Synthetic Diamonds: Fast, Rad hard particle detectors for ATLAS MiniFCal upgrade

Carleton, Montreal, Toronto, TRIUMF and Victoria ATLAS groups

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Plus engineering & technical support from TRIUMF: Ray Bula, Dan Gray, Andy Hurst, Scott Kellogg, Roy Langstaff, Brian Minato, Bill Rawnsley

And the cyclotron operation group
Motivation for MiniFCal: problems in Forward Calorimeters at High Luminosity LHC intensities – exceeding a luminosity of $1 \times 10^{34} \text{ p cm}^{-2} \text{ s}^{-1}$

- Charge build-up in Liquid Argon gap
  - $\Rightarrow$ recombination
- HV drop on FCal HV distribution resistors
  - $\Rightarrow$ reduces voltage on gap significantly
- Argon beam heating
  - $\Rightarrow$ might exceed boiling point of Liquid
“Strawman” Mini-FCal design

- 12 copper absorber plates with 11 detector planes
- Detector plane:
  - ceramic disc covered with 9 rings of ≈ 1 cm² diamond detectors
- Studying optimized tiling, reducing dead regions, ...
- Mechanical design by Roy Langstaff, TRIUMF/UVic
MiniFCal Shielding Effect

Radial dependence of energy deposited in Fcal1 without and with a MiniFcal present

MeV $10^6$

E deposited Fcal1 - No MiniFcal

30cm Cu MiniFCal
Introduction to Diamond Tests

• **Synthetic diamonds**
  – Attractive possibility for a sensor material in a possible “MiniFCal” for ATLAS high-rate forward calorimetry
    • Large signal
    • Not temperature sensitive
    • Great thermal conductor
    • Sub nanosec timing $\Rightarrow$ Integrate one bunch crossing
  – Critical worry: radiation damage with fluences above the $10^{17}\text{cm}^{-2}$ level expected in MiniFCal in 10 years @ $10^{35}\text{cm}^{-2}\text{s}^{-1}$
    • Previous tests (RD42 et al): 20% signal at $16\times10^{15}\text{cm}^{-2}$ running with protons at the PS
    • Need to push > an order of magnitude
Detectors used in tests

- Detectors purchased from Diamond Detectors Limited (DDL) in U.K.
  - Effectively sole source for packaged diamond detectors
  - Different diamond grades available
    - **EL**: electronics grade, least nitrogen, largest signal, most £££
    - **OP**: optical grade, medium signal, middle £
    - **PC**: pc grade, most nitrogen, smallest signal, least £
  - Different metalizations
    - Au-Pt has been used more extensively
    - TiW-Al (now TiPt-Au) hoped to be more rad hard
  - NBIF (cylotron vault) irradiation:
    - 8 mm diameter, 800 μm thick EL-grade with Au-Pt metallization
  - BL1A irradiation:
    - 1) 8 mm dia 200 μm thick EL-grade with TiW-Al metallization
    - 2) 8 mm dia 300 μm thick OP-grade with TiW-Al metallization
    - 3) 8 mm dia 300 μm thick EL-grade with Au-Pt metallization
    - 4) 8 mm dia 300 μm thick OP-grade with Au-Pt metallization
DD Lab Studies

- **Started at TRIUMF in 2009 and at Carleton in 2010.**
- **Summer / term students**
  - TRIUMF - M. Shannon and C. David
  - Carleton, C. Collins-Fekete
- **Similar set-ups with diamond detector(s) plus preamp/(shaper) and DAQ via digital scopes.**
- **Control via Testpoint or Labview**
- **Illuminate detectors:**
  - Alpha ($^{241}\text{Am}$)
  - Beta ($^{90}\text{Sr}$)
- **Nominal HV of 1V/micron**
- **Use scintillator to trigger betas, but must use diamond self trigger for alphas.**
Lab studies: UV history

- Diamond Detector performance affected by exposure to UV light.
- This study with Beta source
- 700 μm EL-grade, Au-Pt
- Top plot after DD exposure to UV
- Lower part after extended operation with beta source and at nominal voltage without UV exposure.
- Current understanding is that UV light clears traps in diamond structure
- Extended operation with source re-fills traps and signal amplitude is regained.
- Time period of days under moderate irradiation to regain consistent output.

After UV exposure

No U.V. exposure

Plots from C. Collins Fekete

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DD lab studies: Polarization

- There is a polarization effect with DD detectors.
- Plots at right are for detector with standard DDL gold metallization.
- They show signal output as function of time over a period of 15 minutes after voltage is turned off.
- The inset in the lower plot is for a time period of 4.5 hours.
- Detector outputs stabilize after $\approx 1$ hour.

Plots from C. Collins Fekete
DD Lab studies: Hysteresis

- 300 μm EL-grade Au-Pt
- Detector keeps some “memory”
  - Same time constants as voltage-off effect
- Alpha sources gives larger pulses than betas
  - Alpha results depend on side of irradiation & HV polarity
  - Presumably due to small differences in electron-hole mobility

Figure 4: CVD diamond growth, as reproduced with permission from the CVD Diamond Group, School of Chemistry, University of Bristol, UK.

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Lab studies: Long term stability

- **Initial tests had indicated some problems with detectors ran for extended periods of time (~weeks)**
- Test in Spring of 2010
- 200 \(\mu\)m EL-grade TiW-AL
- Irradiated with Alphas
- Run for one month
- No variation in long term signal output.

Plot from C. David
Lab/beam studies: spatial stability

- Test by (RD42 grad student -?) on spatial response – plot on right →
- Initial lab tests with Alpha and Beta sources and collimators
- Initial test showed variation in response of ±10%
- Hope is to test spatial response in muon beam with M11 at TRIUMF using DD and USBPix detector from Pixel upgrade work.
- Problem is adapting the USBPix software to work with another detector.
- Timeframe for test at TRIUMF is prior to mid-December
- If we miss this window then TRIUMF beams not available until summer 2011

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Radiation Tests

• **Proton irradiation tests at TRIUMF**
  – 1) “Neutral Beam Irradiation Facility” (NBIF) in TRIUMF cyclotron vault
    • 500 MeV protons, significant neutron backgrounds in vault (preamps also in vault)
    • Run: \( \approx \frac{1}{2} \times 10^{15} \) p/cm\(^2\) per day, 1 May – 1 Aug 2010
  – 2) TRIUMF beam line 1A (BL1A)
    • 500 MeV protons in controlled environment
    • Robust tests, but had to wait for beam time
    • Run: \( \approx 10^{15} – 10^{16} \) p/cm\(^2\) per day, 1-13 Sep 2010
Detector packaging for tests
Detector Readout

- Bias detectors with 0.7 – 1 volt/μm
- Preamp locally built with SiGe technology with ~short cable between preamp and detector
- Regular calibration runs to test preamp
- 100’-180’ cables to HV, LV, calibration pulser and scope
  - Signal cable: LMR400 (double shielded foam dielectric cable)
- Preamp schematic for NBIF (Leonid):

BL1A preamp improved version (better 50 Ohm match, wider frequency band, larger dynamic range)
BL1A: 4 detector readout
NBIF and BL1A

- TRIUMF 23 MHz pulse-rate cyclotron, H⁻ beam
- Stripper probes ⇒ multiple beams
- Electromagnetic stripping ⇒ ”neutral beam”
  - ½ x 10^{15} p/cm² day
  - Can use for irradiation “for free”
- Downsides:
  - Needed to build
  - High background fields
  - Accessible only ~once per month
NBIF

Design: Dan Gray / TRIUMF
NBIF: Fluence from Air Ionization Chamber

- Simple device, slow but very radiation hard
- Gives absolute ~5% normalization of beam current
- Split into “top” and “bottom” for tracking alignment
- Use this device for O(sec) normalization and integrate for tracking irradiation
- Precision calibration with activation of Al foil (checked once from first month)
- Ran 800 um Au-Pt EL-grade detector to $0.5 \times 10^{17}$ p/cm²
  - Now drawing too much dark current to run
  - Need to inspect to see if detector or cables/connector are the problem

- Ionization Chamber – first month

- Activation foil y-profile – first month

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TOTAL

BOTTOM

TOP

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Ac Science Seminar

Ewart
Blackmore
TRIUMF Beam Line 1A

- One of TRIUMF’s main beam lines
- Run 500 MeV protons up to 150 μA
- We run at lower beam currents
  - 4 – 40 nA
  - Gives $10^{15} – 10^{16}$ p/cm² per day
- Monitor flux/fluence with secondary emission monitors and Cyclotron “stripper” currents
- Final precise normalization will come from activation of Al foils installed with diamond detectors (in progress)
- 1-13 Sept 2010: ran 4 detectors beyond $2 \times 10^{17}$ p/cm²
  - All still alive and giving good signal/noise
  - “flat-line” (not quite) ≈ 5% of initial amplitude
WE RAN HERE (MON BOX M6.6)
After $2 \times 10^{17}$ p/cm$^2$

$800$ p/pulse $\Rightarrow 0.5$ fC (2700 e) per p per detector

First beam ($\approx 0$ fluence)

$800$ p/pulse $\Rightarrow 0.5$ fC (2700 e) per p per detector

After $2 \times 10^{17}$ p/cm$^2$

$8000$ p/pulse $\Rightarrow 0.02$ fC (120 e) per p per detector
Typical Analysis

• Record both detector data and cyclotron RF clock with digital scope
  – Use relative timing to
    • Measure pedestal where no signal
    • Overlay pulses, build average pulse per channel
    • Measure pulse charge, height, width …
    • And plot normalized:
      – (pulse charge) / beam current vs. fluence
• Also record detector(s) bias (HV) current
  – Compare bias current to average pulse charge
  – Look at
    • bias current normalize to beam current vs. fluence
• Note: BL1A data only 2 weeks old …
  – Analysis is work in progress.
**NBIF results**

*(800 μm EL-grade Au-Pt)*

- Detector response reaches ~20% after ~$2 \times 10^{16}$ p/cm² (consistent with RD42)
- Response is then ~flat with fluence
- Bias current consistent with pulse charge $\times$ rate
- At $\sim 0.5 \times 10^{17}$ p/cm² see increase in dark current and now won’t old bias voltage
- Not sure why
- Eg, cables, connectors in high fluence zone (not rad hard)
- Also don’t really know background field level
- Will know more after detector assembly cool enough to dismantle for inspection/tests and irradiation foil analyzed
First beam ($\approx 0$ fluence)  
Beam Current $\approx 4$ nA  
(about 800 p/pulse)

- Some evidence for pulse narrowing with irradiation
- Requires further study
  - Cyclotron pulse width structure
  - Relative phase of signal w.r.t. cyclotron RF
  - ...

After $2 \times 10^{17}$ p/cm$^2$  
Beam Current $\approx 40$ nA  
(about 8000 p/pulse)
BL1A: response curve data (log scale)

- Black = EL200 TiW-Al
- Blue = OP300 TiW-Al
- Red = EL300 Au-Pt
- Green = OP300 Au-Pt

Need to zoom ...

Consistent with previous irradiation tests

≈ 5% of Max

Pulse Area / Beam Current (arb. Units)

Need to zoom ...

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x $10^{15}$ p/cm$^2$
BL1A: response curve data (linear scale)

- Black = EL200 TiW-Al
- Blue = OP300 TiW-Al
- Red = EL300 Au-Pt
- Green = OP300 Au-Pt

Need to zoom ...

Consistent with previous irradiation tests

$\approx 5\%$ of Max

$35 \times 10^{15} \text{ p/cm}^2$
BL1A: fit double exponential
\[ p_0 + p_1 e^{p_2 x} + p_3 e^{p_4 x} \]
BL1A: zoom 1\textsuperscript{st} 10^{16} p/cm\textsuperscript{2}

Scatter partly due to beam current logging granularity (in normalization)

**Normalized Integral Detector 1 EL200 TiW-AI**

- **Fit**: $p_0 + p_1 e^{p_2 x}$

- **Fit parameters**:
  - $P0$ 122
  - $P1$ 301
  - $P2$ -0.100

**Normalized Integral Detector 2 OP300 TiW-AI**

- **Fit**: $p_0 + p_1 x$

- **Fit parameters**:
  - $P0$ 345
  - $P1$ -13.33

**Normalized Integral Detector 3 EL300 Au-Pt**

- **Fit**: $p_0 + p_1 e^{p_2 x} + p_3 e^{p_4 x}$

**Normalized Integral Detector 4 OP300 Au-Pt**

- **Fit**: $p_0 + p_1 x$

- **Fit parameters**:
  - $P0$ 321
  - $P1$ -11.96
Detector bias current sum

fit to: \( p_0 + p_1 e^{p_2 x} + p_3 e^{p_4 x} \)

- Sharp initial drop
- No great multi-exp fit
- Never completely flattens out
Bias Current Sum (all 4 detectors)
After $2 \times 10^{17}$ p/cm$^2$
Beam current 40 nA
“Hysteresis” (HV scan): Pulse Charge
After $2 \times 10^{17}$ p/cm$^2$ with Beam current 40 nA

**Amplitude Hysteresis Detector 1** EL200 TiW-Al

**Amplitude Hysteresis Detector 2** OP300 TiW-Al

**Amplitude Hysteresis Detector 3** EL300 Au-Pt

**Amplitude Hysteresis Detector 4** OP300 Au-Pt

fit to: $p_0 + p_1 x + p_2 x^3$
Linearity check: beam current scan after $2 \times 10^{17}$ p cm$^{-2}$ s$^{-1}$ (last day)

Detector1 = EL200 TiW-Al

fit to: $p_0 + p_1 x$
Time resolution after $2 \times 10^{17} \text{ p/cm}^2$ (last day)

- After full irradiation, check time stability
  - Take 10 “waveforms” (4550 pulses)
  - Plot pulse time – RF time $\Rightarrow$ Upper limit on diamond time resolution
  - Note: “infinite stats” ($\approx 8000$ protons / pulse)
    - Convolution of detector, preamp, and cyclotron bunch stability

Mean = 7.919 nsec
\[ \sigma = 0.1914 \text{ nsec} \]
Summary

• **Diamond irradiation scans to fluences relevant for sLHC ATLAS MiniFCal**
  • **Pushed to proton fluences 10x larger than previous measurements**
    – Detectors continued to run above $2 \times 10^{17}$ p/cm$^2$ (10$^{10}$ RAD, 60,000 kGy)
    – Amplitude $\approx 5\%$ of initial
    – No evidence of heating observed
    – Detector timing remained good (< 200 psec) throughout test
• **Do not see enormous differences among different detectors**
  – EL seems to have faster initial drop than OP, merging @ high fluence
  – Also that Ti-based metalization a bit more robust that Au-Pt
• **Analysis continuing**
  – Precise fluence normalization with activation foils, pulse shape/timing evolution analysis, detailed comparisons of different detectors…
• **Future tests**
  – Monitor detectors from BL1A – look for annealing?
  – Spatial uniformity tests (M11 at TRIUMF?)
  – Multi-detectors running together to test ganging schemes for MiniFCal
  – Lower energy protons to test damage cut-off thresholds, possibly with Montreal van der graaf which runs 1-11 MeV
• **Neutron tests: reactor? (exploring use of Dubna reactor)**