Power Delivery to Future Physics Detector Front End Electronics with Commercial DC-DC Power Converters

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Kyoto, Japan
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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
- *Oodle Reduction for Energy Efficiency , Rad Resistant PS & Li Nitrogen Tests*

Collaborators:

Yale University: Keith Baker, Hunter Smith

Center for European Nuclear Research (CERN)

-World's Largest Particle Physics Laboratory

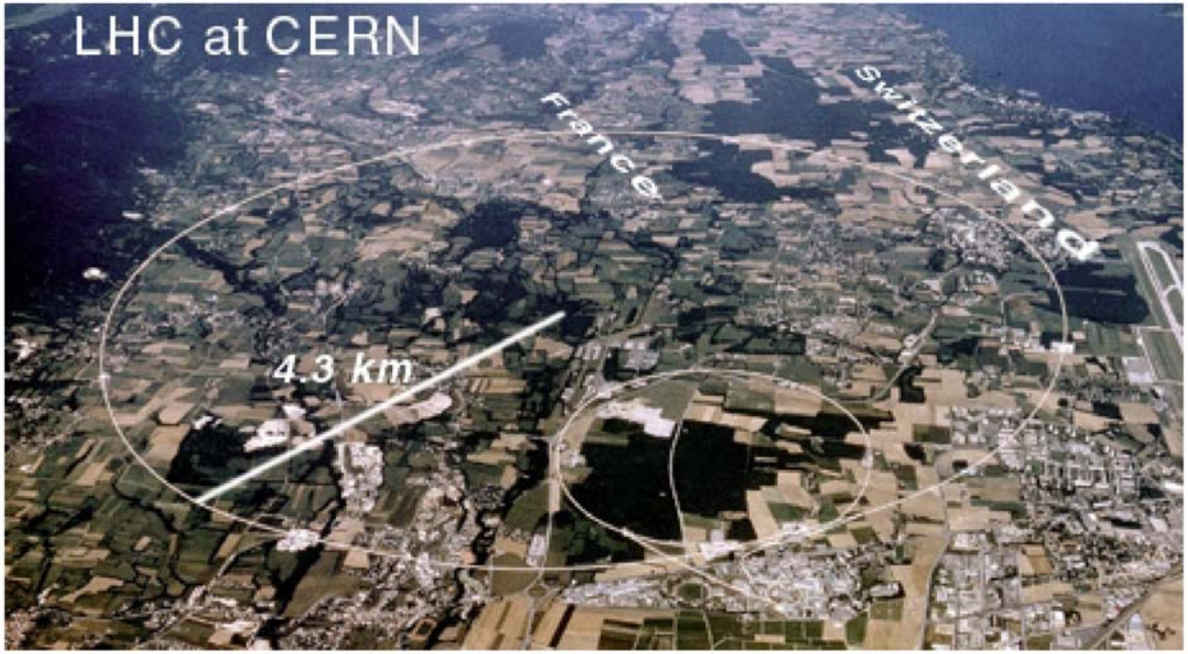
-Located near Geneva, Switzerland on French-Swiss Border

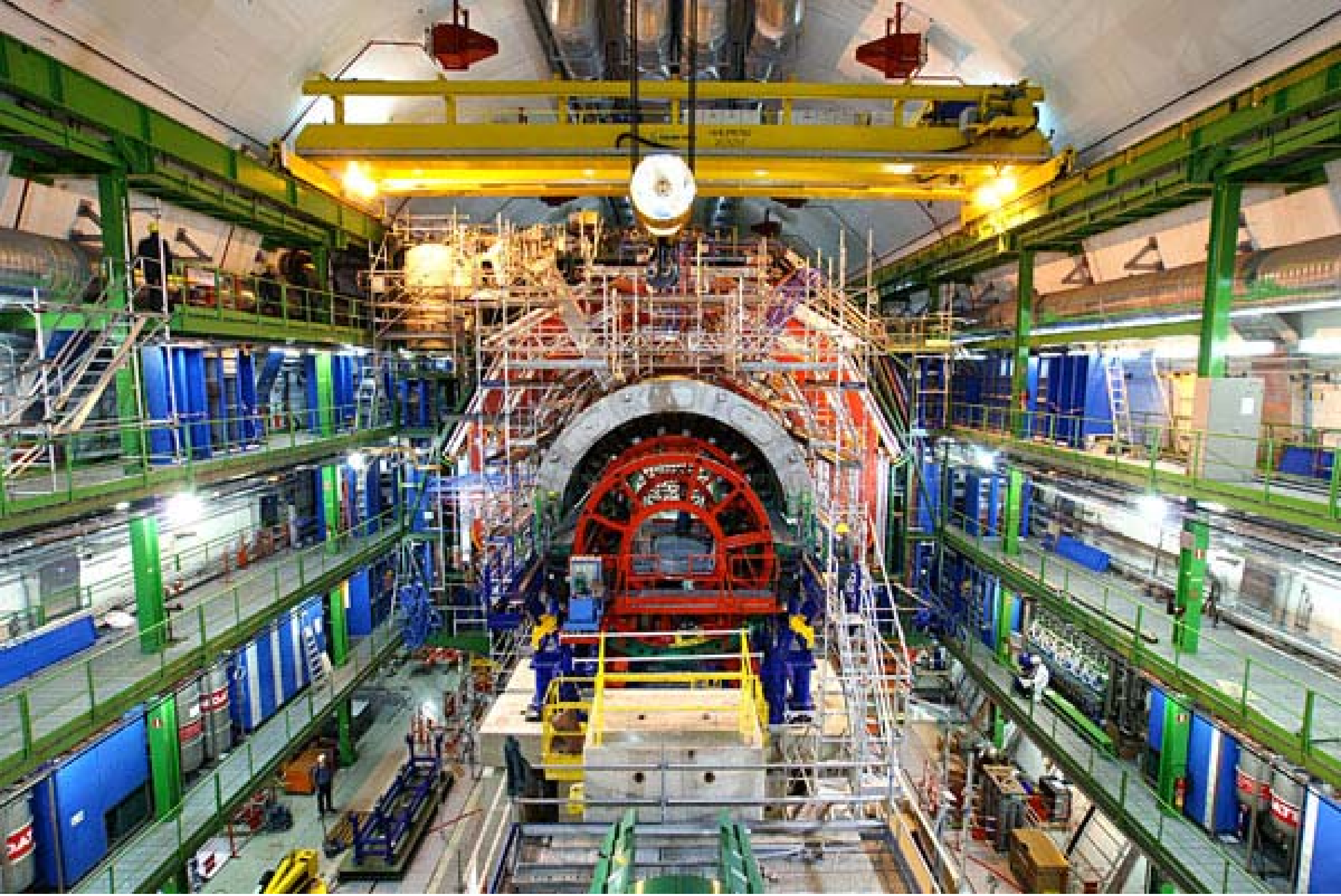
-Also known for creating the WEB in early 1990s

Main Site

Large Hadron Collider

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





CMS Outreach

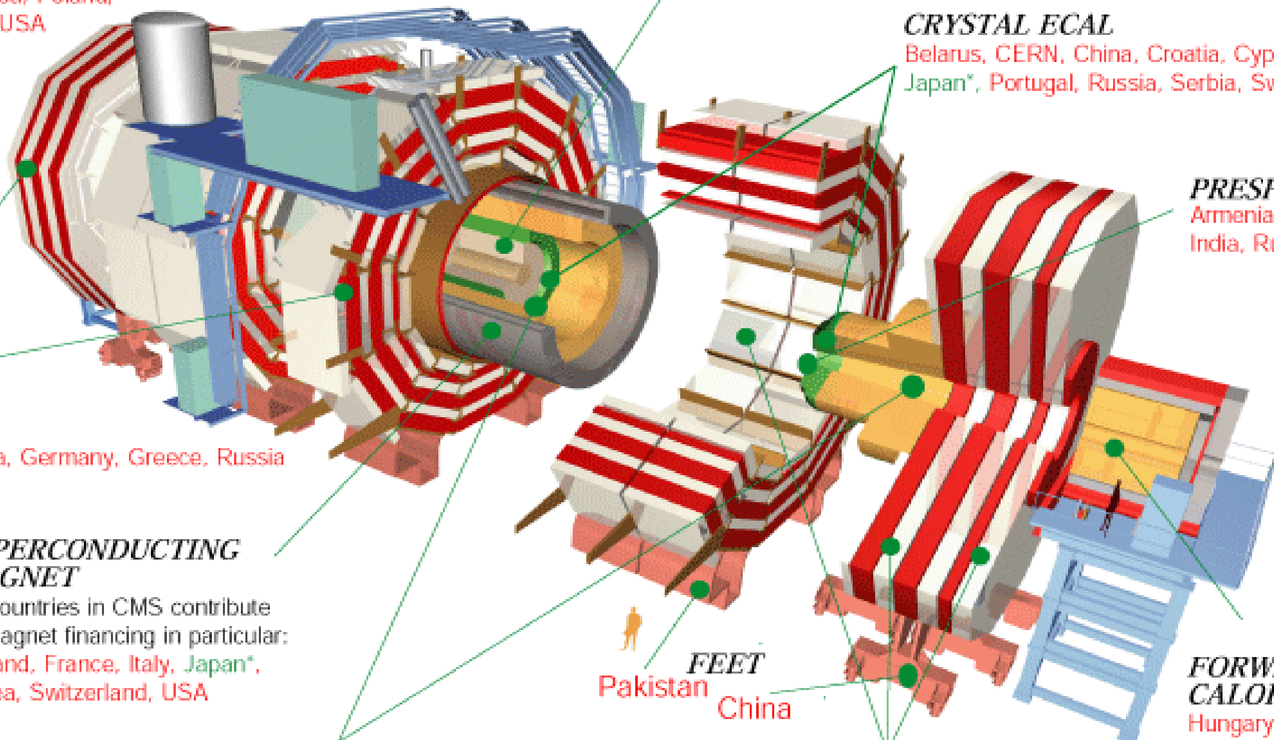
37 Countries, 155 Institutes, 2000 scientists (including about 400 students) October 2006

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

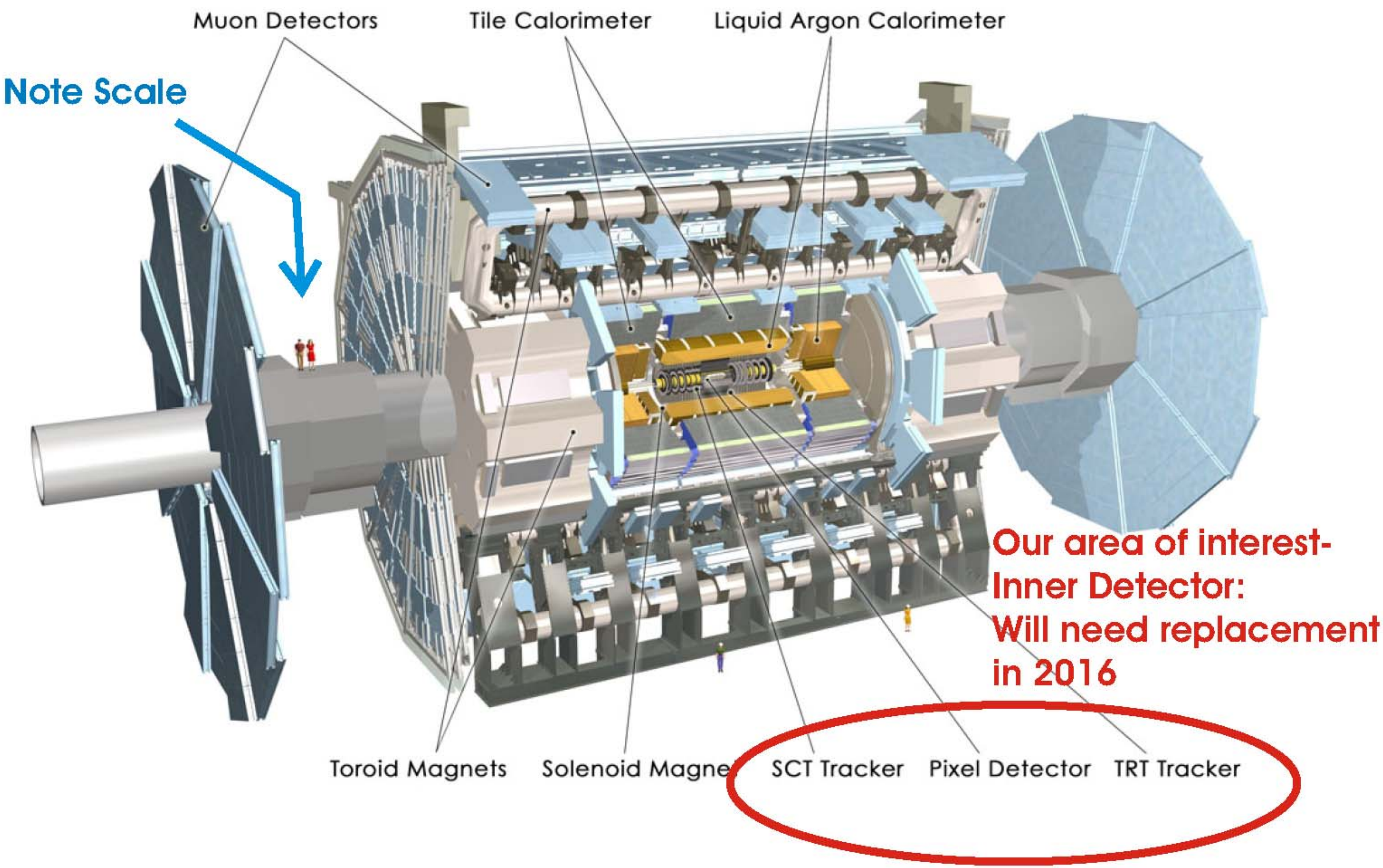
HCAL
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Georgia, Russia, Ukraine, Uzbekistan
HO: India

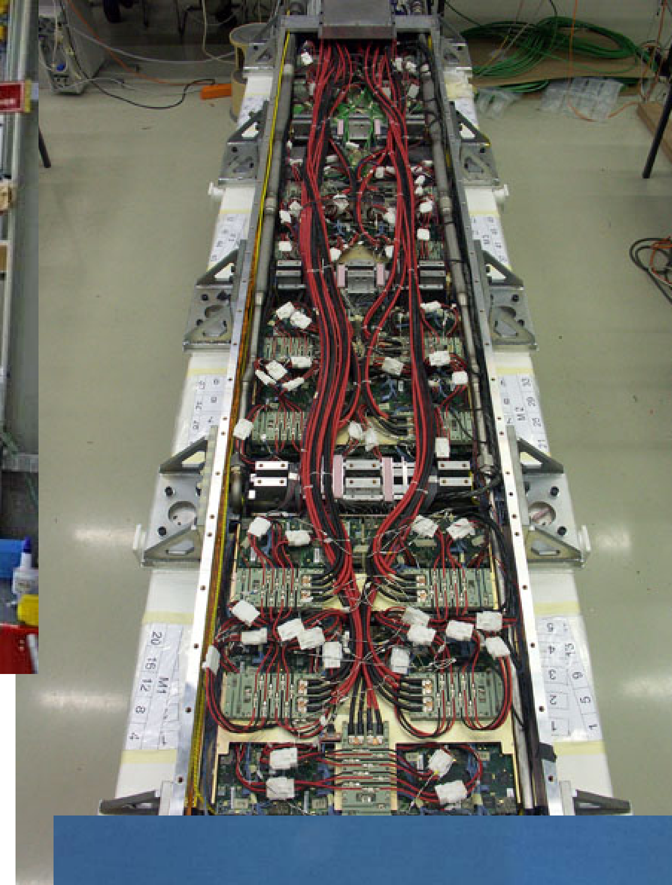
MUON CHAMBERS
Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China, Colombia, Korea, Pakistan, Russia, USA

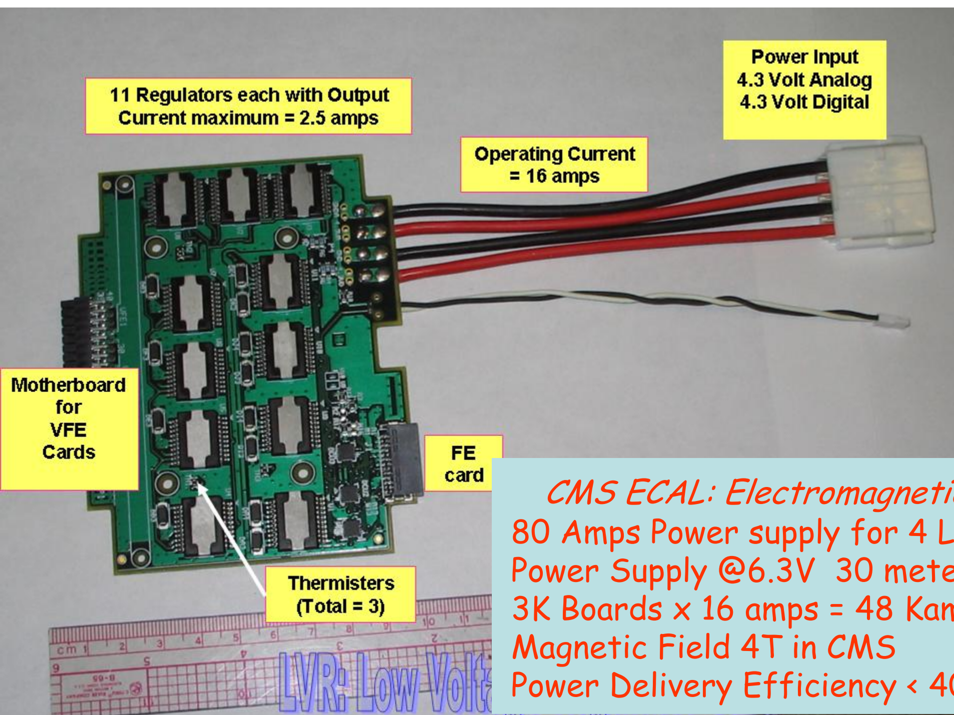
* Only through industrial contracts

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

Atlas Detector Consists of Many Sub-Detectors







CMS ECAL: Electromagnetic Calorimeter

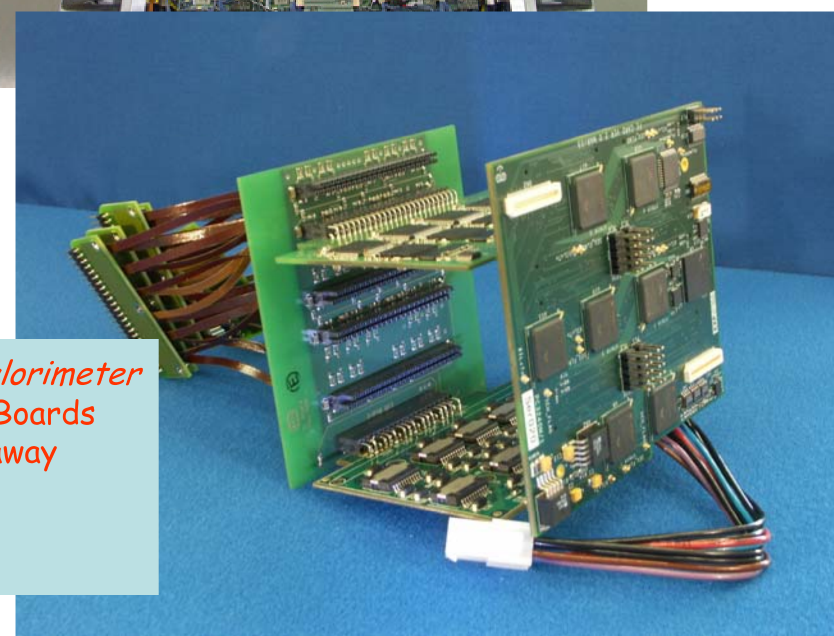
80 Amps Power supply for 4 LVR Boards

Power Supply @6.3V 30 meters away

3K Boards x 16 amps = 48 Kamps

Magnetic Field 4T in CMS

Power Delivery Efficiency < 40 %



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

1 Oodle = 10,000 amps

# 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.

Power Supply
6.3 V

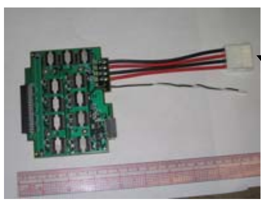
64 Amps

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)

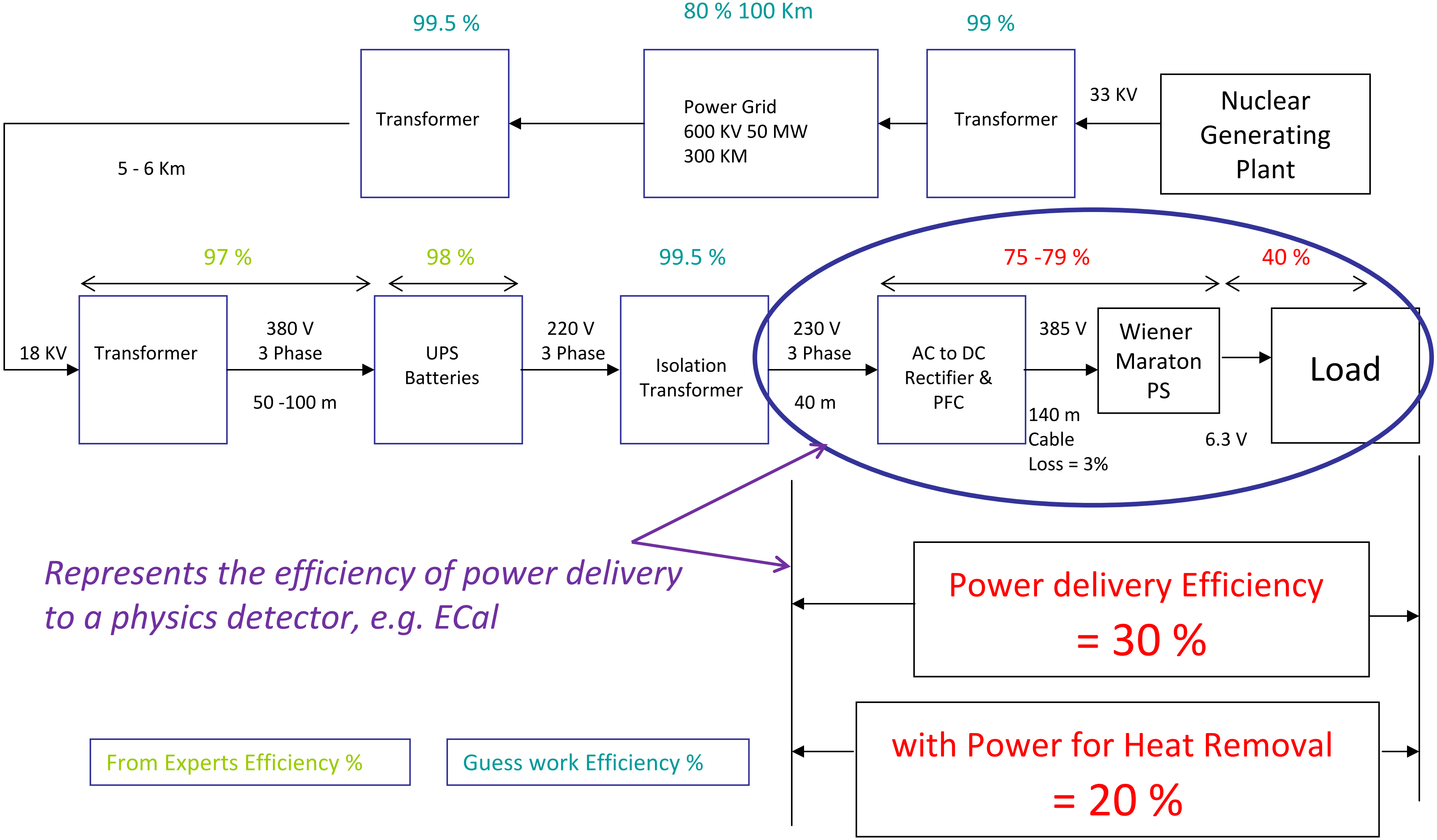
1 to 3 m

2.5V
64 amps
160 W

4 LVR Boards

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

Power Chain Efficiency for CMS ECAL

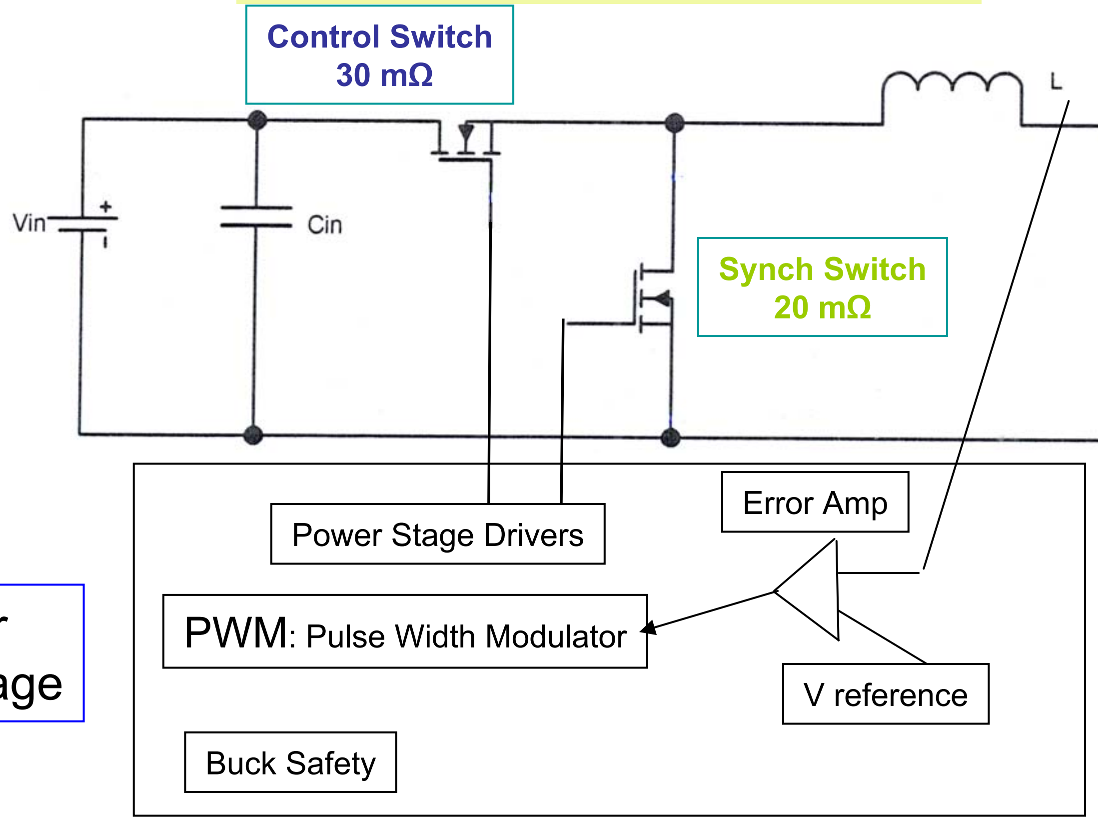


What can we do?

- 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 testing

Synchronous Buck Converter

Power Stage - High Volts

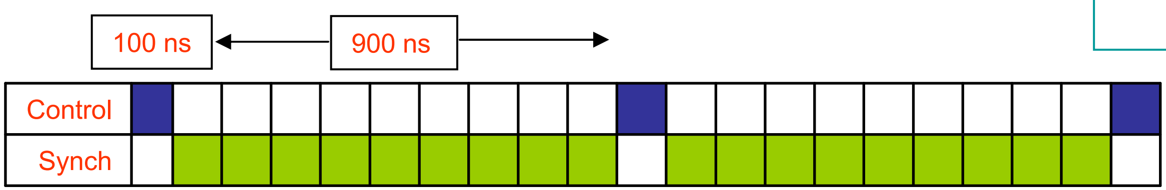


Controller Low Voltage

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

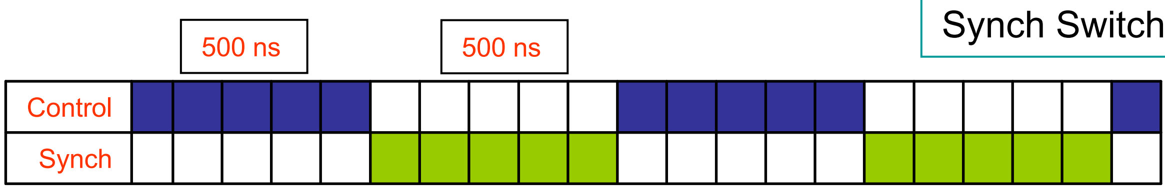
Lower Voltage Ratio
>>>Higher Frequency & Smaller Coil

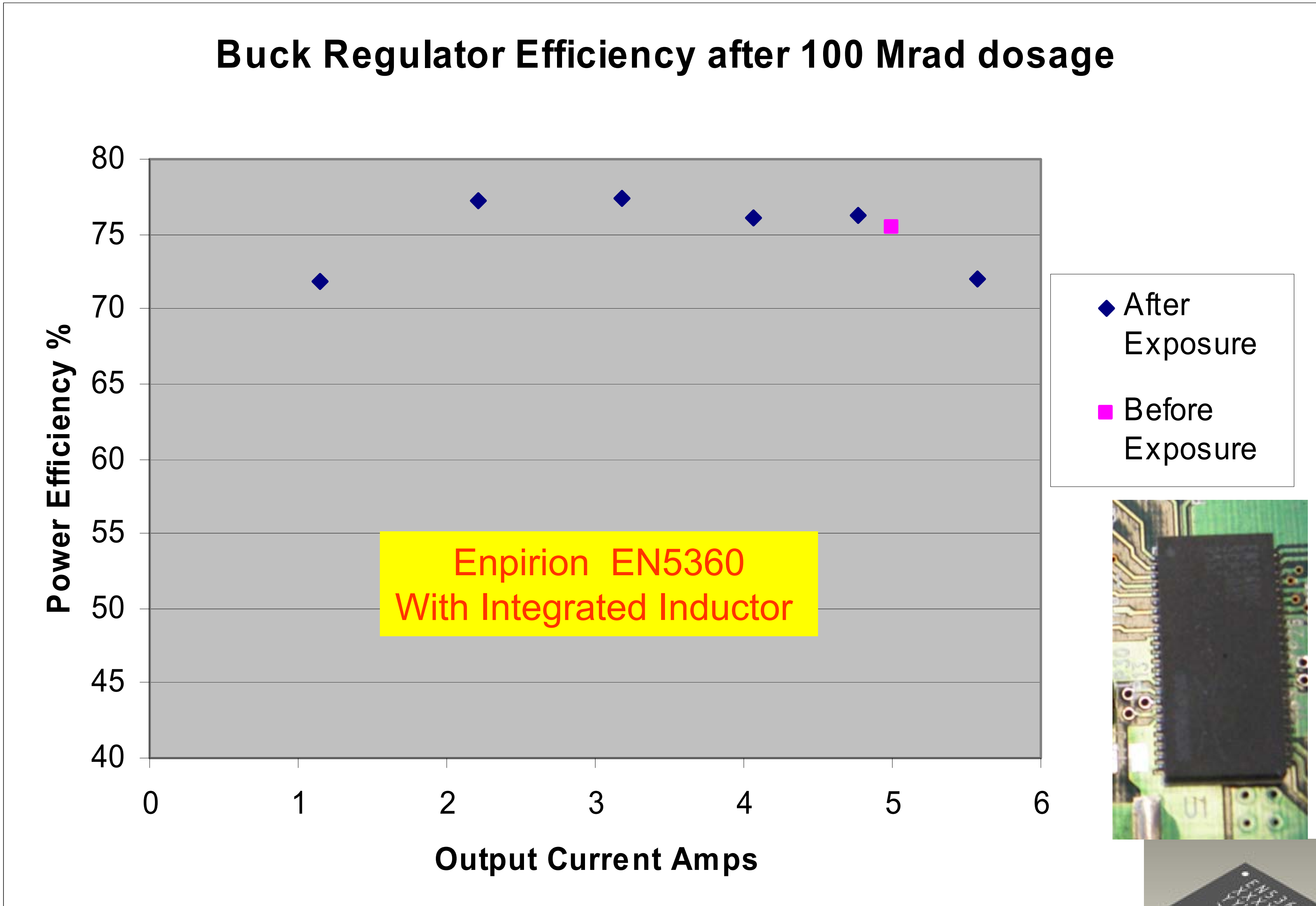
Vout = 11%

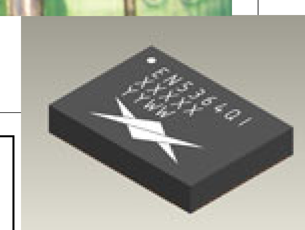


Control Switch: Switching Loss > I^2
Synch Switch: Rds Loss Significant

Vout = 50%





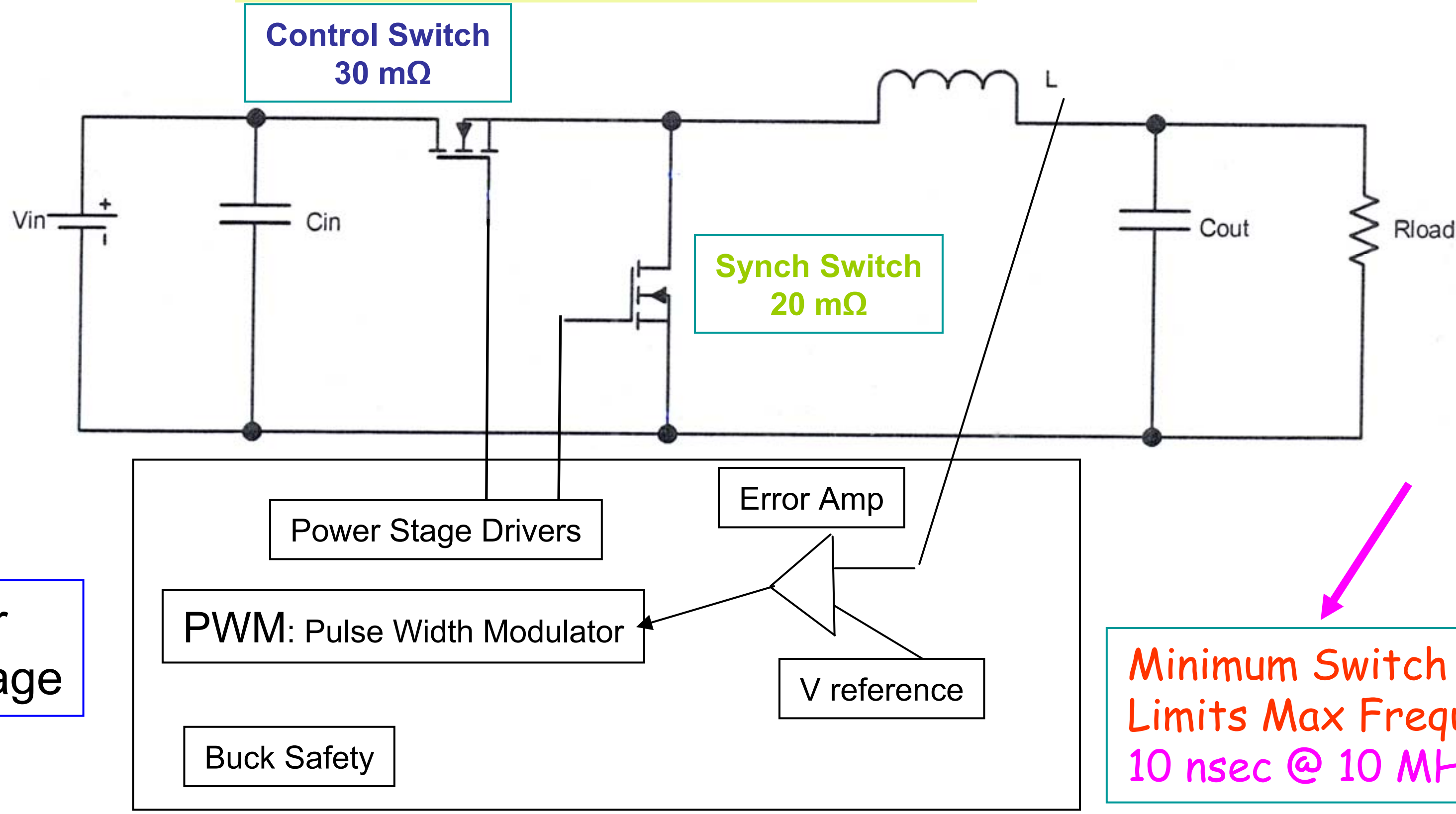


Found out at Power Technology conference 0.25 µm Lithography

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

Synchronous Buck Converter

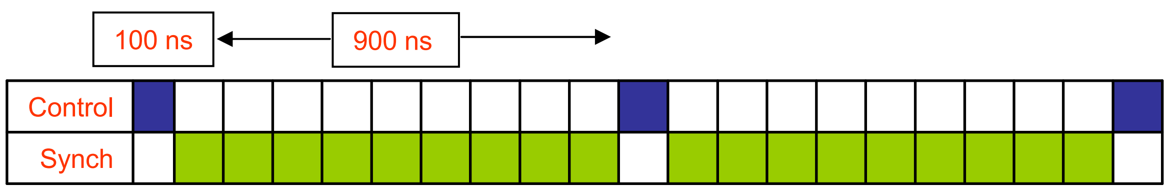
Power Stage - High Volts



Controller Low Voltage

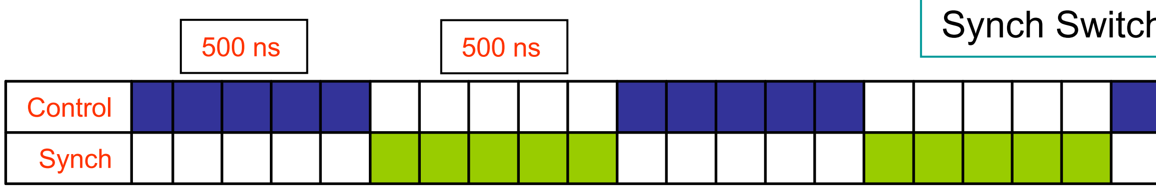
Minimum Switch ON Time Limits Max Frequency
10 nsec @ 10 MHz

Vout = 11%

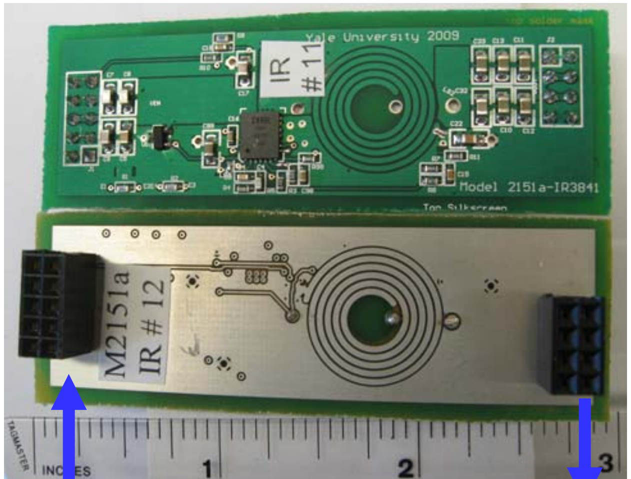


Control Switch: Switching Loss > I^2
Synch Switch: Rds Loss Significant

Vout = 50%



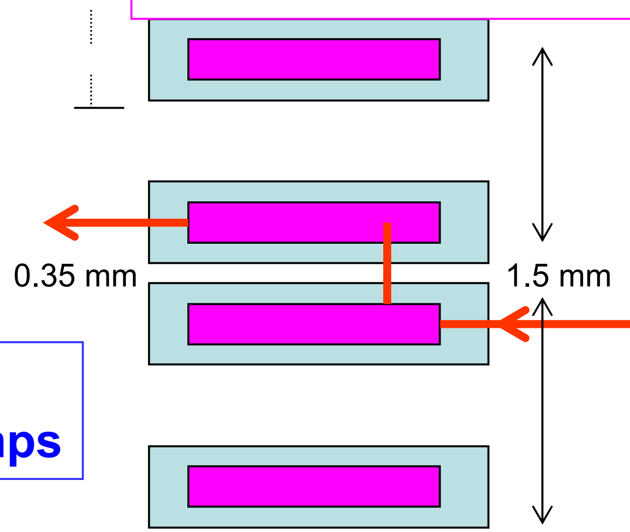
Plug In Card with Shielded Buck Inductor

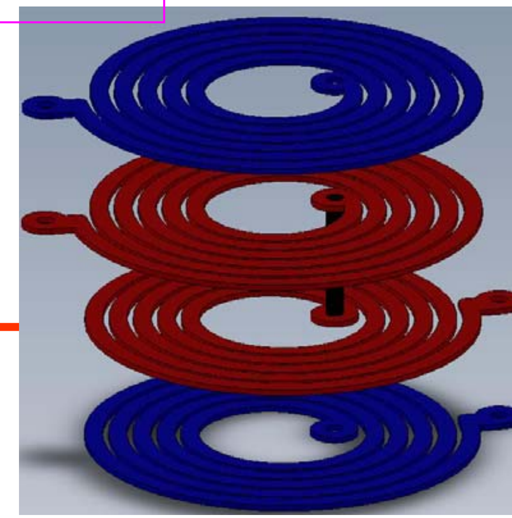


12 V

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

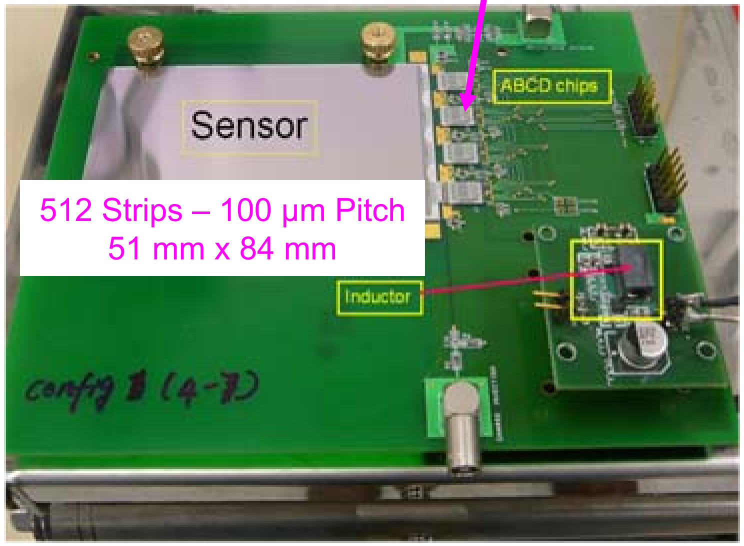
Spiral Coils Resistance in mΩ

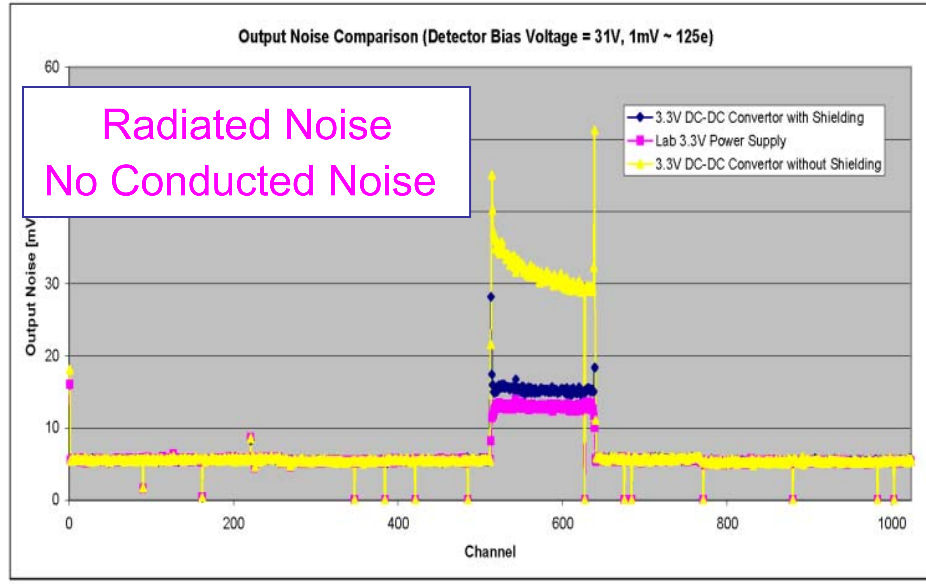
	Top	Bottom
3 Oz PCB	57	46
0.25 mm Cu Foil	19.4	17

Noise Tests with Silicon Sensors

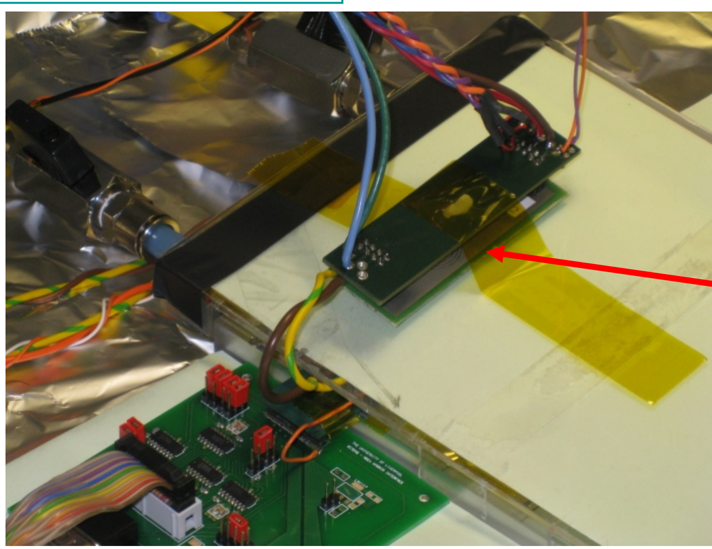
Test @ BNL

Only One Chip Bonded





Test @ Liverpool

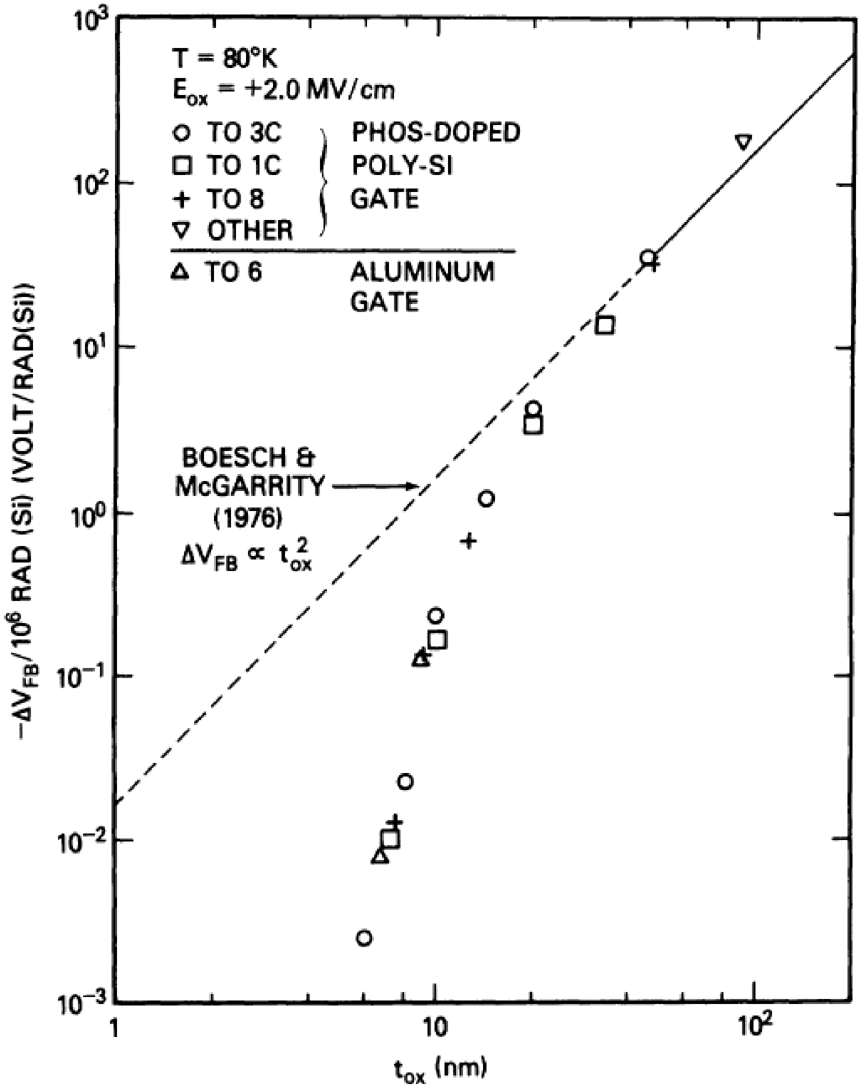


Plug in Card
1 cm from Coil
facing Sensor

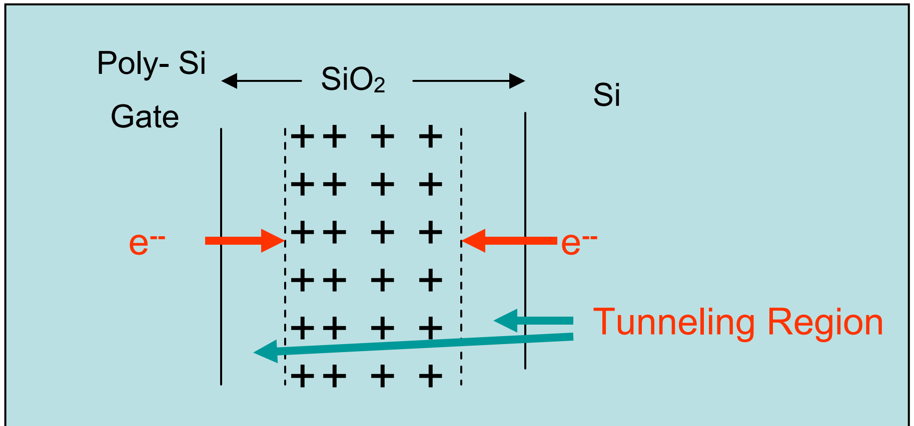
20 µm Al foil
shielding

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

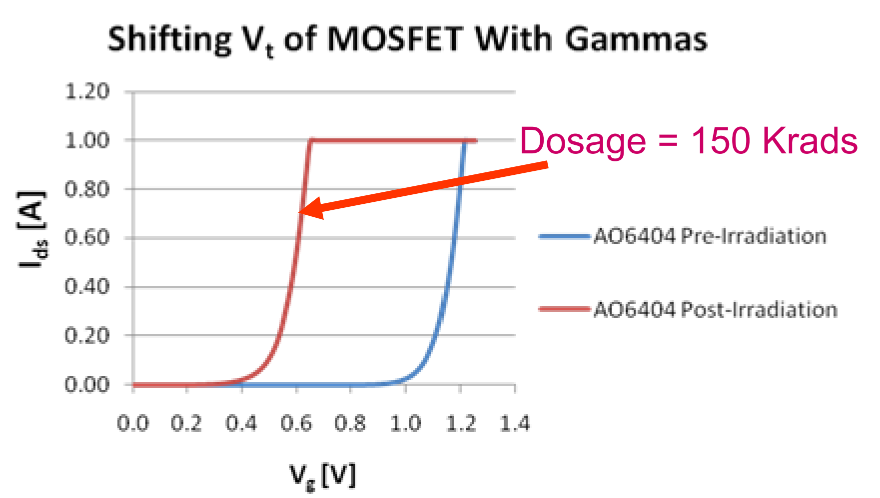
Threshold Shift vs Gate Oxide Thickness



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

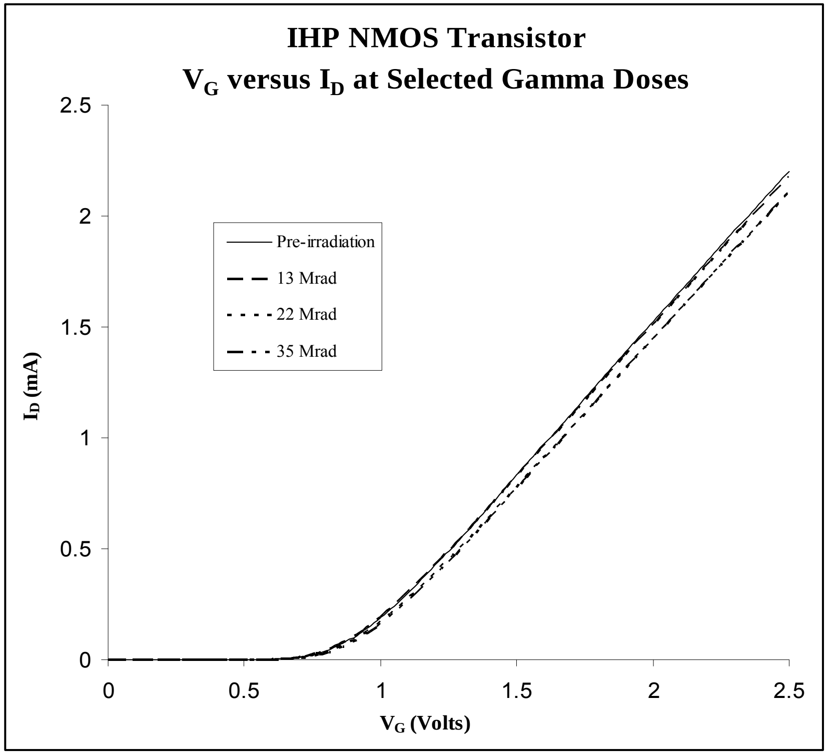
Can We Have
High Radiation Tolerance & Higher Voltage Together ???

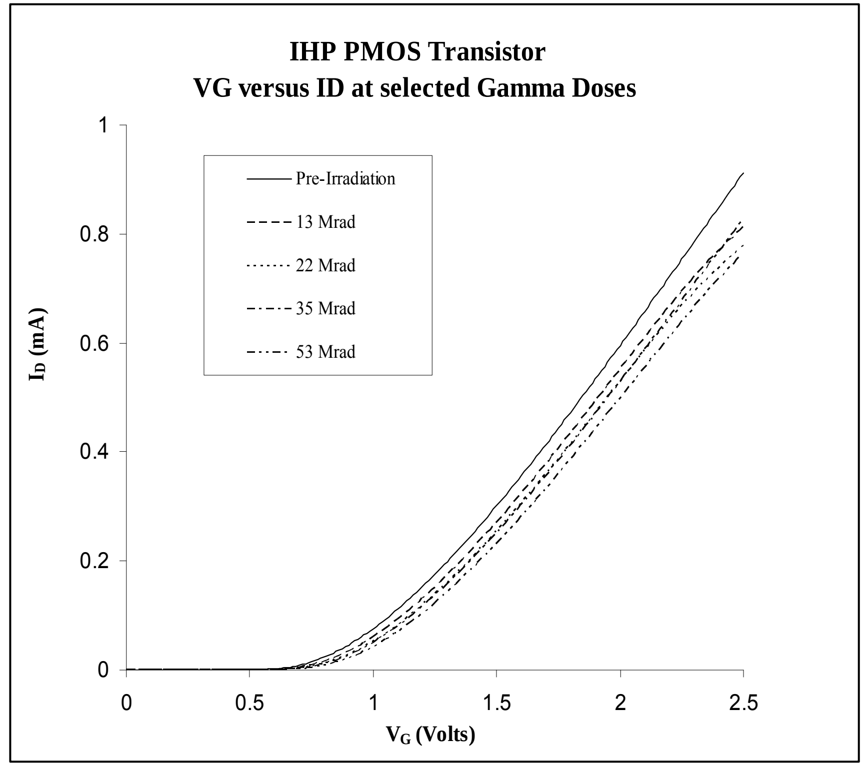
Controller : Low Voltage

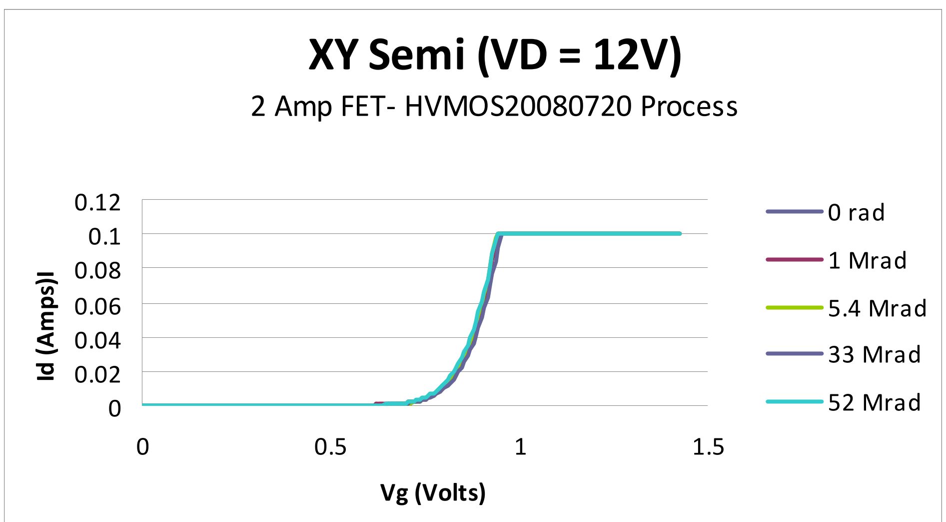
High Voltage: Switches –

LDMOS, Drain Extension, Deep Diffusion etc

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


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


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


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

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

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

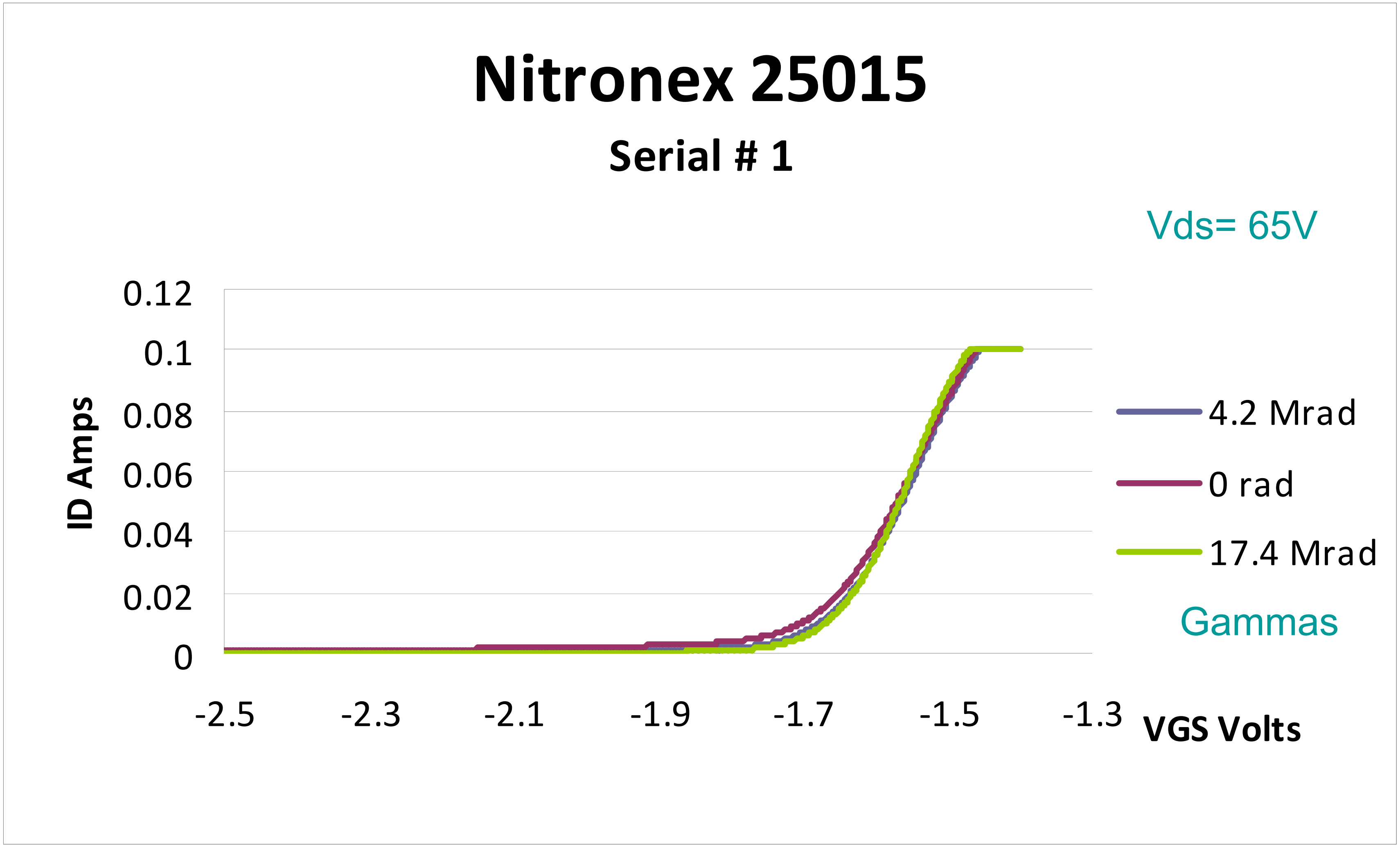
- ❖ 6 pieces: Eudyna EGNB010MK: GaN on siC
  - ✓ Done Neutrons

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



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

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.

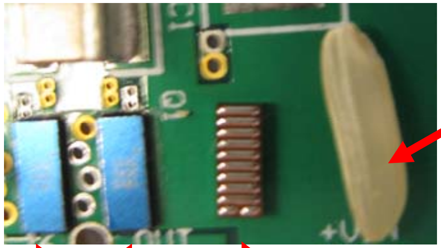
What can be achieved by this Development ?

- Current Reduction from Power Supply by DC-DC near Load
  Losses > Current^2 x Resistance

- Silicon ÷10 Current Reduction 5 Oodle > 0.5 Oodle
  CMOS converters can run @ Li Nitrogen temperature

- GaN ÷ 50 Current Reduction 5 Oodle > 0.1 Oodle
  Power Converters for Beam Line usage

Thermal Challenge

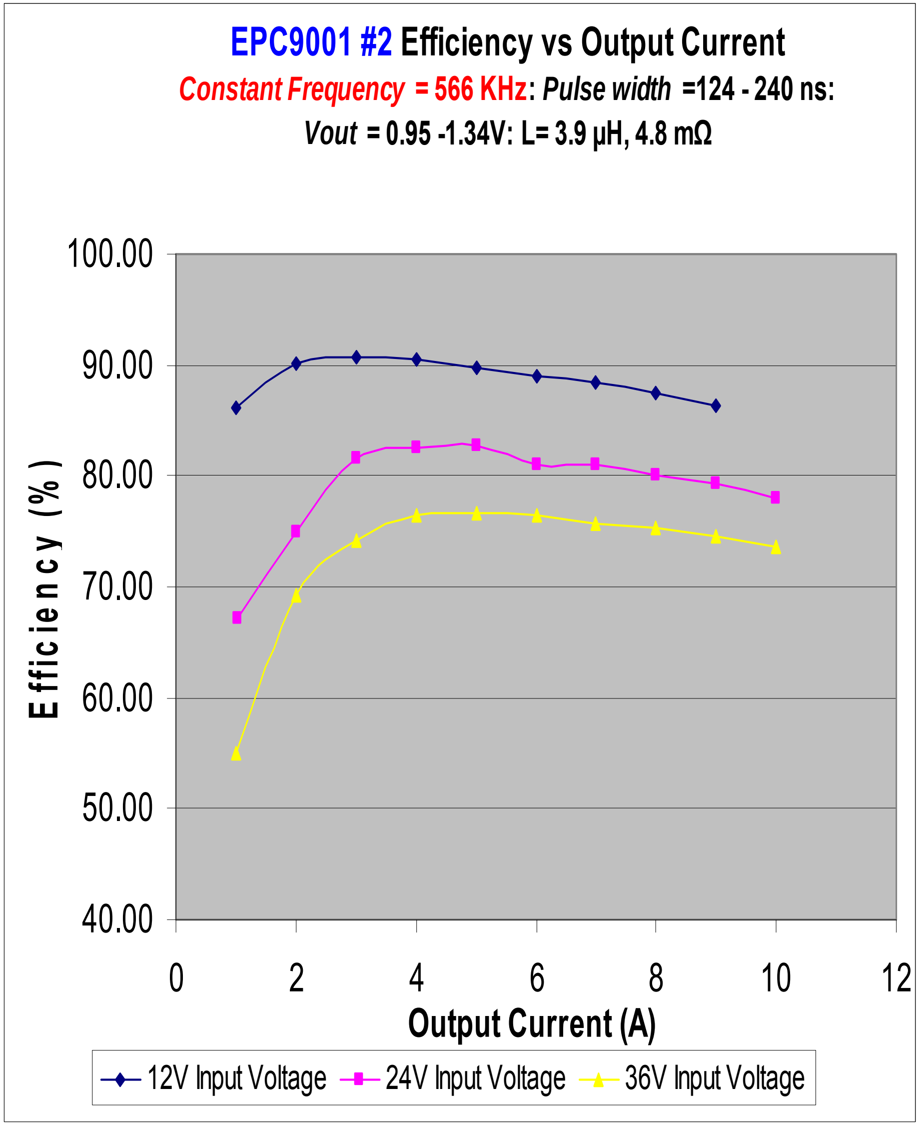


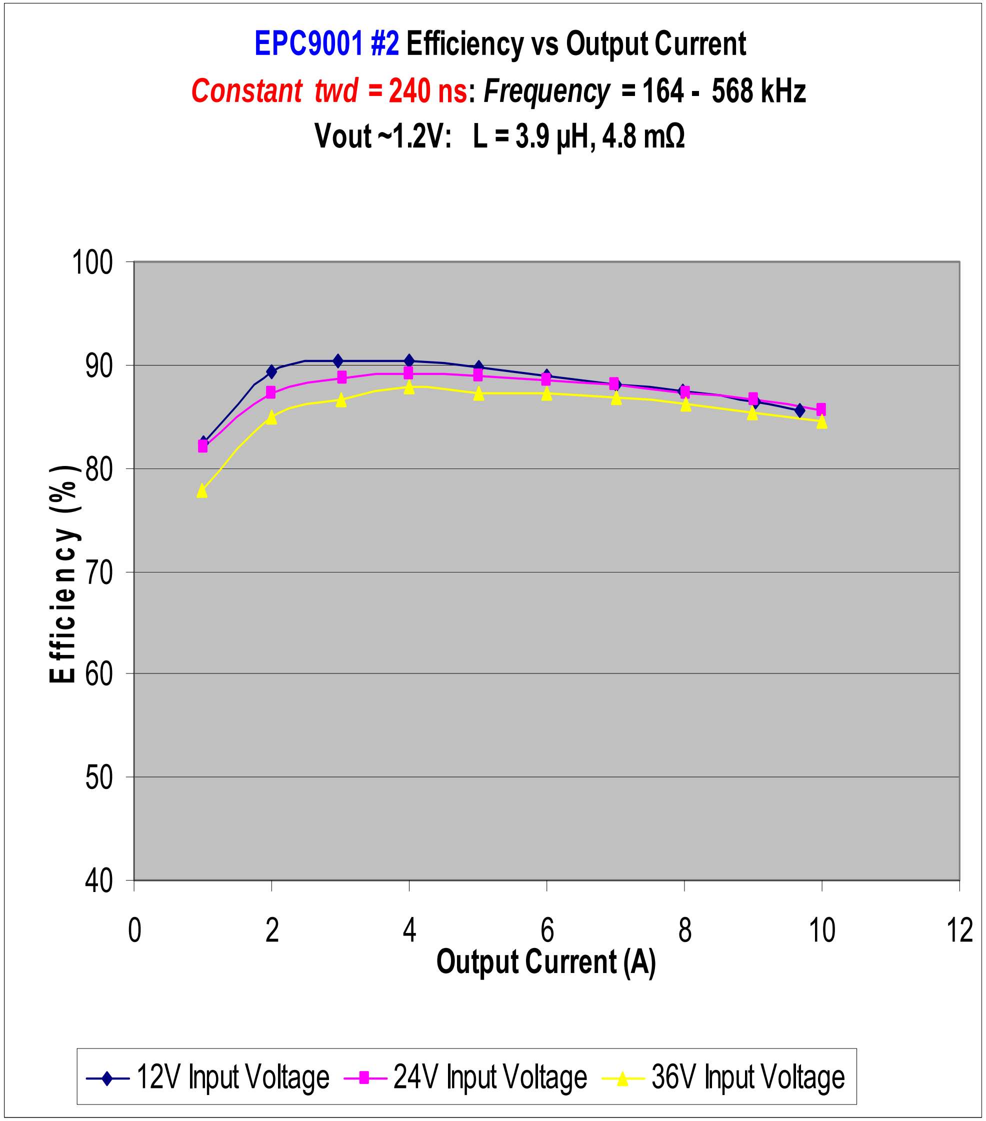
A grain of Basmati Rice
4 watts

GaN FETs
40 V 33 A 4mΩ

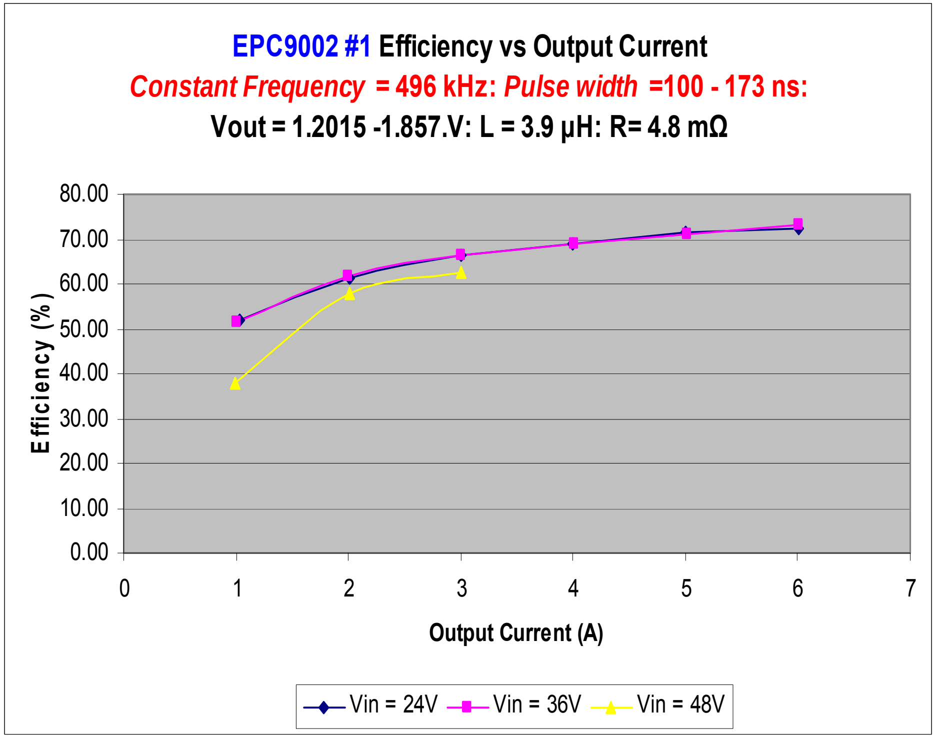
FET Solder side

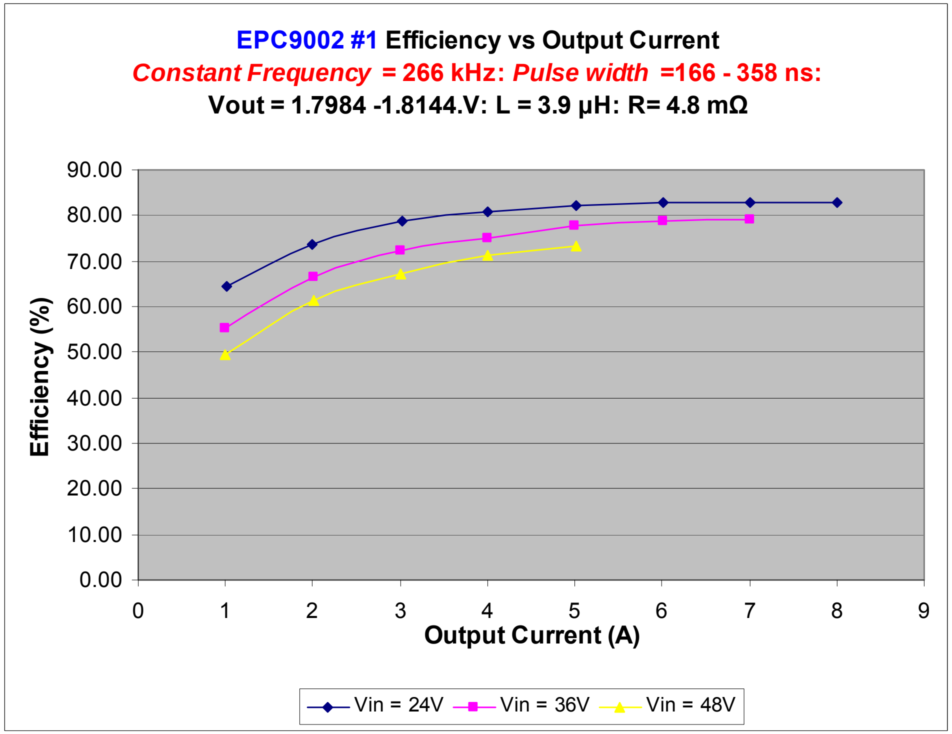
: epc 1015 – 40V: Efficiency with constant frequency and constant on pulse with inputs of 12, 24 & 36 Volts.





: epc 1001 – 100V: Efficiency with 2 constant frequencies. Inputs of 24, 36 & 48 Volts.

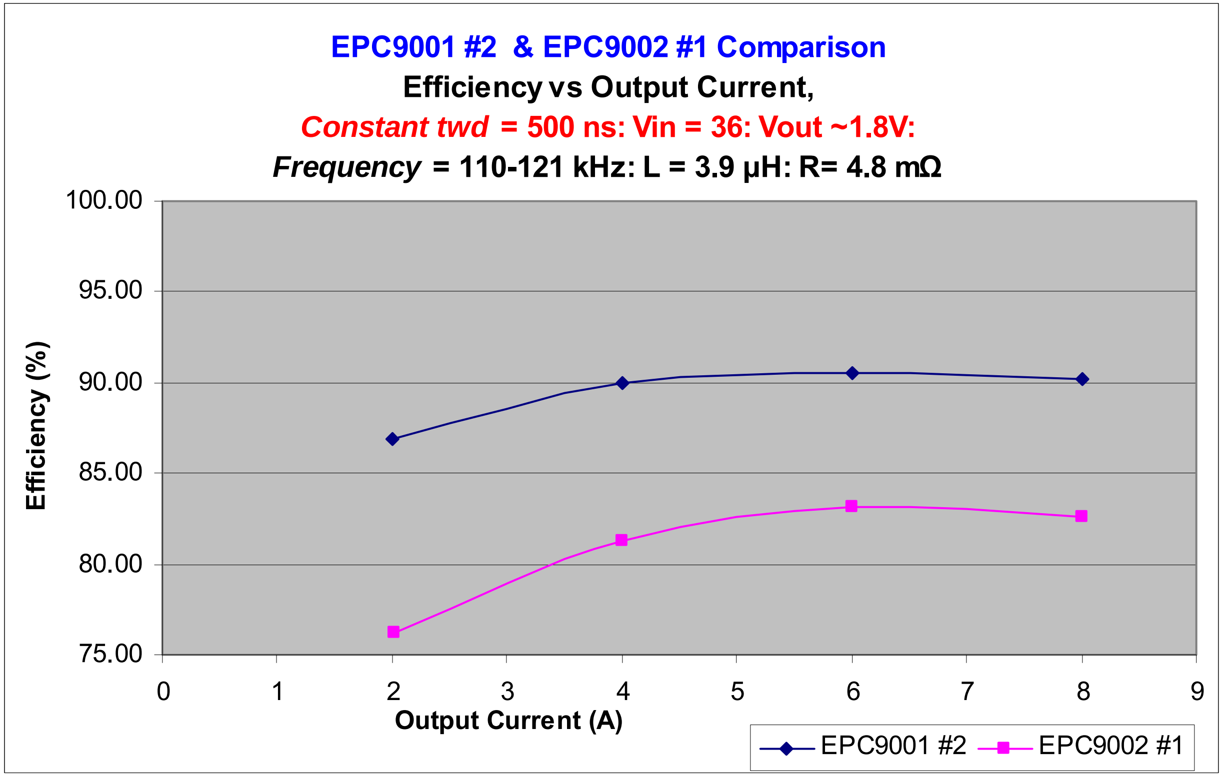


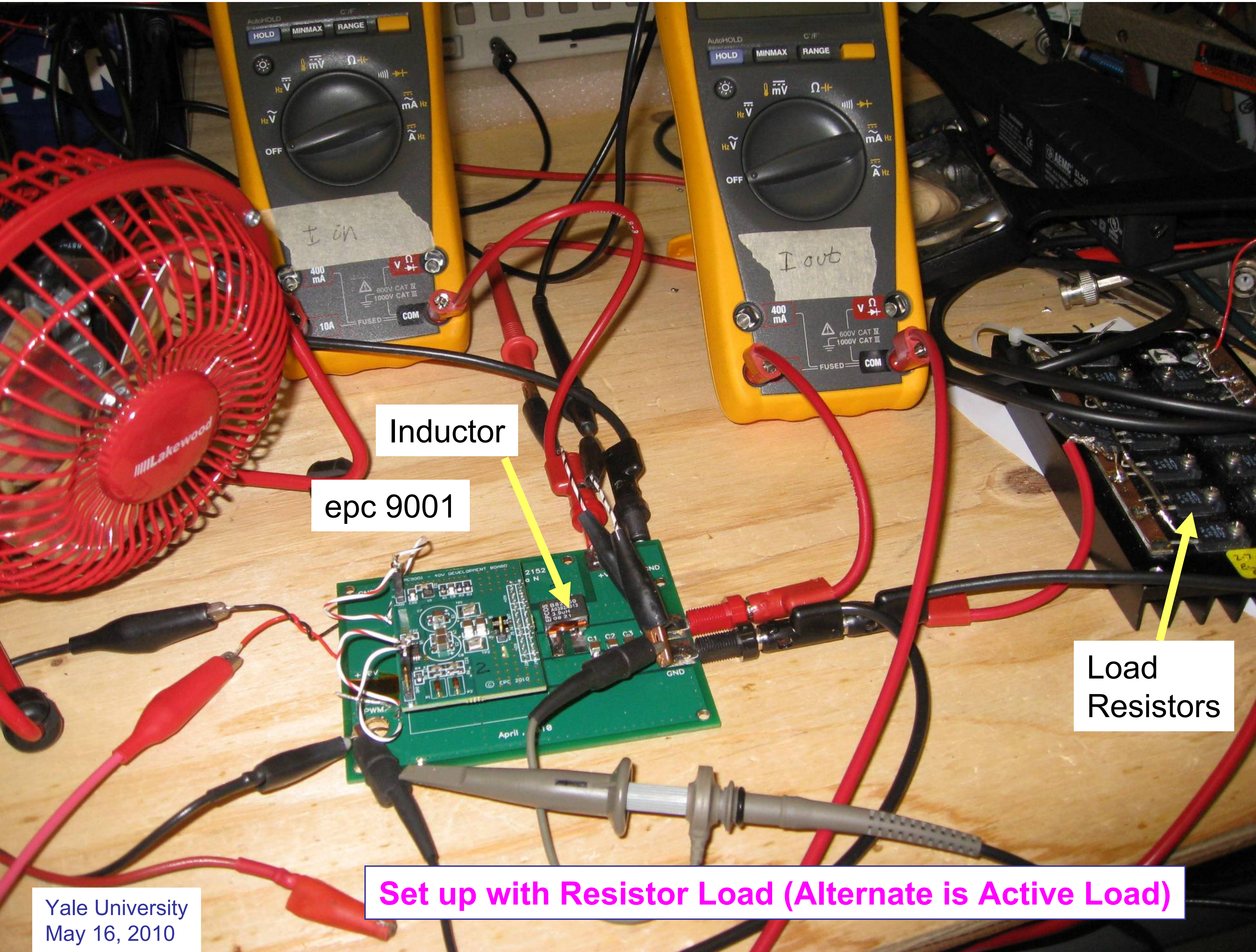


Longer On Time improves efficiency

Yale University
May 16, 2010

: epc 9001 & 9002 Comparison: Efficiency with constant 110 KHz.: **Vin = 36; Vout= 1.8 V.**





Set up with Resistor Load (Alternate is Active Load)

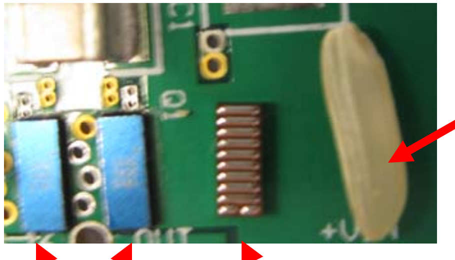
Power Delivery to HEP Detectors

- Need Increase in Power Delivery Efficiency for environment & budget
- Energy and Power are high priorities of current (and future) administration
- Power will be critical for next generation of HEP experiments: power bill and physics reach
- Increase emphasis on Power Electronics in US is needed. In Asia it is a Glamorous field. Best and the brightest going into this.
  Tremendous Economic opportunity
- In US no support for this type of R&D.
  In general, limited support for generic detector R&D.
- This R&D is needed for a viable US HEP program.
  Do we want or should US give up and transfer all HEP to CERN?
- Office of Science is very supportive of innovative, applied R&D with benefits to society.
- Do you agree? If so, how can you help to reverse this situation?

Satish Dhawan, Yale University
April 14, 2010

Supporting Bullets for Power Delivery to HEP Detectors

- Early work at Intel central research lab's AIR Core Coils.
- Bell labs / Lucent investigators started Enpirion (maker of the commercial chip that happens to be Radiation Hard)
- Radiation Hardness: Silicon LDMOS 15 V Few amps
- Gallium Nitride could be a game changer: 100 Volts, tens of amps. Opportunity for Beam line power supplies
- Gallium Nitride: US companies developing for Power switching market.
- Four years ago I started the field of DC-DC Converters for sLHC SiT. Introduced ideas at BNL & CERN meetings to a about 10 person at each lab. David Lissauer was at both. CERN started to work on it with EU funding.
- Basic ideas: Converters to run in high radiation and magnetic fields.



A grain of Basmati Rice
4 watts

GaN FETs
40 V 33 A 4mΩ

FET Solder side

Supporting Bullets for Power Delivery to HEP Detectors

- Yale Work: No base support available. Let CERN do it.
- Current Funding @ Yale: NSF/DoE University LCRD: $47k /year
- ATLAS Si Tracker Phase II has supported.
  Due to delay . FY11 funding = zero
- DoE HEP University Generic R&D: $600K /year. Request enhance base program
- Europe / CERN: With EU funding it is ~25MCHF (total or per year?)
- Balkanization of projects: ATLAS & CMS vertical organization.
  No room for people working on same thing to work together
- Workshop Presentation are considered confidential & cannot be shared/
  examined by the other Group
- Mission Oriented Funding. No room for Generic R&D with long payback
- Fermilab mission is HEP. Support Generic R&D on Power delivery Electronics

Working on Power Supply
Is not Glamorous

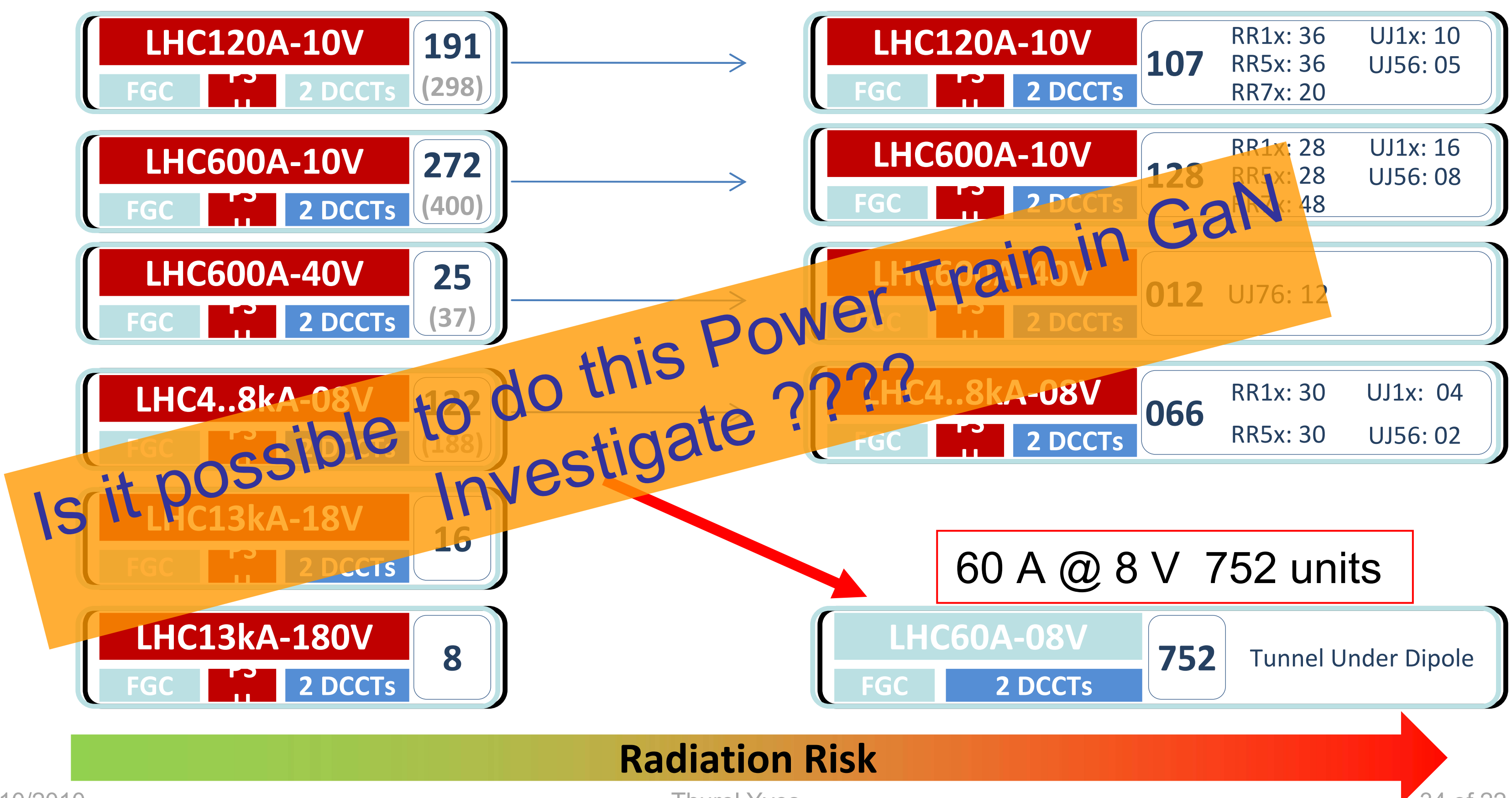
Top of the World is Cool but lonely !
Let us keep it cool with highly efficient PS
Swimming is Great at the North Pole

More Details: www.Yale.edu/FASTCAMAC click on DC-DC

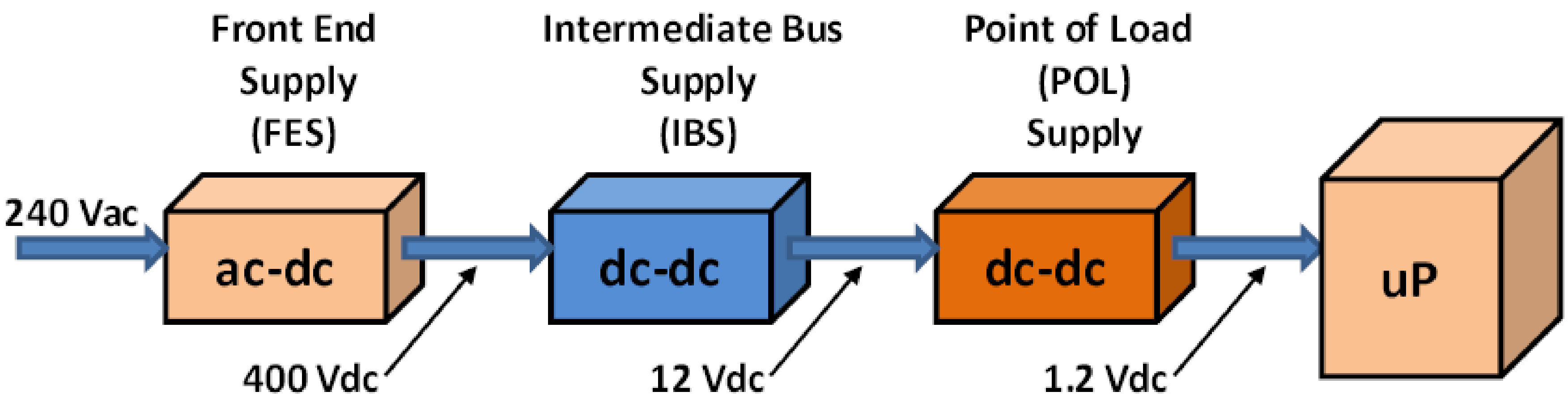
CONVERTERS INSTALLED

CERN – Chamonix 2010 Report

- **LHC CONVERTERS VS RADIATION *[2010]***
  - Rad Tolerant Design *or* standard Design with low Rad sensitivity (safe components)
  - Standard Design *and* Rad sensitivity unknown (too many components, sub-assemblies...)



AC - DC Power Efficiency Challenge by IBM September 2007



	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%***

Bodo’s Power System April 2010

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