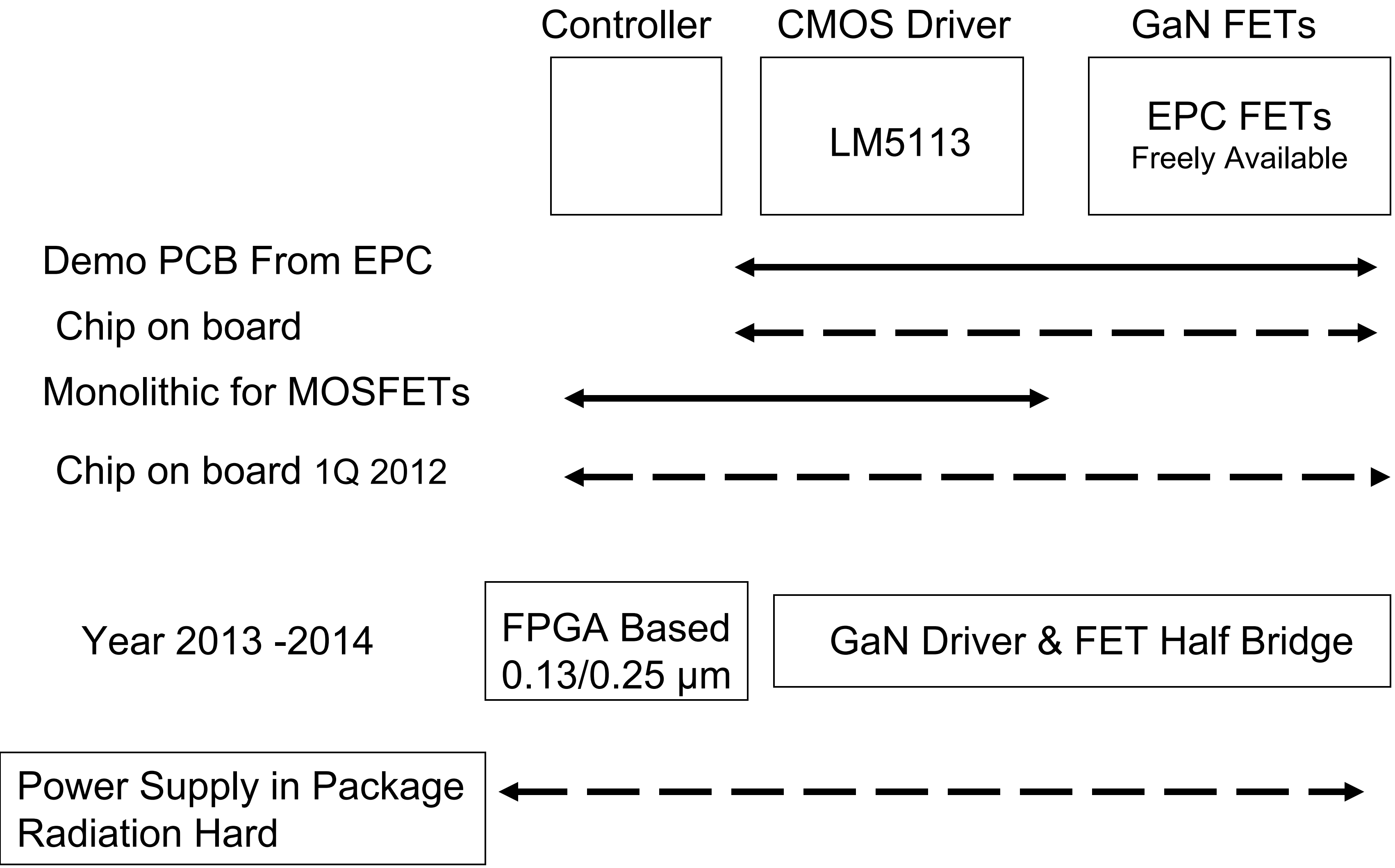


90% x **97%** x **90%** x **86%** = **67%**



97% x **99%** x **94%** x **86%** = **76%**

Market Trend



Controller

CMOS Driver

GaN FETs

LM5113

EPC FETs
Freely Available

Demo PCB From EPC

Chip on board

Monolithic for MOSFETs

Chip on board 1Q 2012

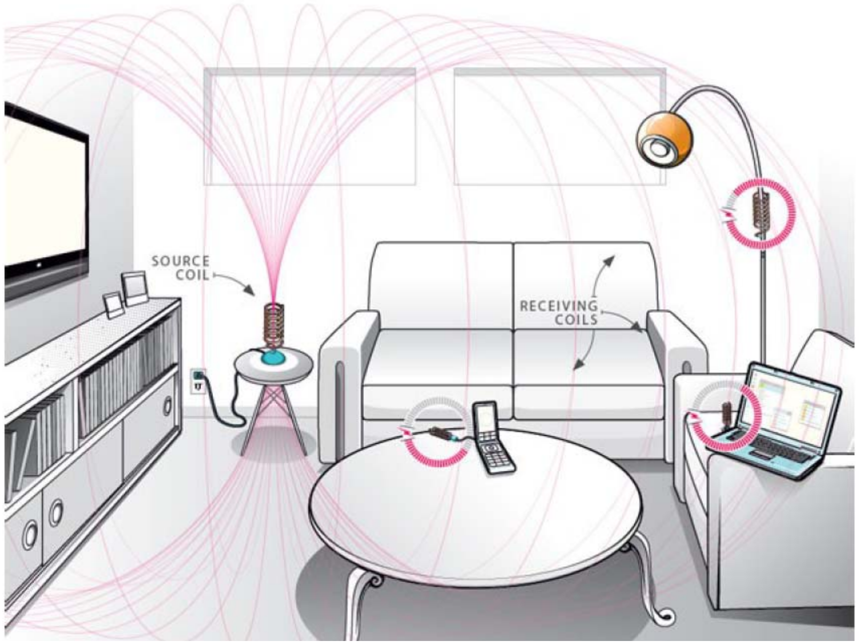
Year 2013 -2014

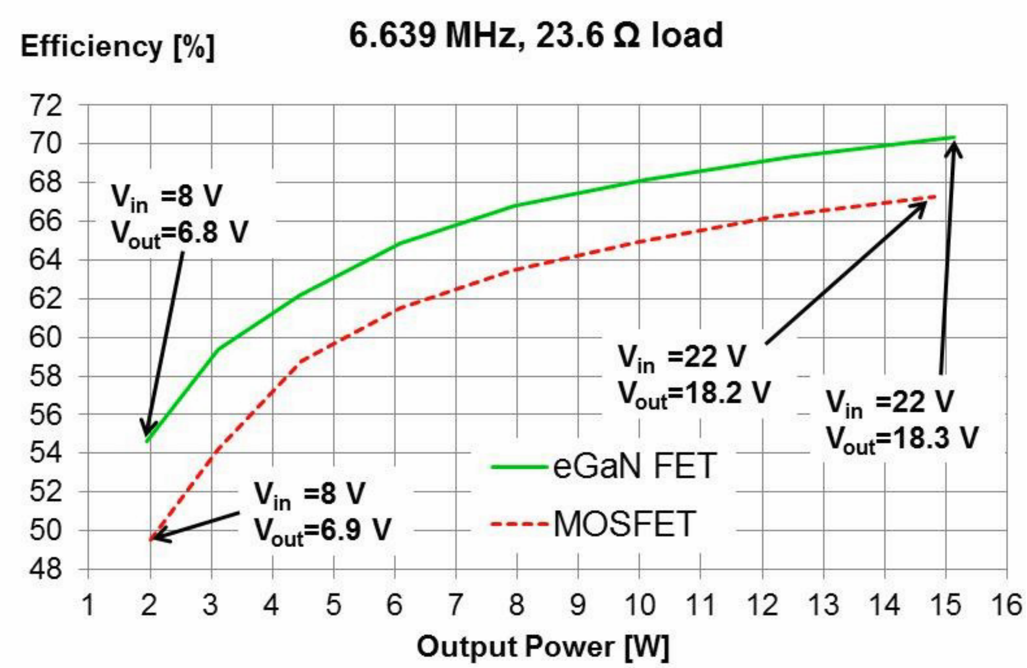
FPGA Based
0.13/0.25 µm

GaN Driver & FET Half Bridge

Power Supply in Package
Radiation Hard

Wireless Power





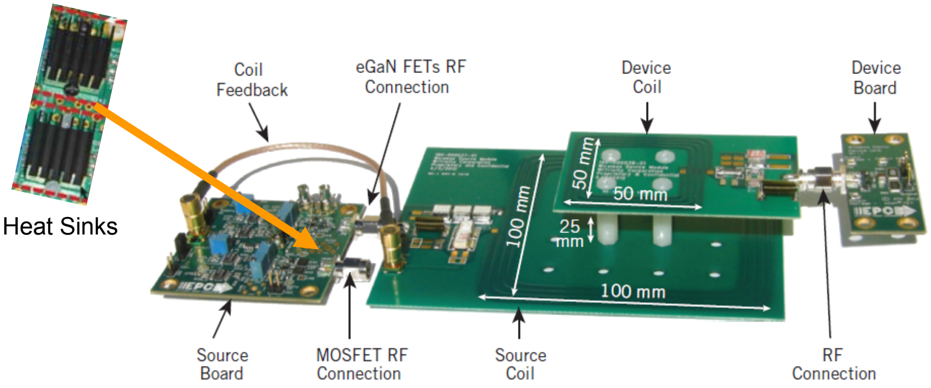
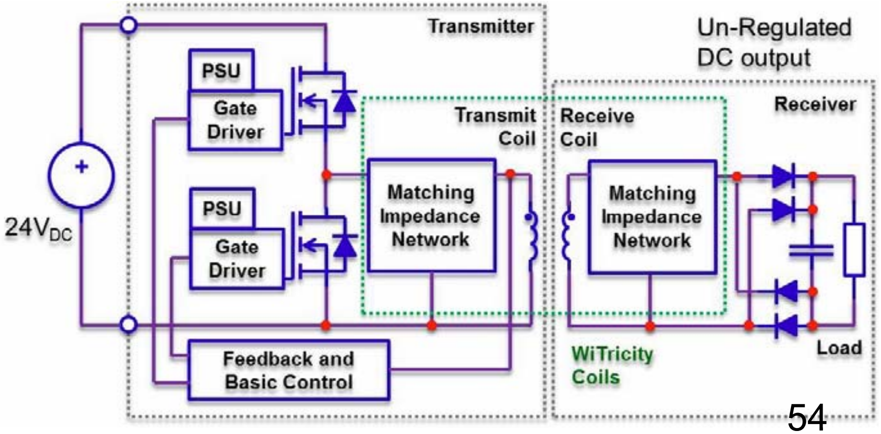


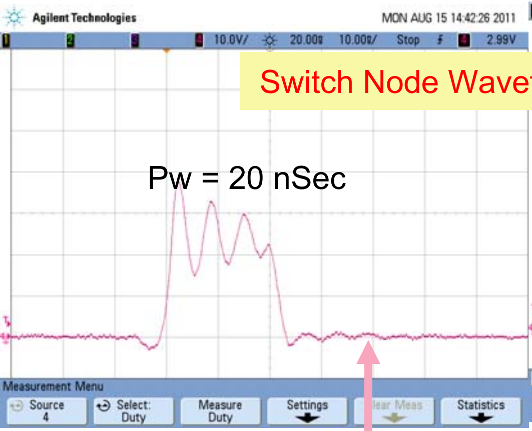
Fig. 3. Wireless energy system setup, with 50Ω SMA connectors used to interconnect each board. Boards were co-developed by EPC and WiTricity.



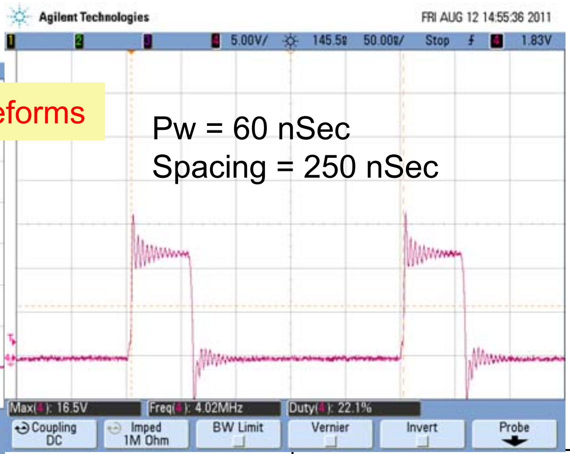
Ref: WiTricity & EPC

eGaN with discrete & LM5113 Driver

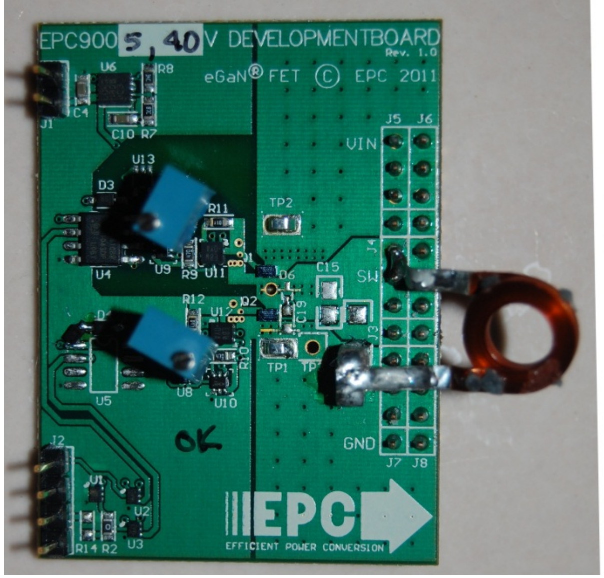
Switch Node Waveforms



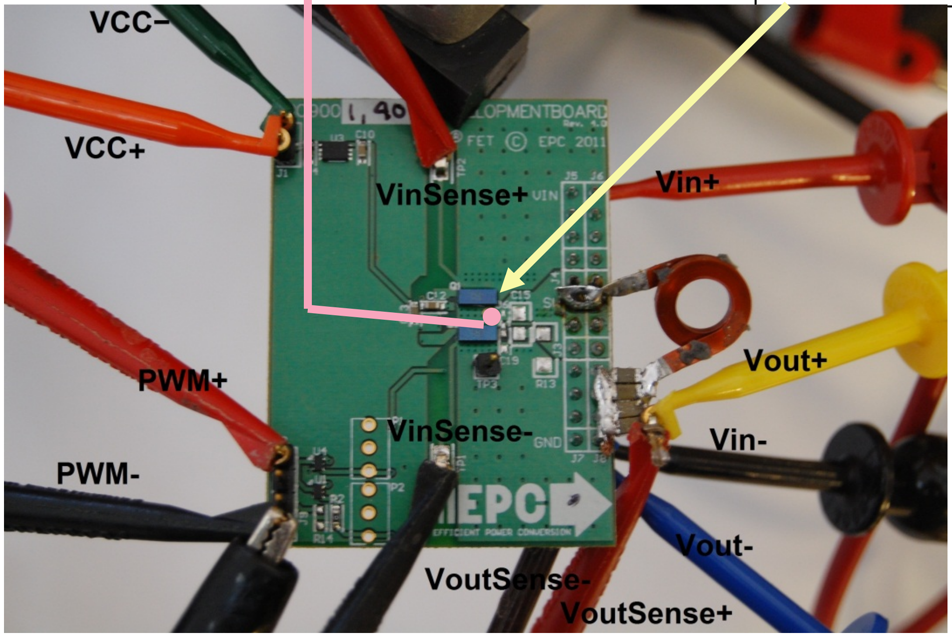
Pw = 20 nSec

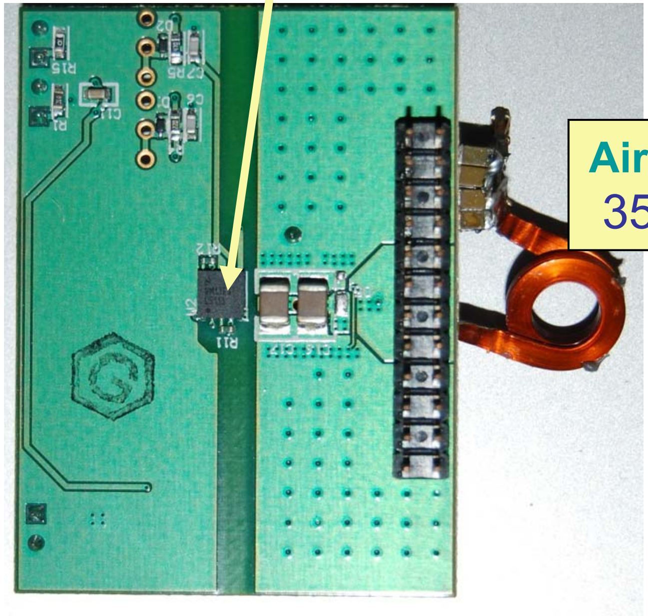


Pw = 60 nSec
Spacing = 250 nSec



National eGaN Driver LM5113 on Bottom
eGaN on Top side





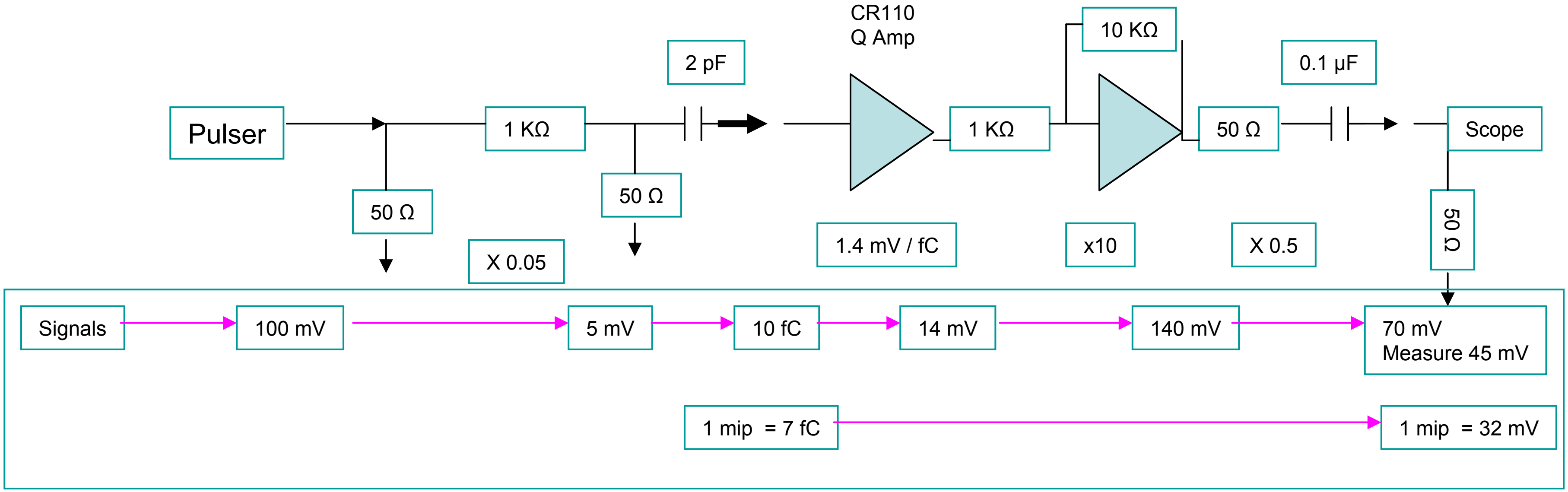
Air Core Coil
355 nH

Aircoil *EPCOS-B82559A0392A013* 3.9 µH / 355 nH without Ferrite. 5 mΩ

Three Foundries with Thin Oxide LDMOS Process Non IB

Company	Device	Process	Foundry	Oxide	Time in	Dose before	Observation
		Name/ Number	Name	Thickness	Seconds	Damage seen	Damage Mode
			Country	nm			
IHP	ASIC custom	SG25V GOD	IHP, Germany	5		53 Mrad	slight damage
XySemi	FET 2 amps	HVMOS20080720	China	7		52 Mrad	minimal damage
XySemi	XP2201	HVMOS20080720	China	7			In Development
XySemi	XPxxxx	HVMOS20080720	China	7			In Development Synch Buck
XySemi	XP5062		China	12.3	800	44 krad	loss of V_{out} regulation
TI	TPS54620	LBC5 0.35 µm		20	420	23 krad	abrupt failure
IR	IR3841			9 & 25	230	13 Krads	loss of Vout regulation
Enpirion	EN5365	CMOS 0.25 µm	Dongbu HiTek, Korea	5	11,500	85 krad	Increasing Input Current,
Enpirion	EN5382	CMOS 0.25 µm	Dongbu HiTek, Korea	5	2000	111 Krads	loss of V_{out} regulation
Enpirion	EN5360 #2	SG25V (IHP)	IHP, Germany	5	22 Days	100 Mrads	Minimal Damage
Enpirion	EN5360 #3	SG25V (IHP)	IHP, Germany	5	10 Days	48 Mrads	Minimal Damage

Signal Chain



Pulser

50 Ω

1 KΩ

X 0.05

50 Ω

2 pF

CR110
Q Amp

1.4 mV / fC

1 KΩ

10 KΩ

x10

50 Ω

X 0.5

0.1 μF

Scope

50 Ω

Signals → 100 mV → 5 mV → 10 fC → 14 mV → 140 mV → 70 mV
Measure 45 mV

1 mip = 7 fC → 1 mip = 32 mV