Automated SiPM Quality Control for the ePIC Longitudinal Forward Hadronic Calorimeter (LFHCal)

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ePIC Central Detector Systems

Hadronic Calorimeters

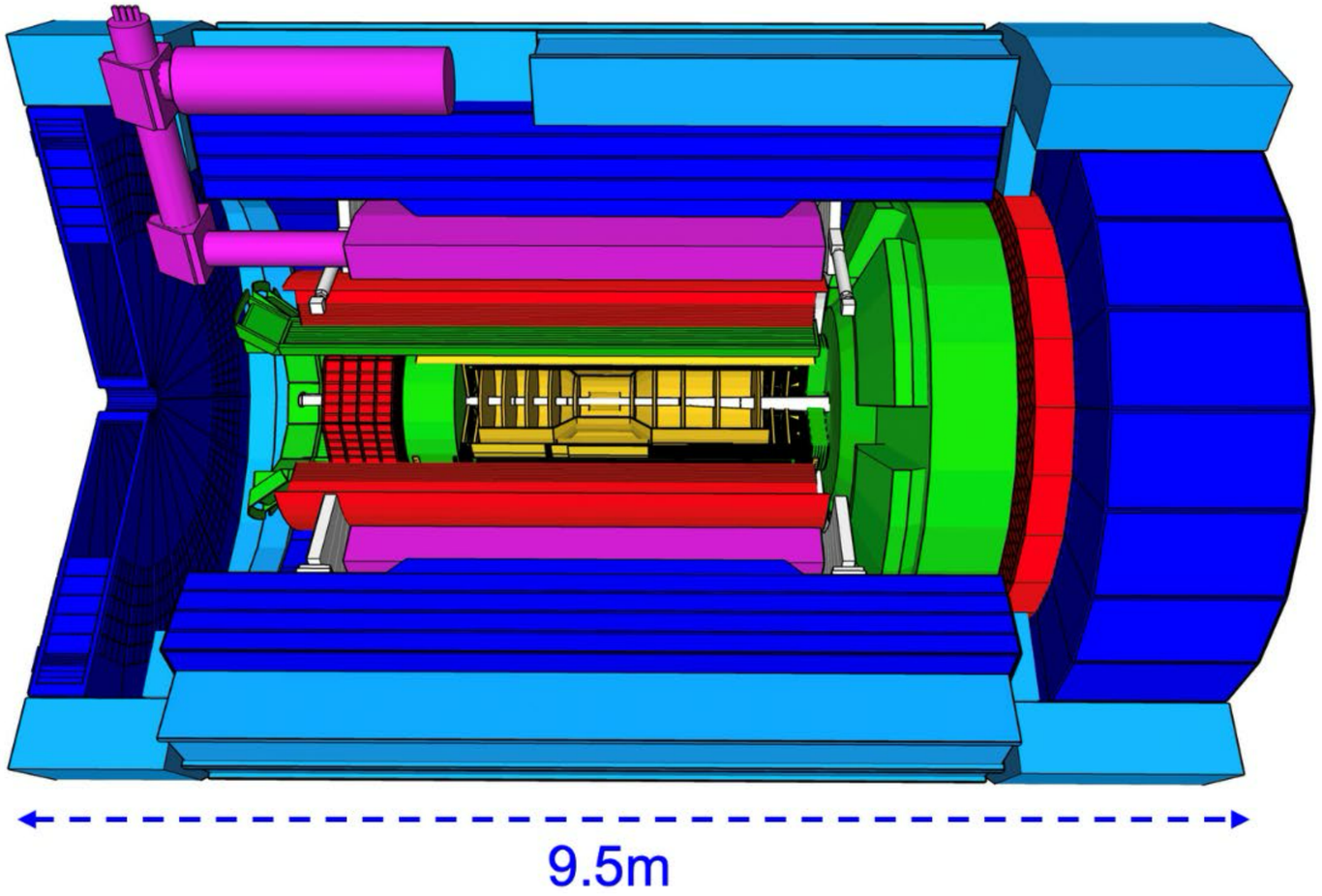
Solenoidal Magnet

Electromagnetic Calorimeters

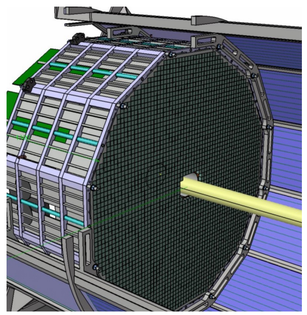
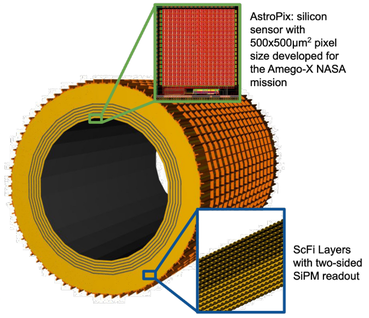
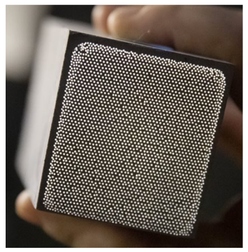
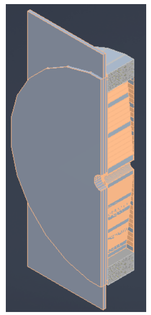
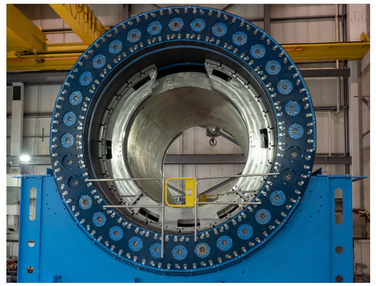
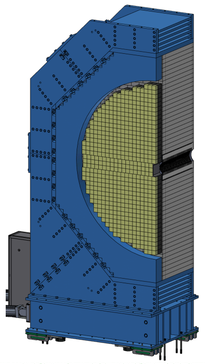
ToF, DIRC, RICH Detectors

MPGD Trackers

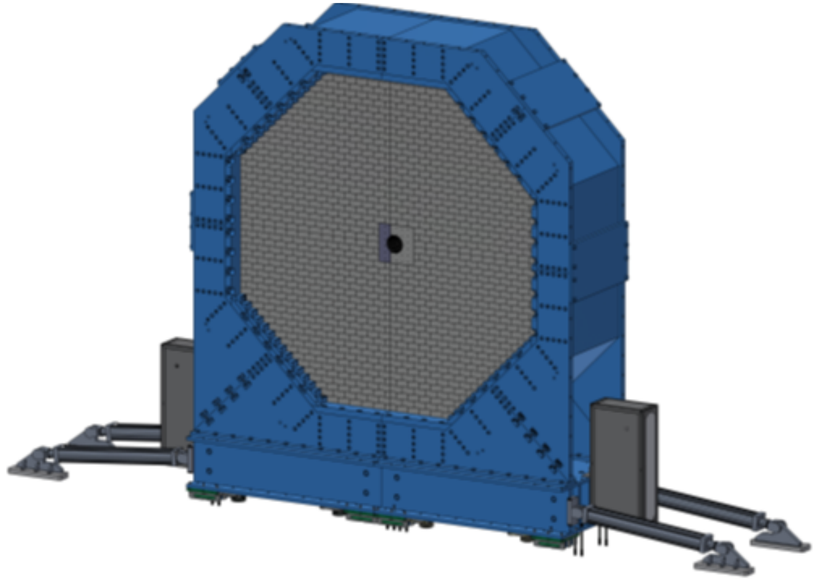
MAPS Trackers



Calorimeters at ePIC

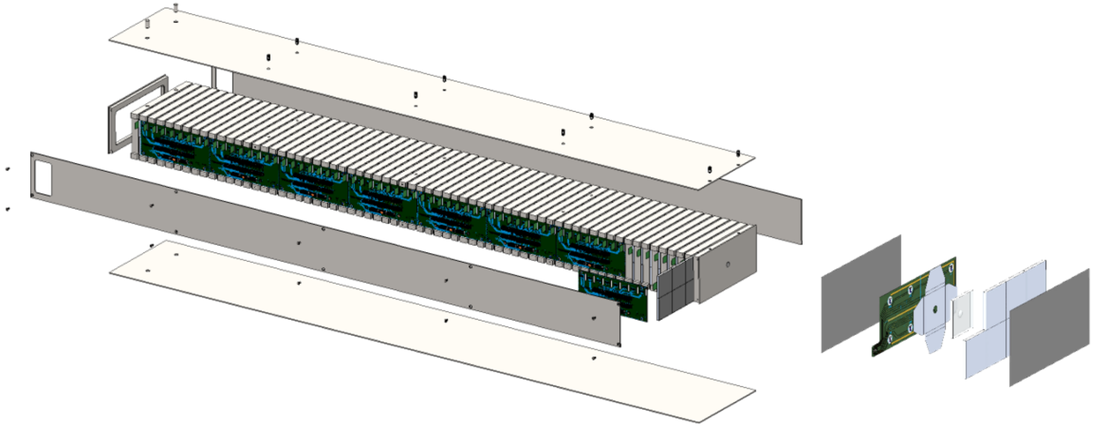
	Backward ECal	Barrel ECal	Forward ECal	Backward HCal	Barrel HCal	Forward HCal
						
Main Function	scattered lepton detection -> very high-precision	scattered lepton and γ detection, hadronic final state characterization	lepton and γ detection, hadronic final state characterization → π^0, γ separation	muon and neutral detection→ improved jet Energy reconstruction	muon and neutral detection →improved jet Energy reconstruction	particle-flow measurements
Proven Technology	PbWO4 – crystals →long lead procurement	Pb/SciFi sampling part using SiPMs combined with imaging section (6 layers) interleaving Pb/SciFi with ASTROPIX	Tungsten-powder + SciFi SPACAL design Developed through EIC R&D and applied successfully in sPHENIX	Steel + Scintillator SiPM-on-tile	Steel + Scintillator design re-used from sPHENIX	longitudinal segmented Steel + Scintillator SiPM-on-tile Pioneered by CALICE analog HCal High resolution insert next to beam-pipe
World's first at ePIC	SiPM as Photon sensors	Use of ASTROPIX in Calorimetry				first-time full-size CALICE like calorimeter in collider experiment

Longitudinally segmented forward Hcal (LFHCal)



Motivation:

- Maximum coverage for charged & neutral hadron reconstruction
- Reconstruct jets at high rapidities
- Explore hadronization by studying identified particles and substructure within jets



Requirements:

- Energy resolution: $\sigma(E)/E \sim 50\%/\sqrt{E} \oplus 10\%$ (with EMCal)
- Transverse granularity: ~5x5 cm² for $\eta < 3.5$
- Fine longitudinal segmentation to find shower start and maximum, finer at higher η where particle density is higher

LFHCal in Numbers

8M & 4M modules

- Acceptance: 1.2 < η < 3.5
- Inner modules (R < 1m): 3 mm SiPMs -> ~ 11% = 57,800 SiPMs
- Outer modules: injection molded tiles & 1.3 mm SiPMs -> ~ 89% = 467,320 SiPMs

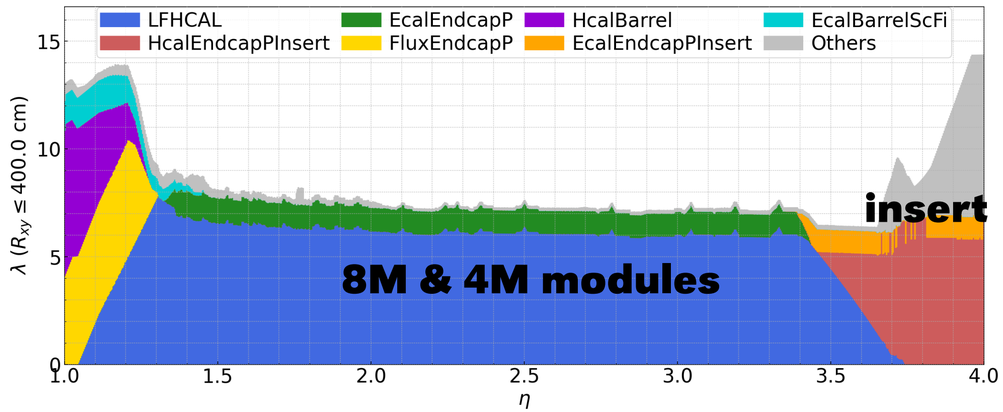
~ 525,120 SiPMs, 70,016 read-out channels

Insert modules

- Acceptance: 3.5 < η < 4.0
- ~ 94 tiles/layer with 3 mm SiPMs

~ 5,640 SiPMs/tiles & read-out channels

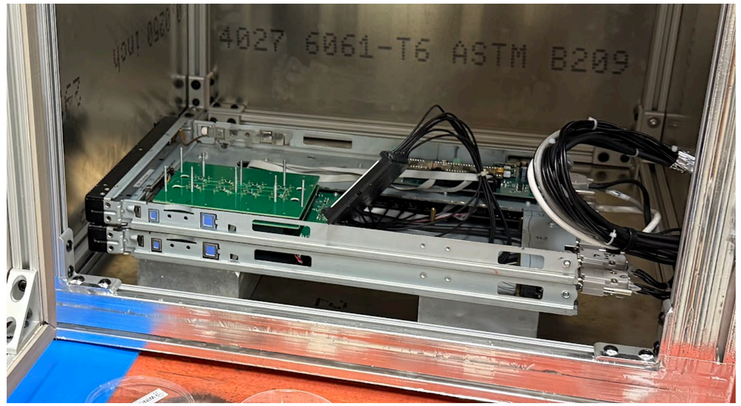
parameter	LFHCal 8M & 4M modules	insert modules
inner x,y (R)	-20 cm $> x >$ 40 cm, -30 cm $> y >$ 30 cm	$R >$ 17 cm
outer R (x,y)	$R <$ 270 cm	-20 cm $> x >$ 40 cm, -30 cm $> y >$ 30 cm
η acceptance	$1.2 < \eta < 3.5$	$3.5 < \eta < 4.0$
tower information		
x, y	5 cm	5 cm
z (active depth)	120 cm	120 cm
z read-out	$\approx$ 8.4 cm	$\approx$ 8.4 cm
# scintillator plates	60 (0.4 cm each)	60 (0.3 cm)
# absorber plates	60 (1.52 cm)	60 (1.52 cm)
interaction lengths	5.8-6.5 λ/λ_0	5.8 λ/λ_0
# towers	8752	
# modules		2
8M	1058	
4M	72	
# read-out channels	8 x 8752 = 70016	5640

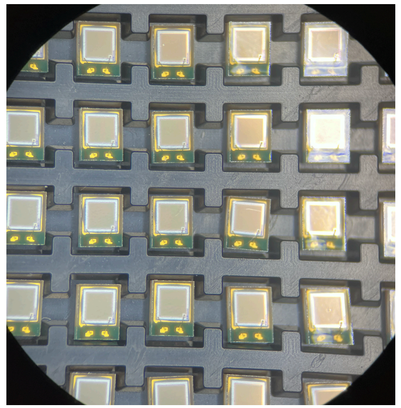


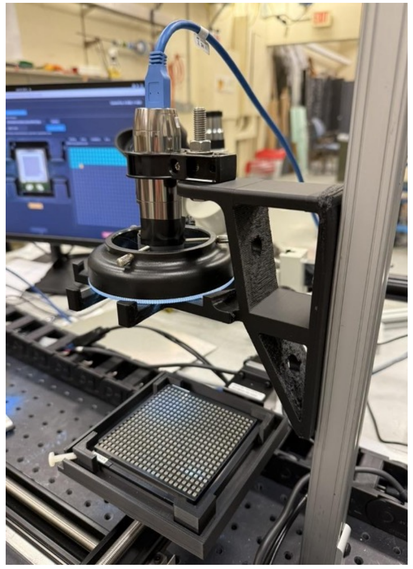
SiPM Quality Control for CD-3A

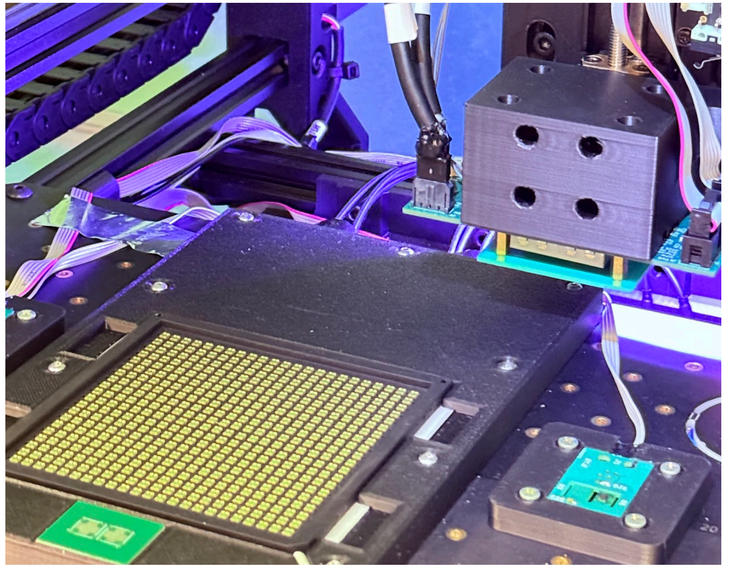
SiPM Delivery & Acceptance Testing

- 2025-2026: ~33K SiPMs delivered per month (341.4K total)
- Acceptance testing procedure established: 5% of trays tested
  - 09/2025: Manual test set-up at Yale (32 SiPMs per load)
  - 02/2026: Automated test setup build by the University of Debrecen and Yale (460 SiPMs per load)
- 19.3K SiPMs tested at Yale so far, focusing on breakdown voltage measurements and visual inspection





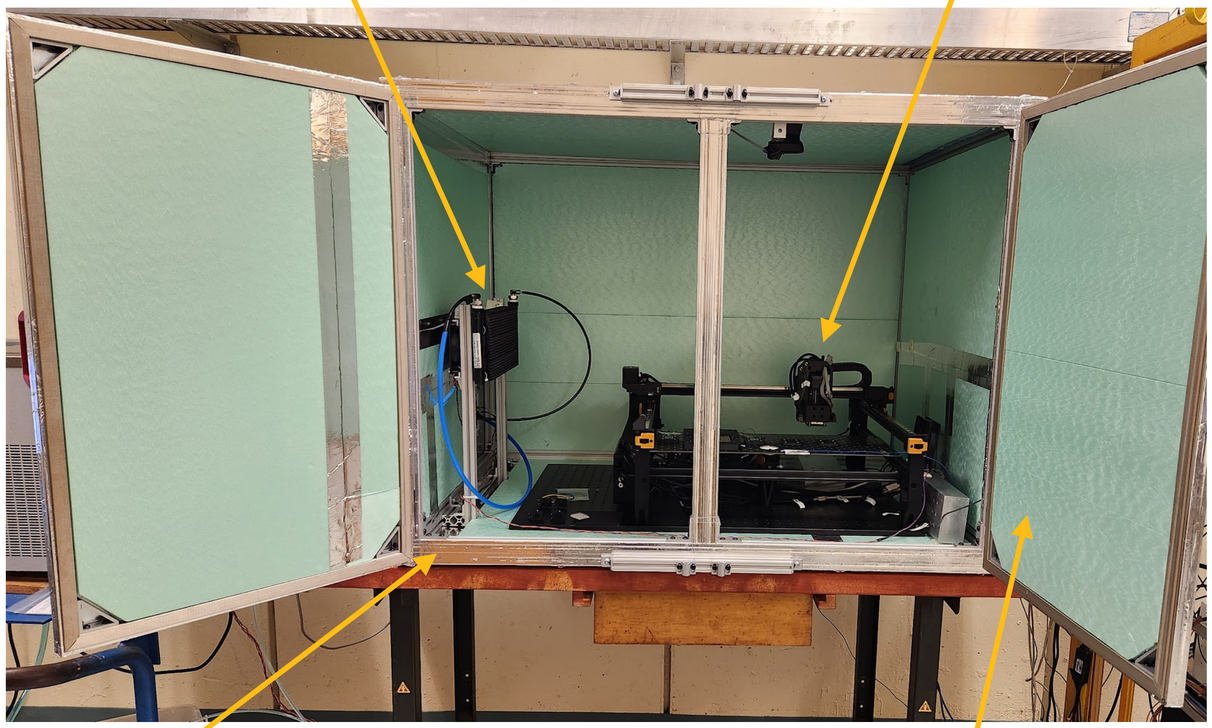




Automated Test Setup for SiPM V_{br} Studies

Glycol convection cooling (@ 20°C)

SiPM Testing Robot



3ft x 4ft enclosure
(dark box, Faraday cage
and thermal insulation)

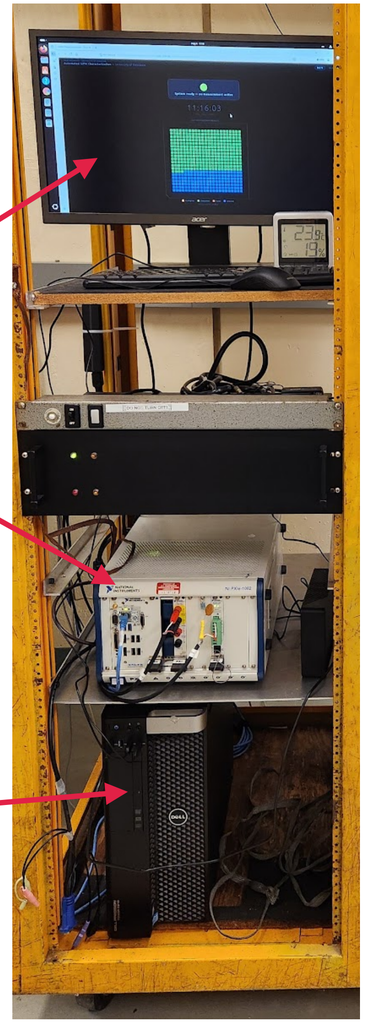
Thermal insulation

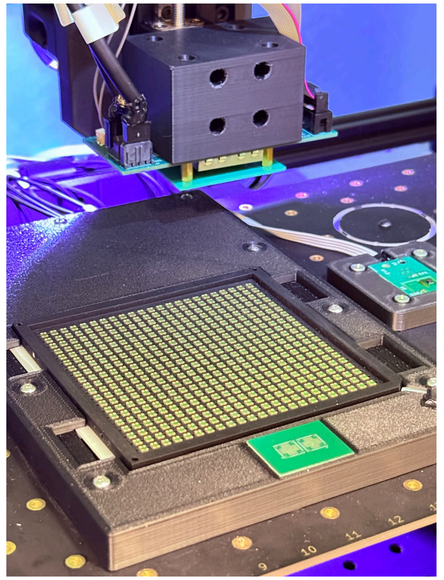
Online
Monitoring

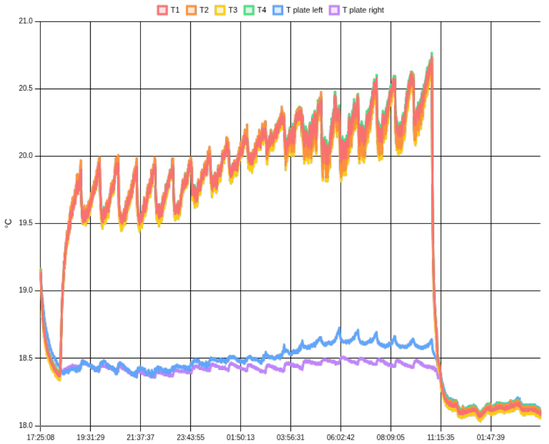
PXIe-8135
controller

SMU (PXIe-4136)
and DMM
(PXIe-4081)

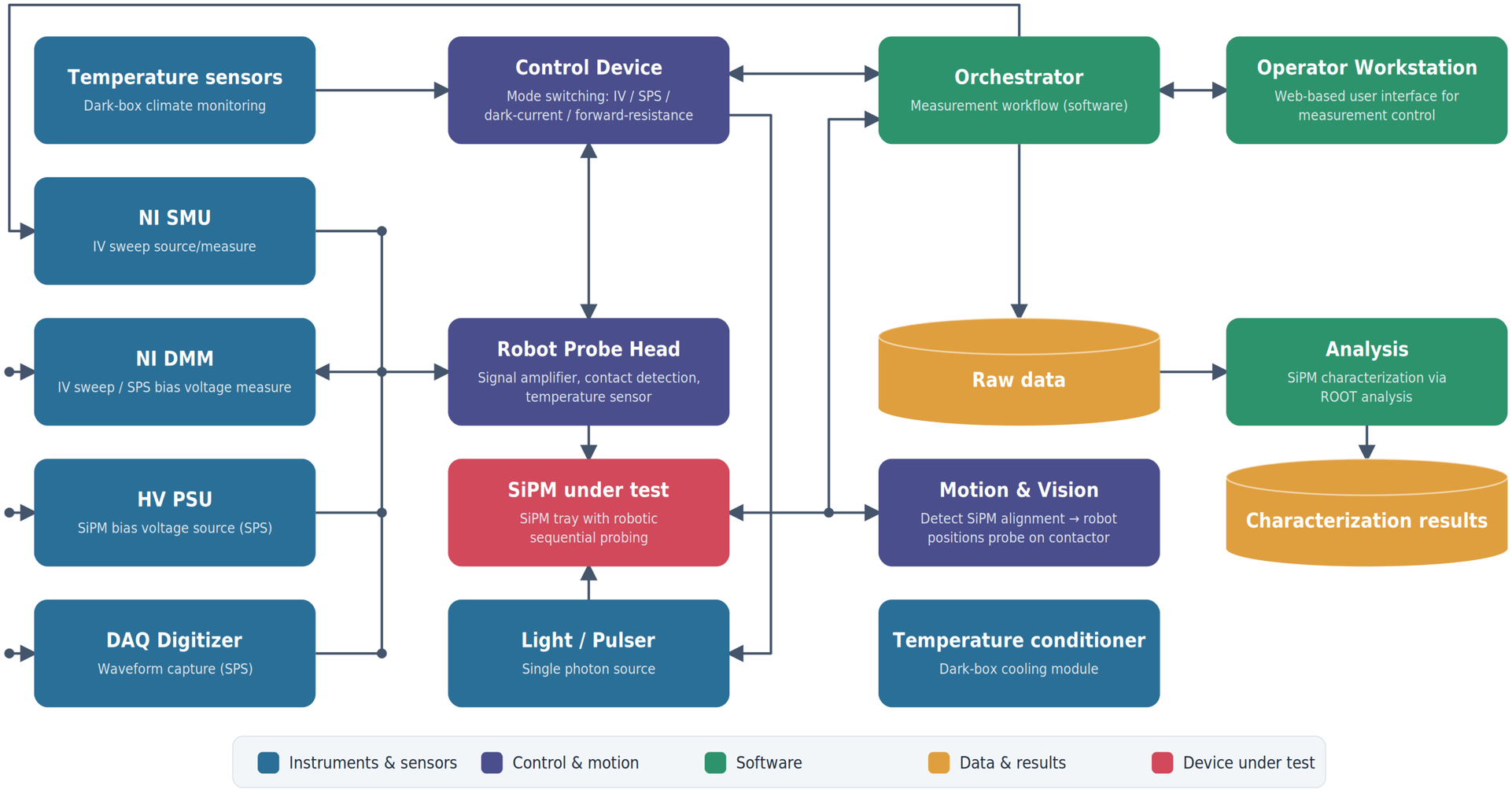
DAQ PC



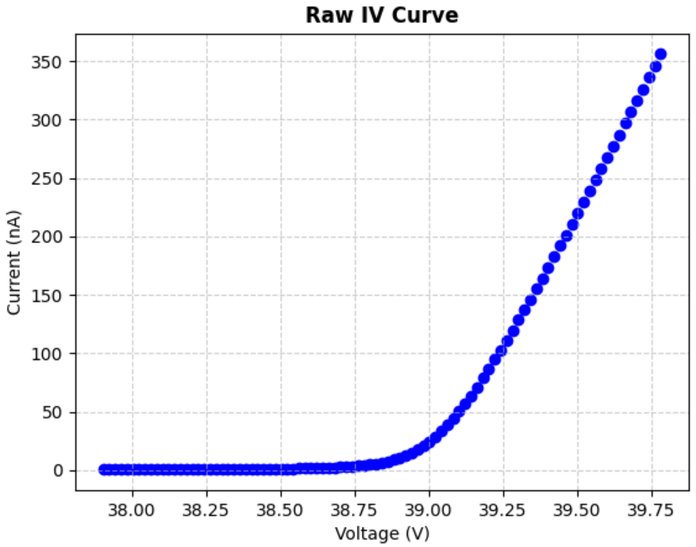


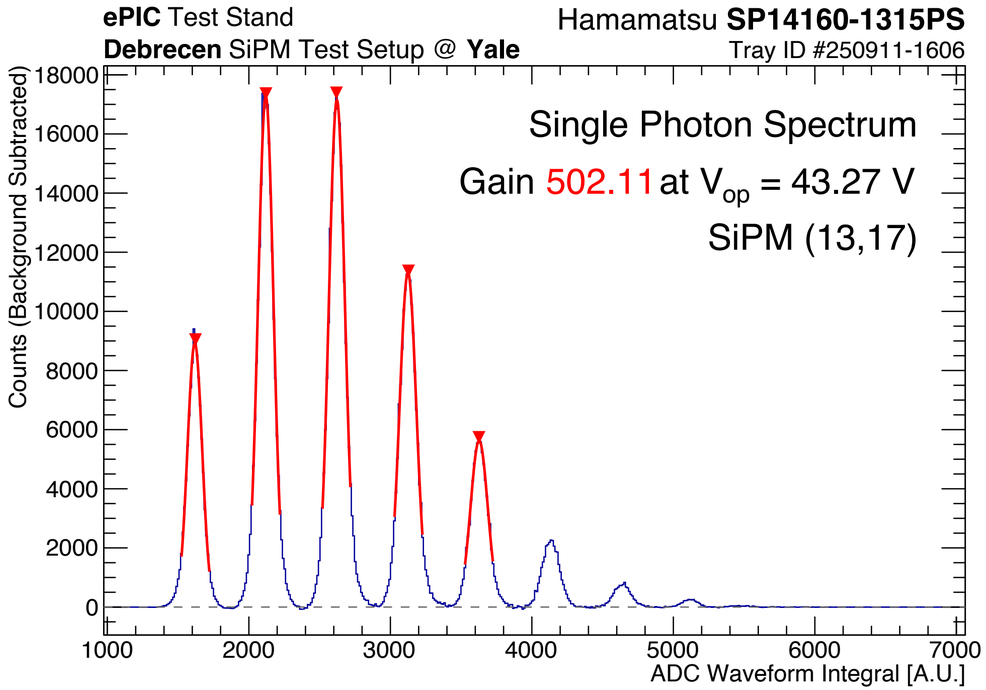


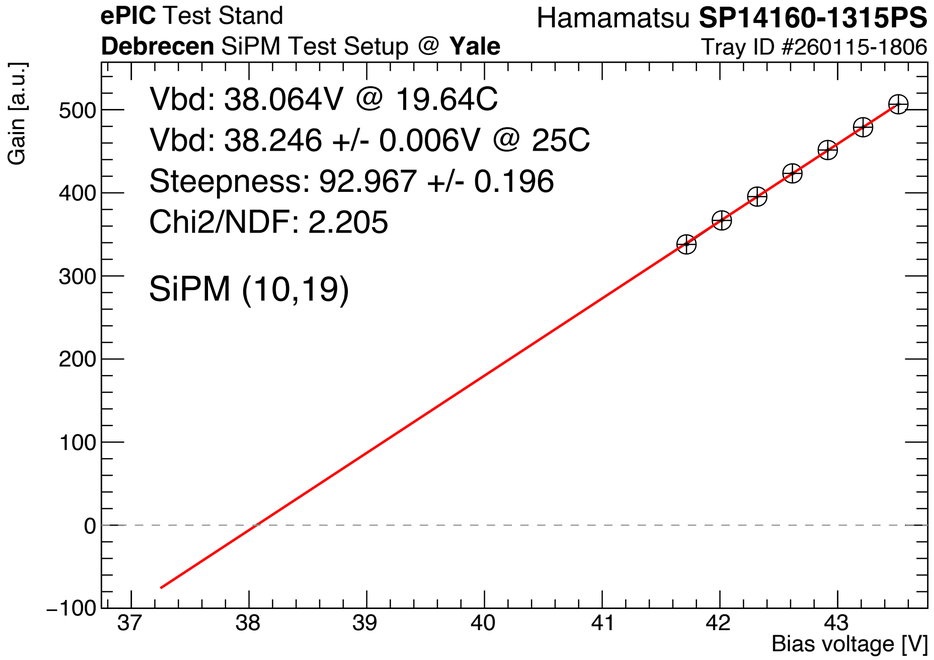
Characterization Setup: Flow Chart



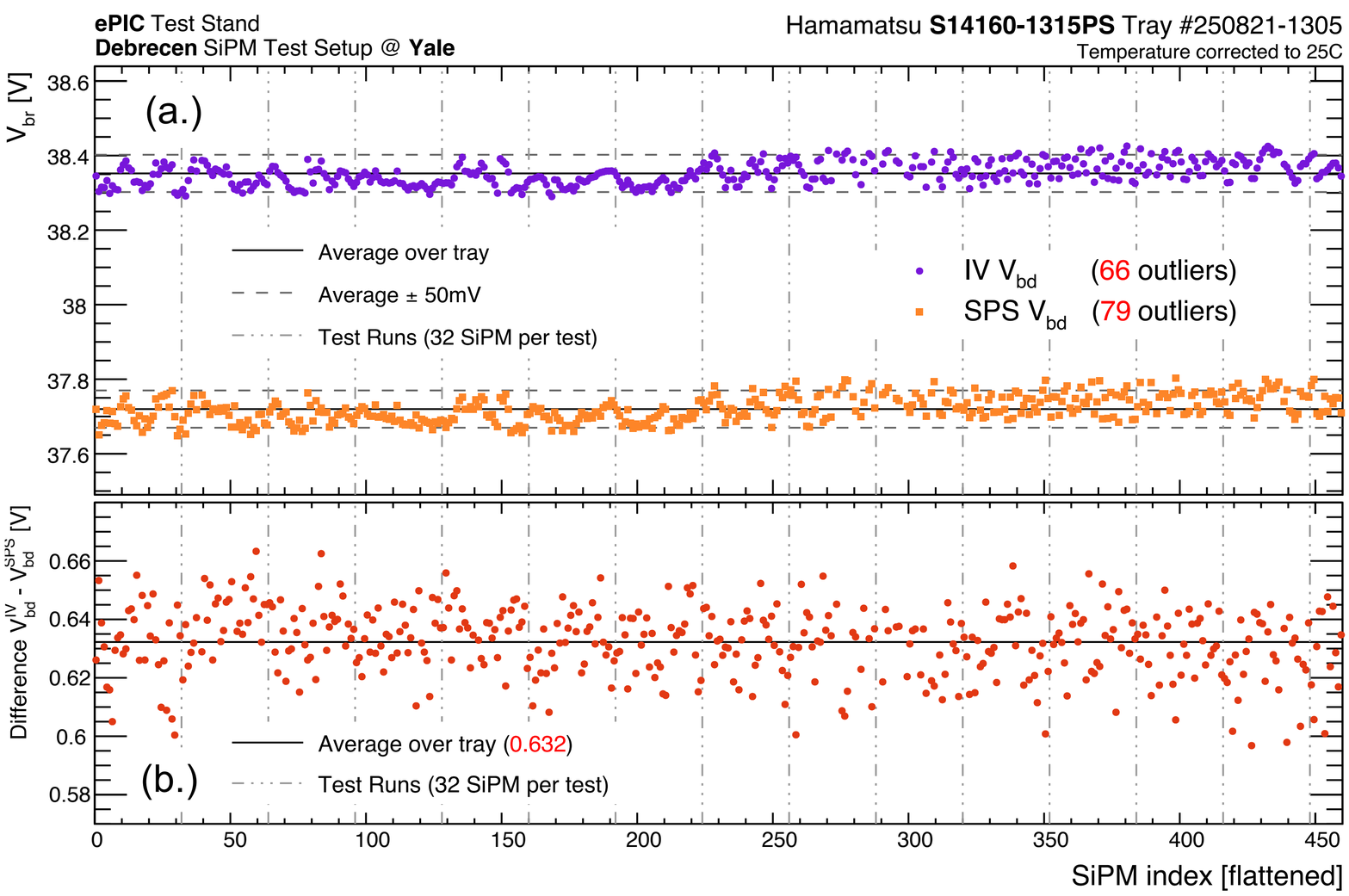
Example IV and SPS Breakdown Voltage Determination

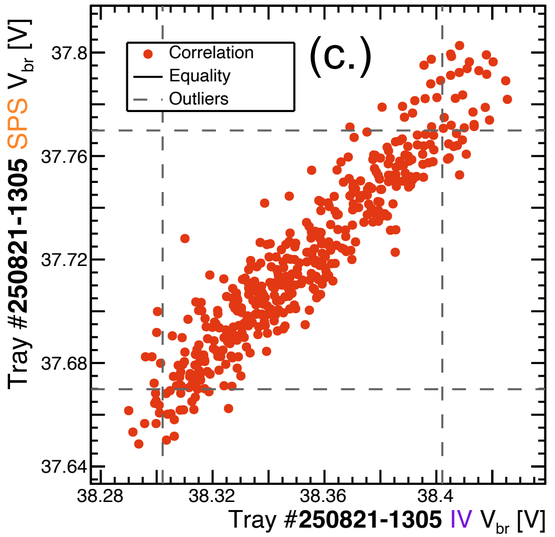


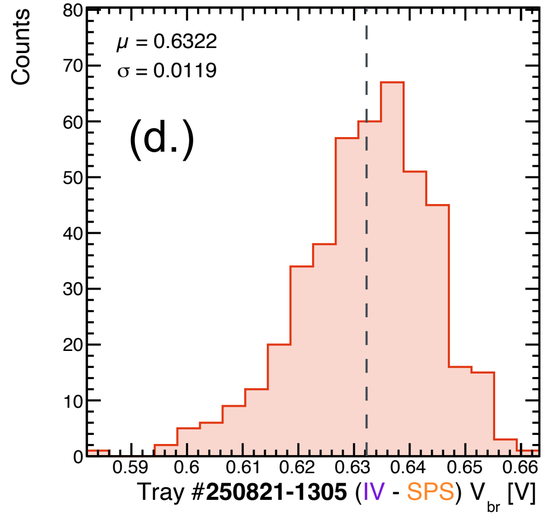




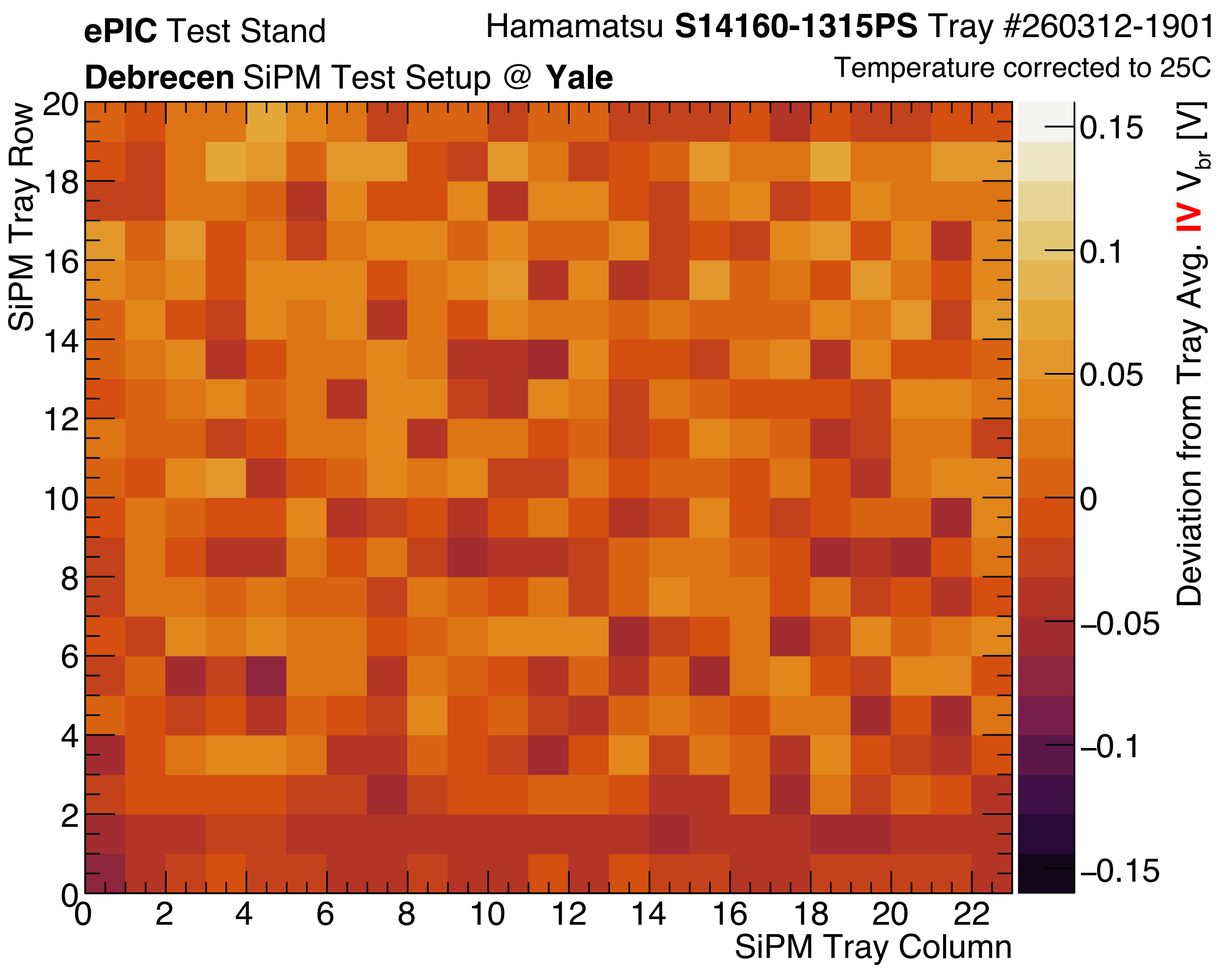
IV vs. SPS Breakdown Voltage Comparison (Single Tray)

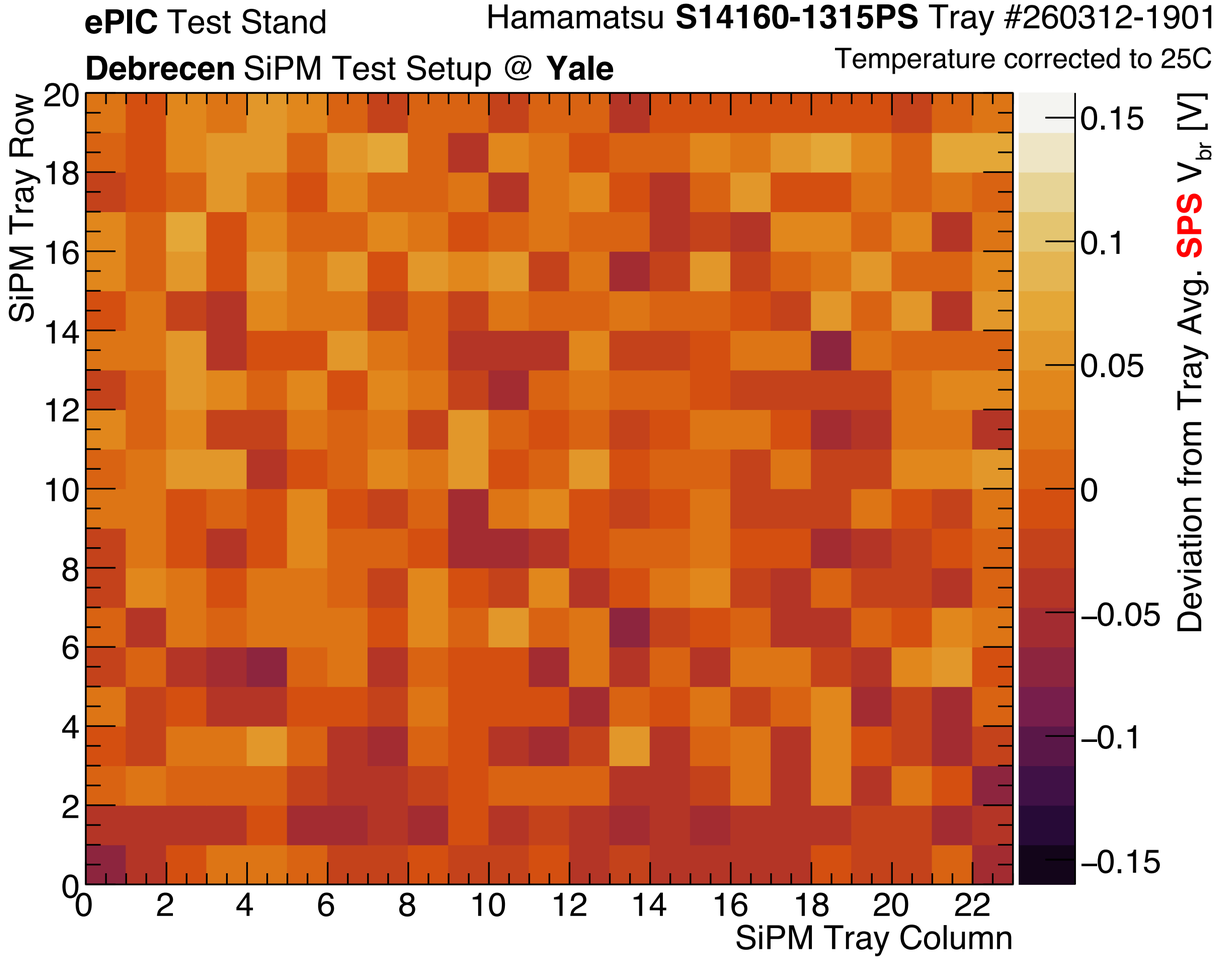




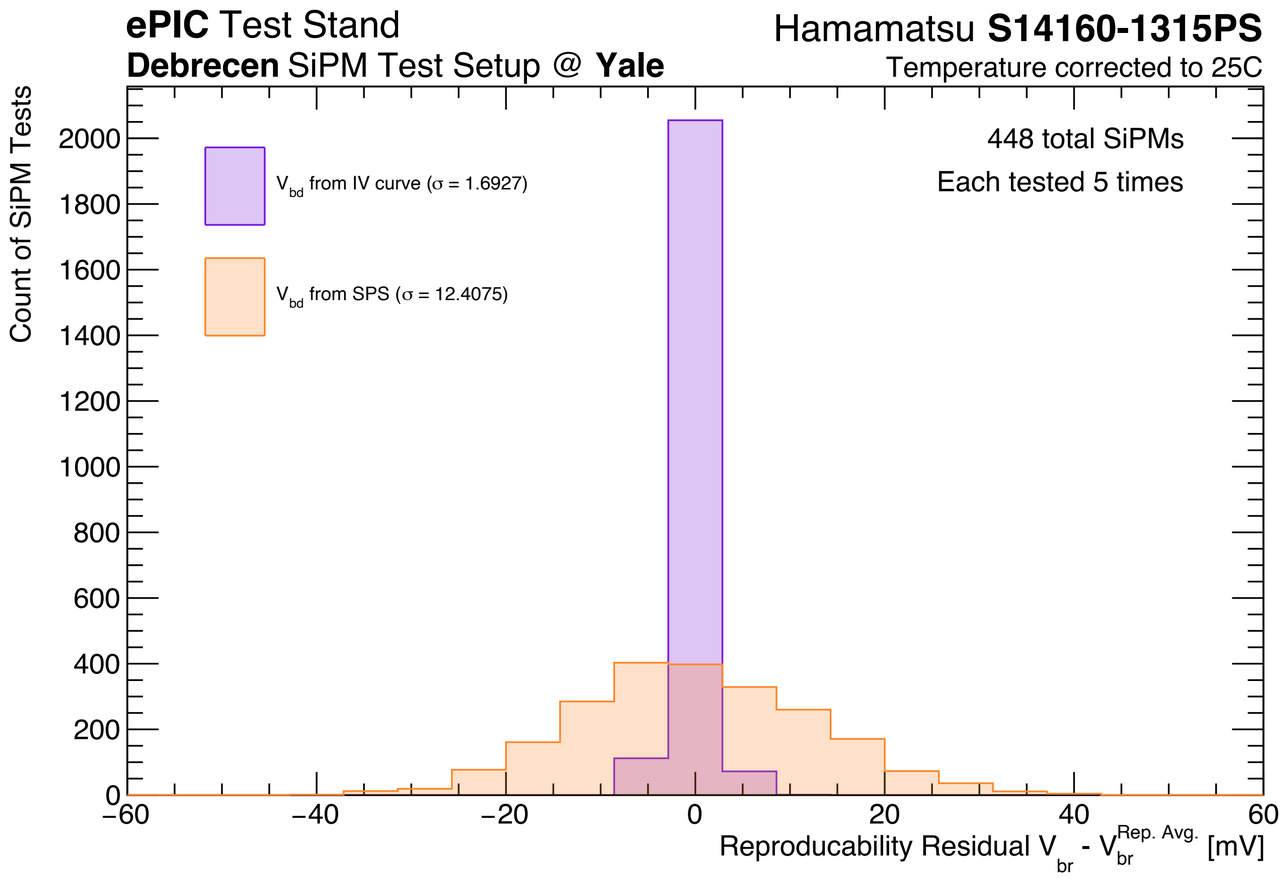


V_{br} Uniformity within a Tray: IV and SPS (25 °C)

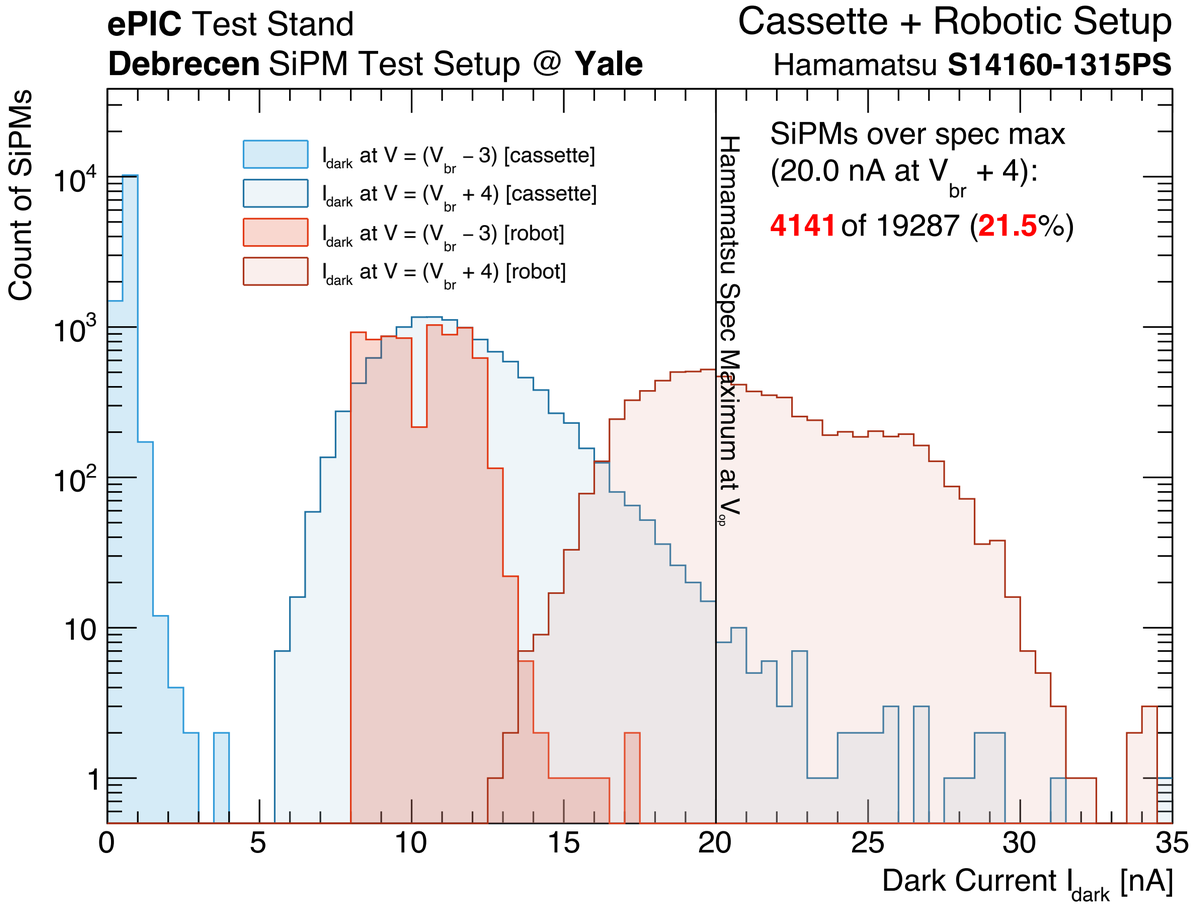




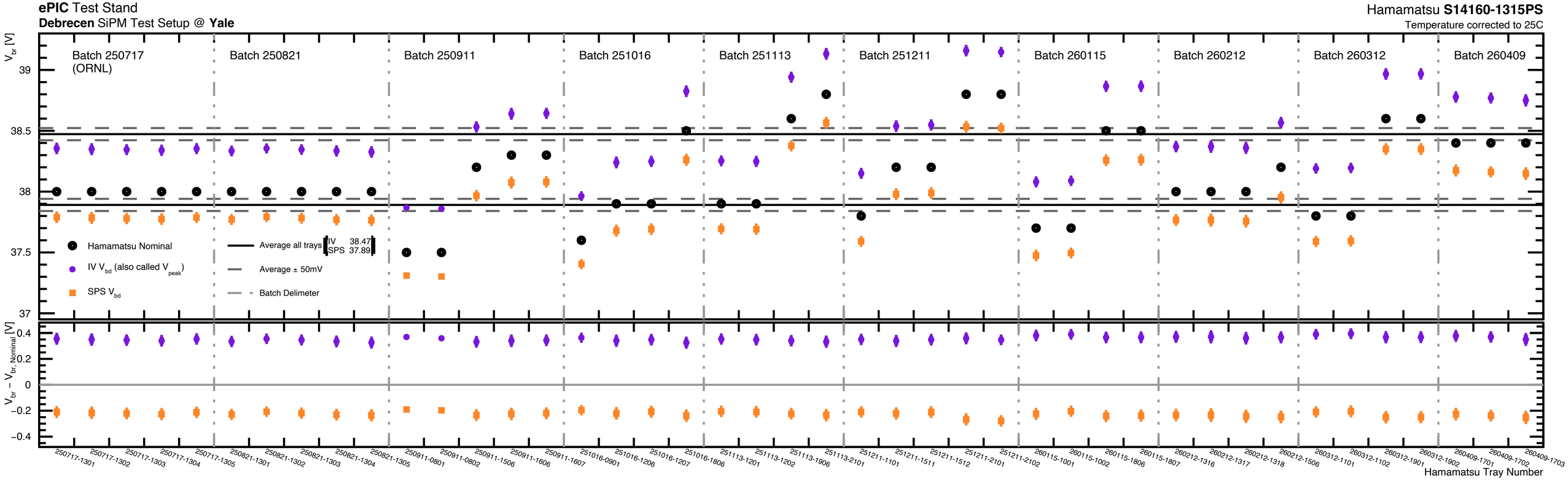
Reproducibility of the Setup



SiPM Dark Current at V_{br} - 3 V and V_{br} + 4 V



Breakdown Voltage of All Trays (25 °C)

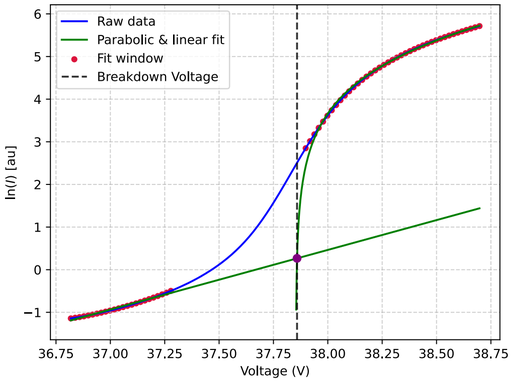


Very consistent and well within requirements

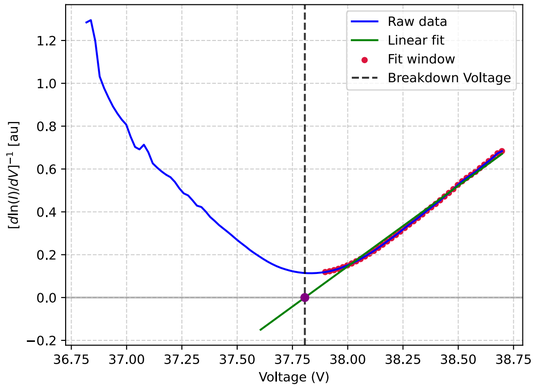
IV V_{br} Extraction Methods

A consistent difference between IV and SPS breakdown voltages may be due to the extraction method.

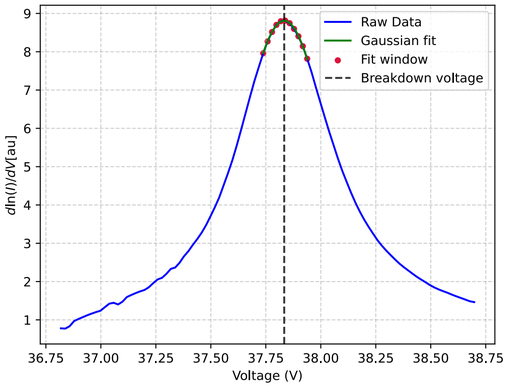
Parabolic fitting



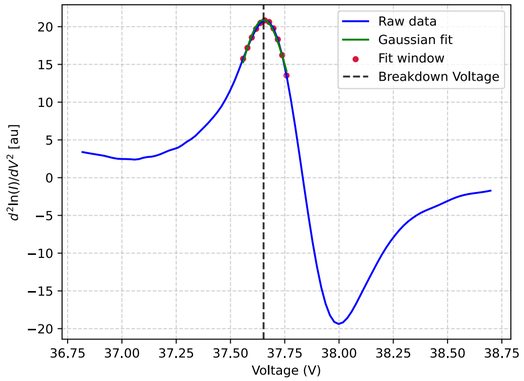
Inverse relative derivative



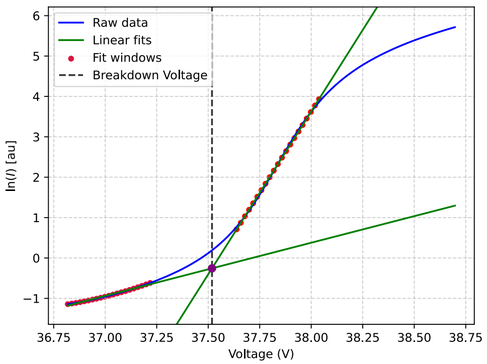
Relative derivative



Second derivative

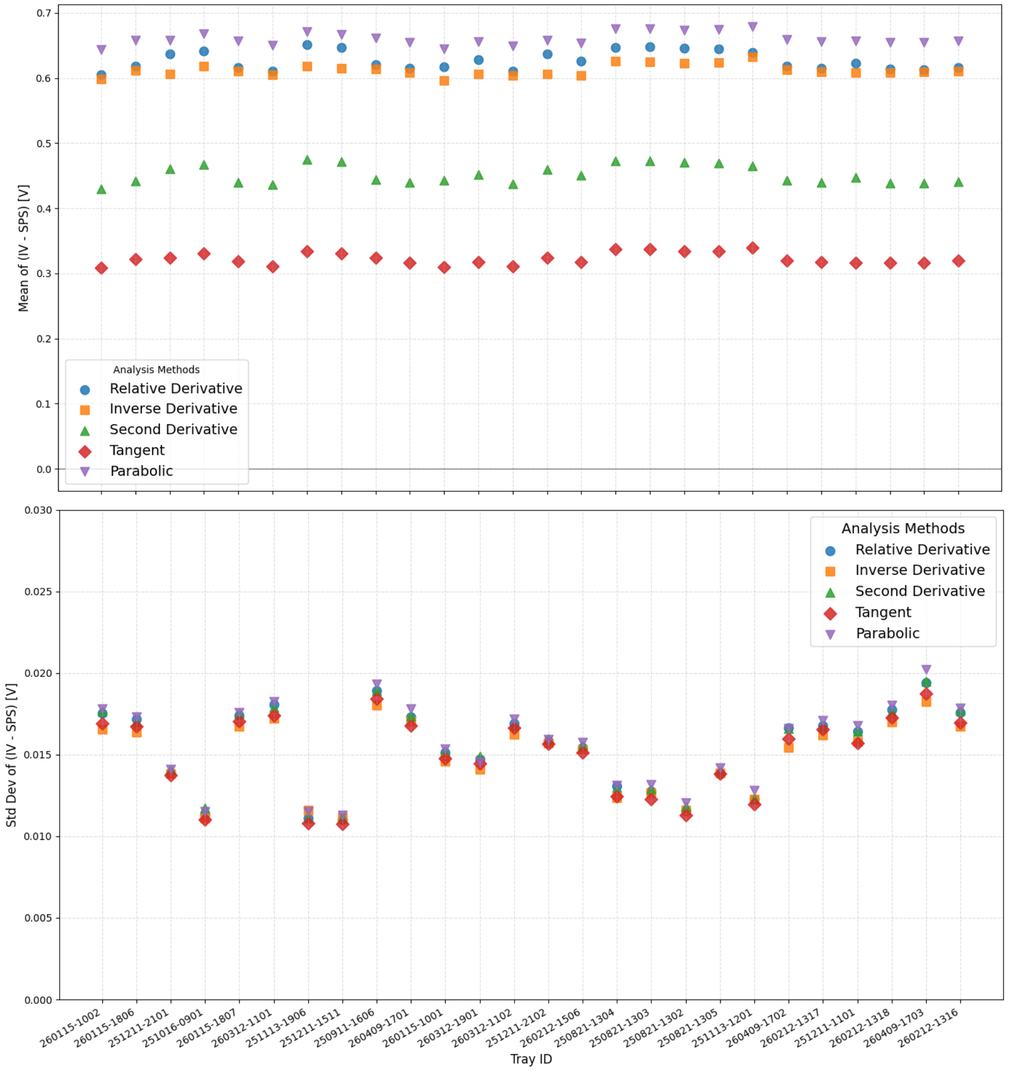


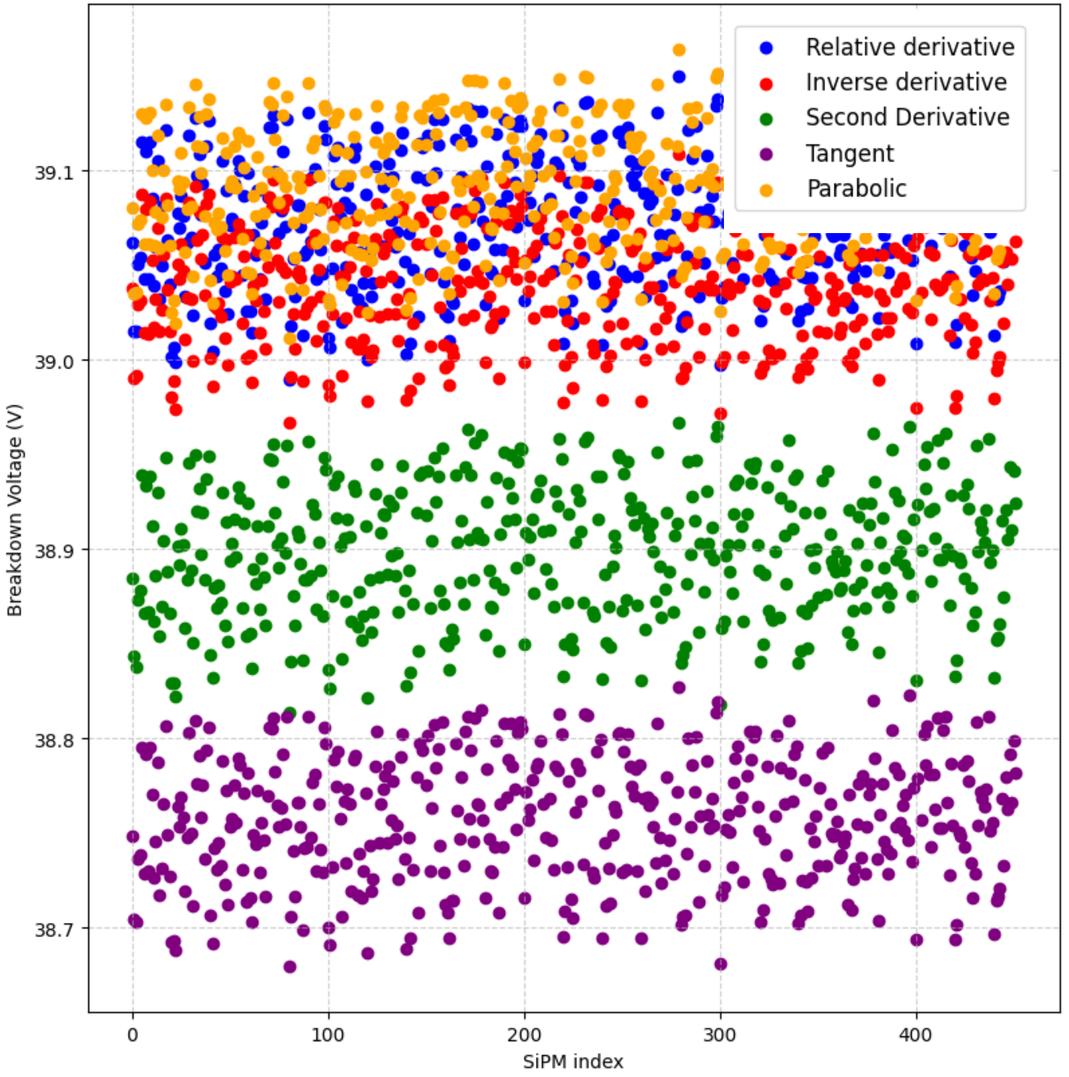
Tangent method



Ref: NIM-A 849 (2017) 55–59

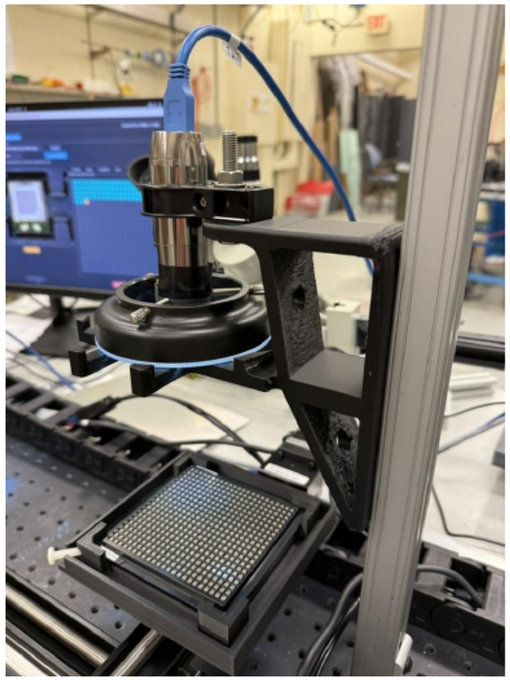
IV V_{br} Results for Different Extraction Methods

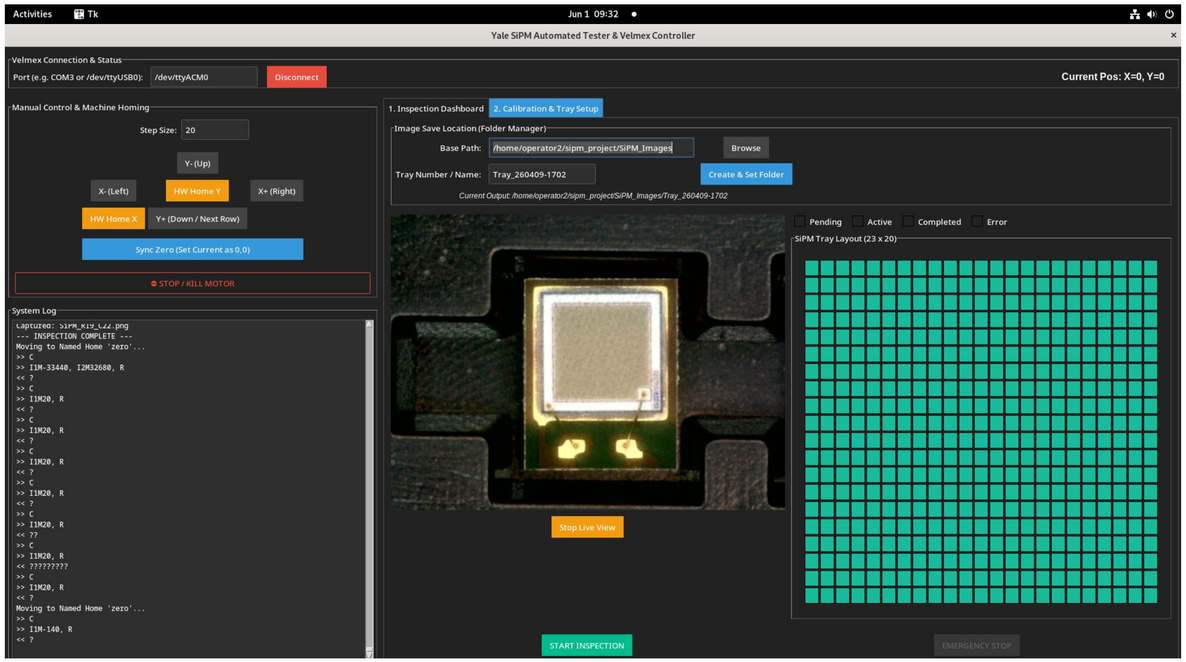




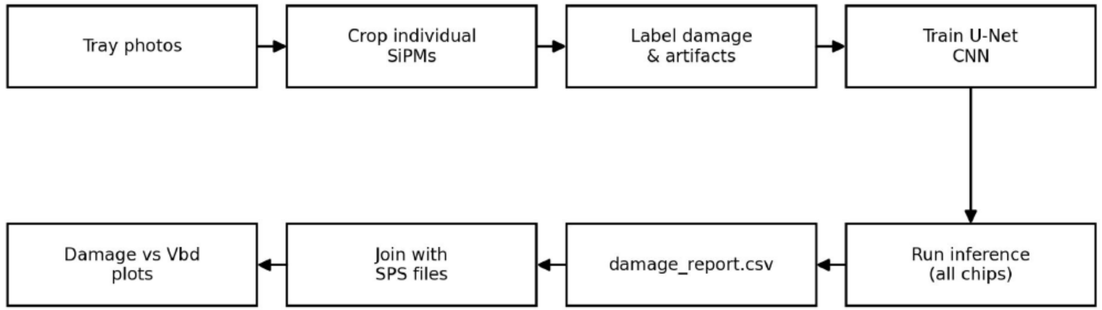
Optical Inspection: Setup and Method

- Microscope camera with ring light mounted above the SiPM tray (460 SiPMs)
- One tray photographed in ~40 min
- Crop individual SiPMs and paint damage / debris masks for training
- U-Net with ResNet-34 encoder gives a 3-class pixel mask (background / damage / debris)

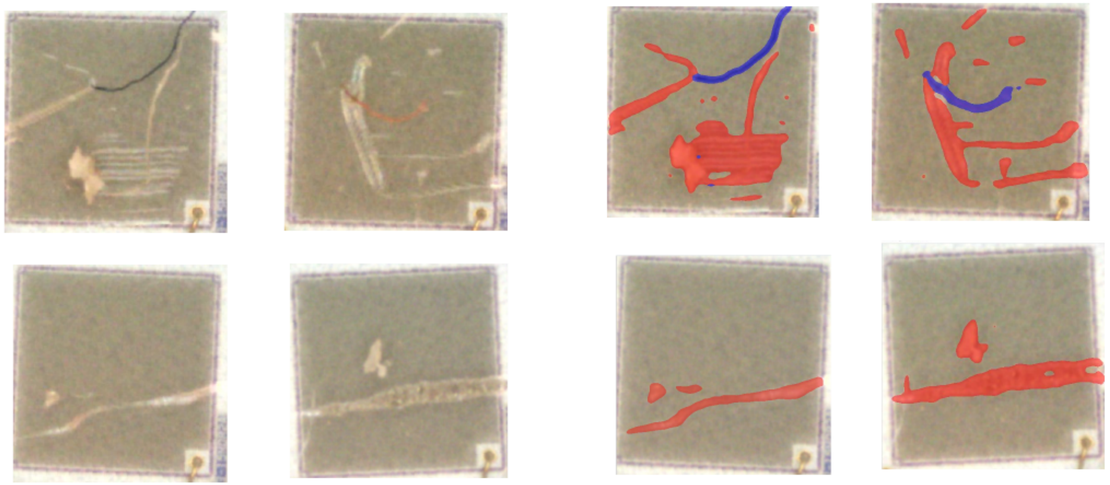




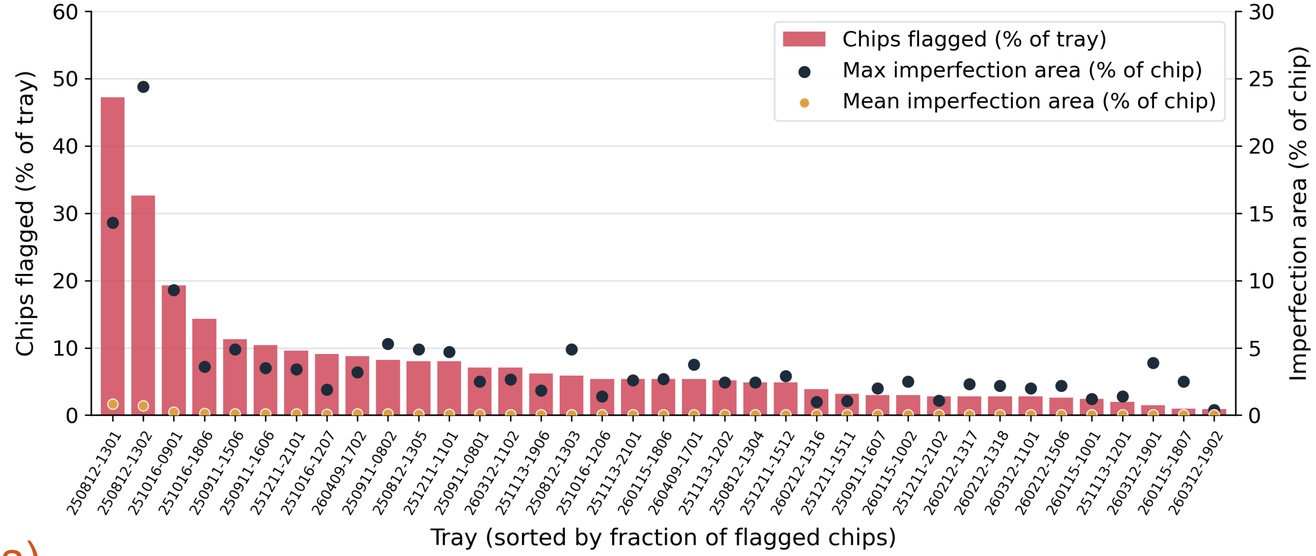
Automated Optical Inspection of SiPMs



- 95% of 43 damaged SiPMs correctly identified (held-out tray)
- ~17,000 SiPMs analyzed; 7.7% flagged with imperfections
- Outliers: trays 250812-1301 (47%) and 250812-1302 (33%)
- Most trays: only minor scratches
- Debris on 8.8% of chips, uncorrelated with imperfections



Input photos and CNN output (red: damage, blue: debris)



Summary

- Automated test setup built with Debrecen tests whole trays of SiPMs at once
- Breakdown voltage measured two ways (IV and SPS); a consistent offset between them is being studied
- All trays passed the criterion except one SiPM (large data current)
- ML-based optical inspection finds scratches and debris automatically
- In near future more long lead procurements are expected to arrive