I do not name in following slides all people who have dedicated time to the tests and analysis, or to simply help ... Their work is what has made these slides possible ...

The LHC experiments (ALICE, ATLAS, CMS, LHCb) have worked along the same paths to face the radiation concerns. The examples that I choose are mainly from the ATLAS detector, but many other examples, data, exist from the tests carried out by teams of all experiments.
Radiation Concerns in Power Supplies

• Outline

➢ Radiation effects reminder – Specific effects on power devices

➢ Single Event Breakdown – Single Event Gate Rupture

➢ Initial Tests for CERN Experiments

➢ The qualification for Power supplies in the ATLAS calorimeter

➢ “Generic” power supplies for experimental areas

➢ Some conclusions …
Radiation Concerns in Power Supplies

Radiation effects reminder – Specific effects on power devices

<table>
<thead>
<tr>
<th>TID</th>
<th>NIEL</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SEU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single Event Upset</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electrical charge corruption,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not a component damage</td>
</tr>
</tbody>
</table>

These two effects are specific to power devices
Radiation Concerns in Power Supplies

 Radiation effects reminder – Specific effects on power devices

<table>
<thead>
<tr>
<th>TID</th>
<th>NIEL</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Ionizing Dose</td>
<td>Non Ionizing Energy Loss</td>
<td>Single Event Upset</td>
</tr>
</tbody>
</table>

- Charges accumulate in isolant
- Current gain degradation in BJT
- Data corruption

<table>
<thead>
<tr>
<th>SEB</th>
<th>SEGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Event Breakdown</td>
<td>Single Event Gate Rupture</td>
</tr>
</tbody>
</table>

- Induced breakdown at Vds > 50V
- Gate rupture at negative Vgs (Off)

---

June 2nd, 2009 R2E Radiation Workshop&School - F.Anghinolfi PH/ESE
Radiation Concerns in Power Supplies

➢ Single Event Breakdown

From early literature (1987)

SEB/SEGR were first reported on space satellites, breakdown at random on power MOSFETS (not a dose effect)

Similarity with SEB observed on high voltage diodes used in electric transportation (trains) : induced at ground level by atmospheric neutrons. These are very large area devices.

SEB were analyzed first with heavy ions (space environment)

SEB was detected with low LET ions, then later on with high energy protons and neutrons
Radiation Concerns in Power Supplies

- Single Event Breakdown

[1] Experimental studies of single-event gate rupture and burnout in vertical power MOSFETs
Titus, J.L.; Wheatley, C.F.;
Nuclear Science, IEEE Transactions on
Volume 43, Issue2, Part 1, April 1996 Page(s):533 - 545

[2] First observations of power MOSFET burnout with high energy neutrons
Oberg, D.L.; Wert, J.L.; Normand, E.; Majewski, P.P.; Wender, S.A.;
Nuclear Science, IEEE Transactions on
Radiation Concerns in Power Supplies

- Single Event Breakdown

SEB seen with atmospheric neutrons (14 MeV) at ground level
No SEB seen at 1MEV range
Equivalence of SEB cross sections with protons or neutrons (Oberg, Normand)

From [2], previous slide (WNR data : up to 180 MeV neutrons spectrum)
Radiation Concerns in Power Supplies

- Single Event Breakdown

A figure of the SEB mechanism

A side note about protons:

The proton does not release enough energy to trigger a direct breakdown mechanism as heavy ions do.

The breakdown with protons is modeled as a two step process:
- 1- nuclear recoil (Si atom hit by the proton, transformed, eventually release α particle)
- 2- An avalanche phenomenon, which is responsible of the charge amount up to breakdown

SEB concerns only the N-Channel devices
Observed on “D-MOS”, BJT and IGBT Transistors
Radiation Concerns in Power Supplies

- Single Event Breakdown

SEB failure rate drops by derating Vds

Three transistors (Vds = 500, 400, 300V) tested in the WNR (high energy neutrons reactor)

400V Vds max device failure rate vs. effective Vds

500V Vds max device failure rate vs. effective Vds

3 orders of magnitude less with 50V Vds drop
Radiation Concerns in Power Supplies

- Single Event Breakdown

SEB failure rate does not decrease in proportion of increased max Vds rated devices

75% of 400V device: SEB @ 8E-5
75% of 500V device: SEB @ 2E-3
Radiation Concerns in Power Supplies

➢ Single Event Gate Rupture

Consists of gate oxide rupture initiated by the ion energy release in the gate oxide, in presence of an electric field

SEGR tests with Heavy ions (ref [1] in slide 6)

Occurs at low Vds, negative Vgs (N-channel)
Affects both P or N type devices
Radiation Concerns in Power Supplies

- Single Event Gate Rupture

SEGR have been observed with protons (from 1998)

However the tests here are difficult (destructive)

There was no explicitly identified SEGR failure during our protons tests performed on the power systems for experiments

Titus et al.
“Proton Induced Dielectric Breakdown”
Radiation Concerns in Power Supplies

- Initial Tests for CERN experiments

  - NIEL effects on commercial systems measured with neutrons
  - SEB Tests on Power devices

Note: NIEL (Non Ionizing Energy Loss) affects the crystalline structure of the Si material. Both protons and neutrons are doing NIEL effect damages. The proton reaction is more complex to analyze because of the charge interactions (ionizing dose). The neutron field is preferred because it comes with limited ionizing dose.

In term of NIEL damage, $1 \times 10^{11}$ protons @ 60MeV or $1.6 \times 10^{11}$ 1MeV neutrons are equivalent.
# Radiation Concerns in Power Supplies

- **Initial Tests for CERN experiments, commercial power units**

## TEST AGAINST NEUTRONS, PROSPERO REACTOR, France, fluence at 1MeV

<table>
<thead>
<tr>
<th>Type</th>
<th>Input Voltage</th>
<th>Output Current</th>
<th>First phase</th>
<th>Second phase</th>
<th>Voltage difference</th>
<th>N-dose at end of first acquisition</th>
<th>Output Voltage difference</th>
<th>N-dose at end of second acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta AC/DC 75SX5</td>
<td>230Vac</td>
<td>9.75A</td>
<td>Vout start of acquisition (V): 4.9960</td>
<td>Vout at end of first acquisition (V): 5.0093</td>
<td>N-dose (n/cm²): 0.197</td>
<td>10^12</td>
<td>0.0133</td>
<td>Vout at end of second acquisition (V): 5.0103</td>
</tr>
<tr>
<td>CEA DC/DC C000071003</td>
<td>48Vdc</td>
<td>4.5A</td>
<td>Vout start of acquisition (V): 4.8959</td>
<td>Vout at end of first acquisition (V): 4.9898</td>
<td>N-dose (n/cm²): 0.197</td>
<td>10^12</td>
<td>0.0030</td>
<td>Vout at end of second acquisition (V): 4.9027</td>
</tr>
<tr>
<td>Melcher DC/DC 48IMR-25-05-2</td>
<td>48Vdc</td>
<td>3.75A</td>
<td>Vout start of acquisition (V): 4.9724</td>
<td>Vout at end of first acquisition (V): 4.9800</td>
<td>N-dose (n/cm²): 0.197</td>
<td>10^12</td>
<td>0.0076</td>
<td>Vout at end of second acquisition (V): 4.9824</td>
</tr>
<tr>
<td>Lambda DC/DC RM-30-48-5</td>
<td>48Vdc</td>
<td>4.5</td>
<td>Vout start of acquisition (V): 4.9128</td>
<td>Vout at end of first acquisition (V): 4.9101</td>
<td>N-dose (n/cm²): 0.197</td>
<td>10^12</td>
<td>-0.0027</td>
<td>Vout at end of second acquisition (V): 4.9134</td>
</tr>
<tr>
<td>Artesyn DC/DC BX4048S05SM</td>
<td>48Vdc</td>
<td>6</td>
<td>Vout start of acquisition (V): 4.9760</td>
<td>Vout at end of first acquisition (V): 4.9825</td>
<td>N-dose (n/cm²): 0.197</td>
<td>10^12</td>
<td>0.0065</td>
<td>Vout at end of second acquisition (V): 4.9892</td>
</tr>
<tr>
<td>Syko DC/DC SRI-U-50-05-60</td>
<td>48Vdc</td>
<td>4.5</td>
<td>Vout start of acquisition (V): 5.0899</td>
<td>Vout at end of first acquisition (V): 5.0745</td>
<td>N-dose (n/cm²): 0.197</td>
<td>10^12</td>
<td>-0.0154</td>
<td>Vout at end of second acquisition (V): 5.0754</td>
</tr>
<tr>
<td>Traco DC/DC TED 0511</td>
<td>5Vdc</td>
<td>300mA</td>
<td>Vout start of acquisition (V): 5.0515</td>
<td>Vout at end of first acquisition (V): 4.9421</td>
<td>N-dose (n/cm²): 0.197</td>
<td>10^12</td>
<td>-0.1094</td>
<td>Vout at end of second acquisition (V): 5.0583</td>
</tr>
</tbody>
</table>

Tests carried out by PH/ESS team (Chris Parkman, Bruno Allongue)
Radiation Concerns in Power Supplies

- Initial Tests for CERN experiments, commercial power units

TEST AGAINST NEUTRONS, PROSPERO REACTOR, France, fluence at 1MeV

All failures were related to components using the junction (bipolar) technology: optocouplers and voltage references are damaged by the NIEL effects

<table>
<thead>
<tr>
<th>Firm</th>
<th>Reference</th>
<th>Type</th>
<th>Input</th>
<th>Output</th>
<th>Quantity</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta</td>
<td>75 SX 5</td>
<td>AC/DC</td>
<td>230Vac</td>
<td>5V/13A</td>
<td>2</td>
<td>Standard (not modified)</td>
</tr>
<tr>
<td>Delta</td>
<td>75 SX 5</td>
<td>AC/DC</td>
<td>230Vac</td>
<td>5V/13A</td>
<td>4</td>
<td>Modified optocoupler 6N138</td>
</tr>
<tr>
<td>Delta</td>
<td>75 SX 5</td>
<td>AC/DC</td>
<td>230Vac</td>
<td>5V/13A</td>
<td>4</td>
<td>Modified optocoupler 6N139</td>
</tr>
<tr>
<td>Lambda</td>
<td>RM 30 48 5</td>
<td>DC/DC</td>
<td>36 to 60 Vdc</td>
<td>5V/6A</td>
<td>2</td>
<td>Modified optocoupler 6N139</td>
</tr>
<tr>
<td>Melcher</td>
<td>48 IMR 25 05 2</td>
<td>DC/DC</td>
<td>36 to 72 Vdc</td>
<td>5V/5A</td>
<td>2</td>
<td>Modified optocoupler 6N138</td>
</tr>
<tr>
<td>Melcher</td>
<td>HBS050ZG-A</td>
<td>DC/DC</td>
<td>32 to 75 Vdc</td>
<td>5V/10A</td>
<td>2</td>
<td>Magnetic coupling</td>
</tr>
<tr>
<td>Vicor</td>
<td>V48C5C100A</td>
<td>DC/DC</td>
<td>36 to 75 Vdc</td>
<td>5V/20A</td>
<td>4</td>
<td>Magnetic coupling</td>
</tr>
<tr>
<td>Vicor filters</td>
<td>VIRAME2</td>
<td>Ripple filter</td>
<td>5 to 50 Vdc</td>
<td>20A</td>
<td>2</td>
<td>Connected to DC/DC Vicor</td>
</tr>
<tr>
<td>Actil filters</td>
<td>AXC102</td>
<td>Ripple filter</td>
<td>3 to 28 Vdc</td>
<td>20A</td>
<td>2</td>
<td>Connected to AC/DC Delta</td>
</tr>
<tr>
<td>Actil regulator</td>
<td>AXV102R</td>
<td>Linear regulator</td>
<td>2 to 6 Vdc</td>
<td>2.7V/20A</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Radiation Concerns in Power Supplies

- Initial Tests for CERN experiments, commercial power units

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Voltage</th>
<th>Current</th>
<th>Voltage Shift</th>
<th>Neutrons Damage</th>
<th>Residual Voltage</th>
<th>Unmod. Optocoupler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta AC/DC 75SX5</td>
<td>Siemens SFH617 optocoupler</td>
<td>230Vac</td>
<td>9.75</td>
<td>4.9927</td>
<td>6.8606</td>
<td>2.98 x 10¹²</td>
<td>1.8679</td>
</tr>
<tr>
<td>Lambda DC/DC RM-30-48-5</td>
<td>HP 6N139 optocoupler</td>
<td>48Vdc</td>
<td>4.5</td>
<td>4.9109</td>
<td>4.9703</td>
<td>2.98 x 10¹²</td>
<td>0.0594</td>
</tr>
<tr>
<td>Melcher DC/DC 48-IMR-25-05-2</td>
<td>HP 6N138 optocoupler</td>
<td>48Vdc</td>
<td>3.75</td>
<td>4.9696</td>
<td>4.9944</td>
<td>2.98 x 10¹²</td>
<td>0.0248</td>
</tr>
<tr>
<td>Melcher DC/DC 48-IMX</td>
<td>Magnetic feedback</td>
<td>48Vdc</td>
<td>6</td>
<td>4.9398</td>
<td>4.8739</td>
<td>2.98 x 10¹²</td>
<td>-0.0659</td>
</tr>
<tr>
<td>Vicor DC/DC V48C5C100A</td>
<td>Magnetic feedback</td>
<td>48Vdc</td>
<td>15</td>
<td>4.8213</td>
<td>4.8626</td>
<td>2.98 x 10¹²</td>
<td>0.0413</td>
</tr>
<tr>
<td>Actil Regulator AXV 102R</td>
<td>Linear feedback</td>
<td>5Vdc</td>
<td>6</td>
<td>2.0861</td>
<td>2.0851</td>
<td>2.98 x 10¹²</td>
<td>-0.0010</td>
</tr>
</tbody>
</table>

After installation of one identified type of radiation tolerant optocoupler, all systems are tolerant to neutrons (NIEL) damage.

The residual voltage shifts can be cured by changing the voltage references.
Radiation Concerns in Power Supplies

➢ Initial Tests for CERN experiments

At last, careful design from manufacturers selecting the proper components (opto, references, etc ...) produced NIEL resistant power systems

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
<th>Start of acquisition (A)</th>
<th>Voltage (V)</th>
<th>End of first acquisition (V)</th>
<th>Voltage difference (V)</th>
<th>Start of acquisition (V)</th>
<th>End of acquisition (V)</th>
<th>at end of acquisition (n/cm²)</th>
<th>Voltage difference (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiener 230Vac</td>
<td>9.3</td>
<td>1.989</td>
<td>1.989</td>
<td>$1.5 \times 10^{11}$</td>
<td>0.000</td>
<td>1.989</td>
<td>1.989</td>
<td>$3 \times 10^{11}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>1.967</td>
<td>1.966</td>
<td>$1.5 \times 10^{11}$</td>
<td>-0.001</td>
<td>1.966</td>
<td>1.967</td>
<td>$3 \times 10^{11}$</td>
<td>0.001</td>
</tr>
<tr>
<td>LV Caen box 72Vdc</td>
<td>2</td>
<td>2.965</td>
<td>2.965</td>
<td>$1.5 \times 10^{11}$</td>
<td>0.000</td>
<td>2.965</td>
<td>2.965</td>
<td>$3 \times 10^{11}$</td>
<td>0</td>
</tr>
<tr>
<td>Caen NIC 48Vdc</td>
<td>8</td>
<td>2.138</td>
<td>2.137</td>
<td>$1.5 \times 10^{11}$</td>
<td>-0.001</td>
<td>2.137</td>
<td>2.137</td>
<td>$3 \times 10^{11}$</td>
<td>0</td>
</tr>
<tr>
<td>LV Caen box 72Vdc</td>
<td>2</td>
<td>1.928</td>
<td>1.927</td>
<td>$1.5 \times 10^{11}$</td>
<td>-0.001</td>
<td>1.927</td>
<td>1.927</td>
<td>$3 \times 10^{11}$</td>
<td>0</td>
</tr>
<tr>
<td>DC/DC Vicor 300Vdc</td>
<td>55</td>
<td>4.998</td>
<td>5.001</td>
<td>$1.5 \times 10^{11}$</td>
<td>0.003</td>
<td>5.000</td>
<td>5.006</td>
<td>$3 \times 10^{11}$</td>
<td>0.006</td>
</tr>
<tr>
<td>DC/DC Vicor 300Vdc</td>
<td>30</td>
<td>11.996</td>
<td>12.004</td>
<td>$1.5 \times 10^{11}$</td>
<td>0.008</td>
<td>12.002</td>
<td>12.013</td>
<td>$3 \times 10^{11}$</td>
<td>0.011</td>
</tr>
<tr>
<td>DC/DC Syko 24Vdc</td>
<td>0.7</td>
<td>24.975</td>
<td>24.974</td>
<td>$1.5 \times 10^{11}$</td>
<td>-0.001</td>
<td>24.973</td>
<td>24.965</td>
<td>$3 \times 10^{11}$</td>
<td>-0.008</td>
</tr>
</tbody>
</table>
Radiation Concerns in Power Supplies

- Initial Tests for CERN experiments
  - NIEL effects on commercial systems measured with neutrons
  - SEB Tests on Power devices
Radiation Concerns in Power Supplies

➢ Initial tests for CERN experiments

Test of Vicor DC-DC converters
(C. Rivetta, B. Allongue, G. Berger, F. Faccio, W. Hajdas, 2001)
Radiation Concerns in Power Supplies

Measurement of the SEB cross-section of the power transistor Q
(C. Rivetta, B. Allongue, G. Berger, F. Faccio, W. Hajdas, 2001)

Test cards with 4 samples were irradiated at each voltage using the PSI 60Mev proton beam

SEB cross-section: Power transistor Q can be of 2 manufacturers (Q1 or Q2), rated 600V, 6A
Radiation Concerns in Power Supplies

Vicor converters operating in different conditions

Estimate of the Vds of the power transistor Q:

With the operating conditions set such as Vds does not exceed 300V, the SEB cross section is below $10^{-12}$ cm$^2$
# Radiation Concerns in Power Supplies

Tests using 60MeV, 200MeV & 300MeV proton beams

## Vicor converter V375B5C200A (nom:375V,5V,40A)

<table>
<thead>
<tr>
<th>Beam Energy</th>
<th>Vin</th>
<th>Vout</th>
<th>Iout</th>
<th>Max.Fluence</th>
<th>Results (Vds conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 MeV</td>
<td>260V</td>
<td>5V</td>
<td>1A</td>
<td>1.0x10^{11}p/cm²</td>
<td>No failure (Vds=275V)</td>
</tr>
<tr>
<td>300MeV</td>
<td>260V</td>
<td>5V</td>
<td>1A</td>
<td>1.0x10^{11}p/cm²</td>
<td>No failure (Vds=275V)</td>
</tr>
<tr>
<td>300MeV</td>
<td>260V</td>
<td>5V</td>
<td>5A</td>
<td>0.5x10^{11}p/cm²</td>
<td>No failure (Vds=290V)</td>
</tr>
<tr>
<td>300MeV</td>
<td>260V</td>
<td>5V</td>
<td>10A</td>
<td>0.5x10^{11}p/cm²</td>
<td>No failure (Vds=310V)</td>
</tr>
<tr>
<td>300MeV</td>
<td>260V</td>
<td>5V</td>
<td>15A</td>
<td>0.45x10^{11}p/cm²</td>
<td>Fail SEB (Vds=330V)</td>
</tr>
</tbody>
</table>

## Vicor converter V375B12C250A (nom:375V,12V,21A)

<table>
<thead>
<tr>
<th>Beam Energy</th>
<th>Vin</th>
<th>Vout</th>
<th>Iout</th>
<th>Max.Fluence</th>
<th>Results (Vds conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60MeV</td>
<td>260V</td>
<td>12V</td>
<td>5A</td>
<td>1.6x10^{11}p/cm²</td>
<td>No failure (Vds=310V)</td>
</tr>
</tbody>
</table>
Radiation Concerns in Power Supplies

Tests using 60MeV, 200MeV & 300MeV proton beams

**Vicor converter V300B12C250A (nom:300V,12V,21A)**

<table>
<thead>
<tr>
<th>Beam Energy</th>
<th>Vin</th>
<th>Vout</th>
<th>Iout</th>
<th>Max.Fluence</th>
<th>Results</th>
<th>(Vds conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60MeV</td>
<td>207V</td>
<td>12V</td>
<td>1A</td>
<td>1.0x10^{11}p/cm^2</td>
<td>No failure</td>
<td>(Vds=210V)</td>
</tr>
<tr>
<td>200MeV</td>
<td>200V</td>
<td>7.5V</td>
<td>20A</td>
<td>2.0x10^{11}p/cm^2</td>
<td>No failure</td>
<td>(Vds=255V)</td>
</tr>
<tr>
<td>300MeV</td>
<td>200V</td>
<td>7.7V</td>
<td>19.77A</td>
<td>3.0x10^{11}p/cm^2</td>
<td>No failure</td>
<td>(Vds=255V)</td>
</tr>
<tr>
<td>300MeV</td>
<td>200V</td>
<td>12V</td>
<td>19.77A</td>
<td>1.6x10^{10}p/cm^2</td>
<td>Fail SEB</td>
<td>(Vds=310V)</td>
</tr>
</tbody>
</table>

**Vicor converter V300B5C200A (nom:300V,5V,40A)**

<table>
<thead>
<tr>
<th>Beam Energy</th>
<th>Vin</th>
<th>Vout</th>
<th>Iout</th>
<th>Max.Fluence</th>
<th>Results</th>
<th>(Vds conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200MeV</td>
<td>200V</td>
<td>5.2V</td>
<td>25A</td>
<td>2.0x10^{11}p/cm^2</td>
<td>No failure</td>
<td>(Vds=290V)</td>
</tr>
</tbody>
</table>
Radiation Concerns in Power Supplies

Tests using 60MeV, 200MeV & 300MeV proton beams

- A methodology based on both the measure of the SEB cross-section of critical devices and the analysis of the power converter has been presented to predict de-rating factors for the input/output variables of power converters that will operate in an environment with high-energy neutrons.

- Experimental results using high-energy proton beams validate the methodology and also qualify the power converter units.

- Further analysis is necessary to predict the reliability (MTBF) of these converters in the foreseen neutron environment.
Radiation Concerns in Power Supplies

- The qualification for Power supplies in the ATLAS “LArg” calorimeter

- TID 450 Gray
- NIEL 7.7 x 10^{12} N/cm^2 for 1MeV neutrons
- SEB < 10^{-15} cm^2

Simulation Table

- Tested to 3000 Gray
- Tested to > 1 x 10^{13}
- Estimated at < 10^{-17}
Radiation Concerns in Power Supplies

ATLAS LArg Power module SEB and SEU tests

Test Conditions:

1) 158 MeV protons
2) Modules tested with minimal load, half load and full load.
3) Power Mosfets hit with $1.3 \times 10^{12}$ cm$^{-2}$ protons. Other active components in the module irradiated with a fluence of $6.7 \times 10^{11}$ protons cm$^{-2}$
4) Switching frequency and module output voltage are monitored.
5) Single power Mosfets tested for SEB cross section as a function of applied voltage to estimate the SEB cross section at the module voltage.

Results:

In the power module no SEB or SEU affects are observed. In extrapolating the data for the single Mosfets the extrapolated cross section at 300 volt bias for the device is $< 10^{-17}$ cm$^{-2}$

Conclusion:

The power module meets the requirements for SEB cross section of being $< 10^{-15}$ cm$^{-2}$ The power module shows no SEU effects.
Radiation Concerns in Power Supplies

Plot of SEB Cross section versus Voltage for On Semiconductor 10N60 600 Volt Power MOSFET

The power MOSFET is biased at 300V (cross section below 10E-17)
Radiation Concerns in Power Supplies

$^{60}$Co Gamma Irradiation Effects on ATLAS LArg Power Modules

- Input current increased in all irradiations with a difference of 5% by end of irradiation (3000 Gray).
- Output voltage decreased by 1-2%.
- Peak to Peak voltage increased by 10%.
- Switching frequency remained constant (166 – 168 kHz).
- One module (minimal load) died when it was turned on after 3150 Gray.
Radiation Concerns in Power Supplies

ATLAS LArg Module 1 MeV equivalent Neutron Testing

Conditions:

1) 2 supplies were simultaneously irradiated.
2) The modules were positioned on the neutron beam axis so that the sensitive components would receive the largest fluence.
3) One supply was fully loaded while the other module was minimally loaded.
4) The fully loaded module was placed closer to the source.
5) Output voltage, switching frequency, and peak to peak voltage is monitored.

Results:

1) No significant changes were observed in any parameters.
2) The center of the fully loaded power module received $10^{14}$ neutrons/ while the center of the minimally loaded module received $8 \times 10^{12}$ cm$^{-2}$. The fluence dropped to $2 \times 10^{12}$ cm$^{-2}$ on the edges for both.

Conclusion:

No changes due to neutron fluence was observed for either the loaded or unloaded power module. However, the unloaded module did not quite meet the qualifying fluence.
Radiation Concerns in Power Supplies

“Generic” power supplies for experimental areas

Aim was to draw specifications for power supplies deliverable from existing manufacturers, with a choice of inputs/outputs fitted to the potential users in ALICE, ATLAS, CMS, LHCb

The power supplies are specified to operate within the experimental areas environment:

- Magnetic field tolerance (several grades)
- Radiation field tolerance (several grades)

Concerning radiation, the prototypes and samples of the productions parts were tested in Neutron field (NIEL damage) and with Proton beam (TID and SEE)
Radiation Concerns in Power Supplies

➢ “Generic” power supplies for experimental areas

Radiation field tolerance:

The highest grade was set as:

- TID 140 Gray
- NIEL $1.0 \times 10^{12}$ N/cm$^2$ for 1MeV neutrons
- SEE test up to $2.0 \times 10^{11}$ protons/cm$^2$ for $>20$ MeV energy
- SEB, SEGR beyond measurable levels (at the above limits)
Radiation Concerns in Power Supplies

“Generic” power supplies for experimental areas

Two companies (A and B) were proposing 2 different systems:

<table>
<thead>
<tr>
<th>System (A)</th>
<th>System (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All logic devices are moved away from exposed power modules</td>
<td>Logic controllers and ICs on exposed power modules</td>
</tr>
<tr>
<td>Control/Monitoring through analog voltages</td>
<td>Control/Monitoring through digital lines</td>
</tr>
</tbody>
</table>
Radiation Concerns in Power Supplies

Solution “A”

1. AC-DC (w. PFC)
2. Control & monitoring
3. “Maraton” 12ch 50A DC-DC (3kW)

230VAC, single phase

385VDC

Ethernet

Water cooled

OPC Server

Radiation & magnetic field tolerance

June 2nd, 2009

R2E Radiation Workshop&Schoo -
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Radiation Concerns in Power Supplies

Solution “B”

1. Harmonic filter
   400VAC
   400VAC

2. Control & monitoring
   Ethernet

3. “EASY A3486 AC/DC”
   2ch 48V/40A/2KW
   48VDC

4. “EASY crate” with “EASY DC/DC”
   ex. 12ch 9A/45W

Air cooled

Radiation & magnetic field tolerance

June 2nd, 2009

R2E Radiation Workshop&School - F Anghinolfi PH/ESE
“Generic” power supplies for experimental areas

For manufacturer (A), the power device was selected after SEB tests performed at CERN on the IRRAD-1 beam line (24 GeV protons)
“Generic” power supplies for experimental areas

A second serie of tests under the nominal conditions: 400 V operational Vds, no SEB at 2E12 protons/cm², showed up good results with 4 components

<table>
<thead>
<tr>
<th>Component</th>
<th>VDS</th>
<th>Nbe of SEB</th>
<th>Fluence</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>W11NB80</td>
<td>400</td>
<td>36</td>
<td>2.00E+12</td>
<td>1.80E-11</td>
</tr>
<tr>
<td>W9NB90</td>
<td>400</td>
<td>0</td>
<td>2.00E+12</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>W9NC80Z</td>
<td>400</td>
<td>0</td>
<td>2.00E+12</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>APT10090BLL</td>
<td>400</td>
<td>0</td>
<td>2.00E+12</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>W8NB100</td>
<td>400</td>
<td>0</td>
<td>2.00E+12</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>

Finally the component W9NB90 (9A, 900 Vds breakdown) was first selected by the manufacturer (production units are using the W11NB90 (11A, 900 VDS breakdown) of the same technology)

B. Allongue, C. Rivetta, CERN/PH 2001
Radiation Concerns in Power Supplies

“Generic” power supplies for experimental areas

For manufacturer (B), the power device was selected from the previous knowledge of a SEB tolerant power device by derating Vds.

R.J. Tesarek, Fermilab, 2004
Radiation Concerns in Power Supplies

“Generic” power supplies (A) for experimental areas

4 power modules (at different specs) tested with 60MeV protons beam at Louvain-La-Neuve. No SEB, NIEL damage eqvlt. to $4.8 \times 10^{11}$ n/cm$^2$, TID 420 Gy
Radiation Concerns in Power Supplies

➢ “Generic” power supplies (B) for experimental areas

Protons beam at Uppsala (150MeV), ~ 20cm diameter
Radiation Concerns in Power Supplies

- “Generic” power supplies (B) for experimental areas

- First campaign, 150MeV protons
  Uppsala, 2005

- Many control losses, manual recoveries

- Protons Fluence: $1.09 \times 10^{11}$ p/cm²
Radiation Concerns in Power Supplies

➢ “Generic” power supplies (B) for experimental areas

Explanations for the observed defects:

- SEU (transient) 
- Reset

Correction:

- SEU (transient)
- Glitch filter

No (less) communication loss
Radiation Concerns in Power Supplies

- “Generic” power supplies (B) for experimental areas

Second campaign
150MeV protons,
Uppsala, 2006

Beam 20 cm
~25 deg. angle
Comm/Control area

Output 1
Output 2

Control loss
and recovery

Output Voltage (V)

Protons Fluence

0 5E+10 1E+11 1.5E+11 2E+11

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Radiation Concerns in Power Supplies

- “Generic” power supplies for experimental areas

Sacha Chilingarvov, for CMS

Neutron field (reactor) 1MeV energy

PROSPERO reactor

Chiller

EASY 3000

MARATON

LOAD
Radiation Concerns in Power Supplies

➢ “Generic” power supplies for experimental areas: NIEL up to $6 \times 10^{12}$ n/cm$^2$
Radiation Concerns in Power Supplies

- TODAY investigations for some detectors upgrade

- Reliability issues are frequent with power systems fabricated on demand. These issues are not related to the radiation damage, but have to do with connectors, power (heat) dissipation, operational point close to the margins ...

- An example with the (current) upgrade of power units for the LArg calorimeter in ATLAS:

  - New units are currently under development to replace the existing parts because of the predicted failure rate (not due to radiations ...)
Radiation Concerns in Power Supplies

- Power units for LArg upgrade: the potential issues are carefully listed:
  
  - In the ATLAS environment MOSFETs can suffer from voltage threshold shifts from ionizing radiation, Single Event Burnout (SEB), and Single Event Gate Rupture (SEGR) both caused by protons/neutrons with energies > 20 MeV.
  
  - Generally, SEGR does not occur unless the gate voltage is below ground. In this design the gate voltage is always above ground so this test is not done. **We do not need to test for SEGR.**
  
  - Generally SEB does not occur for MOSFETs with a maximum \( V_{DS} < 100 \) Volts. This means the only FET needing single event testing is the primary switching MOSFET. **We do not need to test BS170, FDN5630, STP60NE06, or BSH114 for SEB. Only STP9NK90Z and STP11NM80**
  
  - If the gate threshold voltage approaches or = 0 the FET is permanently on. A better device maintains a threshold voltage with a decent margin. **All MOSFETs need to be tested for this.**

Slide for the qualification of the Larg detector power unit upgrade version

James Kierstead and Hucheng Chen

Brookhaven National Lab Feb 27, 2009
TODAY investigations: most of the potential issues are carefully listed:

**TID**

- At our qualifying number of 45 krad, these MOSFETs have a threshold voltage of about 2 volts at that dose.

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James Kierstead and Hucheng Chen
Brookhaven National Lab Feb 27, 2009

Slide for the qualification of the Larg detector power unit upgrade version

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June 2nd, 2009 R2E Radiation Workshop F.Anghinolfi PH/ESE
Radiation Concerns in Power Supplies

TODAY investigations: most of the potential issues are carefully listed:

SEB

- In the design, the maximum voltage on the MOSFET is 280 V. By the time $V_{DS} = 450$ V, the cross section is $< 10^{-10}$ cm$^{-2}$.

James Kierstead and Hucheng Chen
Brookhaven National Lab Feb 27, 2009

Slide for the qualification of the large detector power unit upgrade version

June 2nd, 2009
Radiation Concerns in Power Supplies

➤ TODAY investigations: most of the potential issues are carefully listed:

NIEL

• Shown are changes in forward gain from neutron irradiation followed by gamma irradiation

James Kierstead and Hucheng Chen
Brookhaven National Lab Feb 27, 2009

Slide for the qualification of the Larg detector power unit upgrade version
Radiation Concerns in Power Supplies

- Some conclusions:
  - The SEB, specific defect of “high voltage” power devices, is easily turned down by the proper derating of VDS (tests are necessary).
  - TID, NIEL (neutrons) can still be a problem for long term operations, upgrades ... (Voltage reference drifts, optocouplers functional loss).
  - Logic circuits in exposed areas are subject to functional failures, some of them may be critical in power systems (SEU).
  - Custom made power units (in the case of experiments, “customized” because of the radiation and/or magnetic field tolerance ...) were always (?) presenting some reliability issues after fabrication.
  - THE TESTS IN APPROPRIATE PARTICLE ENVIRONMENT (Ionizing, NIEL, high energy PROTONS) PROVED TO BE USEFUL FOR THE DEFECT ANALYSIS.