DC-DC Converters Using GaN for Collider Physics Detectors

Satish K Dhawan
Yale University

http://shaktipower.sites.yale.edu/
satish.dhawan@yale.edu

ECPE SiC & GaN User Forum: Potential of Wide Bandgap Semiconductors in Power Electronic Applications
ECPE: European Center for Power Electronics e.V.

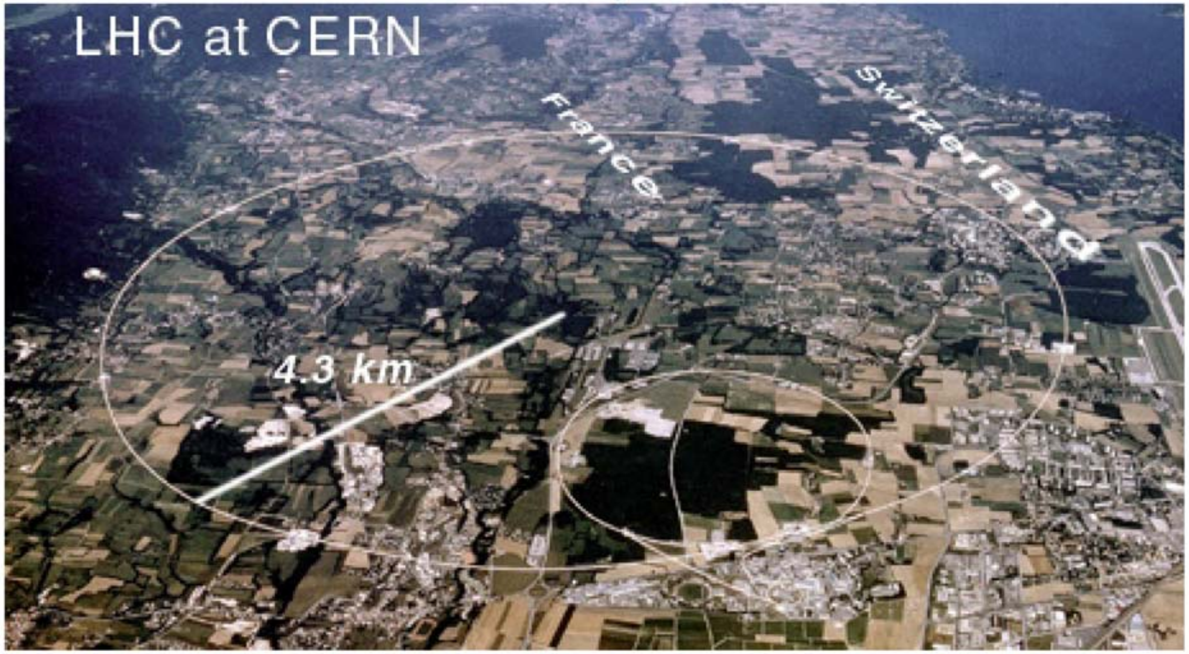
1 - 2 September 201, Birmingham, U.K.

Topics Agenda

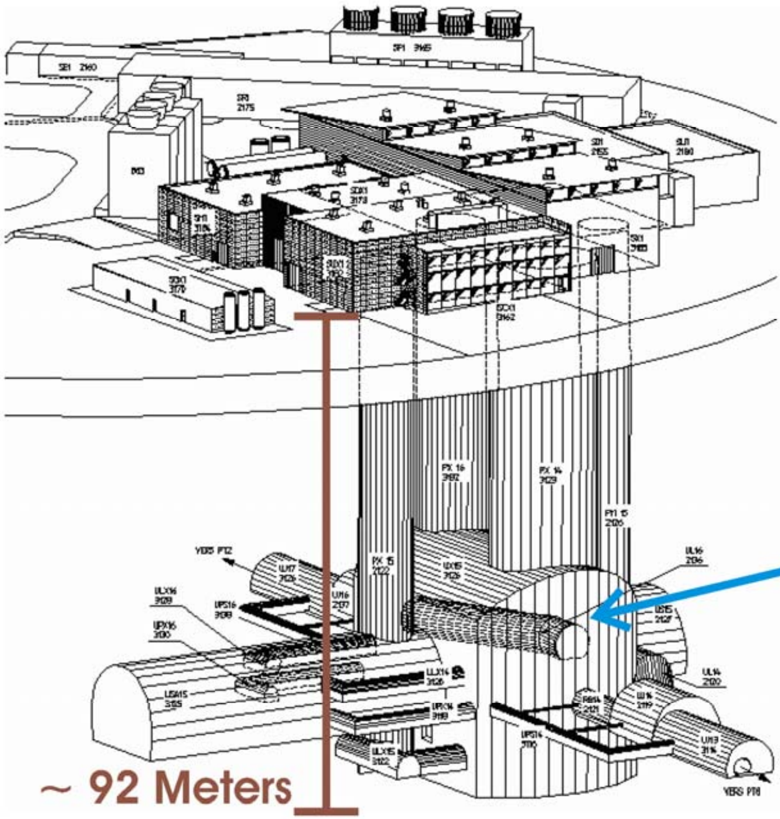
- ❖ CERN: Current Detectors & Powering
  CMS ECAL detector
- ❖ Environment: Magnetic field & Radiation
- ❖ Limits of Silicon
- ❖ Why GaN ?
- ❖ GaN Tests
- ❖ Linear Collider – Low radiation but needs lower mass powering
- ❖ Market Trends
- ❖ Summary Keep Environment cool

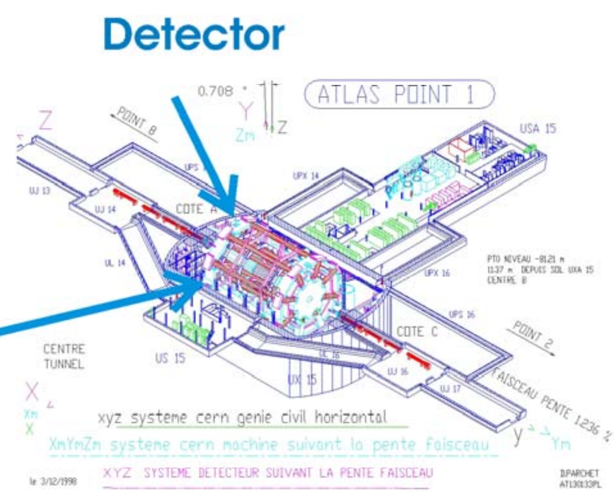
Large Hadron Collider

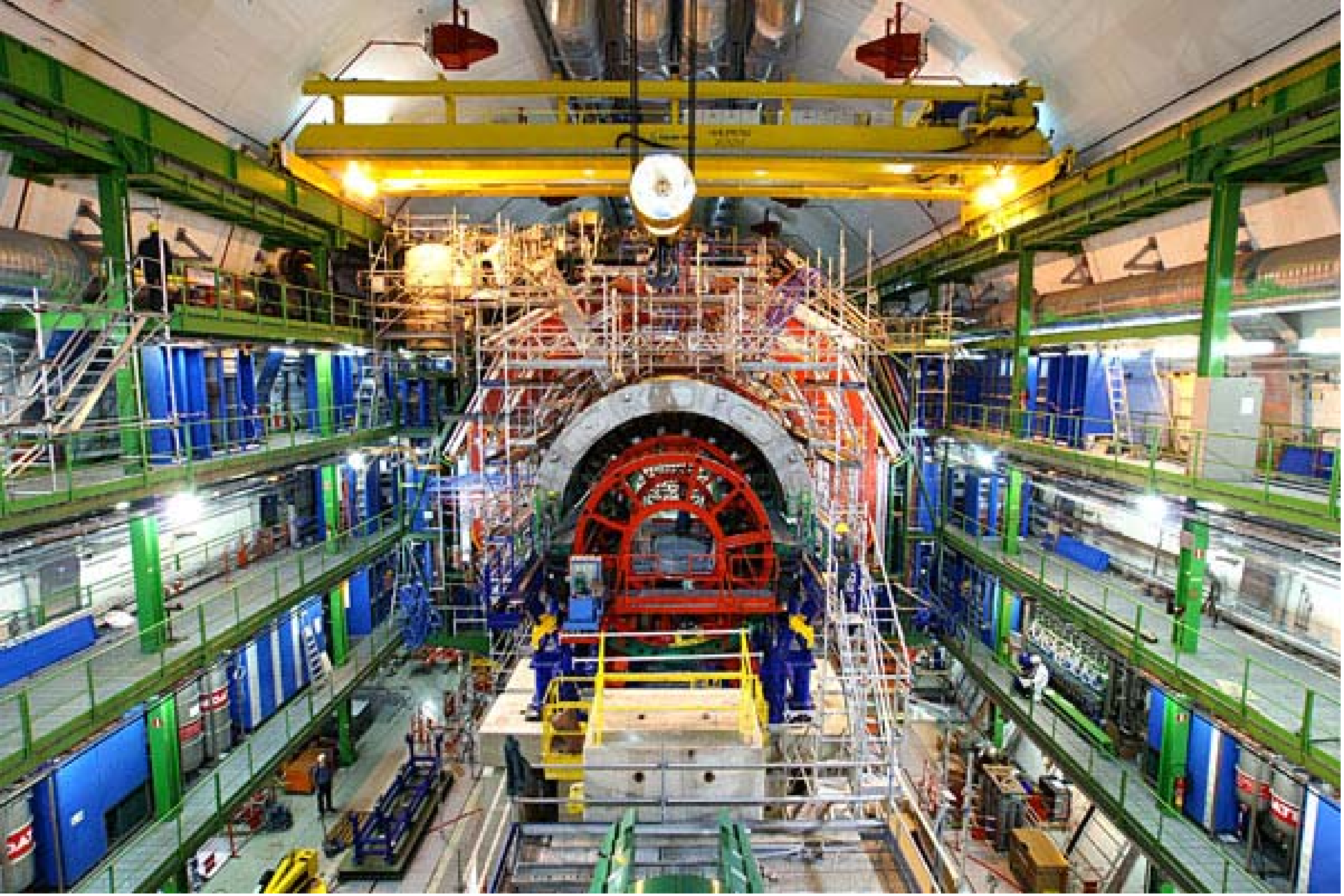
- 16 Mile proton-proton collider
- Tunnel as deep as 100 meters underground
- Four main experiments: *Atlas*, CMS, LHCB, and Alice



Atlas Detector is underground

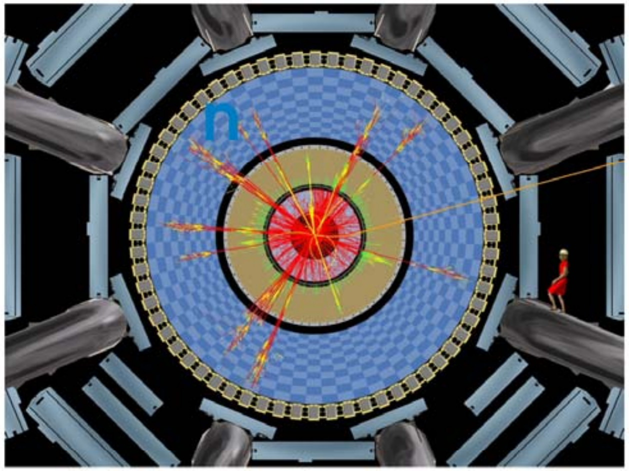


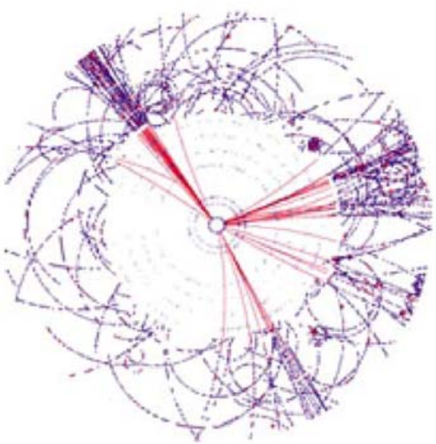


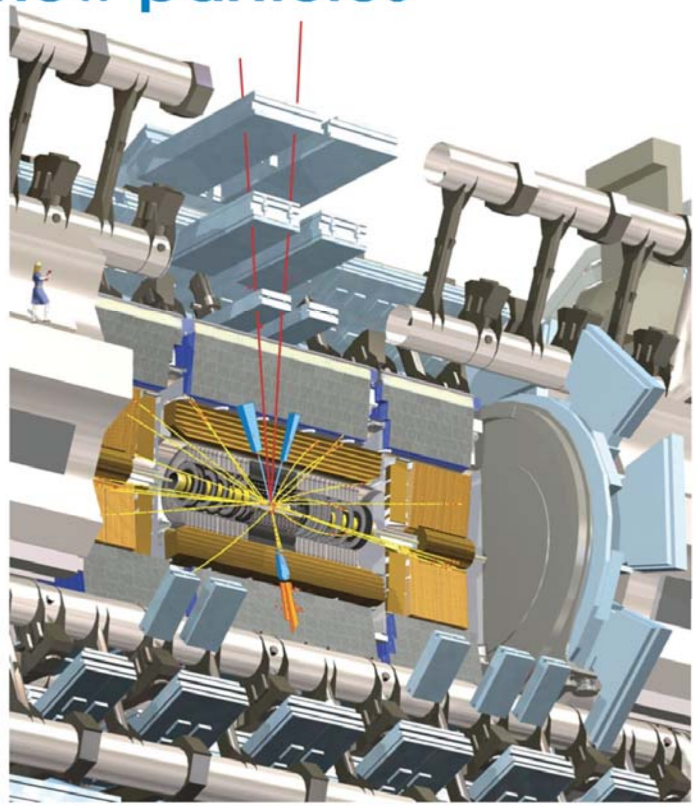



22
13
31
26
16

Various views of a proton-proton collision creating many new particles







CMS Outreach

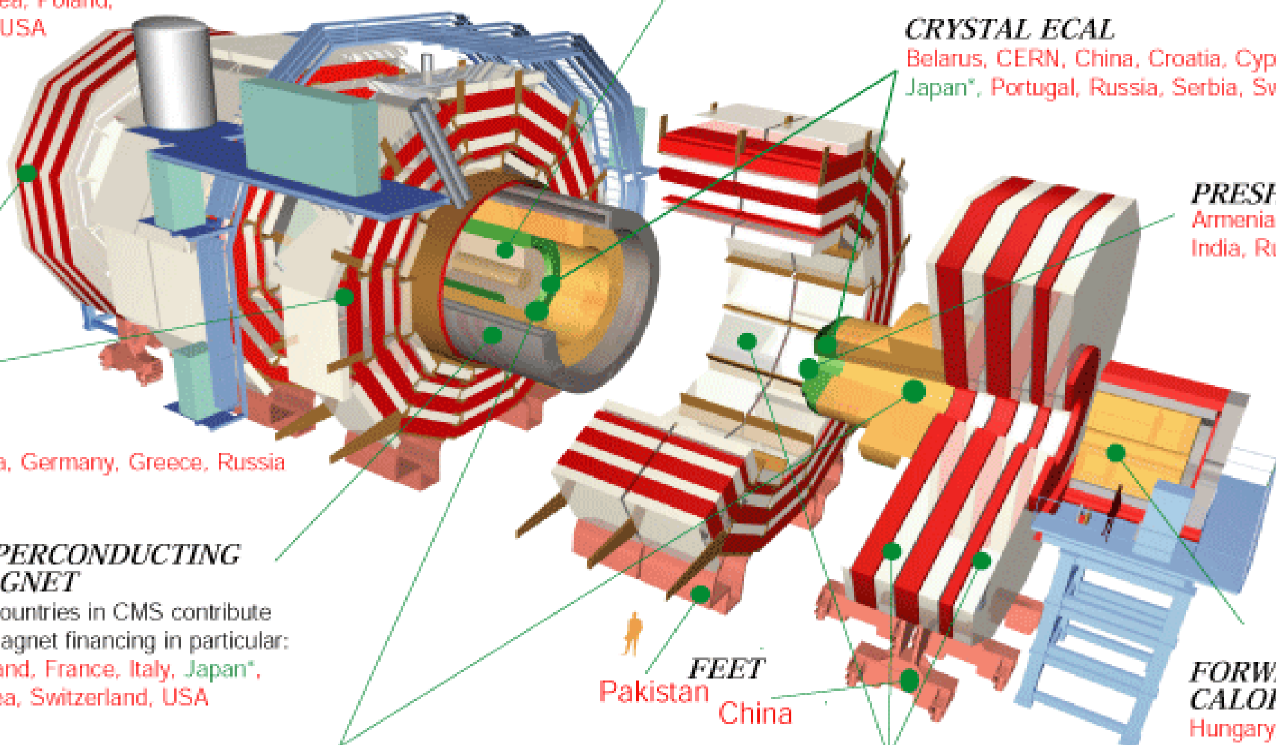
37 Countries, 155 Institutes, 2000 scientists (including about 400 students)   October 2006

TRIGGER, DATA ACQUISITION & OFFLINE COMPUTING
Austria, Brazil, CERN, Finland, France, Greece, Hungary, Ireland, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

TRACKER
Austria, Belgium, CERN, Finland, France, Germany, Italy, Japan*, Mexico, New Zealand, Switzerland, UK, USA

CRYSTAL ECAL
Belarus, CERN, China, Croatia, Cyprus, France, Italy, Japan*, Portugal, Russia, Serbia, Switzerland, UK, USA

PRESHOWER
Armenia, CERN, Greece, India, Russia, Taiwan



RETURN YOKE
Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA

SUPERCONDUCTING MAGNET
All countries in CMS contribute to Magnet financing in particular:
Finland, France, Italy, Japan*, Korea, Switzerland, USA

FEET
Pakistan
China

FORWARD CALORIMETER
Hungary, Iran, Russia, Turkey, USA

HCAL
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Georgia, Russia, Ukraine, Uzbekistan
HO: India

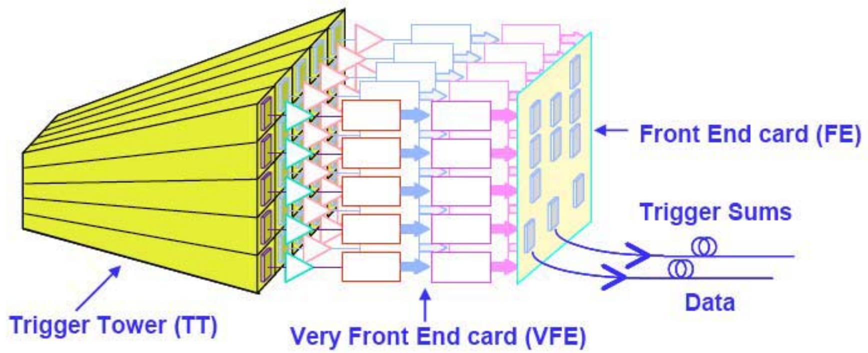
MUON CHAMBERS
Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China, Colombia, Korea, Pakistan, Russia, USA

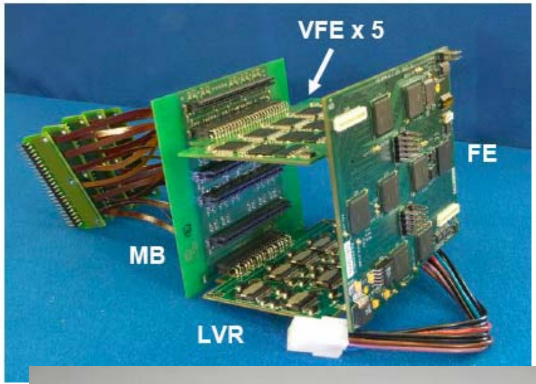
* Only through industrial contracts

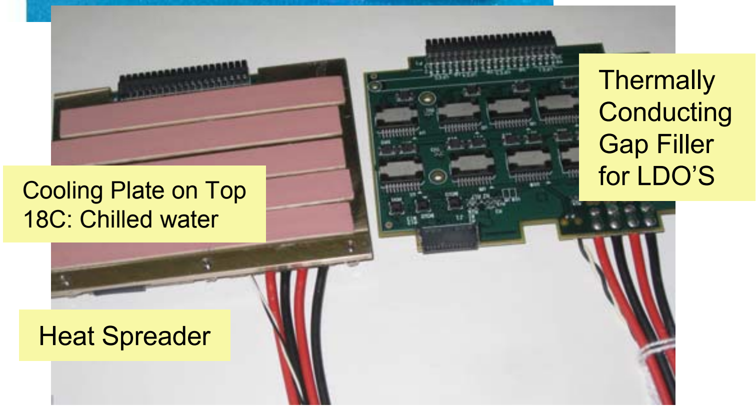
Total weight	:	**12500 T**
Overall diameter	:	**15.0 m**
Overall length	:	**21.5 m**
Magnetic field	:	**4 Tesla**

20th Century State of Power Distribution – *LHC Detectors*

ECAL readout system was:
- designed in ~2000
- produced in 2001-2007
- commissioned in 2006-2007

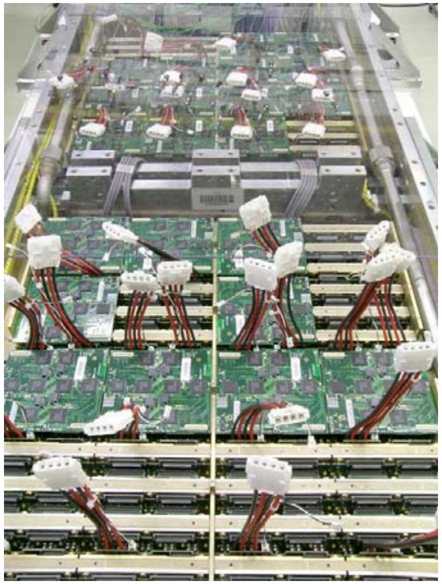


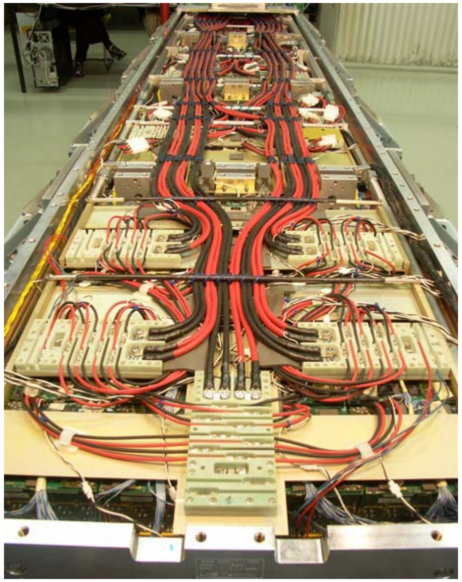


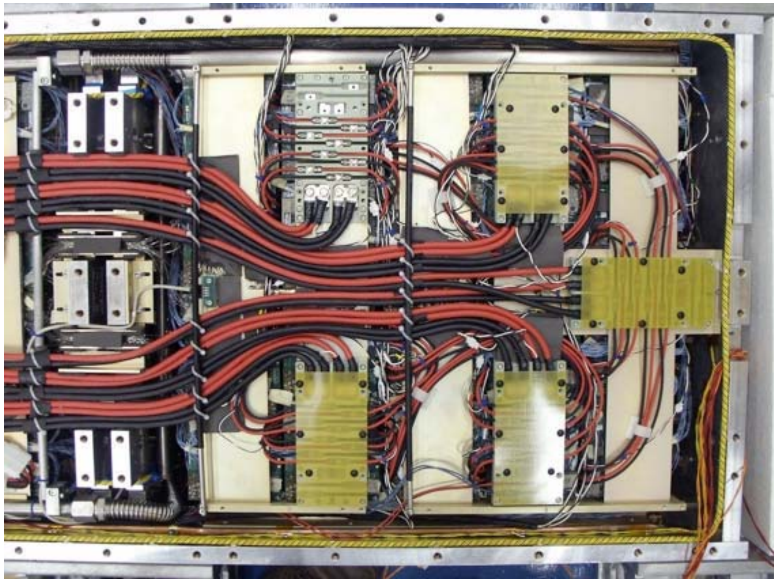


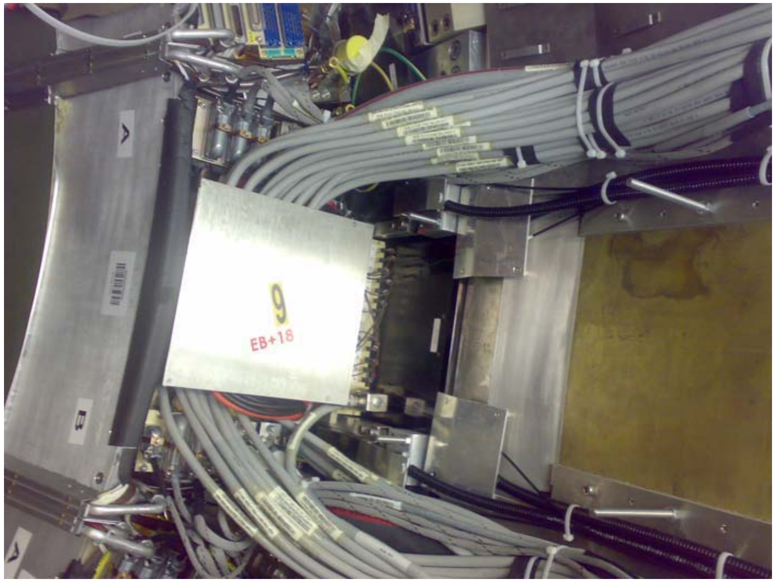
FE produces distributed heat low W/sq cm
Power Boards High W/sq cm. use heat spreaders

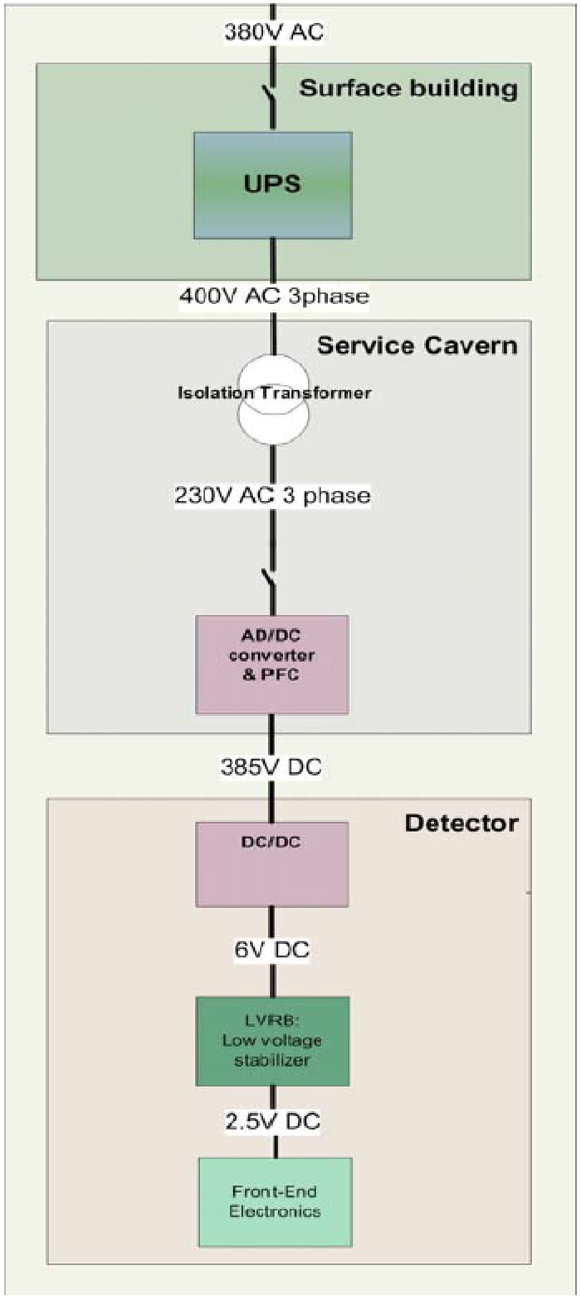
CMS ECAL Super modules



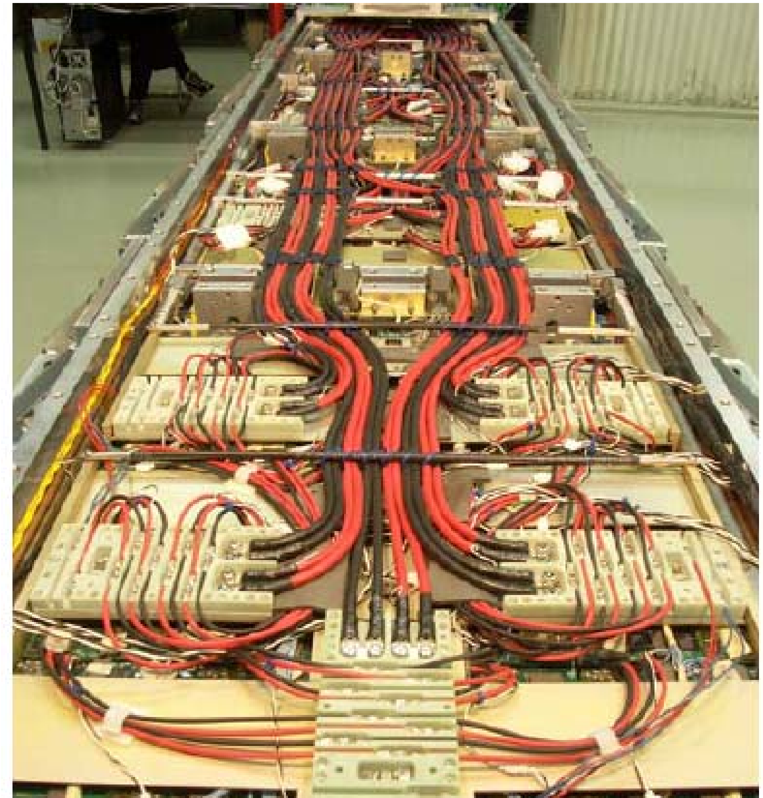


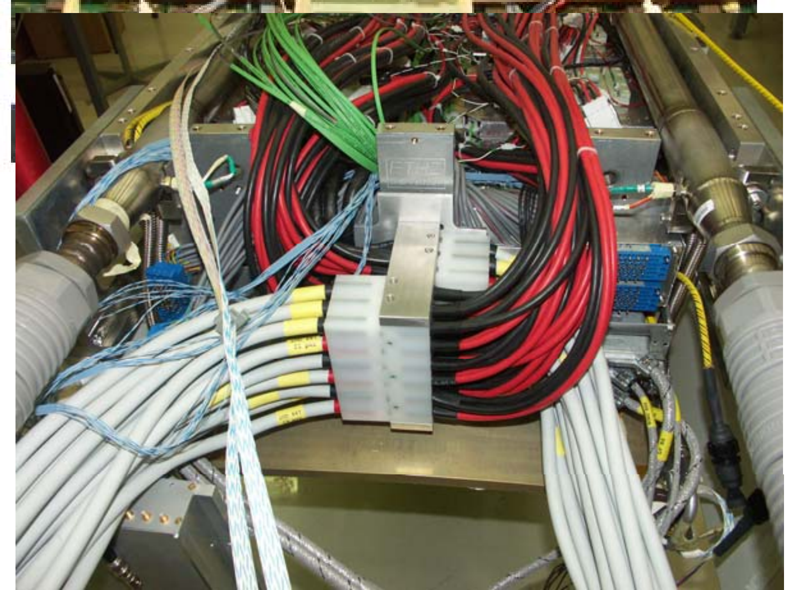






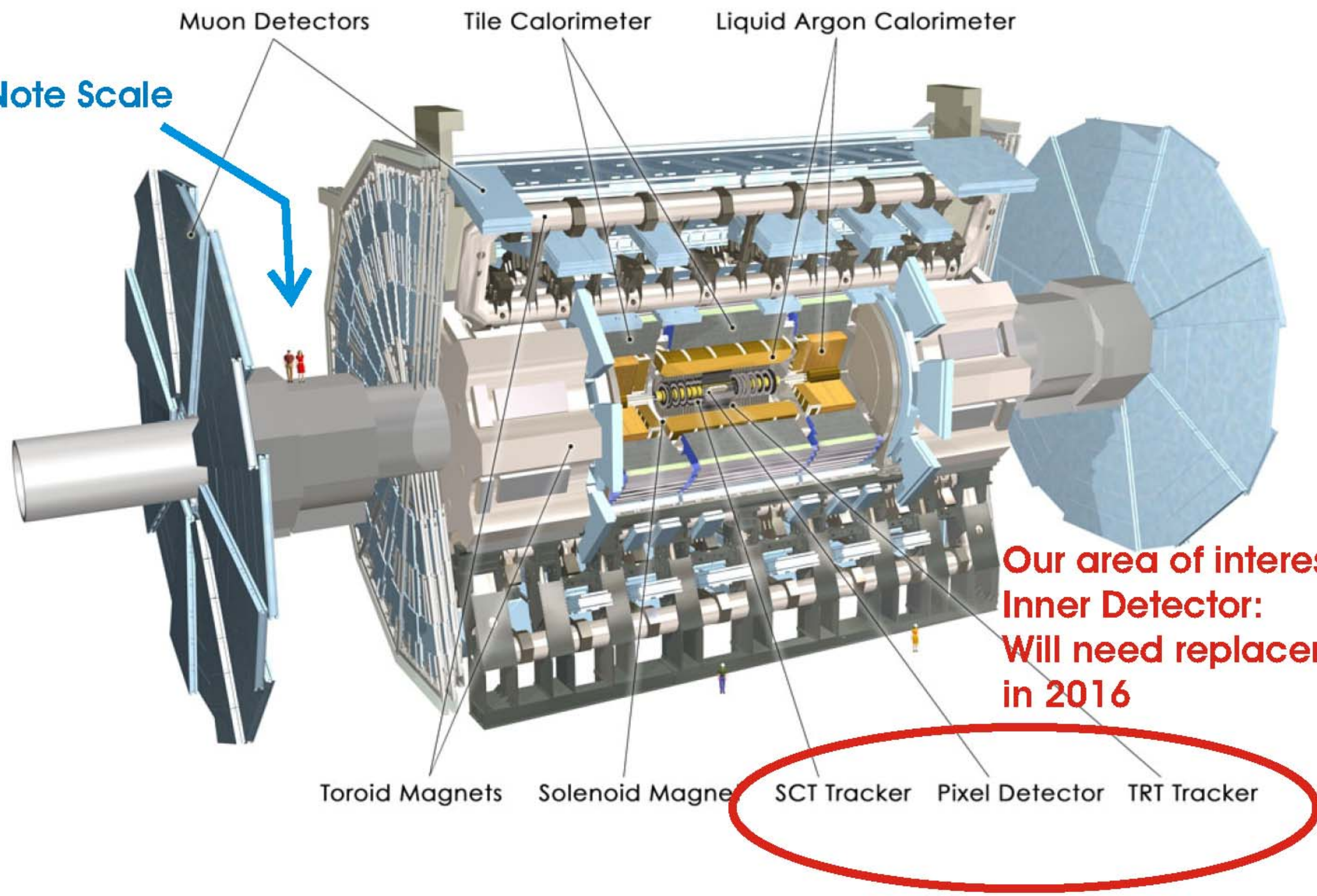
380V AC
↓
400V AC
↓
230V AC
↓
385V DC
↓
6V DC
↓
2.5V DC





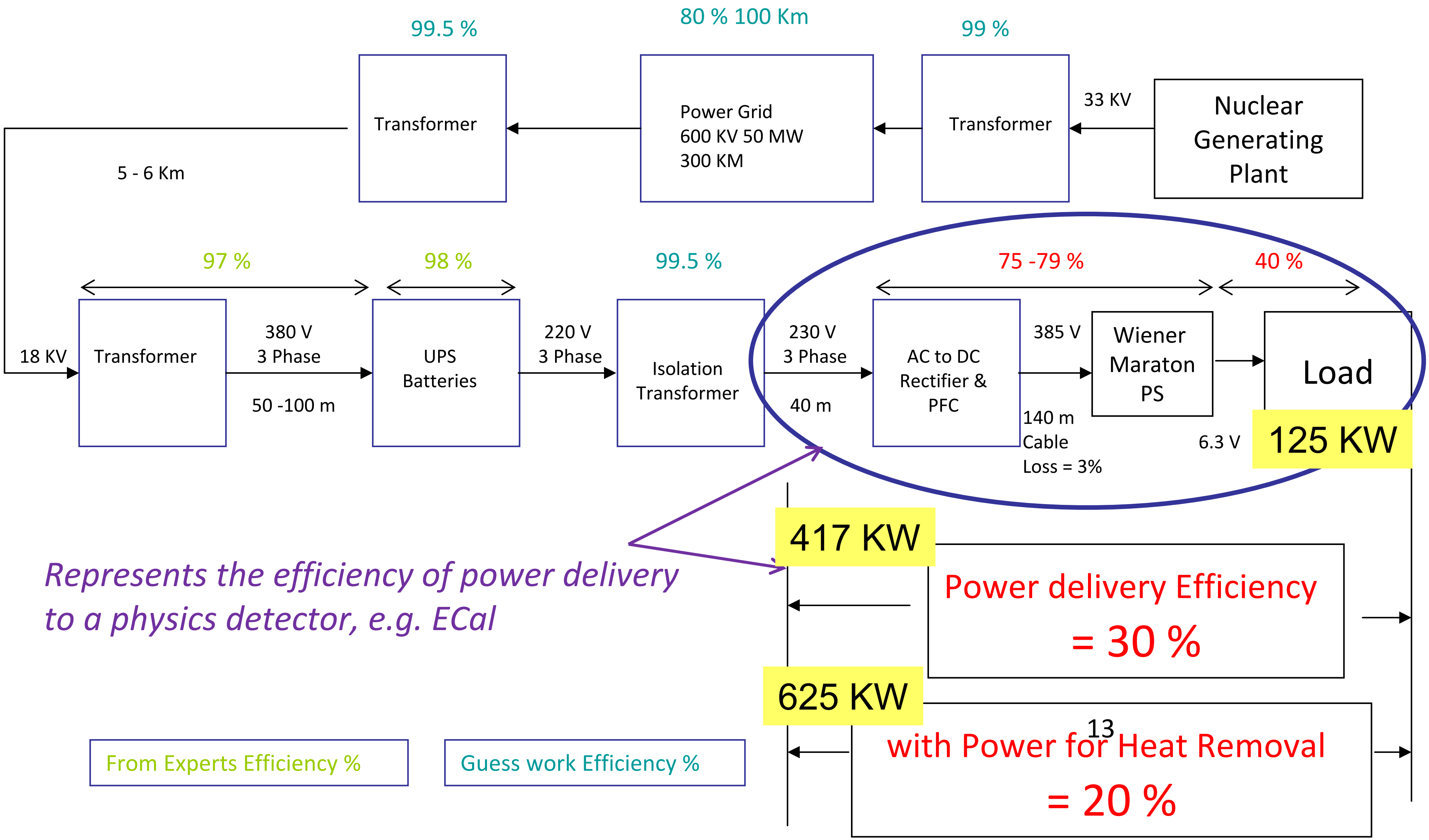
Atlas Detector Consists of Many Sub-Detectors

Note Scale



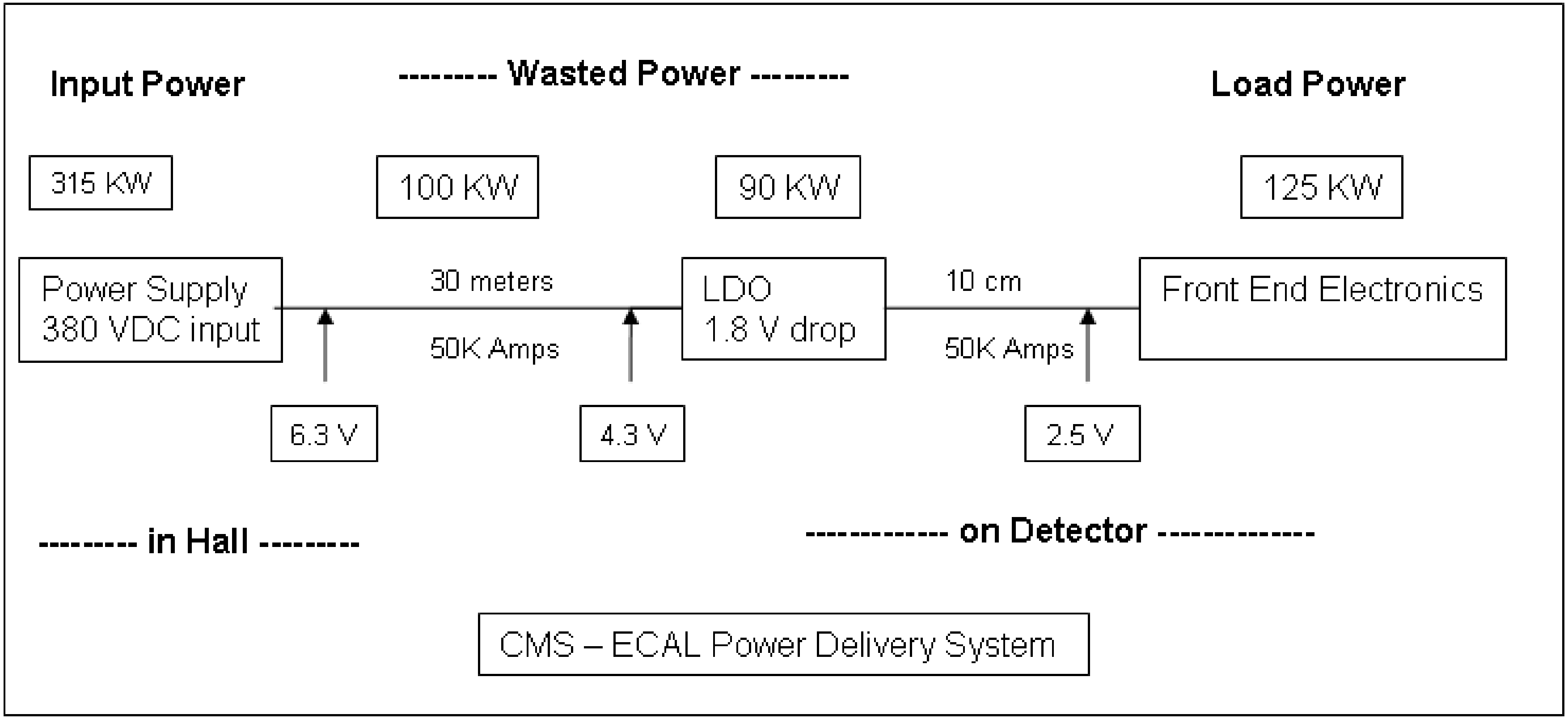
Our area of interest-
Inner Detector:
Will need replacement in 2016

Power Chain Efficiency for CMS ECAL



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

Power Efficiency _ Inefficiency _ Wasted Power



Is there a better way to deliver power?

HV – Low Voltage Converters: Reduce cable delivery losses

- Power Supply cables 30 – 140 meters
- Point of Load Regulators
- DC-DC Buck Converters
- Other schemes are not feasible due to constraints
- Radiation, Magnetic Field (Air Core Coils), Switching Noise, Low Mass

Collider Detector Power Essential

Sub-Systems operate:

Magnetic Field: ATLAS = 2 T: CMS = 4 T
: Outside Magnet 0.1 to 1 T at location of power supplies

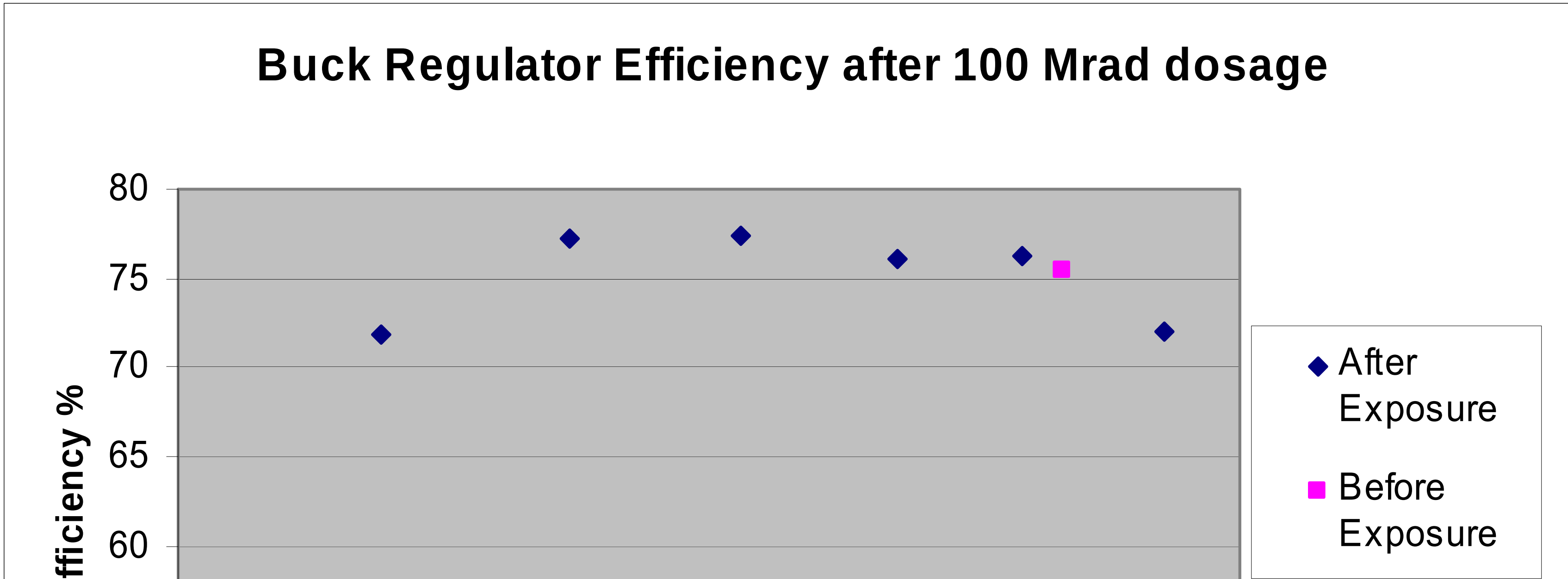
Radiation Tolerance: Highest for trackers ~ 100 (Strips) Mrads
500 (Pixels) Mrads
~ 1 Mrad for outer sub systems

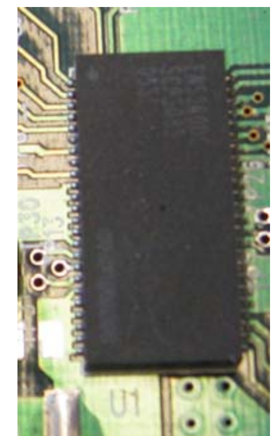
Radiation Testing: Test with Gammas – Cobalt 60 Source

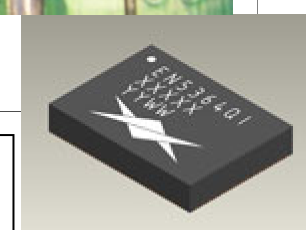
Protons 800 MeV
Neutrons 1 MeV (Equivalent) 1×10^{15} n/cm^2 from research Nuclear Reactors
Heavy Ions produced here are low energy & do not penetrate IC lids

Cooling: Chilled Water, Evaporative Cooling – 5C
Future Liquid Carbon Dioxide -30C

Minimize Material : Radiation length causes extra (noise) tracks

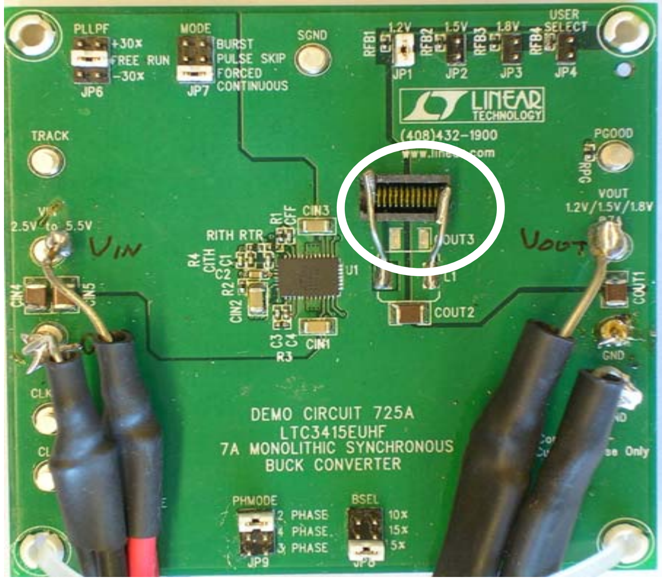






Found out at Power Technology conference 0.25 µm Lithography

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



Buck Converter with Air Coil

Magnetic Field Effect

7 Tesla Field Chemistry Department Super Conducting Magnet in Persistence Mode

Effect:

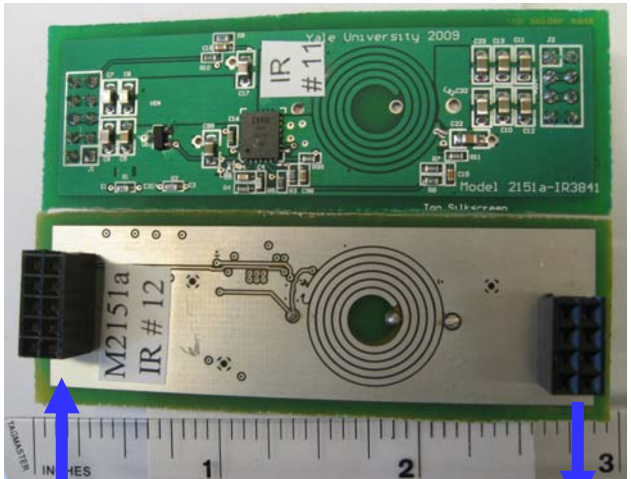
Vout = 3.545 Outside

Vout = 3.546 Edge of magnet

Vout = 3.549 Center of magnet

Change= Increased Vout 1 part in 900 at 7T

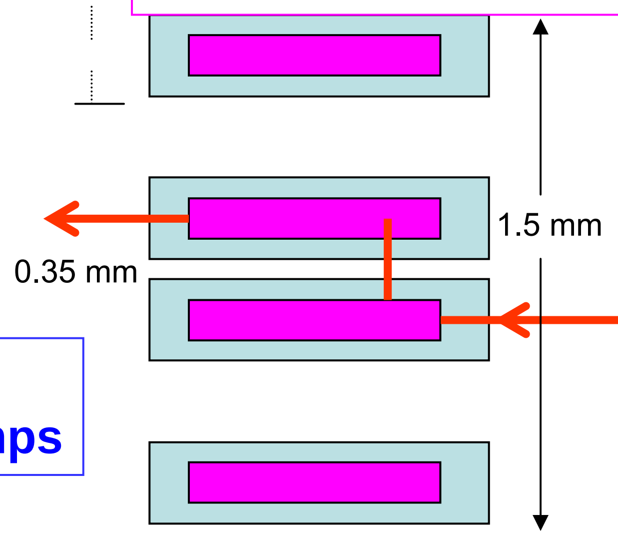
Plug In Card with Shielded Buck Inductor

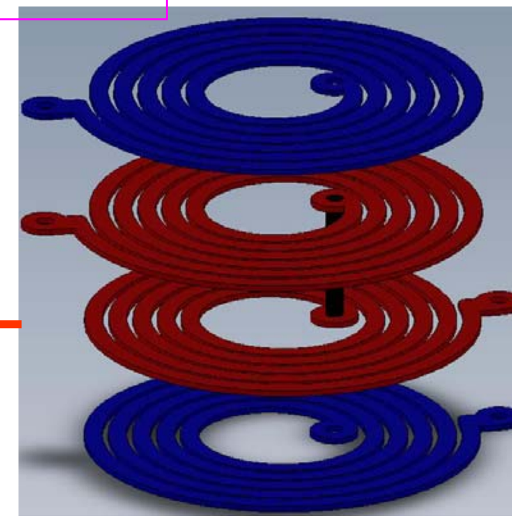


12 V

2.5 V
@ 6 amps

Coupled Air Core Inductor Connected in Series



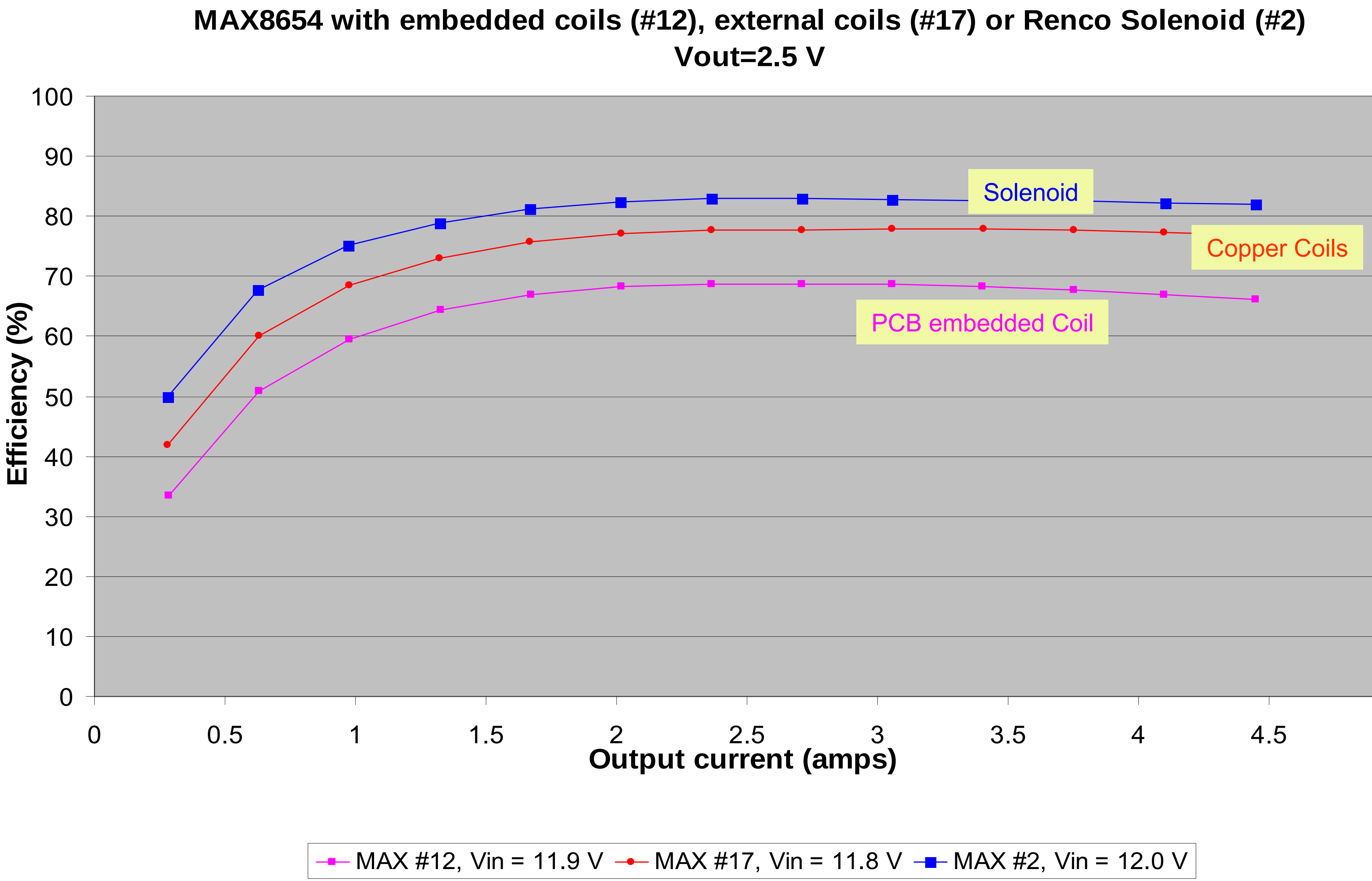


Different Versions

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

Spiral Coils Resistance in mΩ

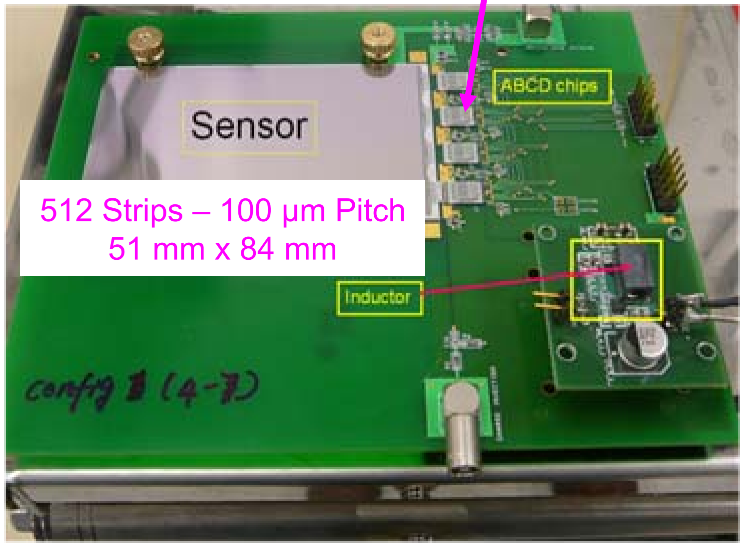
	Top	Bottom
3 Oz PCB	57	46
0.25 mm Cu Foil	19.4	17

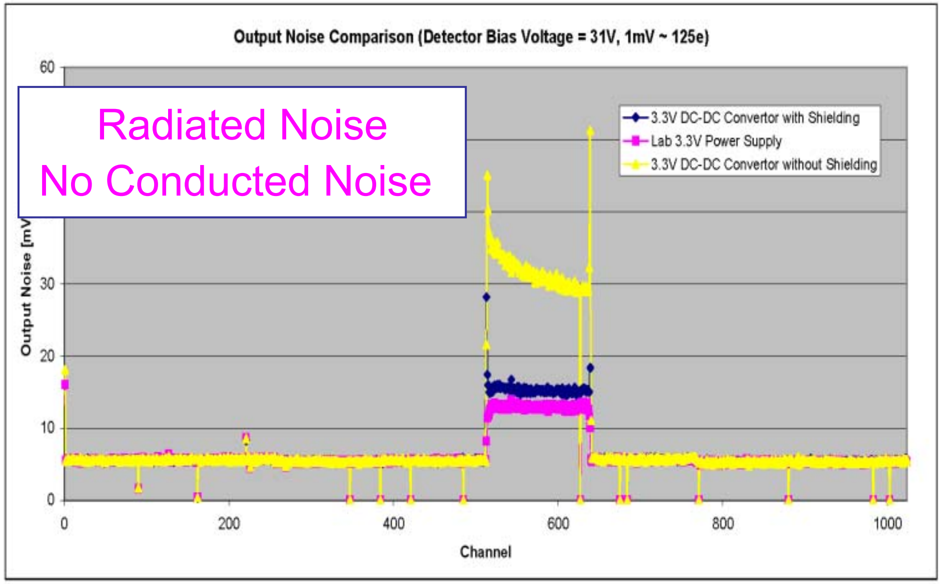

MAX8654 with embedded coils (#12), external coils (#17) or Renco Solenoid (#2)
Vout=2.5 V
Efficiency (%)
Output current (amps)
100
90
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Solenoid
Copper Coils
PCB embedded Coil
MAX #12, Vin = 11.9 V
MAX #17, Vin = 11.8 V
MAX #2, Vin = 12.0 V

Noise Tests with Silicon Sensors

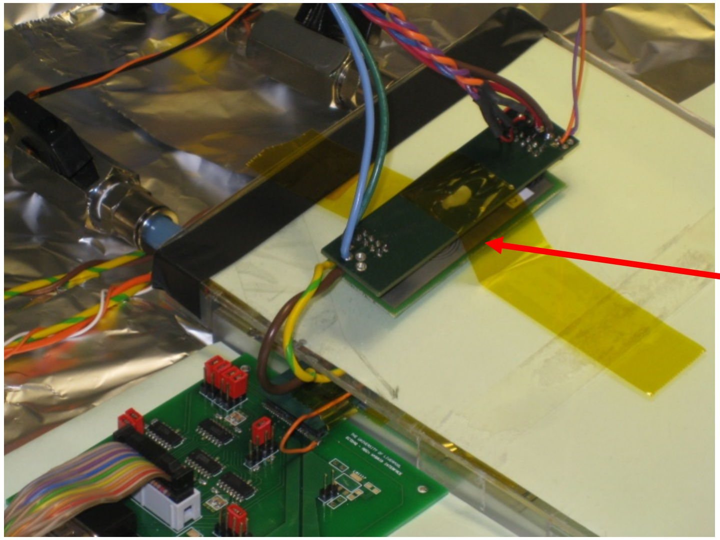
Test @ BNL

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

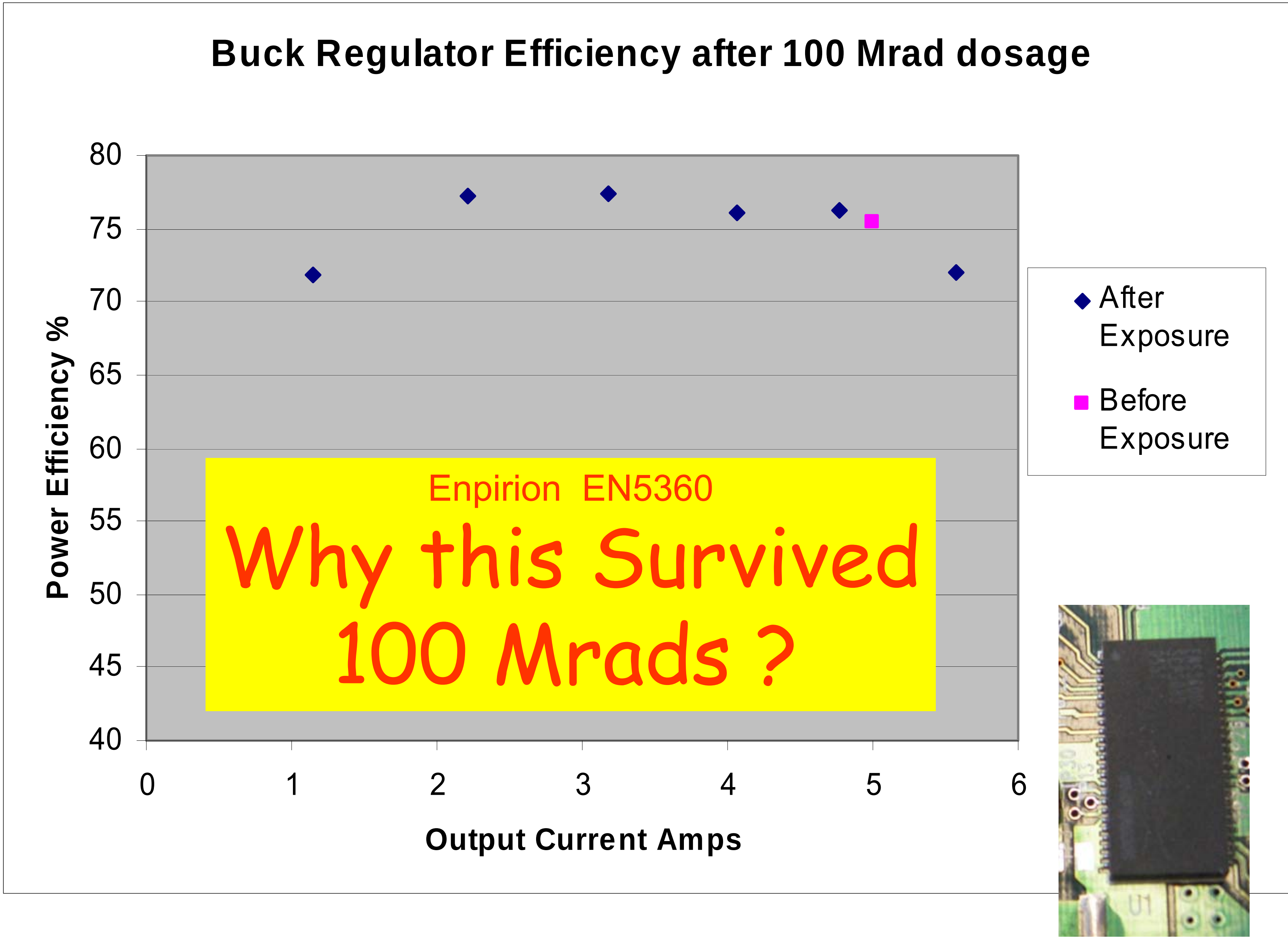
Ionizing Radiation Results – Commercial Converters

Dose rate= 0.2 Mrad/hr

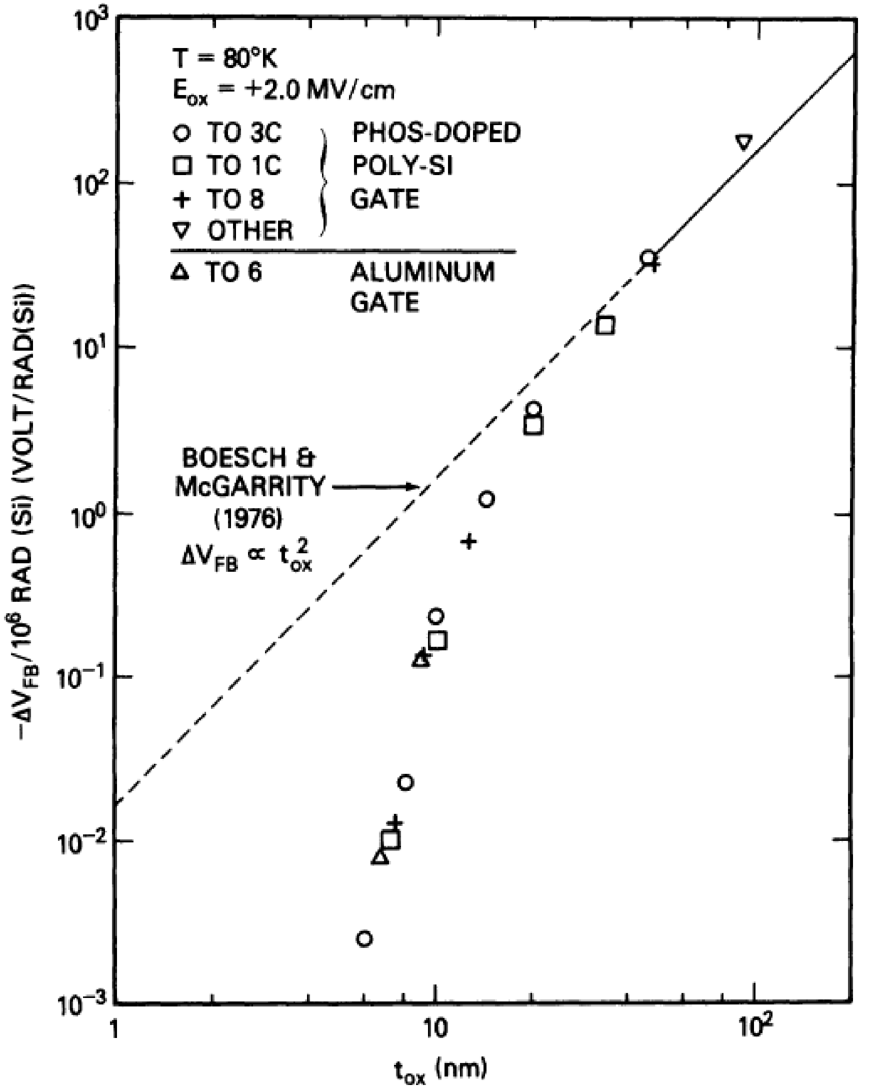
5- 12 nm Gate Oxide

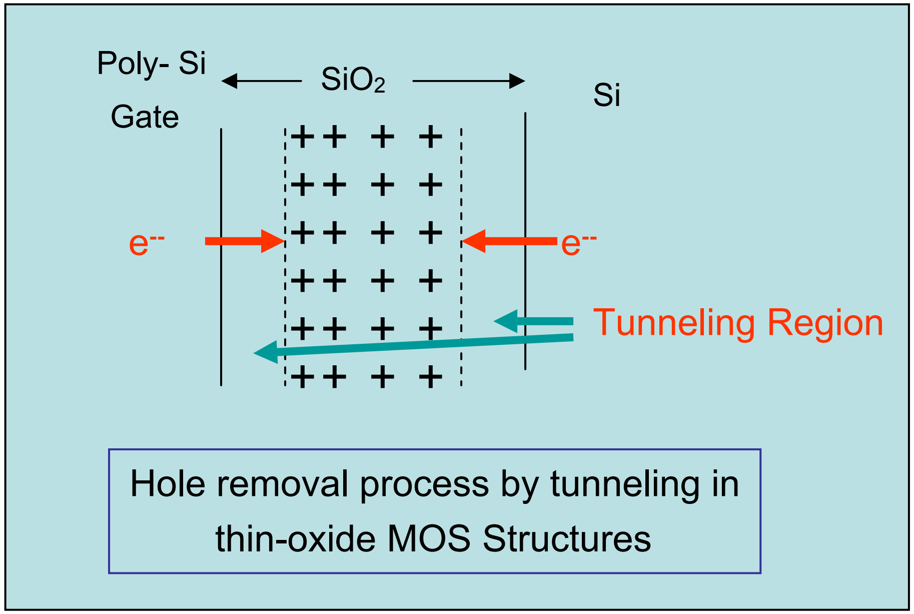
Company	Device	Oxide Thickness (nm)	Dose before Damage	Observation Damage Mode
IHP	ASIC	5	53 Mrad	slight damage
XYSemi	MOS FET	7	52 Mrad	Minimal damage
XYSemi	XP5062	12.3	44 krad	Loss of output voltage regulation
TI	TPS54620	20	23 krad	abrupt failure
Intersil	ISL 8502	unknow n	40.6 krad	Increasing input current
IR	IR3822	unknown	139 krads	Increasing input current
IR	IR3841	9 & 25	13 krads	Loss of output voltage regulation
ST	ST1510	unknown	125 krad	Loss of output voltage regulation
Enpirion	EN5365	5	85 krad	Increasing input current,
Enpirion	EN5382	5	111 krads	Loss of output voltage regulation
Enpirion	EN5360 #2	5	100 Mrads	No significant Changes
Enpirion	EN5360 #3	5	48 Mrads	No significant changes
National Semi.	LM2864	11.8	3 Mrads	Short after power recycle

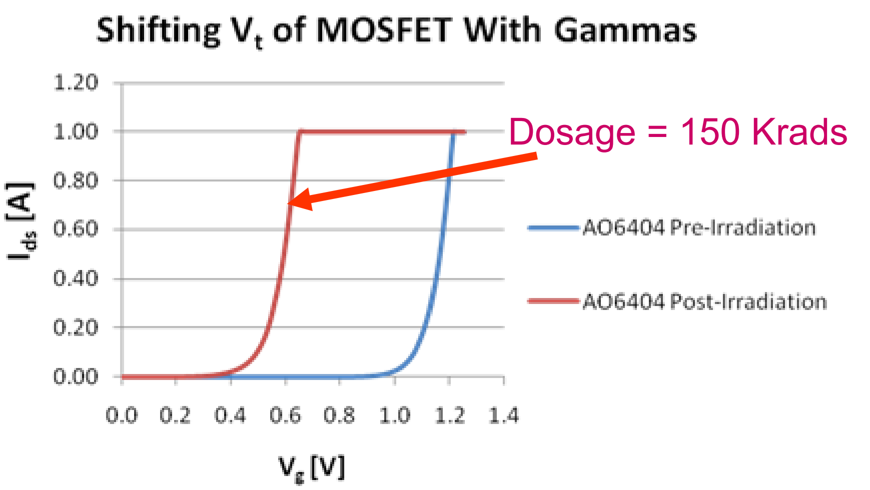
Many more tested but similar failure-
Thin oxide converters survive > 200 Krads


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

Threshold Shift vs Gate Oxide Thickness







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

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

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

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

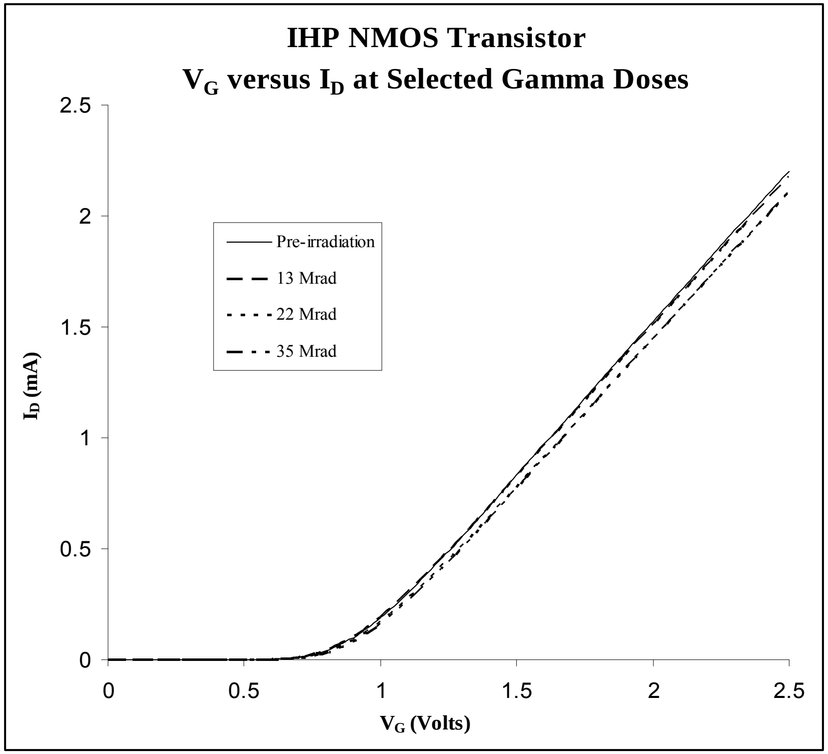
Mixed signal power designs from TI, TSMC, IBM etc - 0.18 µm & 0.13 µm
Automobile Market. Voltage ratings 10 - 80 Volts
Deep sub-micron but thick oxide

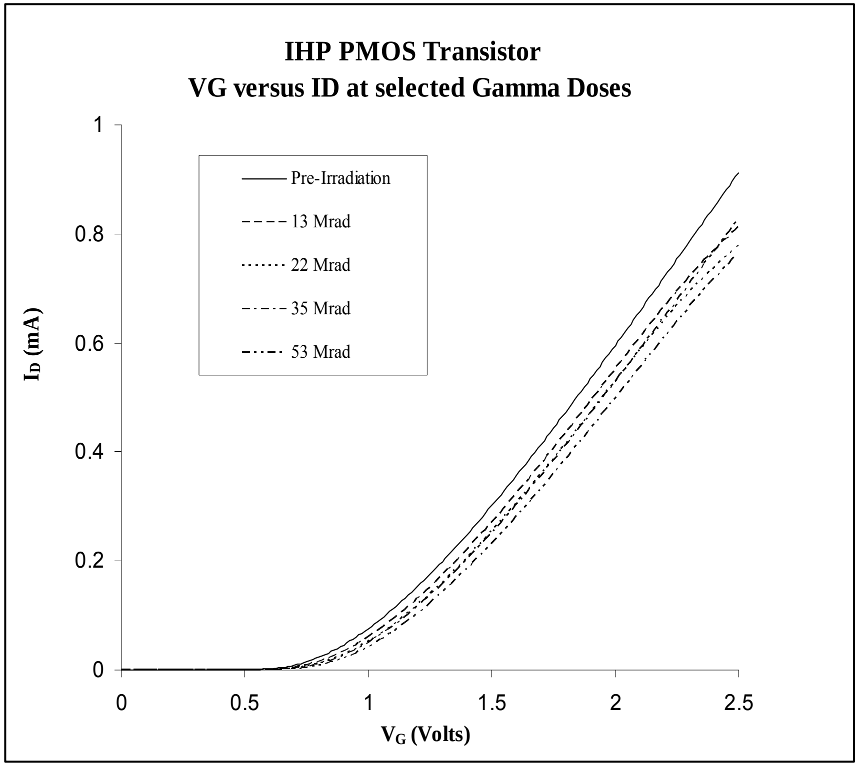
Controller : Low Voltage

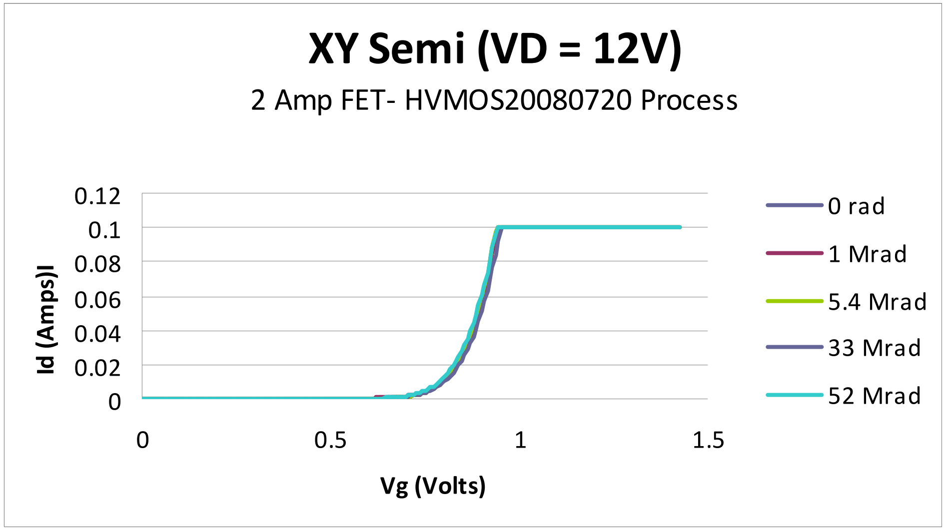
High Voltage: Switches – some candidates HV & Thin oxide

RF Process LDMOS, Drain Extension, Deep Diffusion etc

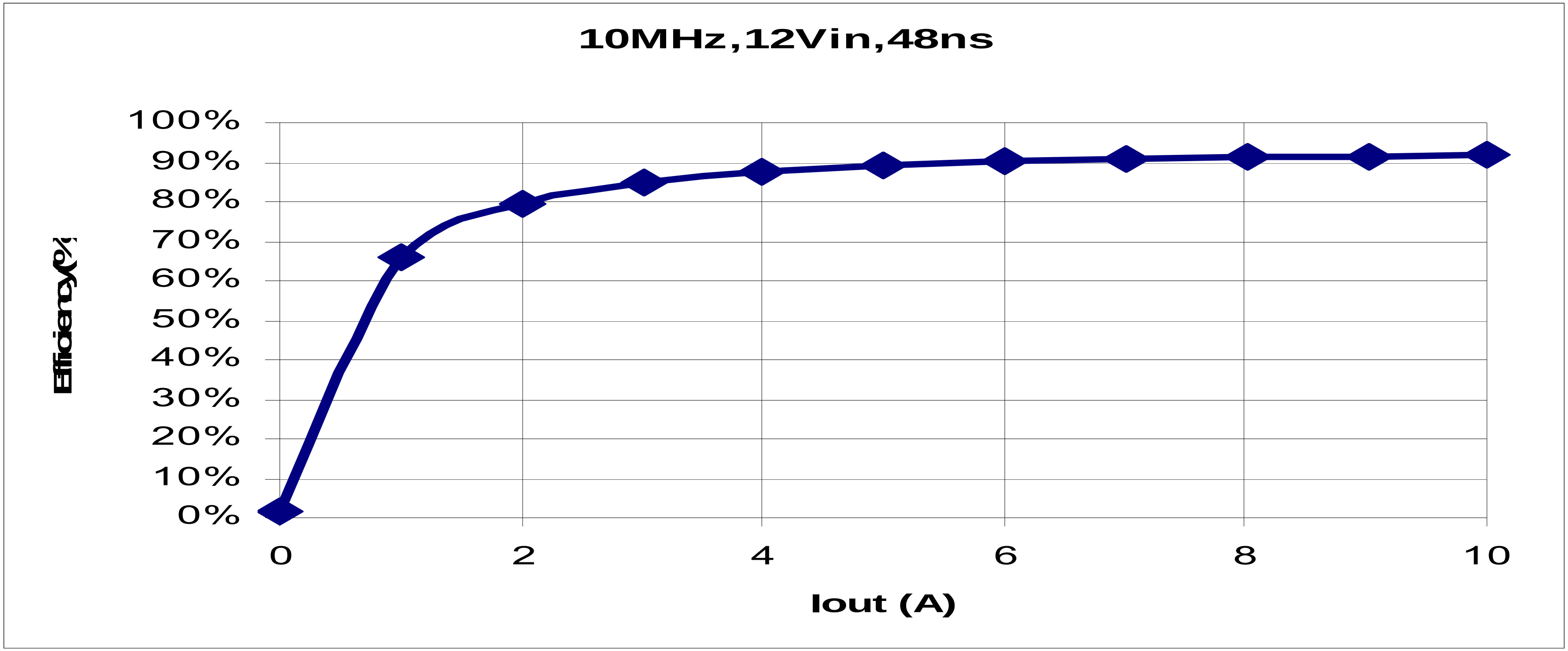
>> 20 Volts HEMT GaN on Silicon, Silicon Carbide, Sapphire


IHP NMOS Transistor
V_G versus I_D at Selected Gamma Doses
I_D (mA)
V_G (Volts)
Pre-irradiation
13 Mrad
22 Mrad
35 Mrad
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
I_D (mA)
V_G (Volts)
Pre-Irradiation
13 Mrad
22 Mrad
35 Mrad
53 Mrad
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
Id (Amps)I
Vg (Volts)
0 rad
1 Mrad
5.4 Mrad
33 Mrad
52 Mrad
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5

Frequency Response IR's Engineering sample in 2009
Half Bridge with CMOS Driver



Good efficiency to >12 MHz Driver limited

International Rectifier: Supplied sample board under NDA

Radiation Results – RF GaN & EPC GaN on Si

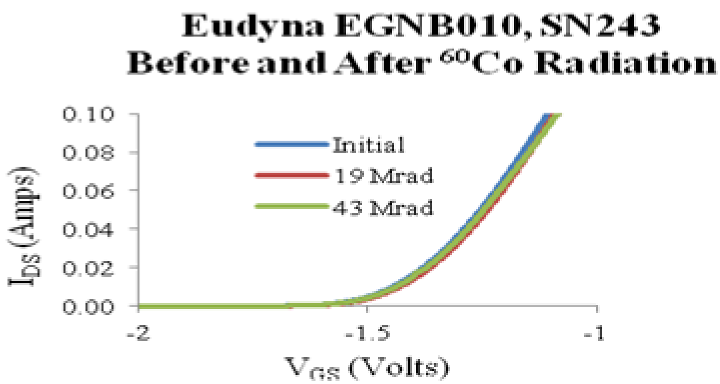


Fig. 7. Eudyna EGNB010 GaN HEMT, VGS versus IDS at VDS = 10 volts and selected doses of 60Co gamma radiation. Little change is apparent even after 43 Mrad of ionizing radiation.

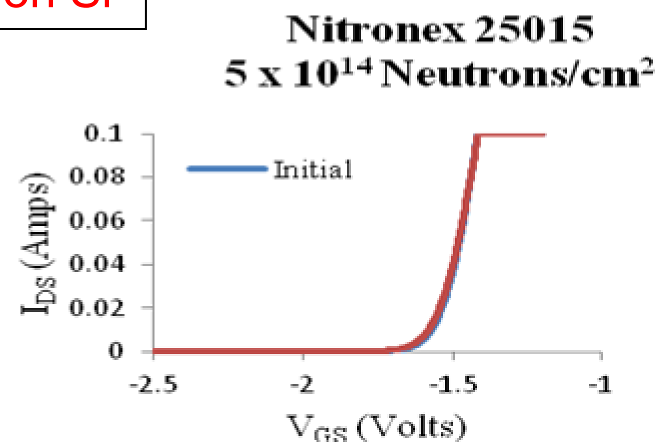


Fig. 6. Nitronex 25015 HEMT irradiate with 5 x 1014 neutrons (1 MeV equivalent). Little change is observed in the response.

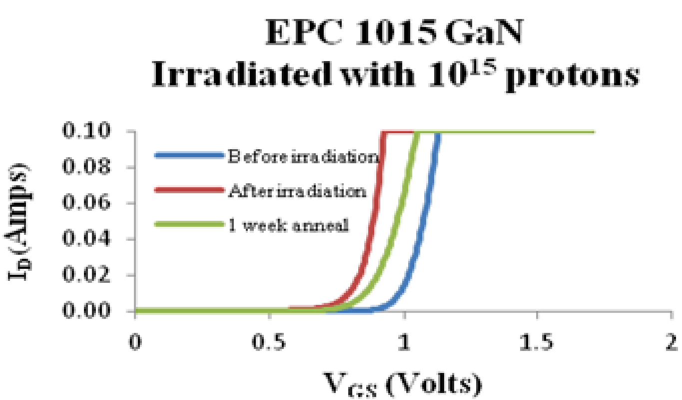


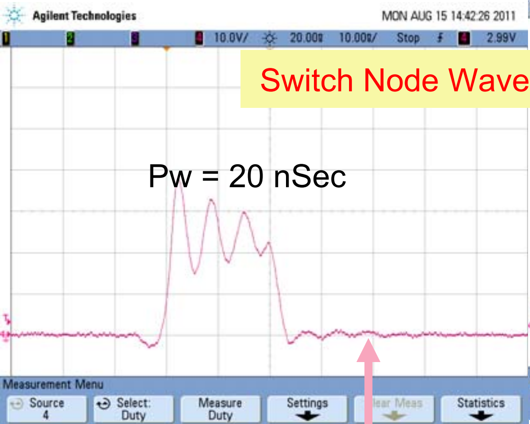
Fig. 8. EPC 1015 HEMT before and after 1015 protons/cm2. During exposure VDS = 24V with a 1 kOhm resistor current limiting the channel to 24 mA. The device was "clocked" with a VGS = 4 V at a 1 kHz frequency

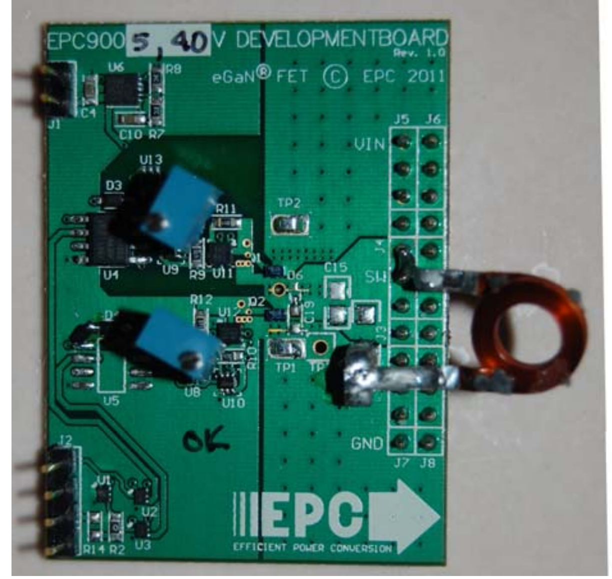
TABLE III Radiation Testing Matrix for GaN Devices

Company	Device	60Co	Neutron Fluence (cm^{-2})	Proton Fluence (cm^{-2})
Nitronex	25015	17.4Mrad	5×10^{14}	1×10^{15}
Cree	40010		5×10^{14}	1×10^{15}
Eudyna	EGNB010	43 Mrad	5×10^{14}	1×10^{15}
EPC	EPC1015	64 Mrad		1×10^{15}

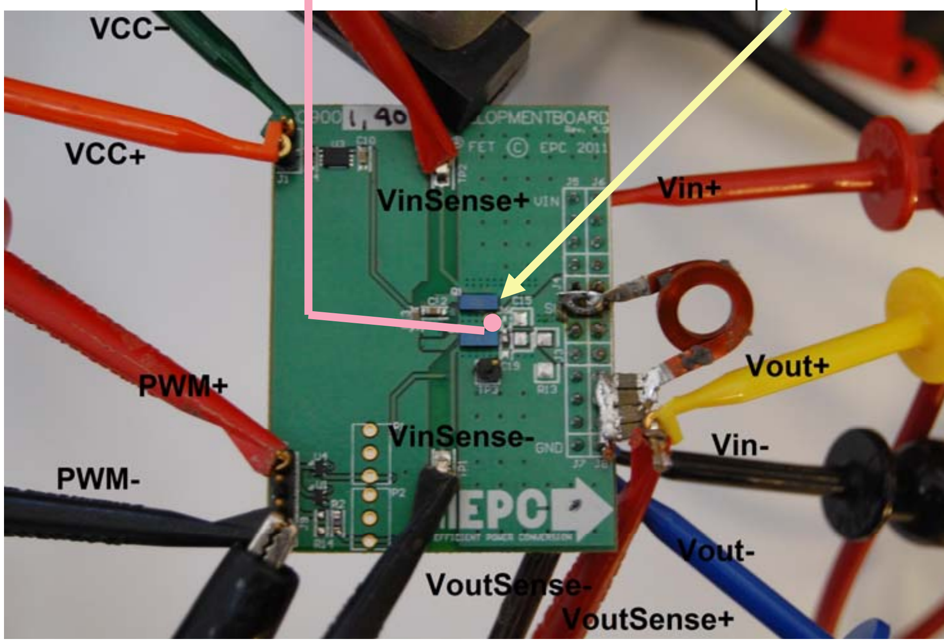
eGaN with discrete & LM5113 Driver

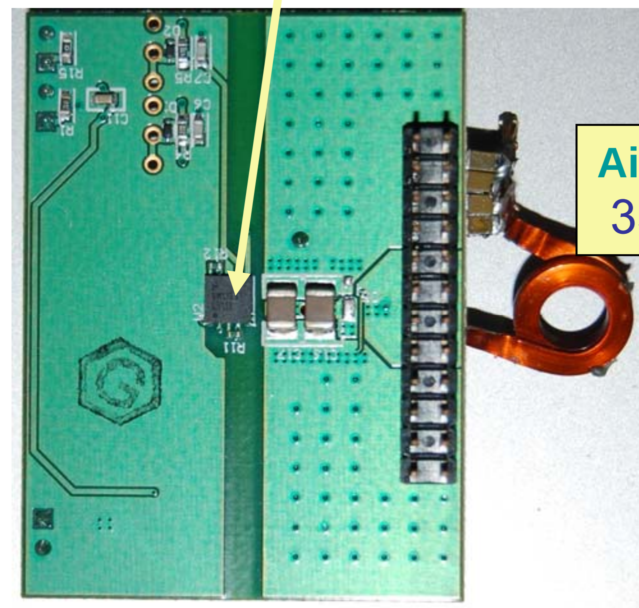
Switch Node Waveforms





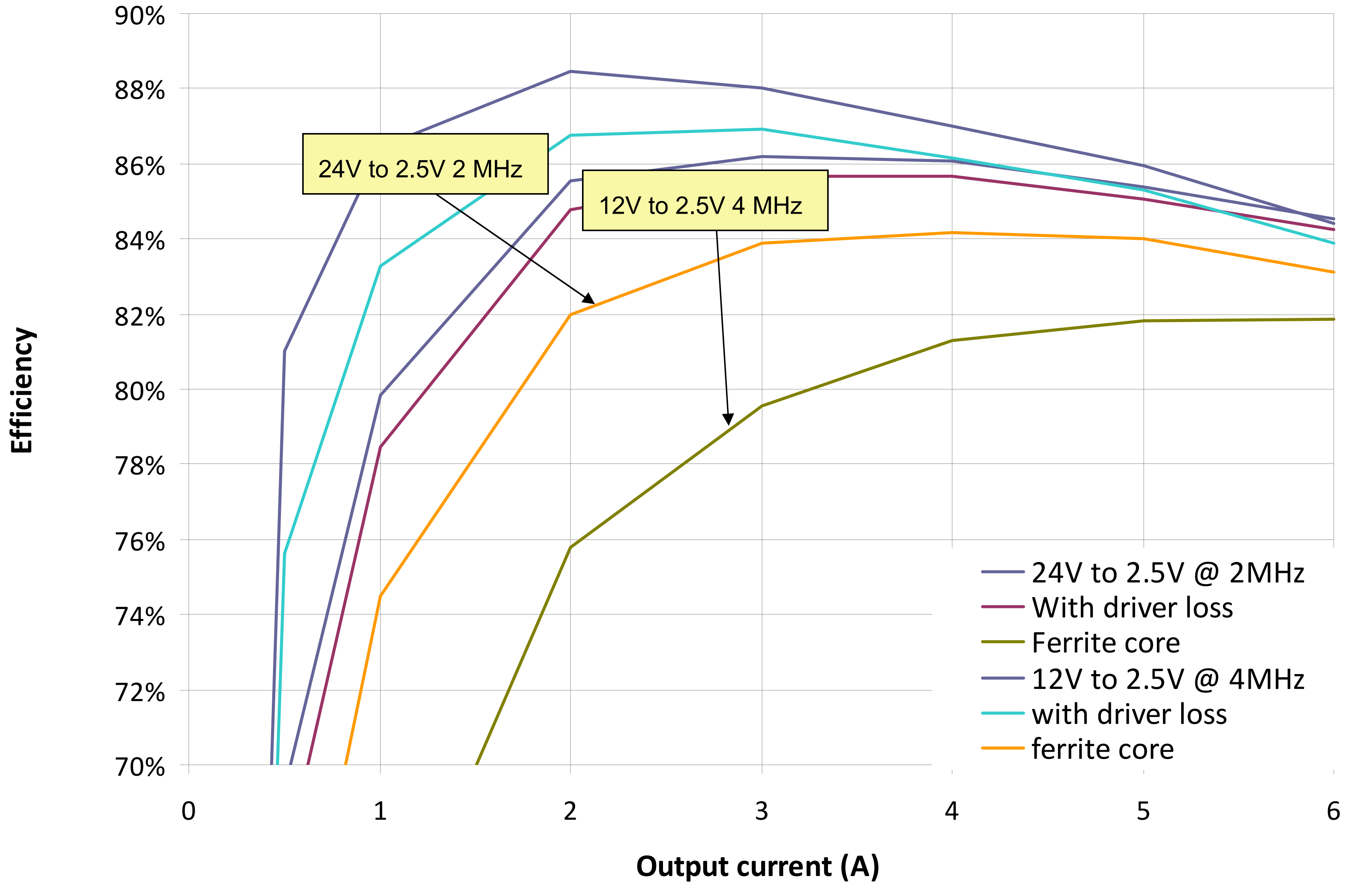
National eGaN Driver LM5113 on Bottom
eGaN on Top side





Air Core Coil
355 nH

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

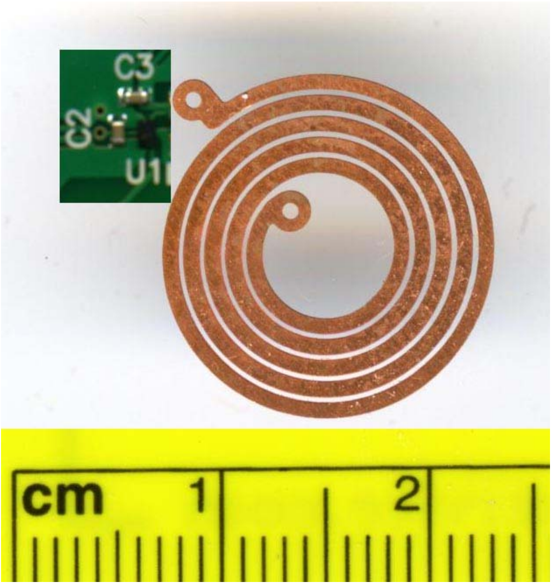


Aircoil *EPCOS-B82559A0392A013* 3.9 µH / 355 nH without Ferrite. 5 mΩ	*MnZn Ferrite Coil 744308euro33* 377 nH 0.37 mΩ

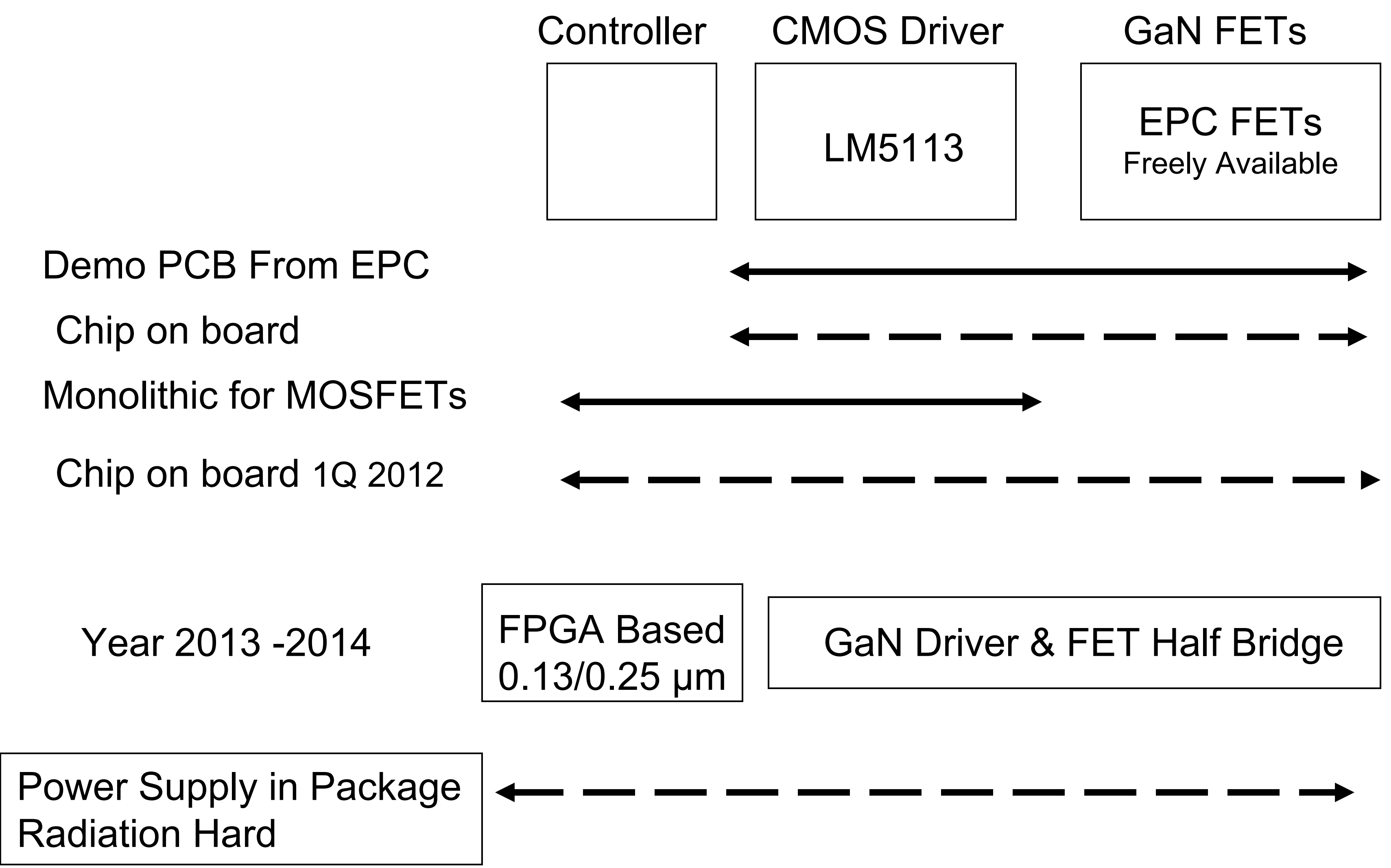
Electron Linear Collider produce low radiation

but material in the interaction regions must be minimized

- High Frequency operation for lower coil size / material
- Commercial cell phone converters 6 - 8 MHz, 1 amp, 5.5 Vin
- 1 -2 turn coil
- Fabricate PCB & Test
- Power Supply in a Package
- Coil simulation needs collaborators ??
- Coil may be buried in the detector PCB
- Feasibility report due summer 2012



Market Trend




Working on Physics Power Supply
Is not considered Glamorous
Top of the World is Cool but lonely !
Let us keep it cool with highly efficient PS
Swimming is Great at the North Pole
August 2010 Fairbanks, Alaska was 33 C – Bye Bye Glaciers !
More Details: http://shaktipower.sites.yale.edu Click on Recent seminars/