

APDs: Requirements for Forward Endcap Usage

Thomas Held

Ruhr-Universität Bochum
Institut für Experimentalphysik I

Forward Endcap EMC Production Readiness Review II, GSI
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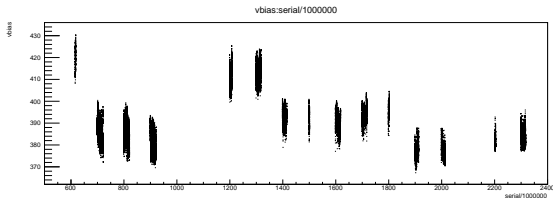
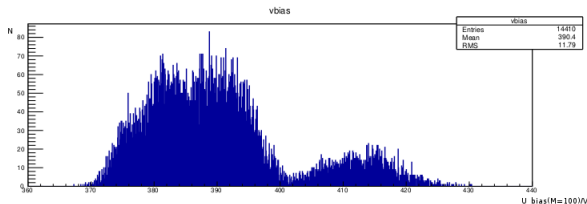


Forward Endcap APD requirements: Numbers

- The Forward Endcap EMC contains 3856 PbWO_4 crystals
- 768 crystals will be equipped with vacuum photo tetrode tubes for read out (inner most region with highest radiation doses and highest single channel data rates)
- 3088 crystals will be read out by 2 APDs each
- Therefore 6176 APDs matched with respect to the bias voltage for a gain of 200 (absolute value and gradient) in groups of 8 pieces each are needed
- For the necessary production rate of one APD subunit a day we correspondingly need 32 APDs (4 matched groups of 8 APDs each) a day
- Reasonable matching criteria (as used for the barrel slice):
 - $\Delta U_{bias}(M=200) \leq 0.1 \text{ V}$
 - $\Delta (1/M \text{ d}M/\text{d}U_{bias}(M=200)) \leq 0.1 \%/\text{V}$

Forward Endcap APD requirements: Numbers

- Barrel slice rejects (for pairs!):
 - 20 % in the beginning (very low APD delivery rate)
 - 10 % finally
- Matching probability increase by suitable preselection regarding to Hamamatsu values of $U_{bias}(M = 100)$



Forward Endcap APD requirements: Test Measurements

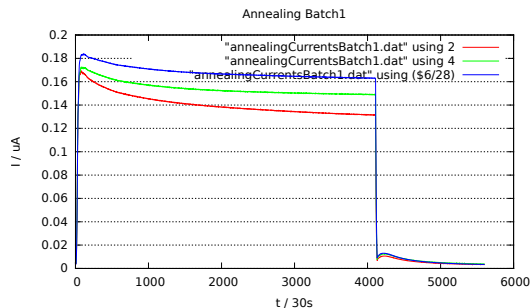
- What is the necessary treatment of the APDs for a safe evaluation of suitability for usage in the forward endcap?
- We conducted test measurements on 90 APDs (non-irradiated) in order to derive a screening scenario that will result in the highest possible throughput without compromising acquisition of necessary data needed for matching and evaluation of suitability for the usage in the forward endcap:
- Recording of
 - Dark current vs. bias voltage curve
 - DC characteristic curve (DC light response vs. bias voltage)
 - AC characteristic curves (AC light response vs. bias voltage)
- The curves have been taken at $-25\text{ }^{\circ}\text{C}$ and $+20\text{ }^{\circ}\text{C}$ and
- Prior to irradiation, before and after thermal annealing

Forward Endcap APD requirements: Irradiation

- Irradiation was done at Strahlenzentrum Giessen with the ^{60}Co source and the usual setup
- However, a subsample of APDs has been irradiated under bias, another one with pins shorted (15 out of 90 pieces)
- Irradiation time was 1 hour 13 min corresponding to 45 Gy (the dose used for the PSL irradiations), to be compared to the $\bar{\text{P}}\text{ANDA}$ life time dose of the APDs in the forward endcap of 4-26 Gy, depending on position mounted
- \Rightarrow Applied doses 1.7 - 11 times the $\bar{\text{P}}\text{ANDA}$ life time dose, depending on position mounted (Why exactly this dose? Reduction may speed up irradiation)

Forward Endcap APD requirements: Thermal annealing

- Thermal annealing was done at +80 °C under common bias of 300 V, monitoring the dark currents (individual APD currents for some APDs, sum currents for the rest)
- Annealing time was 34 h as originally recommended by PSL (contradictory to the 9 h given in the current document), better to be extended to 48 h as obviously necessary in order to return to primary dark currents before irradiation for all APDs



Dark currents during annealing:

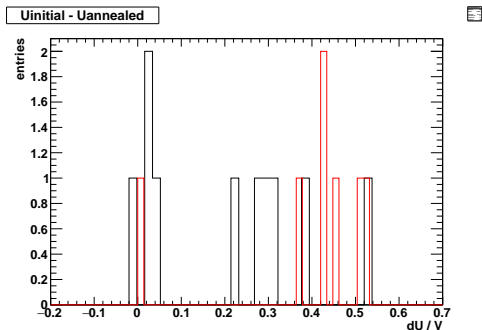
Blue: Scaled current sum of 28 APDs

Green: Current of single APD irradiated w/o bias

Red: Current of single APD irradiated under bias

Forward Endcap APD requirements: Test Results I

- We see no difference in any parameter of the APDs irradiated w/ or w/o bias voltage applied
- e.g. gain 200 bias voltage difference before and after irradiation and annealing



- Black: irradiated under bias, red: irradiated w/o bias supply

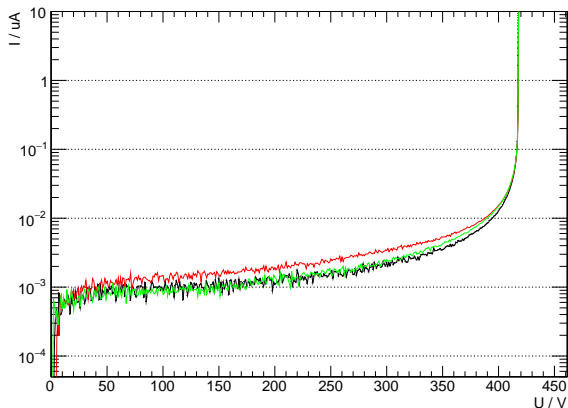
Forward Endcap APD requirements: Test Results I

- Remark:
 - CMS recommended irradiation w/ APD electrodes shorted rather than biasing the APDs (much higher doses/dose rates though)
[CMS NOTE 2004/008]
[“Double screening tests of the CMS ECAL avalanche photodiodes” K. Deiters et al, NIM A 543(2005)549]
 - Astro-H mission satellite experiment: Irradiation with APDs not connected to anything at all (after testwise comparison to irradiation under bias) at comparable doses and dose-rates
[“Expected radiation damage of reverse-type APDs for the Astro-H mission” J. Katako et. al, JINST 7, P06001, 2012]
- We therefore conclude that there is no need to bias the APDs during irradiation which would clearly speed up the irradiation procedure

Forward Endcap APD requirements: Test Results II

- Dark currents at +20 °C:
 - The dark currents of the irradiated APDs slightly increase
 - Some dark current decrease during annealing, net increase reasonably small

Dark_Current_9



Black: Untreated

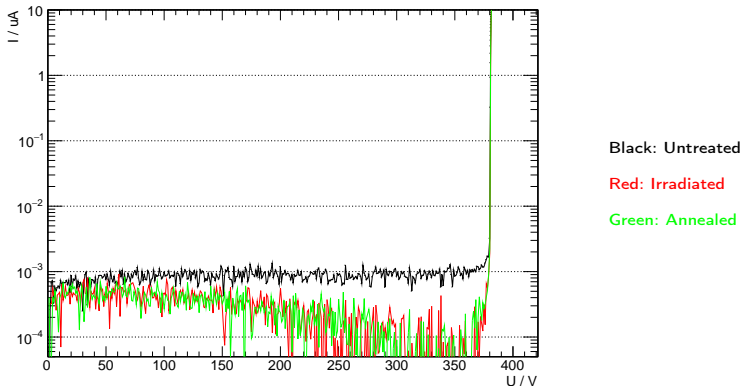
Red: Irradiated

Green: Annealed

Forward Endcap APD requirements: Test Results II

- Dark currents at $-25\text{ }^{\circ}\text{C}$:
 - General remark: Low currents in the sub-nA range (as APD dark currents at $-25\text{ }^{\circ}\text{C}$) are not reliably measurable with the ISEG HV modules (if not constantly calibrated)
 - No increase in dark current after irradiation

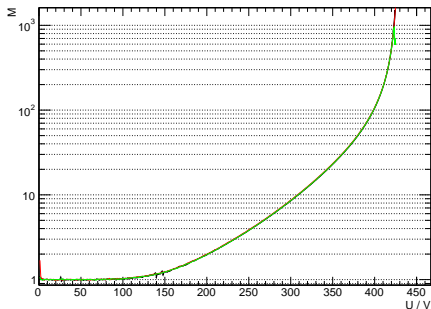
Dark_Current_9



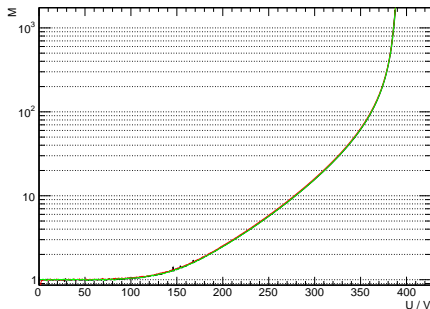
Forward Endcap APD requirements: Test Results III

- Irradiation and thermal annealing each do not change the characteristic curves of the majority of APDs measured (overlaid curves in plots: non-irradiated, irradiated, annealed)
- This applies to AC as well as to DC characteristic curves, each at $-25\text{ }^{\circ}\text{C}$ (right) and $+20\text{ }^{\circ}\text{C}$ (left)

Gain_14

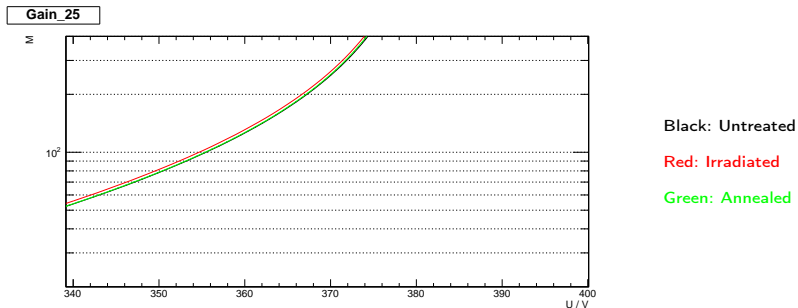


Gain_14



Forward Endcap APD requirements: Test Results III

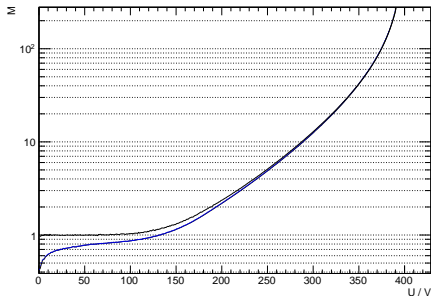
- In some cases the curve after irradiation is shifted to the left (by some 100 mV), moving back right after annealing



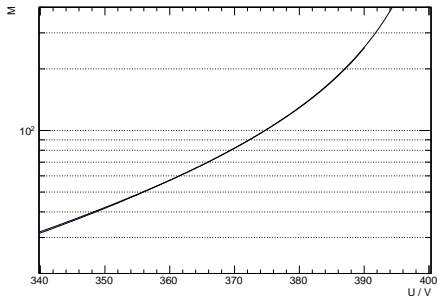
Forward Endcap APD requirements: Test Results II

- Overlaying AC and DC characteristic curves at any reasonable point (response at bias voltage for gain 100, 150, or 200) results in deviations in the region of interest small enough to ignore
⇒ Restrict the measurements to DC characteristic curves only

Gain_5



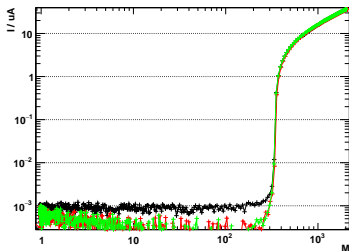
Gain_5



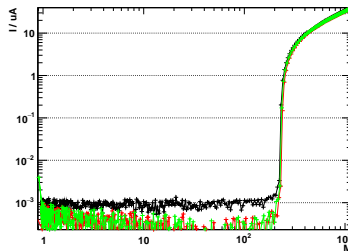
Forward Endcap APD requirements: Test Results IV

- Difference between operating bias voltage and breakdown voltage (gain 200 distance to breakdown gain)

DarkCurrent_vs_Gain_12



DarkCurrent_vs_Gain_6



- Black: untreated, red: irradiated, green: annealed
- Critical with some APDs? → Definition of sort-out margin
- Usability for barrel (gain 150) safe in any case

Forward Endcap APD requirements: Sort-Out Criteria

- Sort-out criteria:
 - Too high dark current at operating voltage (gain 200)
→ not seen within this sample, what noise level will overcome shaping?
 - Operating voltage (gain 200) too close to breakdown (margin to define)
- All other issues (QE changes, capacitance changes, increasing gain 200 bias ...) too small to worry about: Light yield decrease of crystals dominating calorimeter performance
- Small changes in APD behaviour easily calibrated out automatically in the experiment later on

Forward Endcap APD requirements: Summary

- For a sensible matching of APDs in groups of 8 pieces each we need a high number of APDs **immediately**:
 - Necessity to start **high throughput** screening now!
 - Forward endcap only demand: 30 APDs/day
 - At start of production 4 months from now: 2400 need to be available for first matching (the more the better!)
 - Paralleled screening ongoing after start of submodule production (10 months): 6000 more
 - In total 8400 pieces vs. 6200 needed (about 25 % sorting overhead - larger matching groups than in barrel (10 % sorting overhead in slice), but also larger number of APDs)
- Additional barrel demand: module production ongoing in 2018!

Forward Endcap APD requirements: Summary

- Our test screening reveals the necessary scenario for high throughput
- A screening comprising only the necessary measurements must restrict to the following steps:
 - Lot-wise preselection to narrow the spread for matching
 - Dark current and DC light characteristic curves measurements on new APDs
 - Irradiation at Strahlencentrum Giessen (about 30 Gy) w/o bias applied
 - Thermal annealing at 80 °C for 48 hours (common bias)
 - Dark current and DC light characteristic curves measurements on the annealed APDs
 - Matching