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# High Voltage MUX for ATLAS Strip Tracker Upgrade

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on behalf of the ATLAS HVMUX group

RAL PPD 25 May 2022

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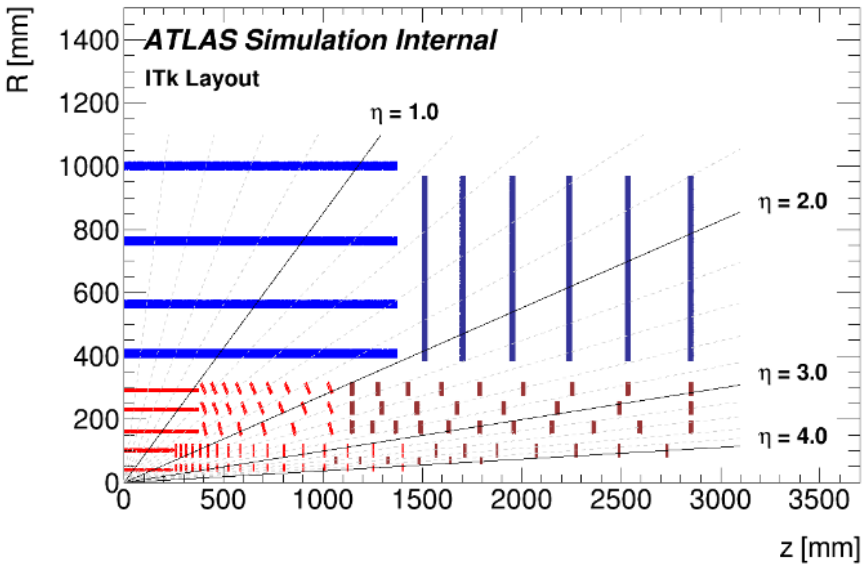
# Overview

- Introduction: needs for HVMUX in ITK in ATLAS Upgrade and current implementation
- HV-MUX details:
  - requirements
  - design
  - radiation hardness
  - reliability
- Summary & conclusions

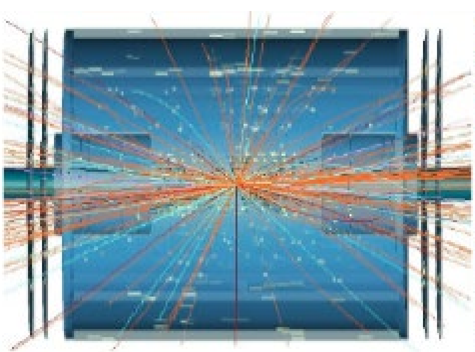
# Introduction



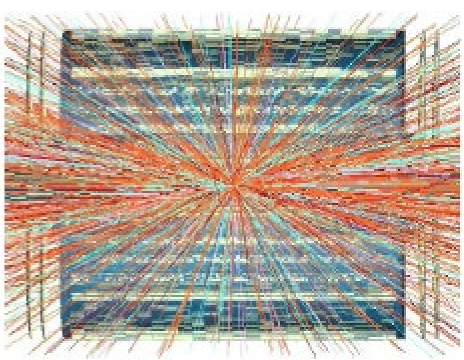

Phase 2 (HL-LHC) will see a replacement of the entire Inner Detector (ID) by an ~ 200 $m^2$ Silicon Tracker (Itk). Detectors arranged on staves (barrel) and petals (end-caps)

Challenges facing HL-LHC detector upgrades

- Higher Occupancies (~ 200 interactions / bunch crossing)
  - ↳Finer Segmentation
- Higher Particle Fluences (~ $10^{14}$ outmost layers to ~ $10^{16}$ innermost layers
  - ↳**Increased Radiation Tolerance (~ 10 increase in dose w.r.t. ATLAS )**
- **Large**r Area (~200 $m^2$)
  - ↳Cheaper Sensors
- More Channels (x100 w.r.t. current ID)
  - ↳**Efficient power/bias distribution / low material budget**



*From 1E33 $cm^{-2}$ $s^{-1}$*



*…to 5E34 $cm^{-2}$ $s^{-1}$*

# HV distribution

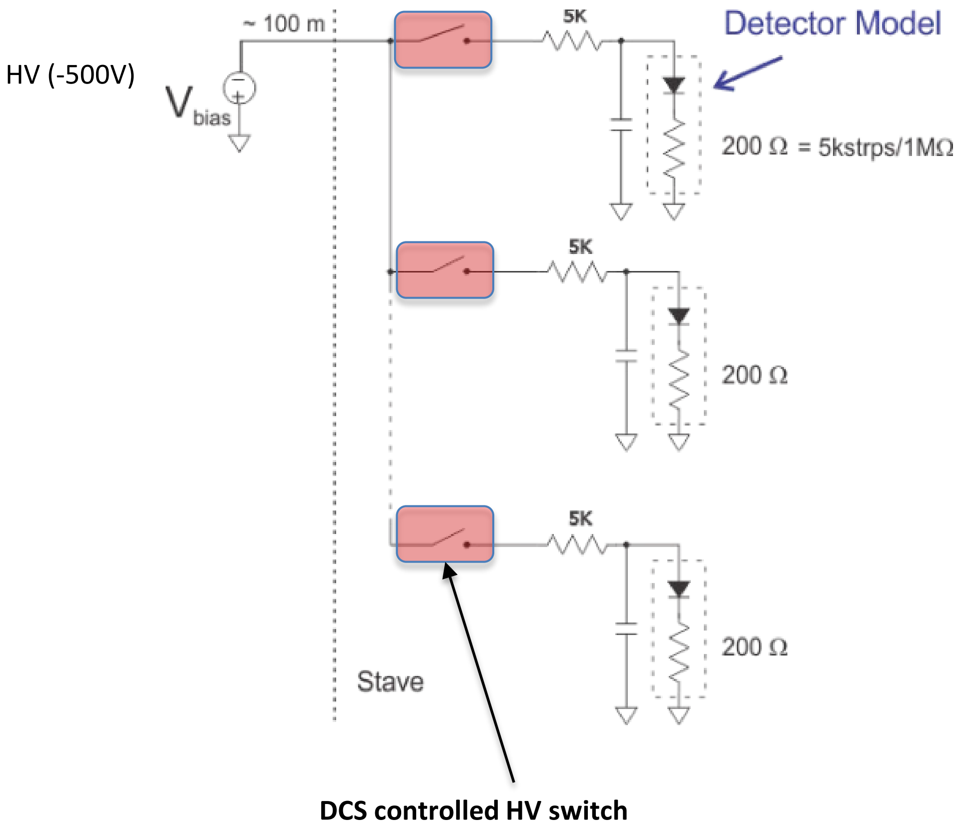
Current SCT uses independent powering for the 4088 detector modules.
Each sensor has its own independent HV bias line.
'Ideal' solution:

- High Redundancy
- Individual enabling or disabling of sensors and current monitoring

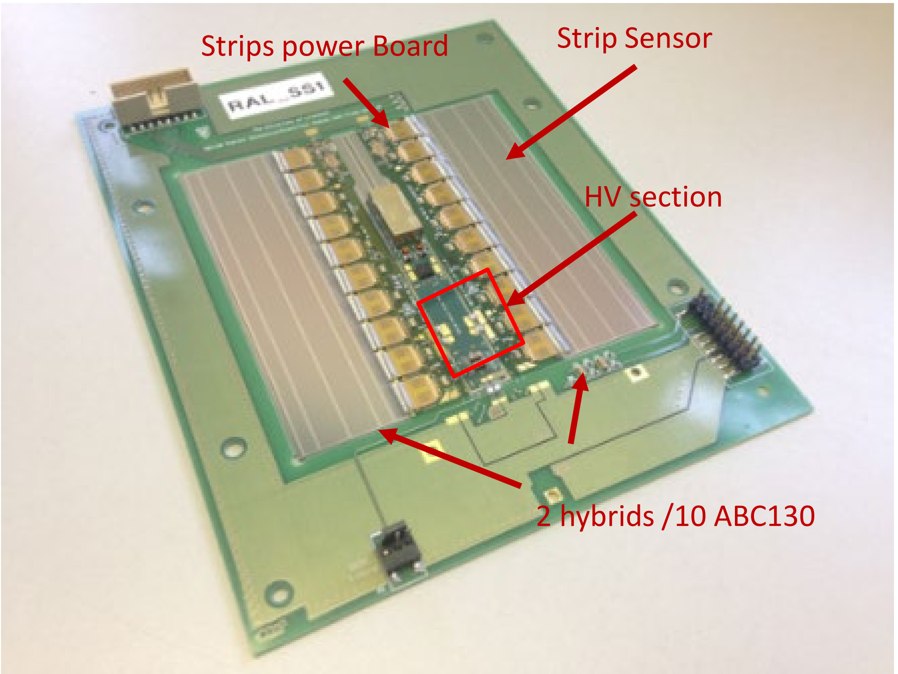
But individual HV cables is not feasible for ITk for material budget and space reasons

# HV-MUX motivation

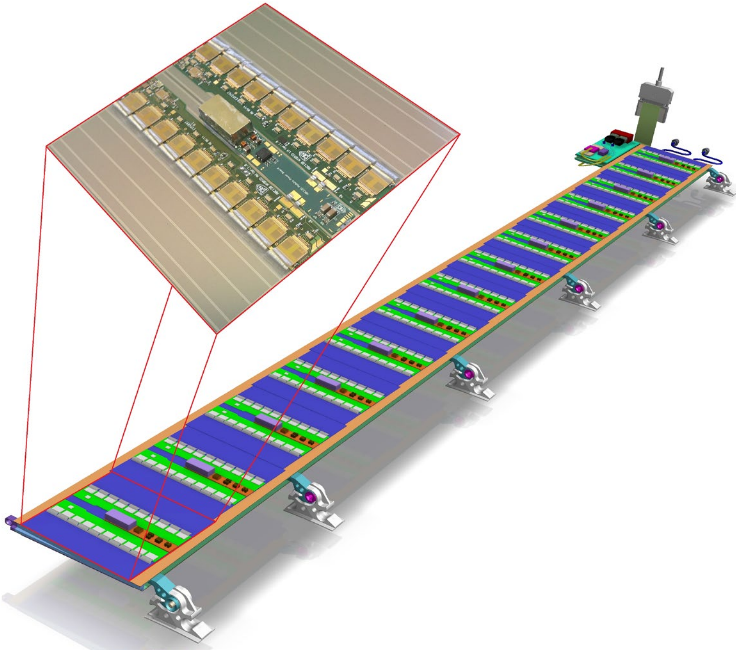
- Use single (or more) HV bus to bias all 14 sensors in a ½ stave and use one HV switch for each sensor to disable malfunctioning sensors: High Voltage Multiplexing ‘HV-MUX’
- The HV switch is Detector Control System (DCS) controlled, with control signals provided by custom ASIC
- First investigation around 2010



# HV-MUX implementation




RAL Barrel Short Strip Module

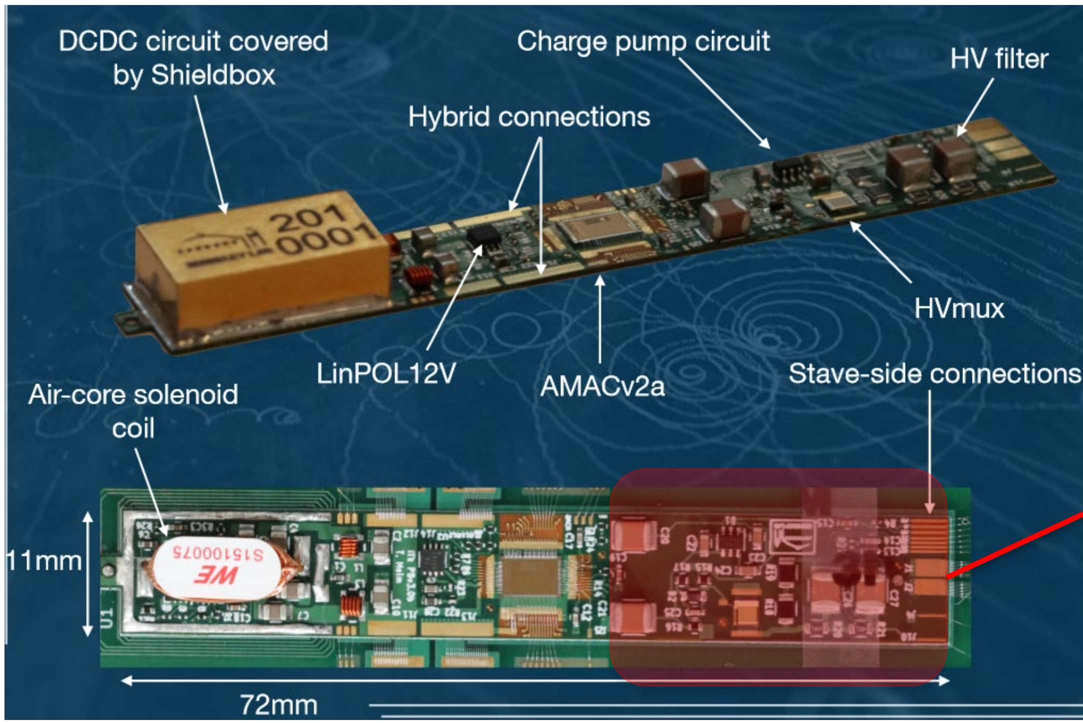


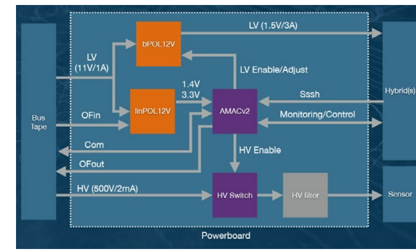
Barrel Long Strip Module

Carbon composite “stave”/”petal” structures hosts up to 14 modules, providing support and services

# HV-MUX implementation

Power board v3.0b



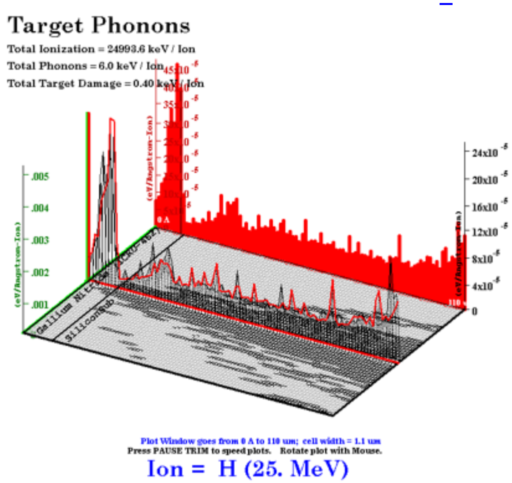



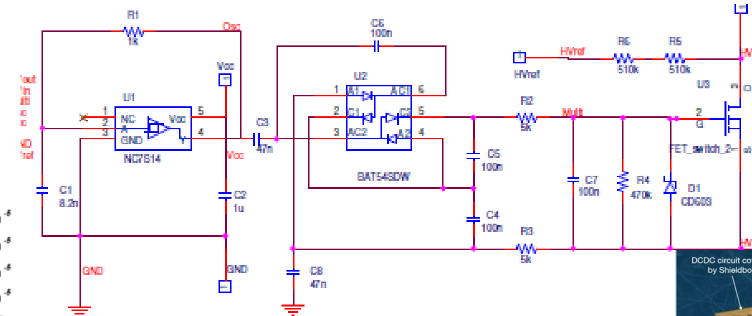

Power board architecture

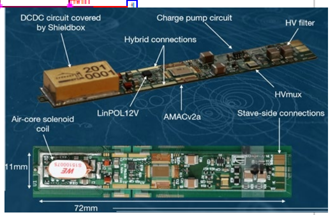
HVMUX section

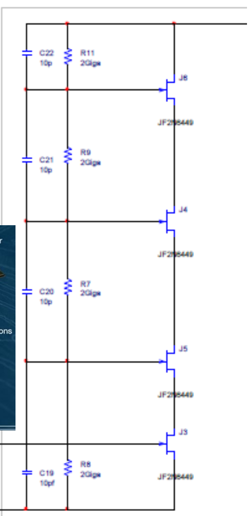
The flexi module powerboard includes HV-MUX circuitry, DC-DC converter for LV distribution and the AMAC (Autonomous Monitor And Control) ASIC for monitoring and control.
HV MUX adopted as baseline for strips in 2019.

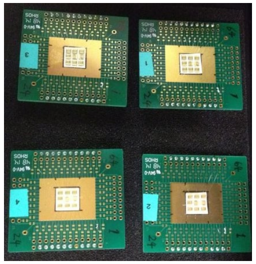
# HV-MUX details

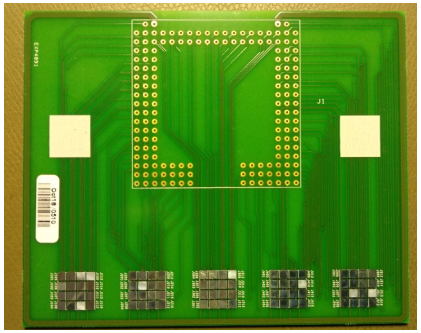


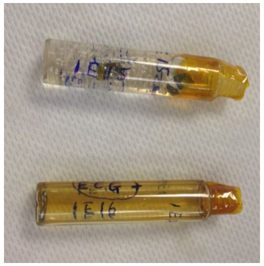



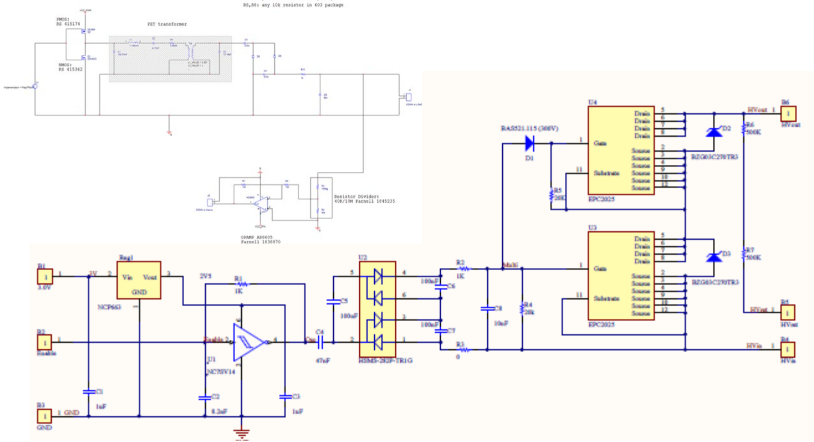









# HV-MUX requirements

**High Voltage switches strip detector requirements:**

- Must be rated to 500V plus a safety margin
- Must be radiation hard, nominal maximum expected over lifetime $\sim 1\text{x}10^{15}$ $n_{eq}/cm^2$ , ~ 30Mrad (Si) for strip end cap. Multiply by 1.5 to include safety margin
- On-state impedance $R_{on} << 1k\Omega$ // $I_{on} \sim 10mA$ (for irradiated strip sensors)
- Off-state impedance $R_{off} >> 1G\Omega$ // $I_{lkg} << I_{sens}$
- Must be unaffected by magnetic field
- Must maintain satisfactory performance at -30° C
- Must have <1% lifetime failure rate
- Must be small (mass/area constraint) and cheap (around 20,000 needed)

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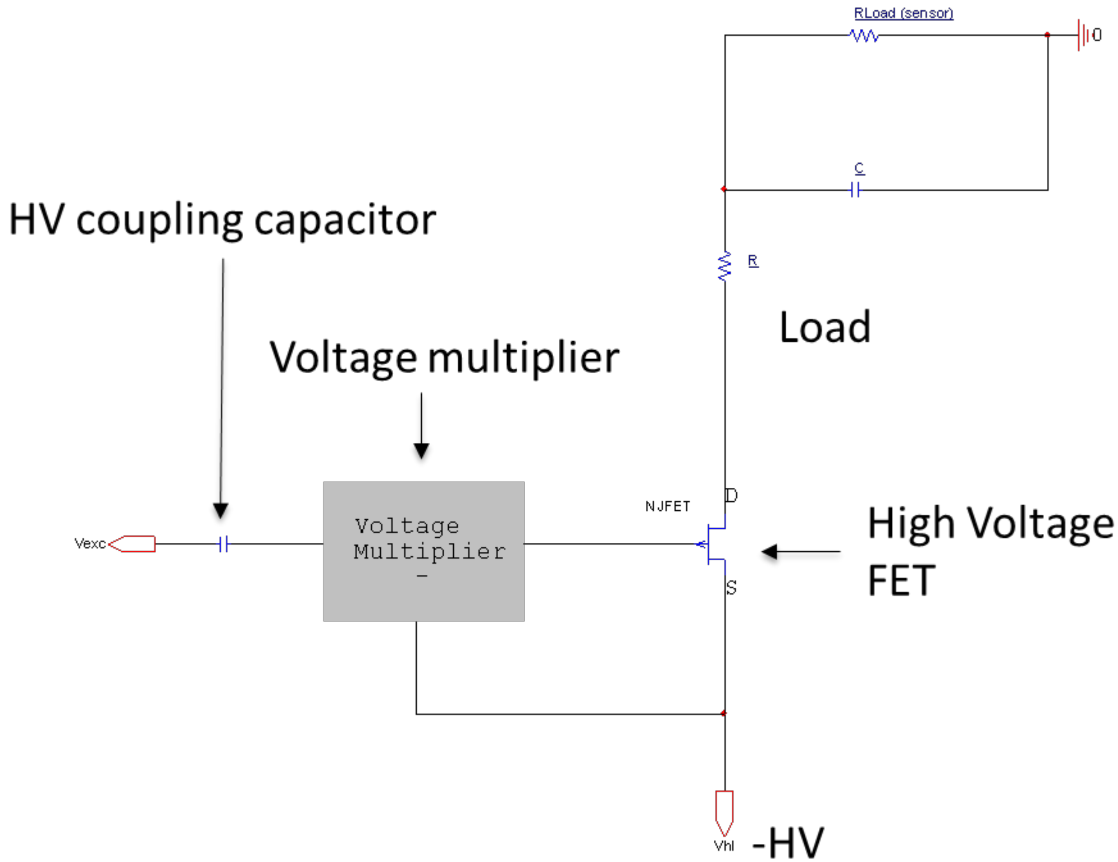
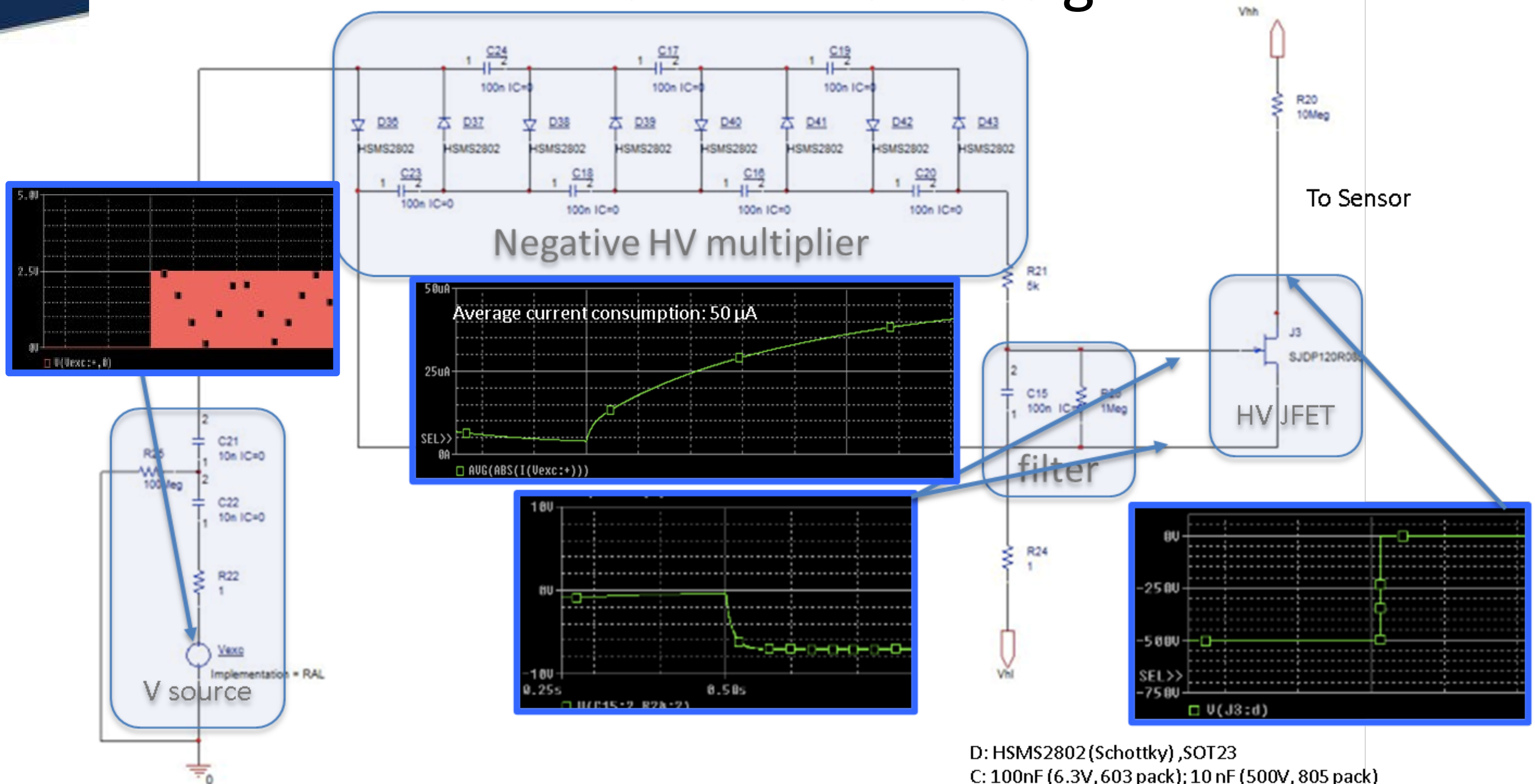
# HV-MUX conceptual design




A circuit solution was identified as promising early in the project:
AC coupled VMPY drives the HV FET device on to enable HV bias to the sensor.
The solution would work regardless of the driving requirement of the HV FET (i.e. negative, positive, several V's of Vth

# First HV-MUX design

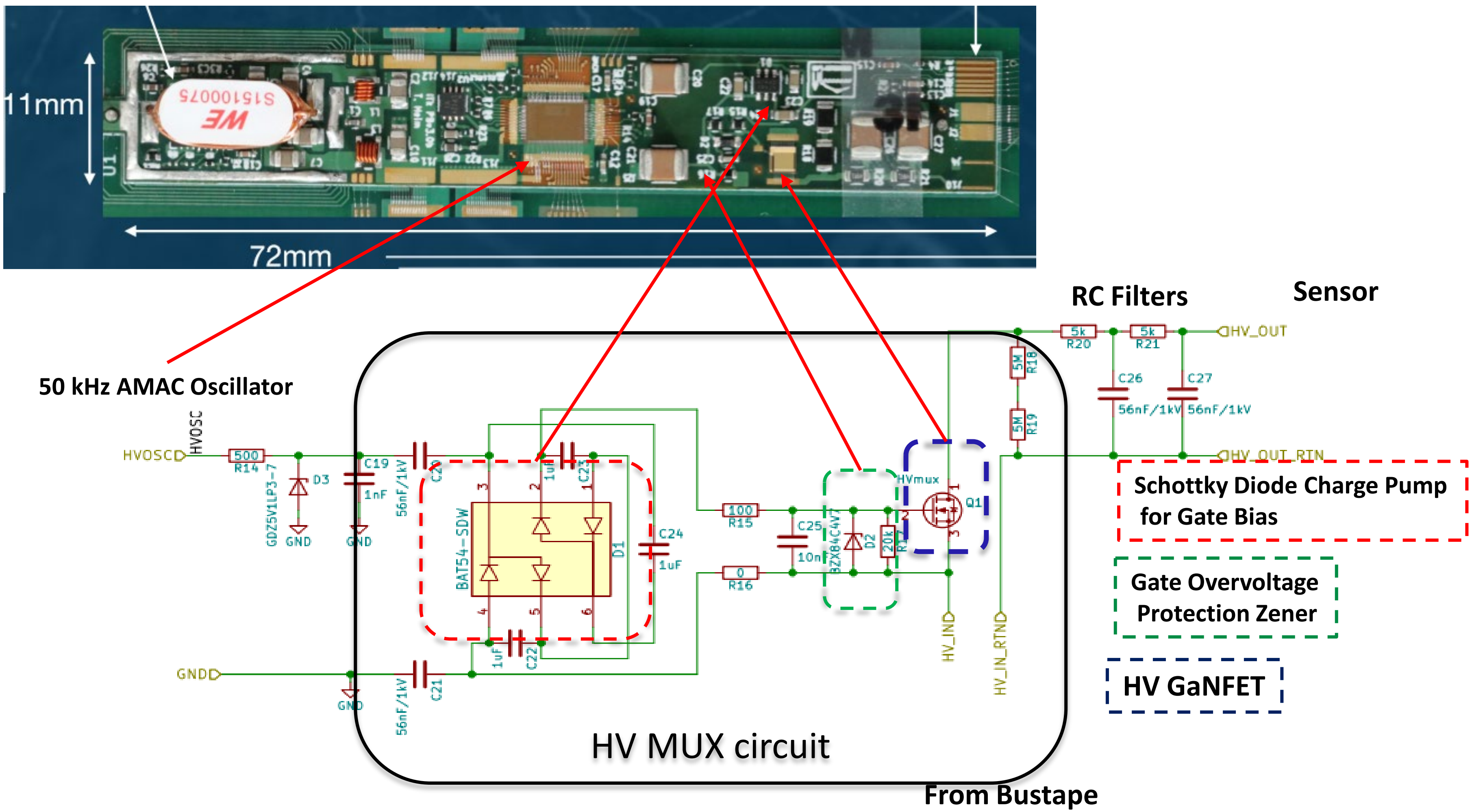



The $V_{src}$ oscillation gets multiplied and reversed in polarity: the negative voltage is used to shut off the depletion JFET;

The negative voltage is generated ONLY when the JFET needs shutting off: no power is needed during normal operation (i.e. when the JFET switch is ON).

# HV-MUX final design

**LBNL V3 PowerBoard with HV Mux**



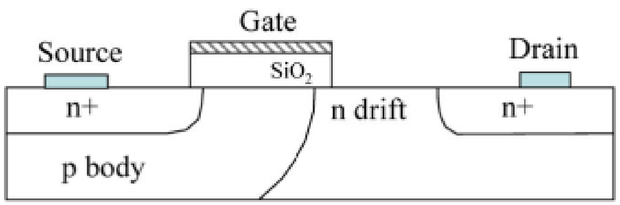
# HV-MUX design: active devices

Si, SiC and GaN based devices have been investigated as HV active FET

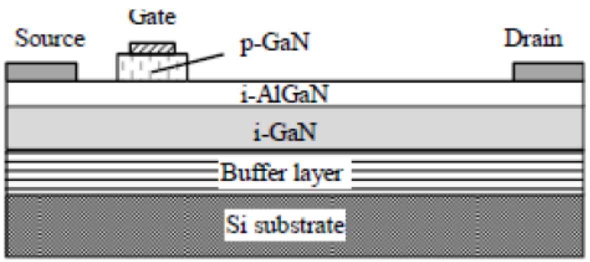
| Manufacturer | Device type, material | Part No | Pass/fail |
| --- | --- | --- | --- |
| Infineon | Si MOSFET | | Fail |
| ROHM | Si MOSFET | | Fail |
| Crystalonic | Si JFET | 2N6449 | Fail |
| Interfet | Si JFET | 2N6449 | Fail |
| IXYS | Si MOSFET | CPC5603 | Fail |
| USCi | SiC depletion JFET | UJN1205 | Fail |
| SemiSouth | SiC vertical enhancement JFET | SJEC170R550 | - |
| | SiC vertical enhancement JFET | SJEP120R063 | - |
| CREE | SiC MOSFET | CPMF-1200 | Fail |
| ROHM | SiC MOSFET | SCT2080KE | Fail |
| ROHM | SiC MOSFET | S2403 | Fail |
| Fairchild/Transic | SiC vertical BJT | FSiCBB057A120 | Fail |
| GeneSiC | SiC vertical SJT (looks like BJT) | GA04JT17 | Fail |
| Transphorm | GaN JFET | TPH2006C | Fail |
| EPC | GaN lateral enhancement JFET | 10112 // EPC2012 | PASS |
| GaN Systems | GaN lateral enhancement JFET | GS66502B | PASS |
| **Panasonic** | **GaN enhancement FET** | **PGA26E19** | **PASS** |

Most devices failed the radiation test

# active devices radiation hardness

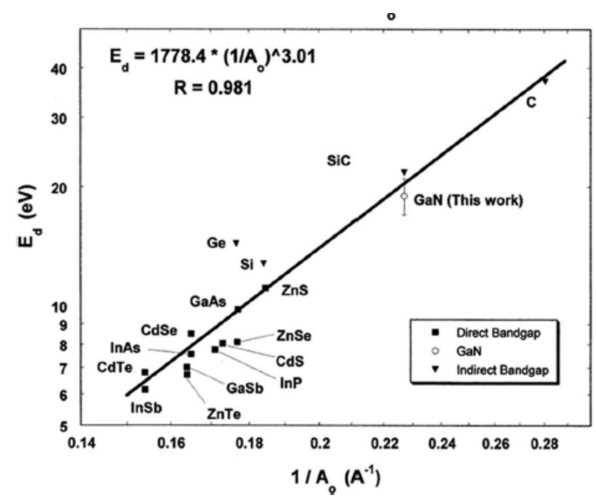



*A Lateral Double-Diffused MOS (LDMOS). A long drift region of lower doping reduces the electric field*




*A cross section of GIT based on GaN. The 2DEG is formed by piezoeffect at AlGaN-GaN*

| Parameter | | Silicon | GaN |
|---|---|---|---|
| Band Gap $E_g$ | eV | 1.12 | 3.39 |
| Critical Field $E_{Crit}$ | MV/cm | 0.23 | 3.3 |
| Electron Mobility $\mu_n$ | $cm^2/V \cdot s$ | 1400 | 1500 |
| Permittivity $\varepsilon_r$ | | 11.8 | 9 |
| Thermal Conductivity $\lambda$ | W/cm·K | 1.5 | 1.3 |




The average threshold energy for displacement in GaN is higher than in Si

The higher critical field should also help radiation hardness

# active devices radiation hardness

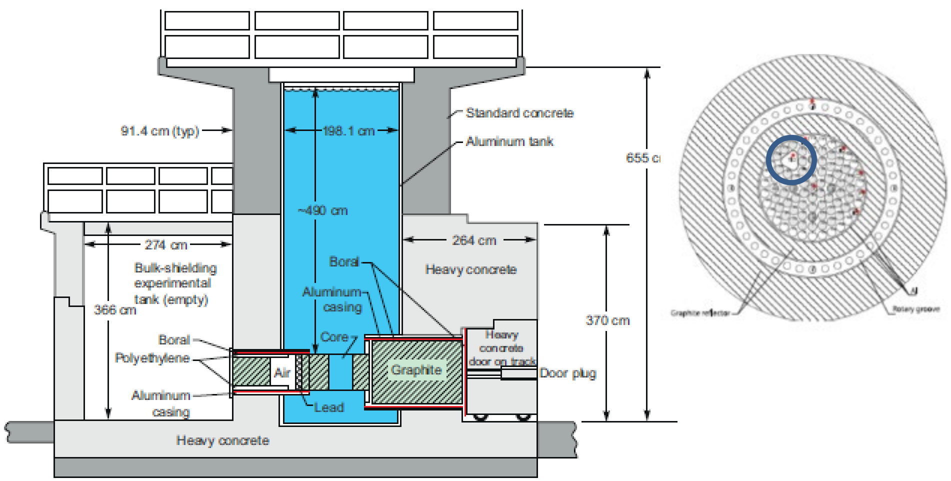
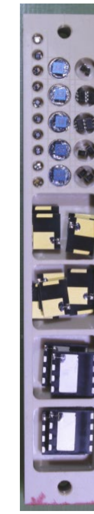



Fig. 1. TRIGA reactor at JSI, side view (Jeraj and Ravnik, 1999).

*TRIGA reactor at Ljubljana*

*Cyclotron at Birmingham*



*'Passive' irradiation*

Radiation tests, on packaged devices and bare die, done at :

- Birmingham cyclotron 26 MeV p+
- Neutron Irradiation at TRIGA reactor in Ljubljana (Slovenia). Broad energy spectrum (channel dependent) with 33% of fast neutrons
- 600 MeV proton beam at Los Alamos (US)
- 300 MeV pions at Paul Scherrer Institute (Zurich, Switzerland
- Heavy Ion for SEE (259 MeV Ge and 210 MeV Ti) at BNL
- 180 GeV Pions at CERN
- Gamma irradiation at BNL
  - *See backup for radiation tests on other HV MUX elements*

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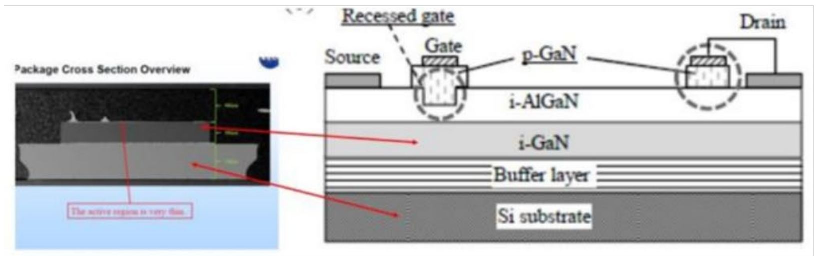
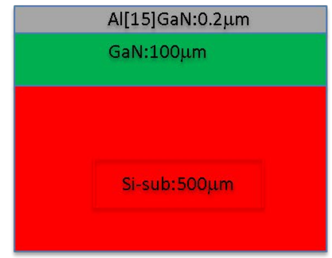
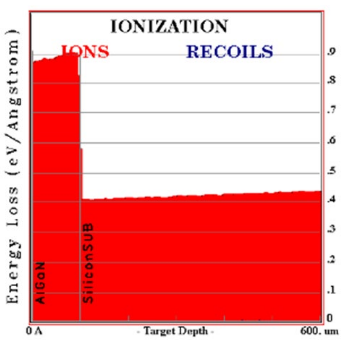
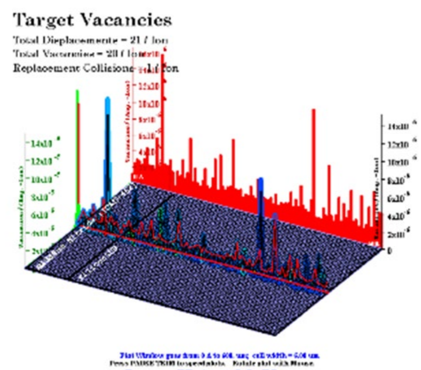
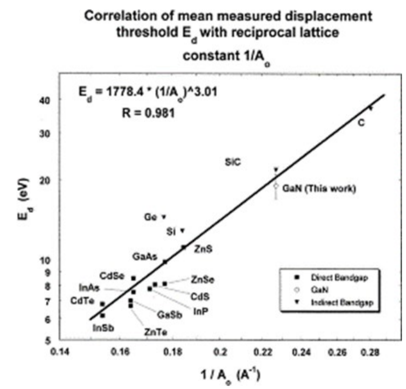
# active devices radiation hardness




SRIM MC to estimate maximum **TID, NIEL and defects from 26 MeV p+**

- Simplified AlGaN/Gan/Si device
- No electrical bias, no annealing
- 10,000 events / run

**GaN TID:** Average Ionization @ 25MeV p+ in the device (1E4 MC events)

$D_{GaN} = \Phi * 2.29 \times 10^{-7}[rad] \rightarrow \Phi = 1*10^{15}$ : $D_{GaN}$ **= 229 Mrad**

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# active devices radiation hardness

| Voltage | Year | Supplier | Beam | particles | Dose (Mrad) | fluence (neq) | n passed | n tested | comments |
|---|---|---|---|---|---|---|---|---|---|
| 600 | 2016 | Panasonic | PSI Zurich | 300MeV pion | 34 | 1.34E+015 | 19 | 20 | unpowered |
| 600 | 2017 | Panasonic | Birmingham | 26MeV p+ | 188 | 8.20E+014 | 9 | 9 | in situ testing passed |
| 600 | 2017 | Panasonic | Birmingham | 26MeV p+ | 229 | 1.00E+015 | 9 | 9 | On-state Ids=10mA |
| 600 | 2017 | Panasonic | Birmingham | 26MeV p+ | 176 | 7.70E+014 | 9 | 9 | On-state Ids=10mA |
| 600 | 2017 | Panasonic | Birmingham | 26MeV p+ | 243 | 1.06E+015 | 9 | 9 | radiation dose approximate |
| 600 | 2016 | Panasonic | Los Alamos | 600MeV p+ | 74-95 | 2.8-3.6E+015 | 16 | 16 | On-state Vgs=2.5V |
| 600 | 2016 | Panasonic | Ljubljana | neutron |  | 1.10E+015 | 20 | 20 | On-state Ids=10mA |
| **Total** |  | **Panasonic** |  |  |  |  | **91** | **92** | **bare die devices** |

Example of Panasonic GaN bare die test from first run

- All but one devices tested survived ( consensus is that it was faulty from the start)
- Tests done passively and actively

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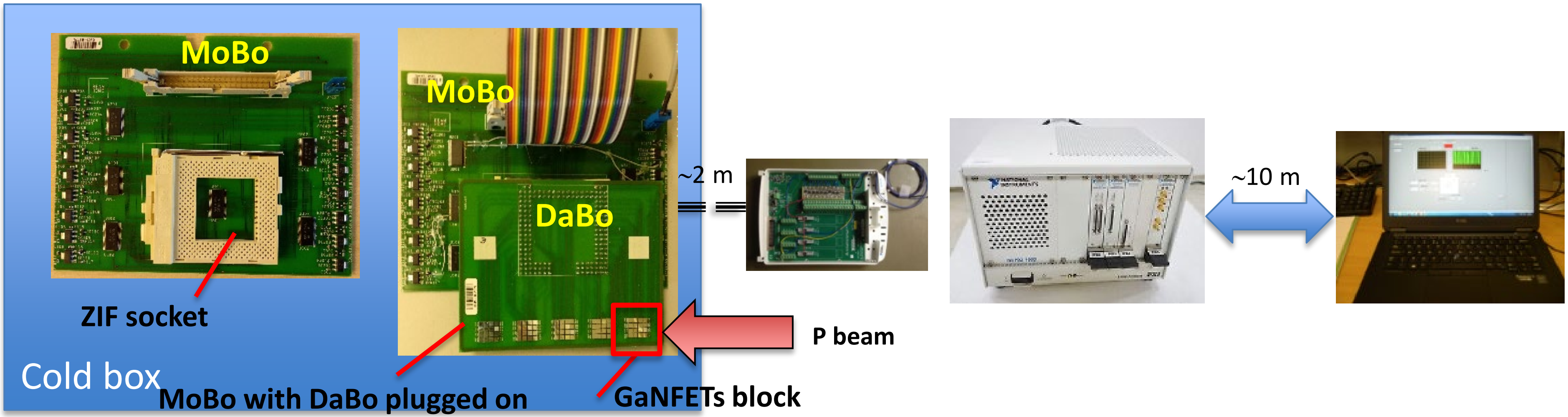
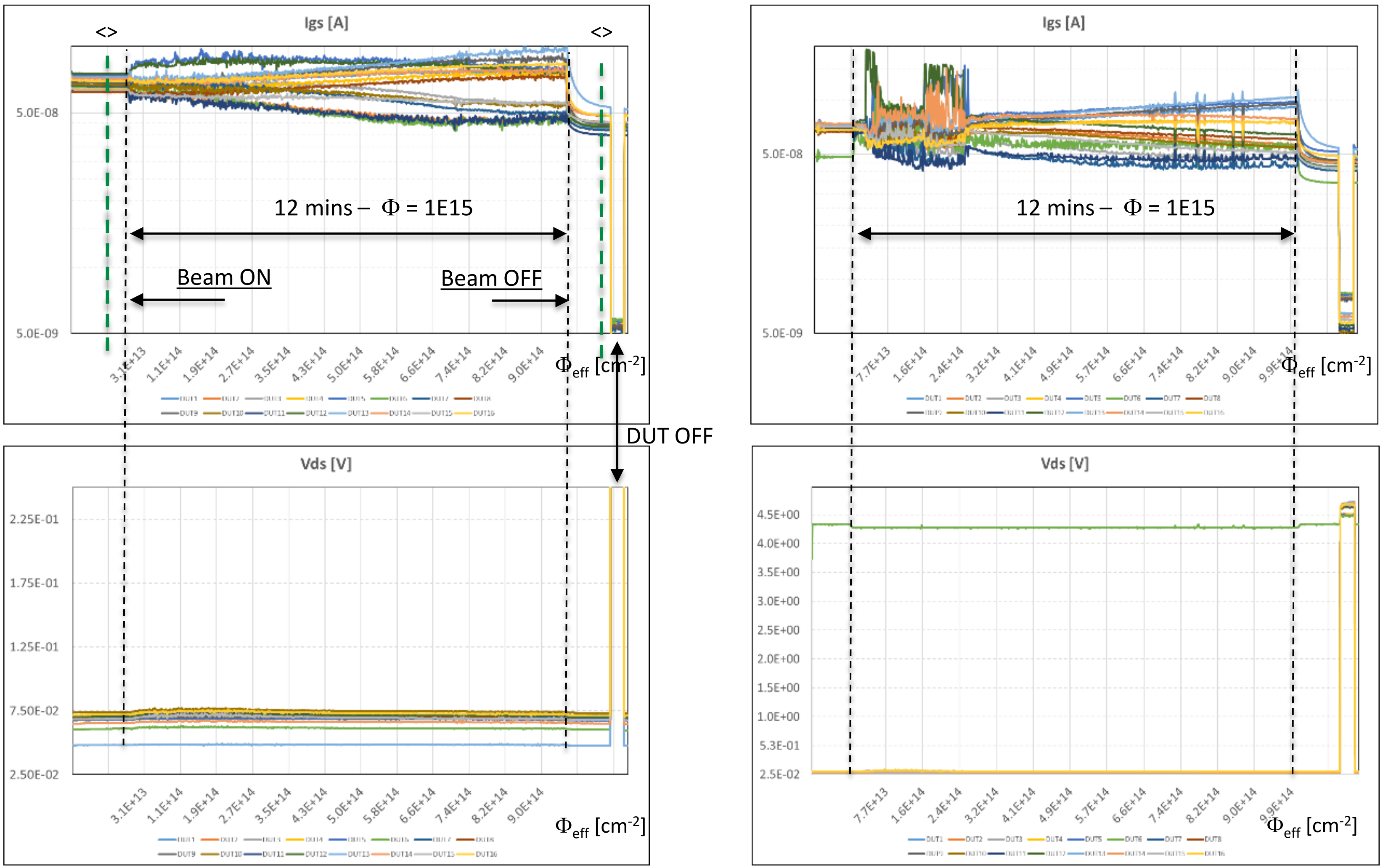
# active devices radiation hardness




- **400 PGA26E19 GaNFETs devices have been tested in ‘real time’, i.e. monitoring, using a dedicated DAQ, their Igs and Vds shifts <u>in the ON state</u> during 26 MeV proton irradiation at University of Birmingham up to Φ = 1e15 cm-2**
- **The 400 GanFETs are divided among 5 boards (DaBo), each carrying 80 devices. On each DaBo the 80 devices are arranged in 5 blocks of 16 devices each**
- **Each block of 16 devices is of size 10 x 10 mm2 (i.e. the proton beam size), inter gap of 10 mm**
- **Each block is individually ‘tested’, i.e. irradiated up to the nominal fluence 1E15, before moving on to the next block. When all the 5 blocks of the DaBo have been tested, the DaBo is unplugged and replaced with the next one**
- **The devices in die form, have been soldered onto the DaBo, with a yield of 96.75%. All the devices (100%) passed the irradiation test.**

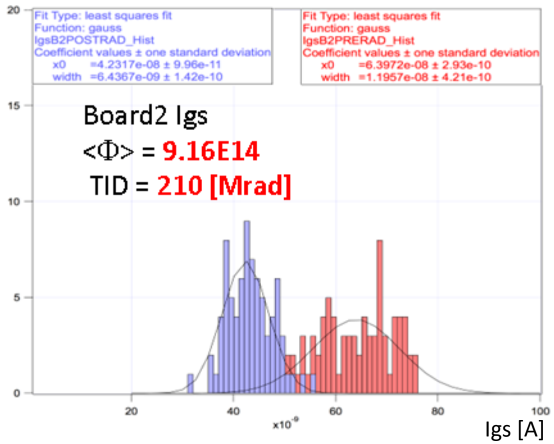
# active devices radiation hardness

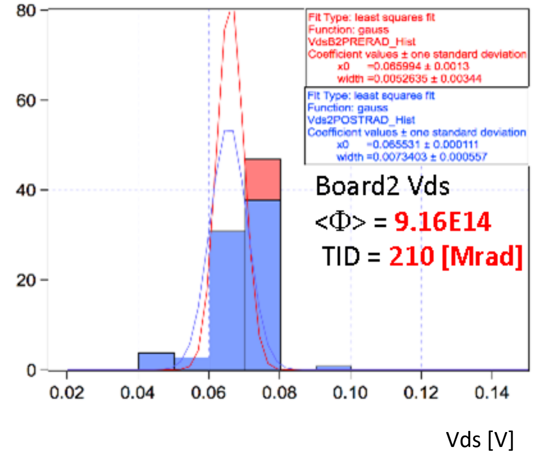
Board2 Block3 | Board1 Block4

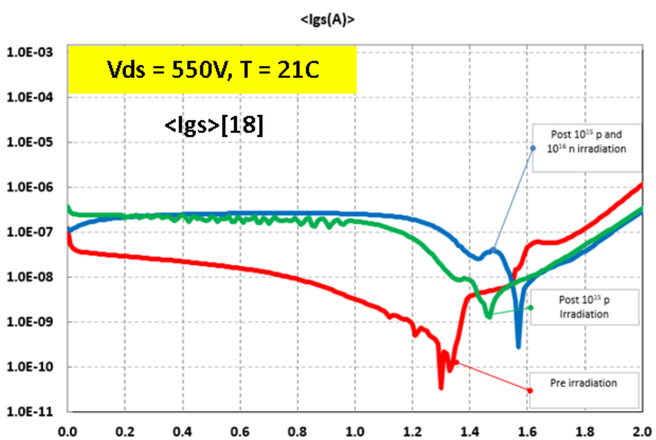


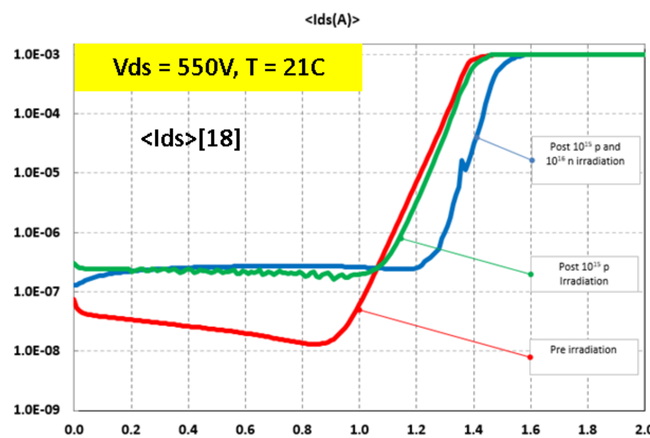

Example of Igs and Vds changes during 26 MeV p+ test

# active devices radiation hardness



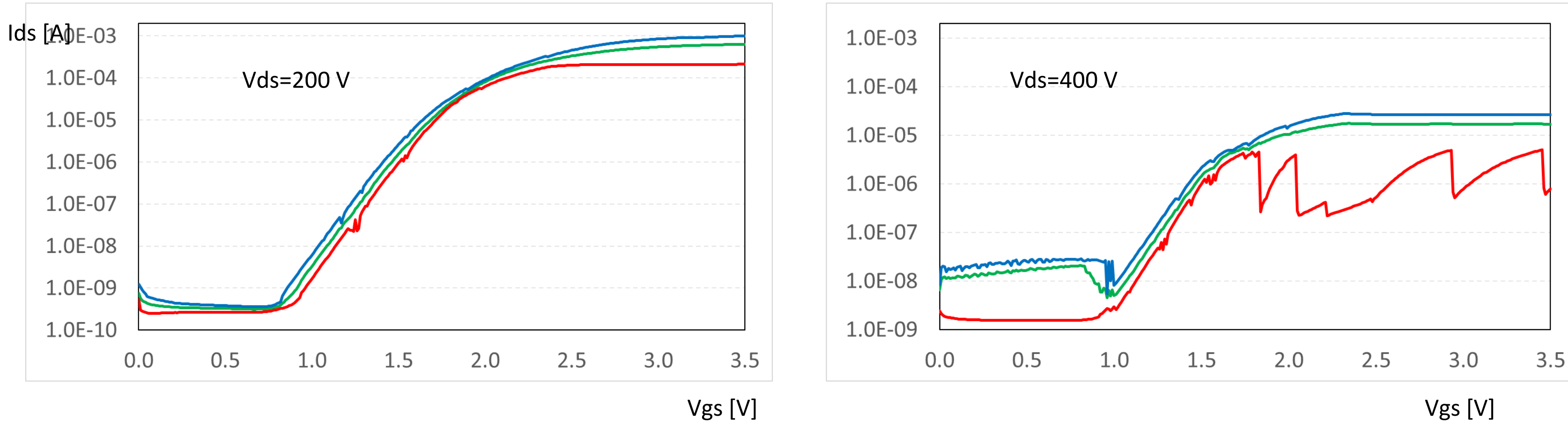




Average of **PGA26E19** Igs and Ids vs. Vgs changes following p (1e15) and n (1e16) irradiation

# active devices radiation hardness
# 1e17 n fluence




Average of 10 **PGA26E19** Panasonic Ids vs. Vgs following **1e17** n- irradiation

The PGA26E19 Panasonic GaN were tested to extreme level of neutron fluence

- All devices 'survived' (they can be turned on and off)
- Much degraded characteristics: conductivity dropped and Ids dependence on Vds

# reliability

## Consider N=4 and N=7 devices on single HV bus

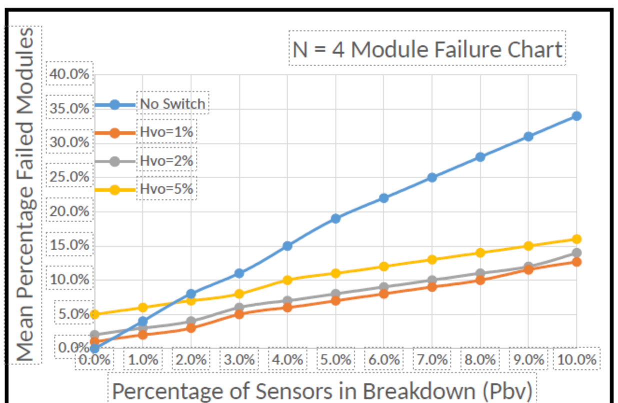
Assumed input probabilities

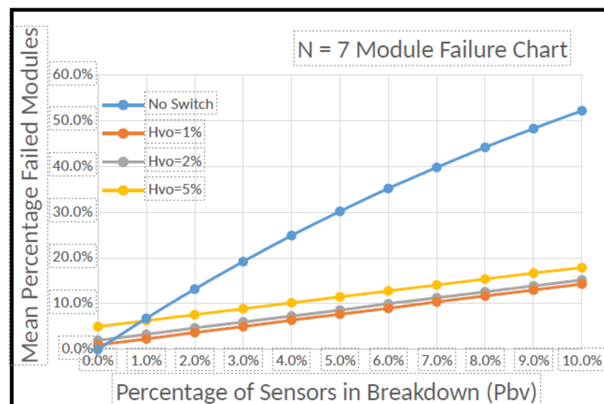
$P_{bv}$ = probability sensor shorts on goes into breakdown
$P_{so}$ = probability HV Switch fails open
PAMAC = probability AMAC fails to deliver clock
$P_{driver}$ = probability HV Driver circuit fails
$P_{sc}$ = probability HV Switch fails closed

Derived probabilities

$P_{hvo}$ = 1- (1 – $P_{so}$ )(1- PAMAC )(1 - $P_{driver}$ ) = probability HV switch circuit fails open
$P_{bus}$ = probability the common HV bus fails with no HV Mux
$P_{hv\text{-}bus}$ = probability the common HV bus fails with HV Mux

Plot Mean Percentage of Failed Modules as function of (unknown) probability a sensor goes into breakdown or shorts with and without the use of HV Mux.
Plot for N = 4 modules on single HV line (default) and N = 7 modules (previous baseline)




HV Mux can be viewed as insurance against > 2% of sensors failing

# Summary and conclusions

- **The HVMUX solution has been proposed for strips ITK as a safety measure against possible failures arising from parallel HV biasing**
- **Many HV devices have been investigated and discarded; HV GaNFETs identified as satisfying the required characteristics**
- **Extensive irradiation campaigns (n, p, $\gamma$, $\pi$) up to n fluences $10^{16}$ $cm^{-2}$ and TID > 200 Mrad, long term reliability studies and SEE sensitivities demonstrated the very high radiation hardness of GaNFETs. Circuitry employing GaN FET to implement HV MUX successfully demonstrated. No issues on extra noise picked up from strips demonstrated.**
- **Additional failure analyses have been carried out**
- **HVMUX solution adopted as baseline for strips ITK in March 2019**
- **About 10 wafers (i.e. 24,000 new devices) order from Panasonic in Jan 2020.**
- **Final additional radiation tests, to confirm previous results, to be performed by May 2020 (postponed to 2022)**

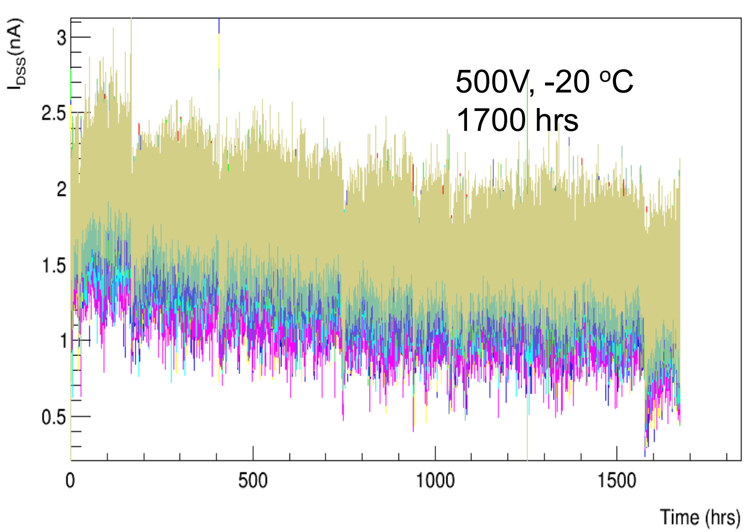
**THANK YOU**

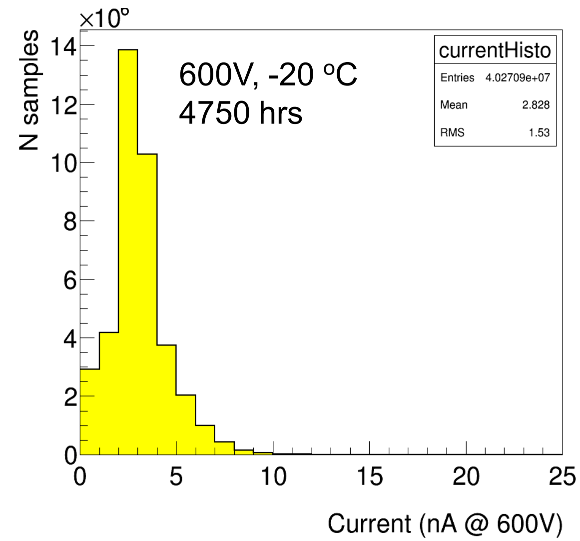
# Backup

10 pion CERN irradiated (5E14) GaNFETs devices were used for long term testing and kept to -20°C, ~30% relative humidity in freezer

- -20 deg C, 500V for 1700 hrs
- -20 deg C, 600V for 4750 hrs
- +21 deg C, 500-600V for 1800 hrs: in bunches of 10 cycles of 2 hours **off**, **22** hours on each.

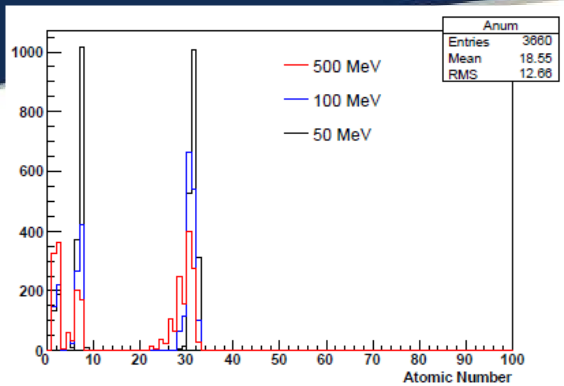
- Off-state: monitor I(dss) with V(ds) 500 or 600V, V(gs) = 0V
- Generally very stable behaviour, with VERY low leakage currents. No failures.
- Variations in the current due to run starting-stopping, fridge cycling etc.

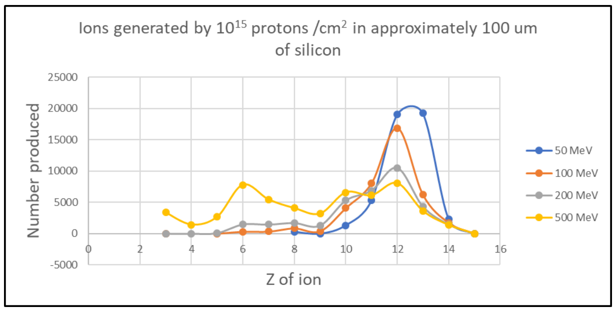



- To the degree that JEDEC standards and models hold, Panasonic data shows there should be negligible losses due to wear-out of devices
- Cold testing demonstrates no other unexpected failure mechanism

# Backup




Si P

Board with 20 GaNFETs for BNL heavy ion irradiation

| | Off-state results at Vds = 300 V | | | | |
|---|---|---|---|---|---|
| Device no | Fluence Ge/cm**2 | | | | |
| 12 | 8.13E+08 | | | Died | |
| 13 | 9.72E+08 | | | Passed | |
| 14 | 1.00E+09 | | | Passed | |
| Total | **2.78E+09** | | | | |
| | | | | | |
| | Inverse cross section increased to 2.78e9 per device | | | | |

| | Off-state results | | | |
|---|---|---|---|---|
| Device no | Fluence Ge/cm**2 | | | |
| 6 | 1.11E+08 | | | Passed |
| 7 | 1.11E+08 | | | Passed |
| | | | | |
| 8 | 1.10E+08 | 1.10E+09 | | Died between these values |
| 9 | 1.10E+08 | 6.11E+08 | | Died between these values |
| 10 | 3.01E+08 | 4.01E+08 | | Died between these values |
| 11 | 5.01E+08 | 6.01E+08 | | Died between these values |
| | | | | |
| | Devices 6, 7 ,8, and 9 imply inverse cross section per device greater than 1e8 | | | |
| | Devices 9, 10, and 11 imply inverse cross section per device between 1e8 and 6e8 | | | |
| | | | | |
| | Devices 10 and 11 suggest best estimate by the average of their ranges | | | |
| | between 3e8 and 6e8 = 4.5e8 per device | | | |

- Investigate susceptibility to Single Event Effects (SEE) that are destructive (recommendation from Module PDR). SEE studies at BNL Tandem Van de Graaff facility using 259 MeV Ge and 210 MeV Ti
- Spallation and fission nuclear processes are capable of generating very high Linear Energy Transfers (LET) or stopping powers dE/dx ions. Protons (or pions) may produce ions which deposit large energies. Spallation may produce ions of atomic number as high as one greater than that of the target nucleus.
- Choose primary irradiation species to be Germanium, atomic number = 32, is one higher than Gallium (Z=31).
- Used motherboard with 20 GaNFETs mounted. These were the same GaNFETs already irradiated to > 60 Mrad with gammas at BNL.
- Initially focused on devices in on-state. No failures to 6 x $10^9$ Ge/cm$^2$ on single device, 1.5 x $10^{10}$ Ge/cm$^2$ total.

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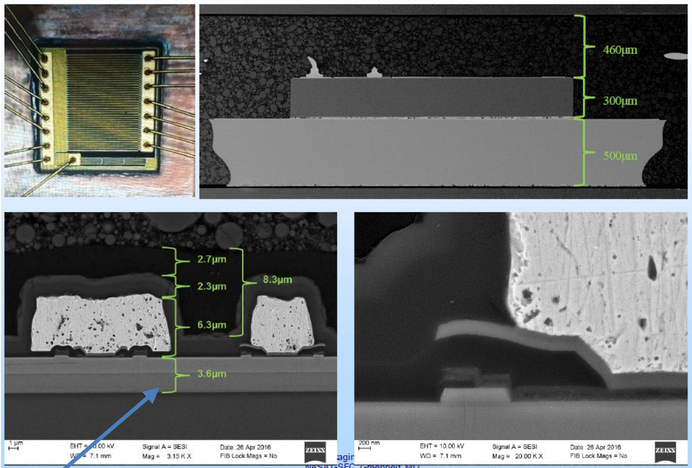
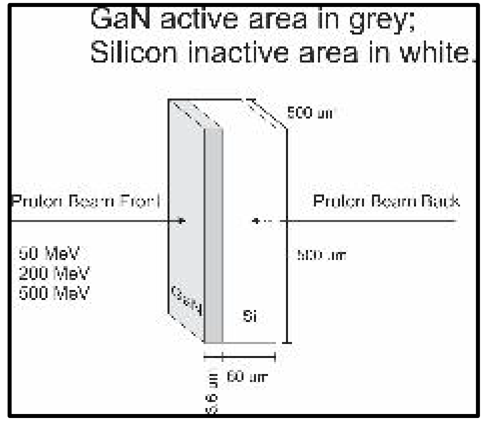
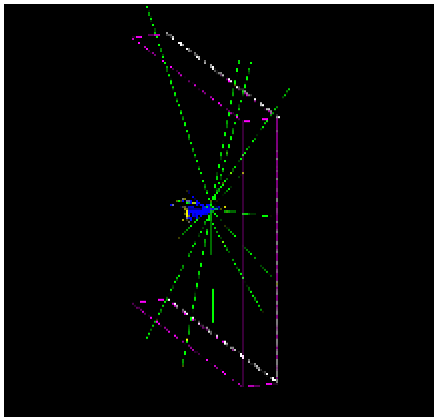
# Backup




GaN + Buffer layer only ~ 3.6 um thick

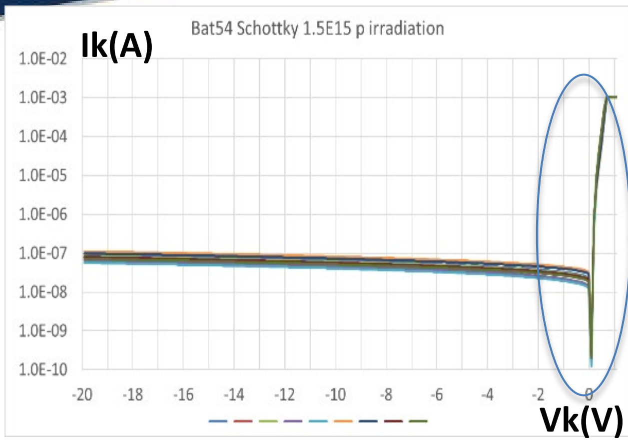


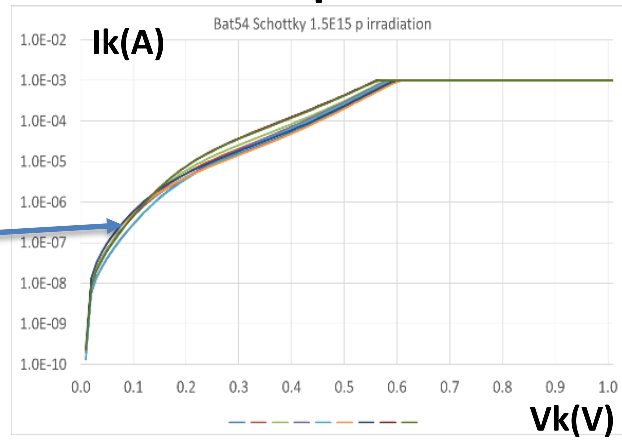



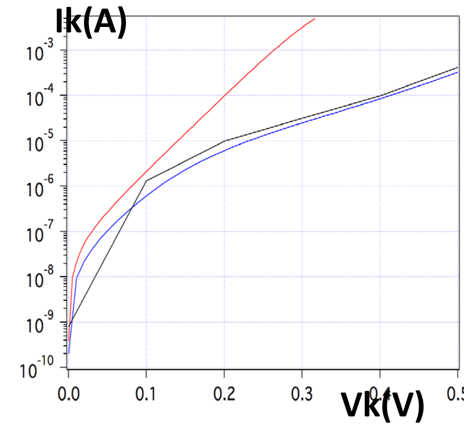
| | Simulation | Irradiation |
|---|---|---|
| Range [um] | ~ 1 | 18 |
| LET [MeV cm$^2$ /mg] | ~ 5 | 27 |
| Energy Deposition in 1.6 um GaN Layer | ~ 1 MeV | 22 MeV |

- Simulation of Nuclear Interactions (Spallation + Fission) in Panasonic GaNFET with Geant4
- 50 MeV, 100 MeV, 500 MeV Protons on GaNFET, 1 x $10^8$ Events
- Energy and LET in 1.6 um GaN layer is significantly higher in actual irradiation than what we would expect in proton (or charged hadrons) nuclear events.
- GaNFETs extremely resistant to SEE effects in on-state even when depositing energy more than 10,000 larger than a 500 MeV proton in 1.6 um thick GaN region via ionization.
- It is possible to eventually kill them in off-state though the survive > 1 x $10^8$ Ge events. Difficult to tie this to actual charged hadron fluence in ATLAS.

# Backup

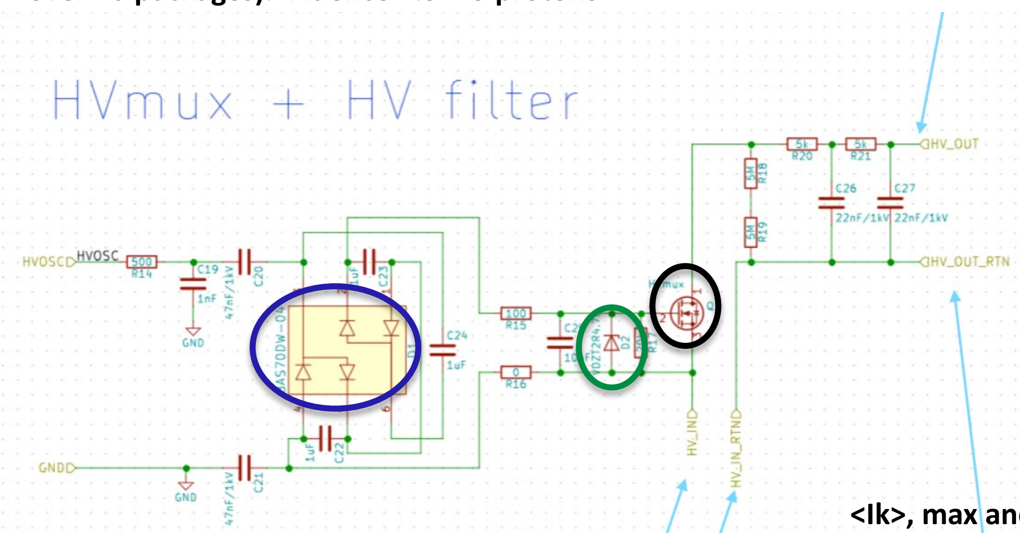


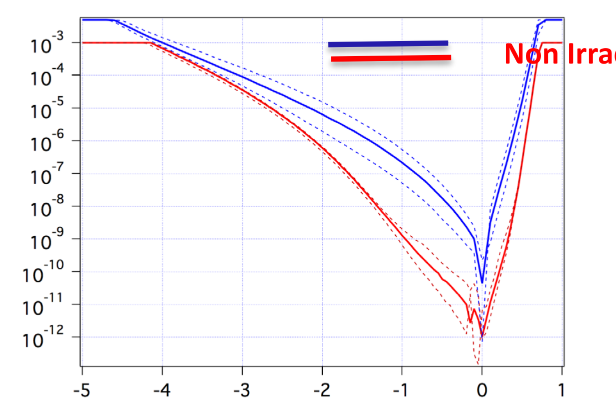




**Ik and Vk of #10 DUTs BAT54STW Schottky diodes (1 DUTs over 10 packages). Fluence 1.5E15 protons**

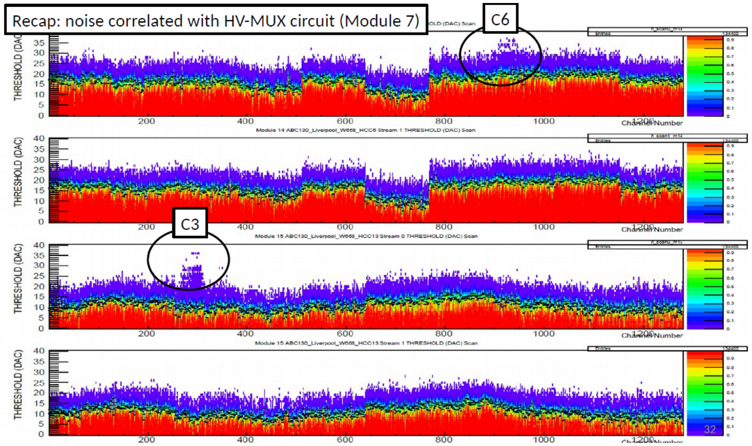
**Comparison in the FWD region of #10 BAT54STW Schottky diodes non irradiated, 6E15 n irradiated, 1E15 p irradiated**

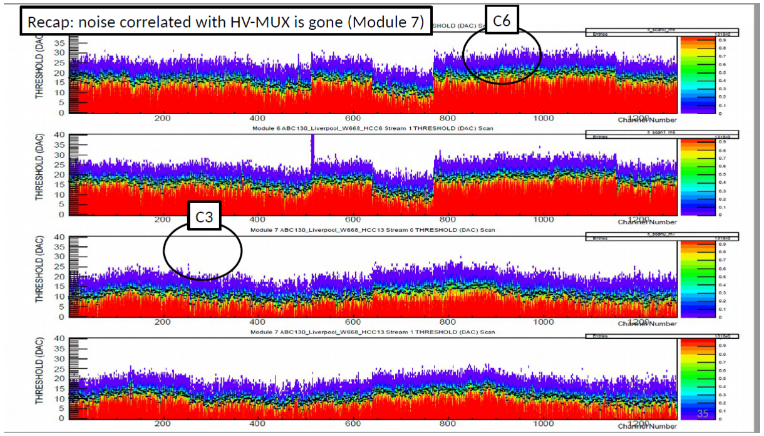


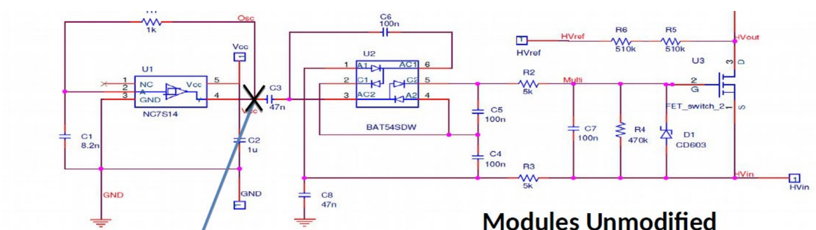



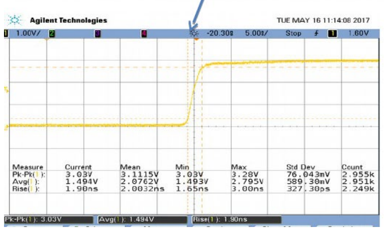

**<Ik>, max and min of #10 pre and post p irradiation BZX84C4V7 Zener diodes . Fluence 1.5E15 protons**

# Backup

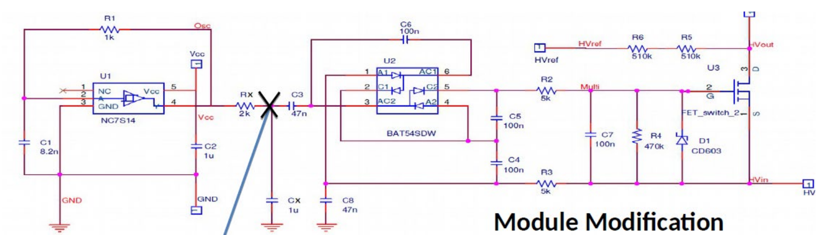


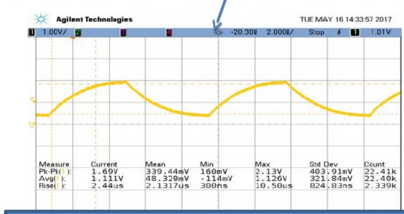




Note: C6 shows DC if probed differentially BUT shows square wave if single terminal probed with respect to GND




Additional RC filter removes high frequency components

Rx

Cx

C3



V