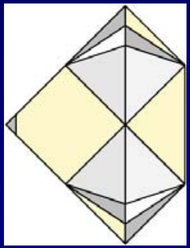

Radiation Hard Diamond Pixel Detectors

- Diamond properties
- ATLAS CVD diamond pixel module
- Single crystal CVD diamond
- Summary & Outlook

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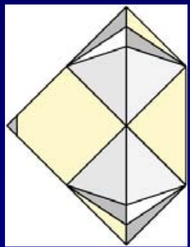
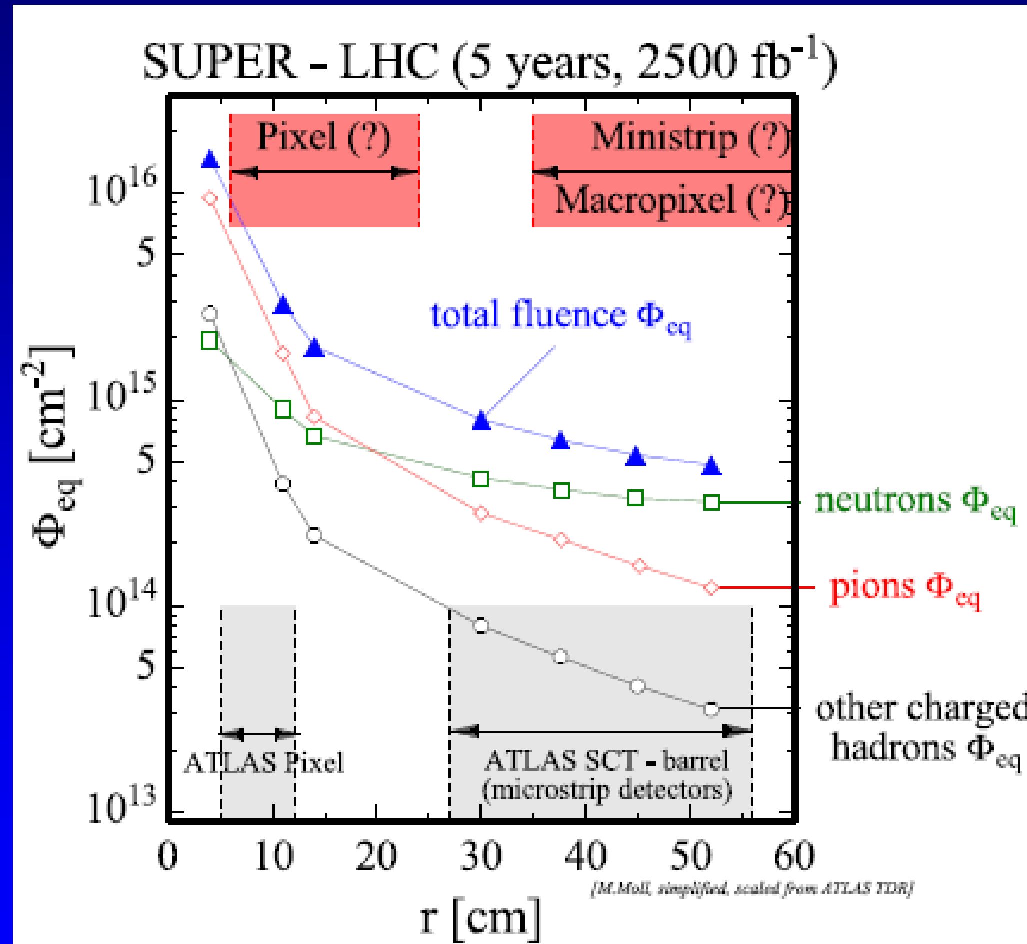
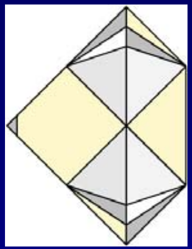


sLHC

- 5 year radiation dose close to beam pipe ~10^{16} n_{eq}/cm^2
  - too high for state-of-the-art silicon sensors
- Most radiation hard material: diamond
  - High bandgap
  - Displacement energy 43eV (13-20 for Si)





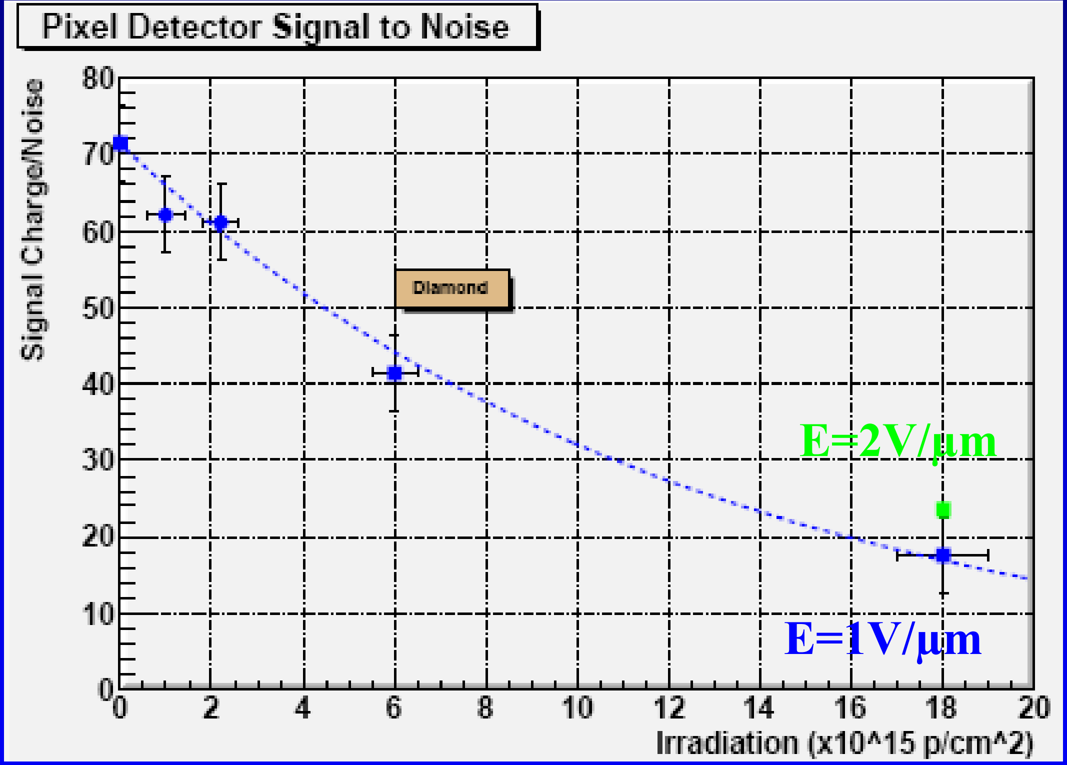
Diamond properties

- Interesting properties:
  - High displacement energy → very rad hard
  - Low dielectric constant → low capacitance
  - High bandgap → low leakage current → low noise
  - High mobility fast → charge collection
  - Large radiation length
  - Room temperature operation
  - No cooling required
  - Excellent thermal conductance
- Disadvantages:
  - Large bandgap → less signal (~0.5/X_0) but $S/N_{detector}$ better than Si
  - Large structures polycrystalline

Property	Diamond	Si
E_g (eV)	5.5	1.12
μ_e ($cm^2\,V\,s^{-1}$)	1800	1500
μ_h ($cm^2\,V\,s^{-1}$)	1200	450
e–h energy (eV)	13	3.6
Displacem. (eV)	43	13-20
Density ($g\,cm^{-3}$)	3.52	2.33
Radiation length, X_0 (cm)	12.2	9.4
e–h pairs/X_0 (106 cm^{-1})	4.4	10.1
Dielectric constant	5.7	11.9
Max E-Field [V/μm]	1000	30
Resistivity [Ω/cm]	$>10^{13}$	10^5-10^6

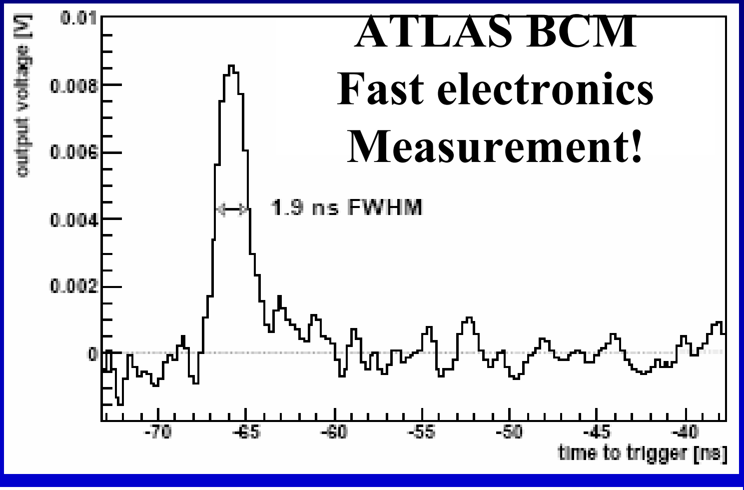
Radiation hardness

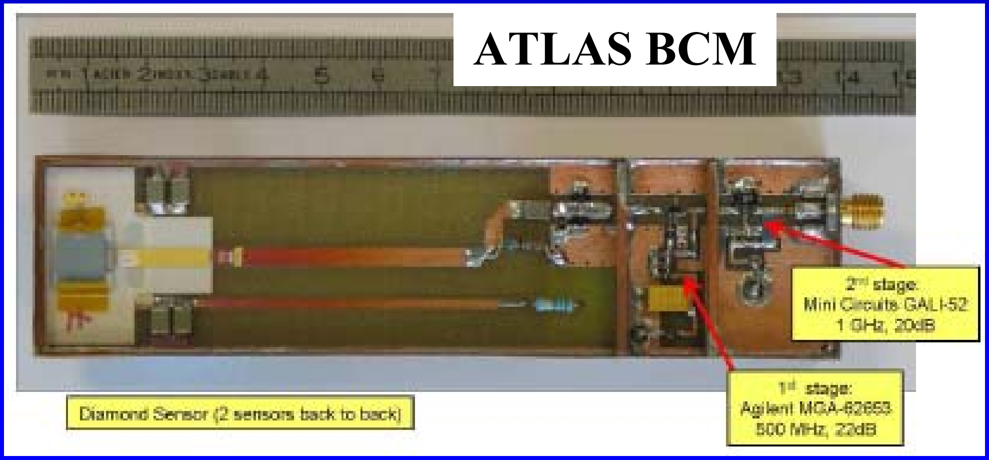
- Still S/N≈18-25 after 1.8×10^{16} p/cm^2 (~500 Mrad) depending on field
- No problem operating in sLHC conditions
  - Noise limited by electronics, NOT by sensor capacitance or leakage current



Beam conditioning monitors

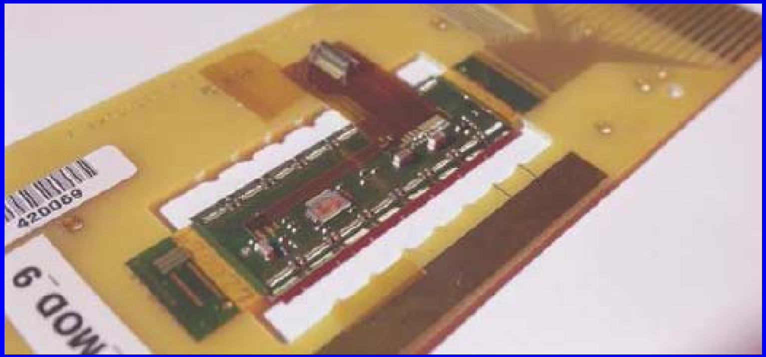
- Most radiation hard sensors required for beam conditioning monitors. Diamonds successfully used at:
  - CDF
  - BaBar
  - Belle
  - ATLAS (see poster)



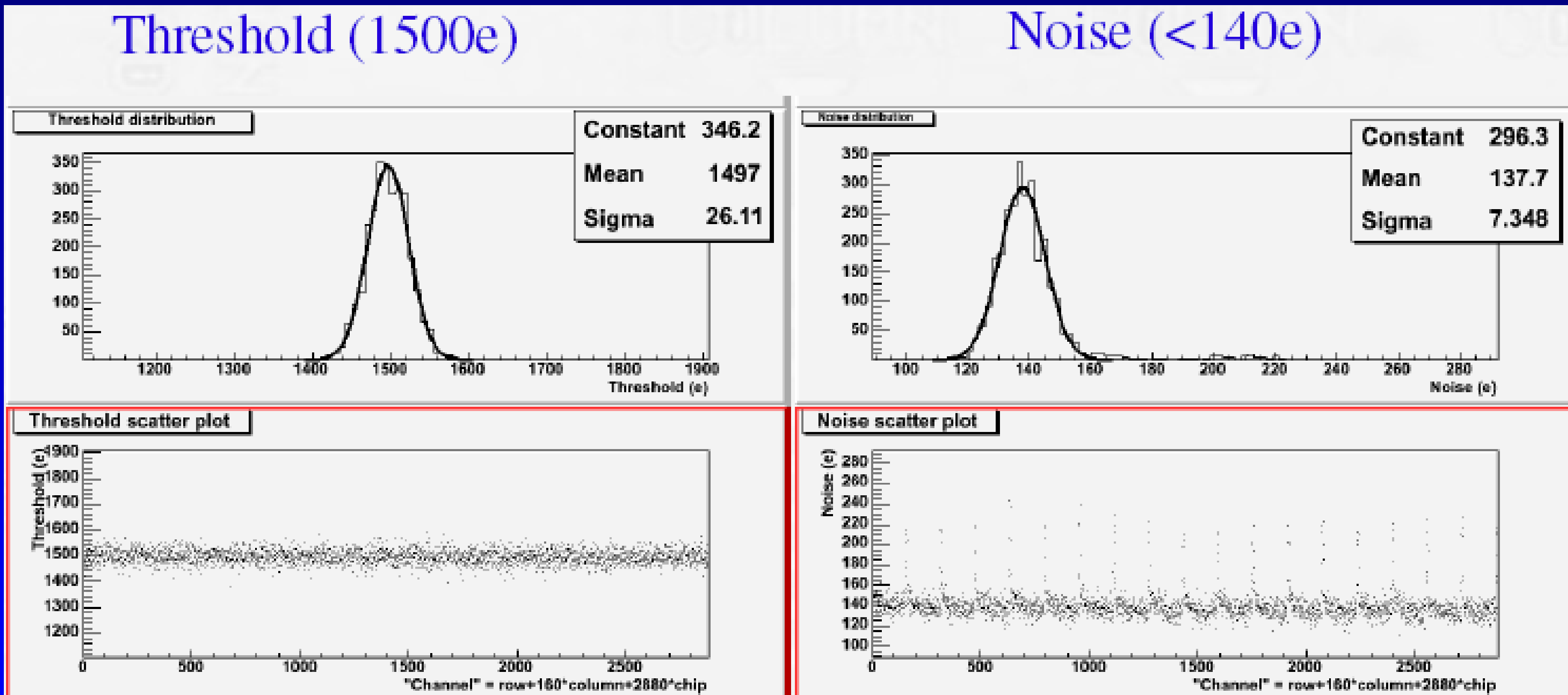


ATLAS CVD diamond pixel module

- Sensor:
  - Active area: 61x16.5mm^2
  - Thickness 800μm
  - Pixel size 400(600)x50μm^2
  - 46k pixels
- ATLAS frontend chip FE-I3
  - 0.25μm IBM
  - Radiation tolerant >50MRad
  - Designed for Si sensors
  - Binary/low res. analog readout
- Noise same as bare FE-chip
  - Noise ≈137e$^-$
  - Threshold ≈1454e$^-$
  - Threshold spread ≈25e$^-$

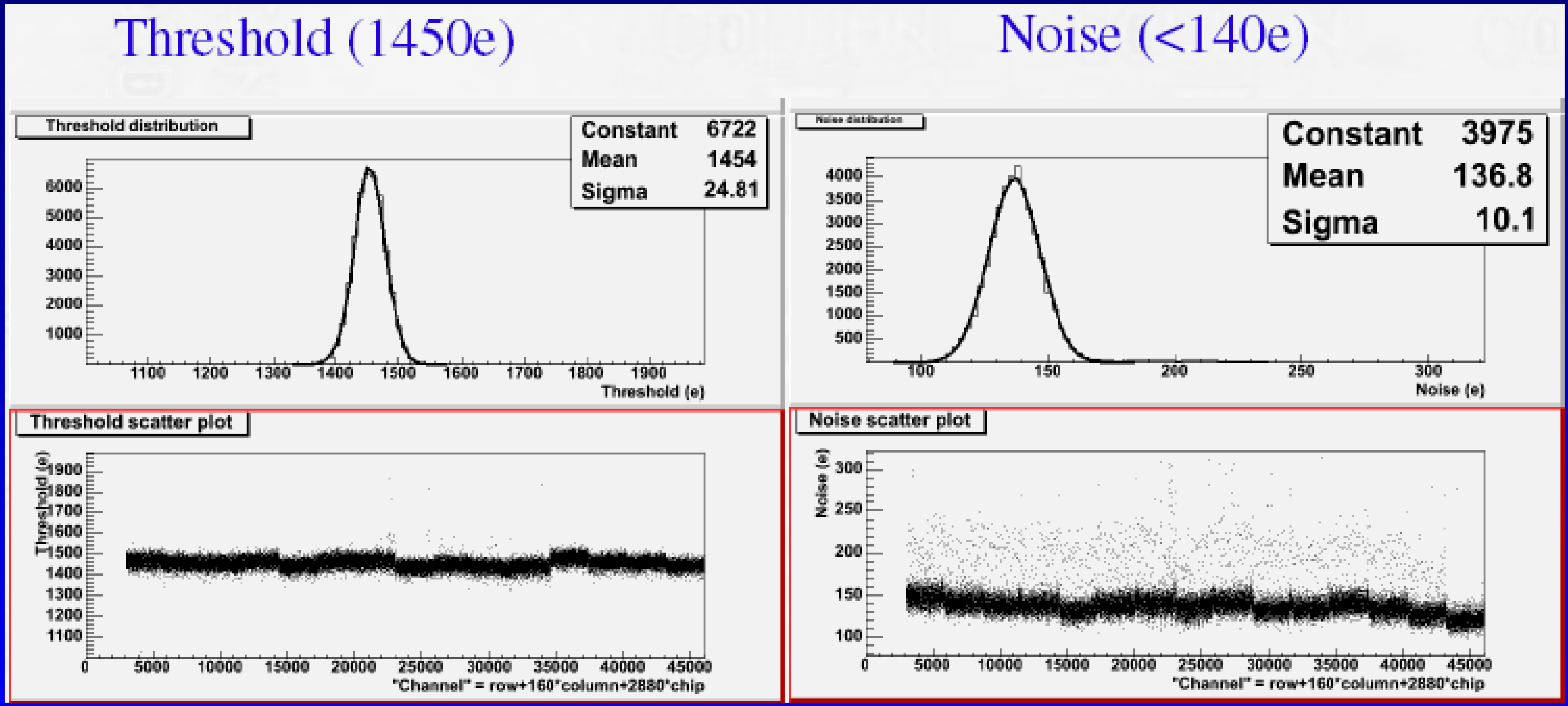


Noise measurement I (Bare chip)



- Binary readout with Time-over-Threshold value

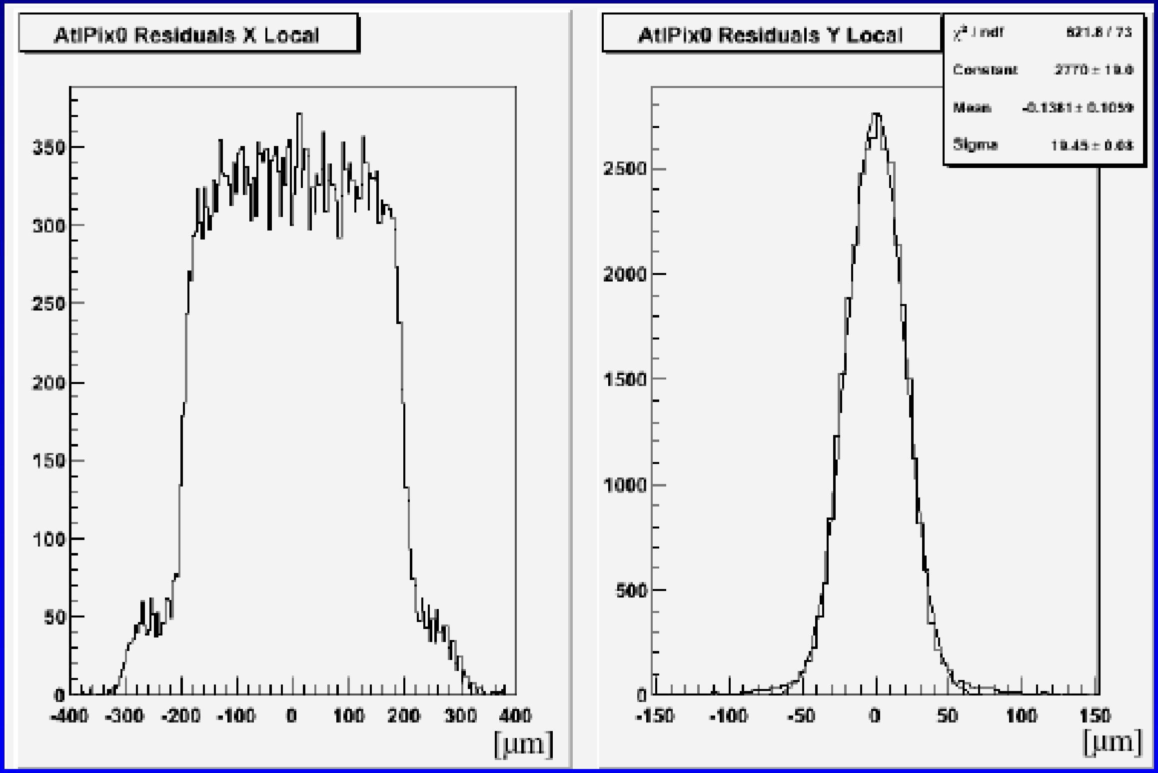
Noise measurement II (diamond)



- Almost no effect of diamond on noise
- Normal ATLAS Si-modules:
  - threshold=3-4ke$^-$, noise 180e$^-$
  - 3D: threshold 3-4ke$^-$, noise: 290-310 e$^-$ depending on type 2E, 3E, 4E

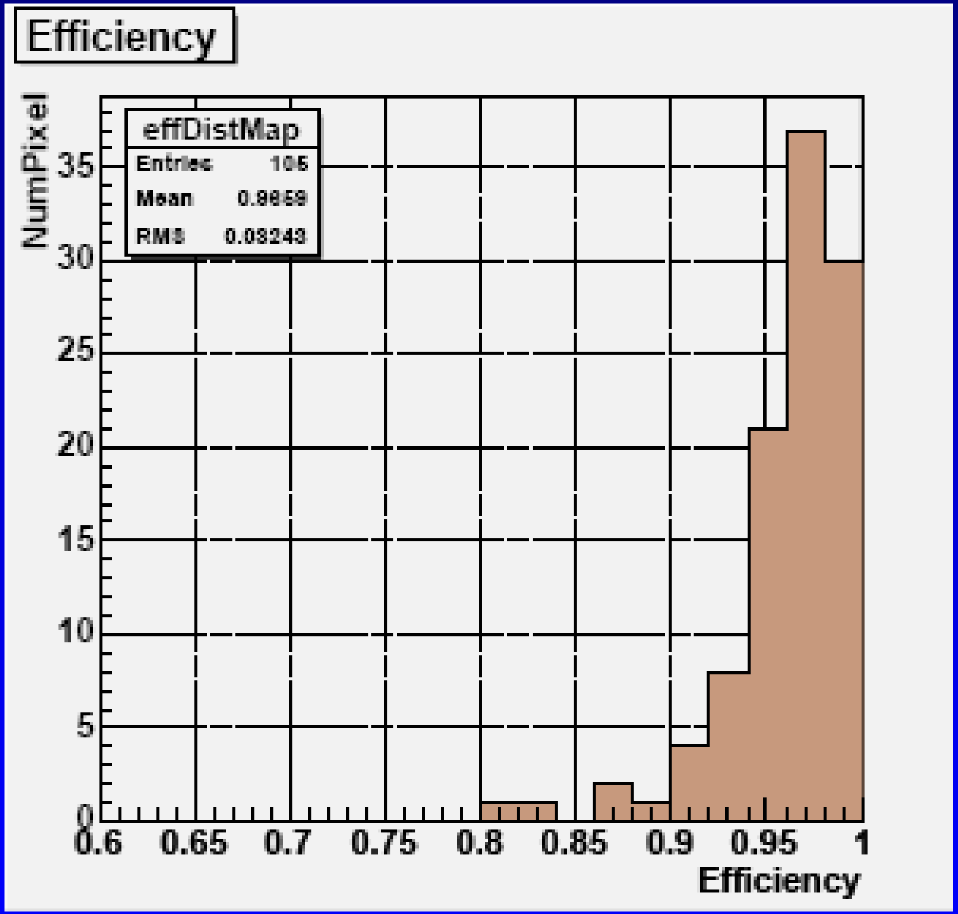
Position resolution

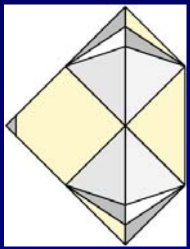
- DESY beam test: 6 GeV e^-: lots of multiple scattering
- Digital position reconstruction
- 400μm and 600μm pixel size visible
- 50μm pixel direction: resolution ~18μm (including multiple scattering tracking error)



Efficiency

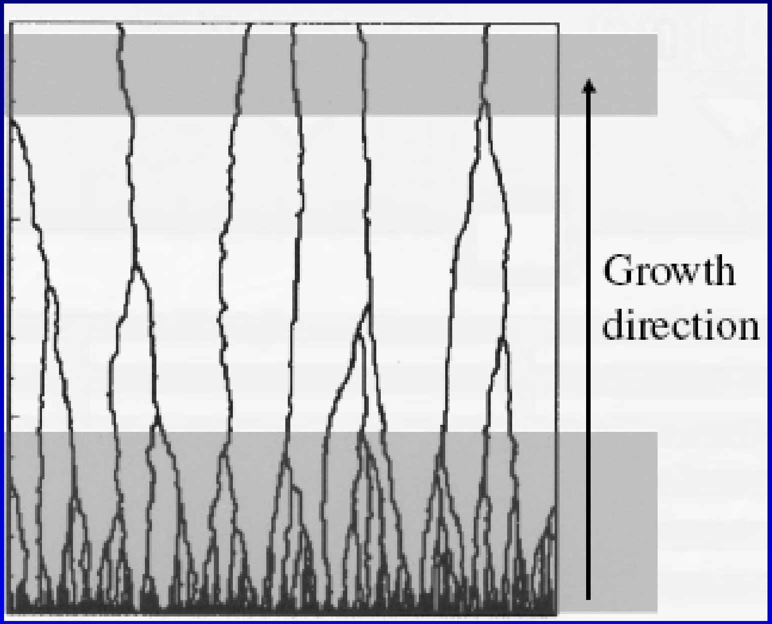
- Preliminary efficiency>97%
  - Still need to correct for tracking errors, multiple scattering
    - data taken DESY 6GeV e⁻, CERN data to be analysed
  - Still need better fiducial region
- Pixel module operates very well!!
- Planning to build 5 more modules this summer
- No problem to produce diamond B-layer

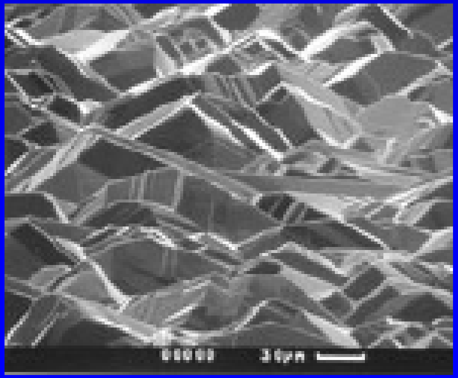




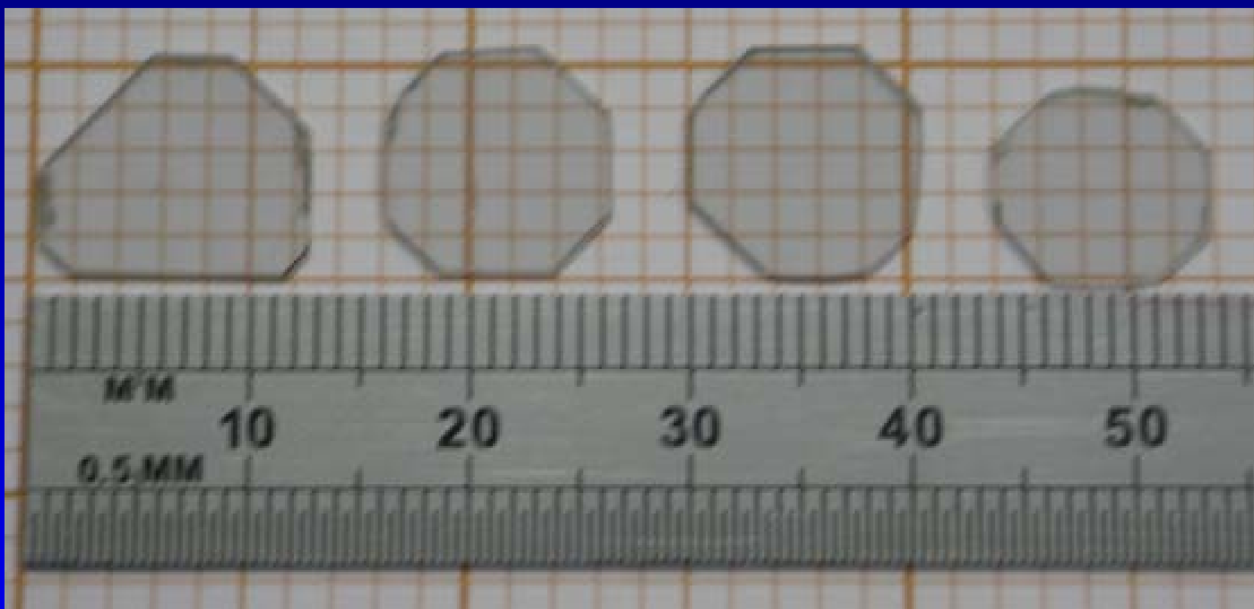
Diamond growth

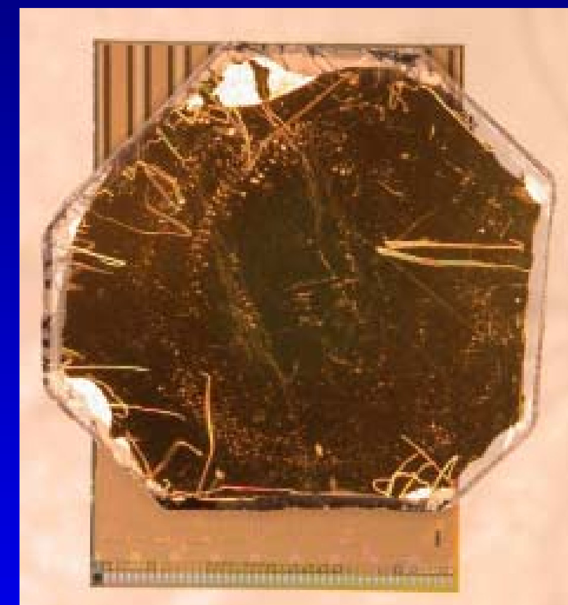
- Trap- and recombination centers limit charge collection
- Trapped charge at grain boundaries builds up a polarization field superimposed on the biasing field
- Substrate and growth side must be ground and polished for good quality





Single crystal diamond

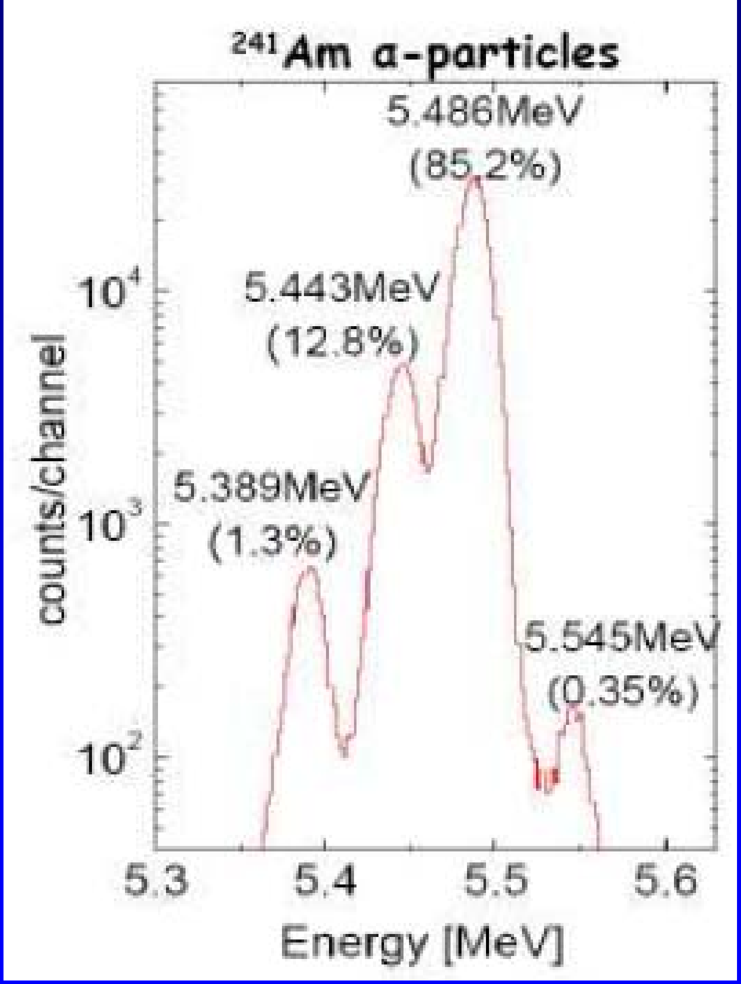




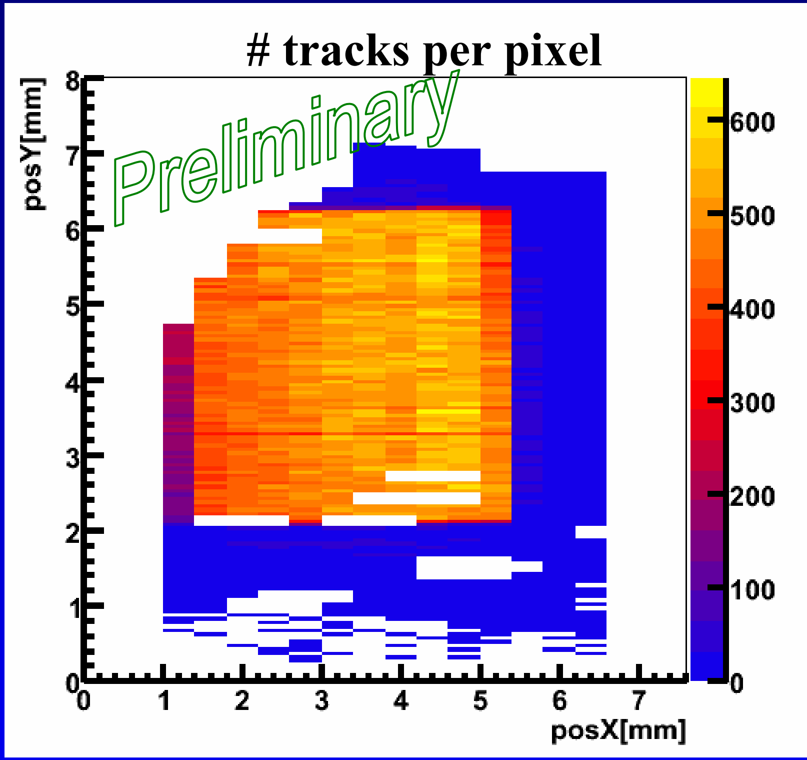
- Largest single crystal diamond 14x14mm
    - No grain boundaries → no trapping
- Produced 400 μm thick single chip sensor using ATLAS FE chip

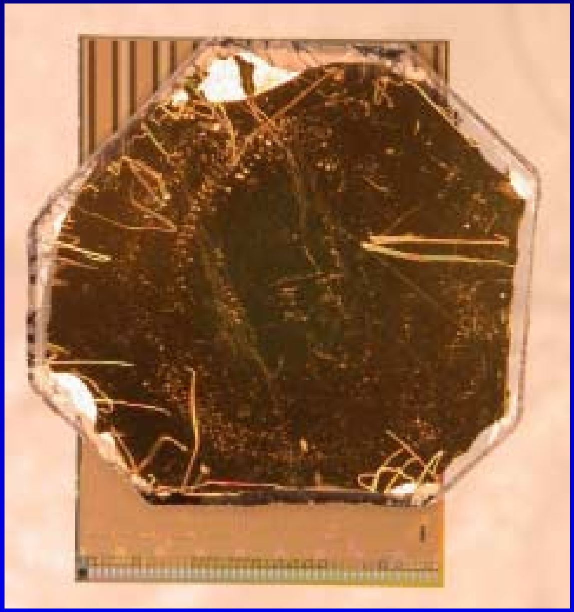
Spectroscopic precision

- Single crystal diamond has a very good energy resolution
  - Measured with ORTEC low noise amplifier, ~μs shaping
  - Single electrode at both sides
- Spectroscopic grade material!
  - Energy res. 17 keV FWHM



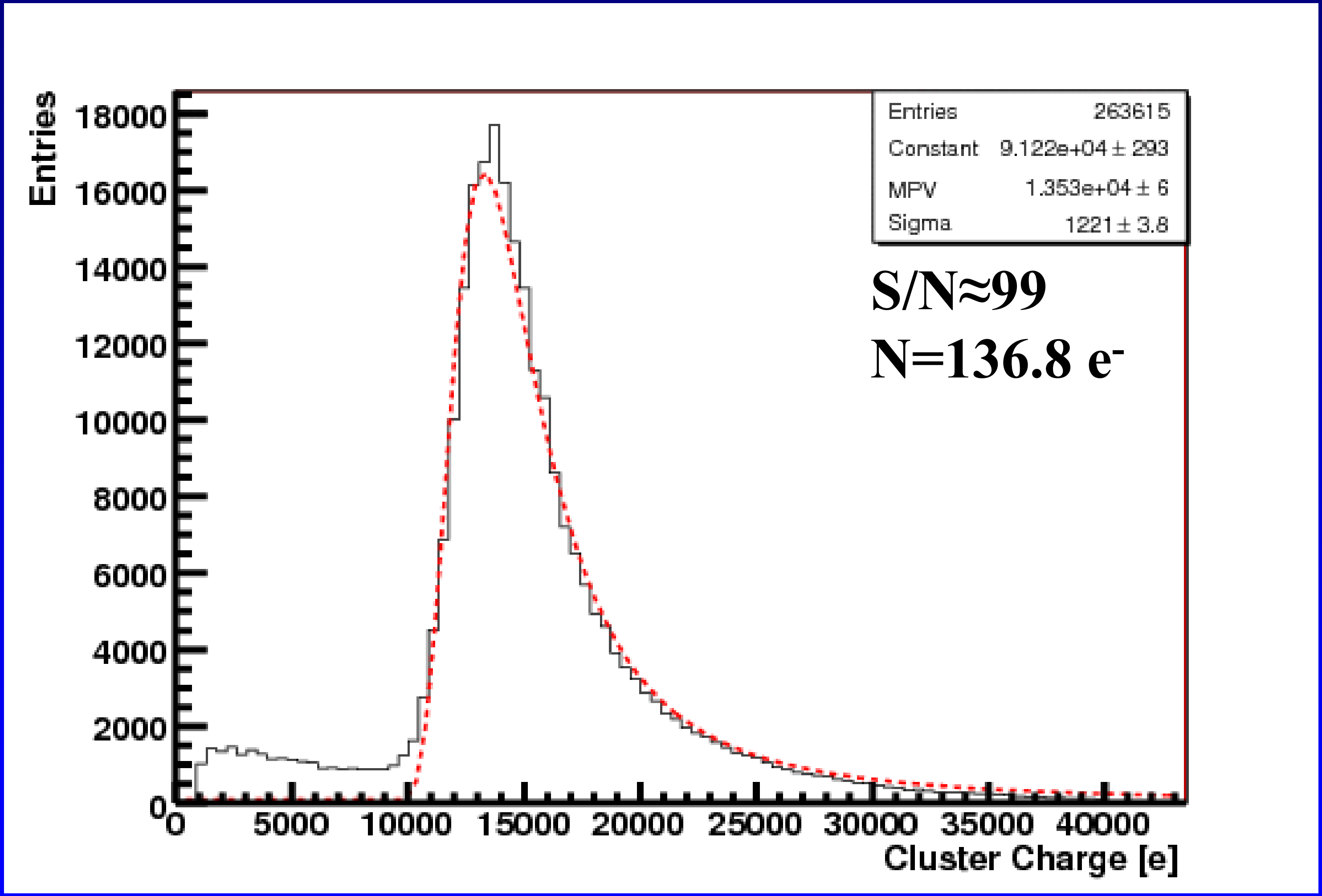
Testbeam results

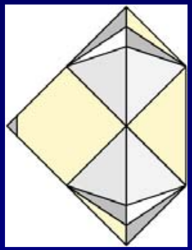




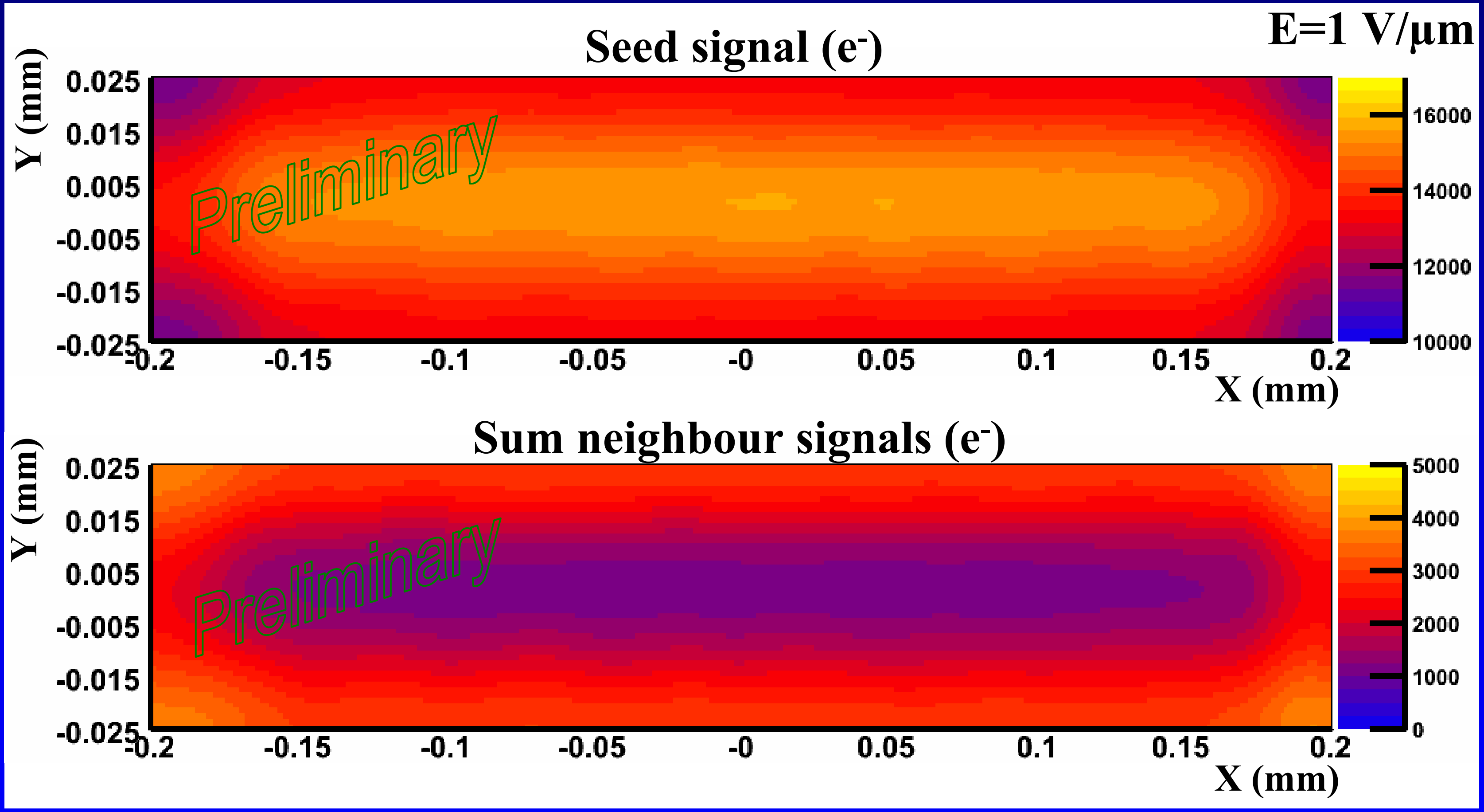
- „Square" is due to trigger scintillator
- White squares: masked pixels (most likely bump bonding errors)
- E=1 V/μm

Signal spectrum



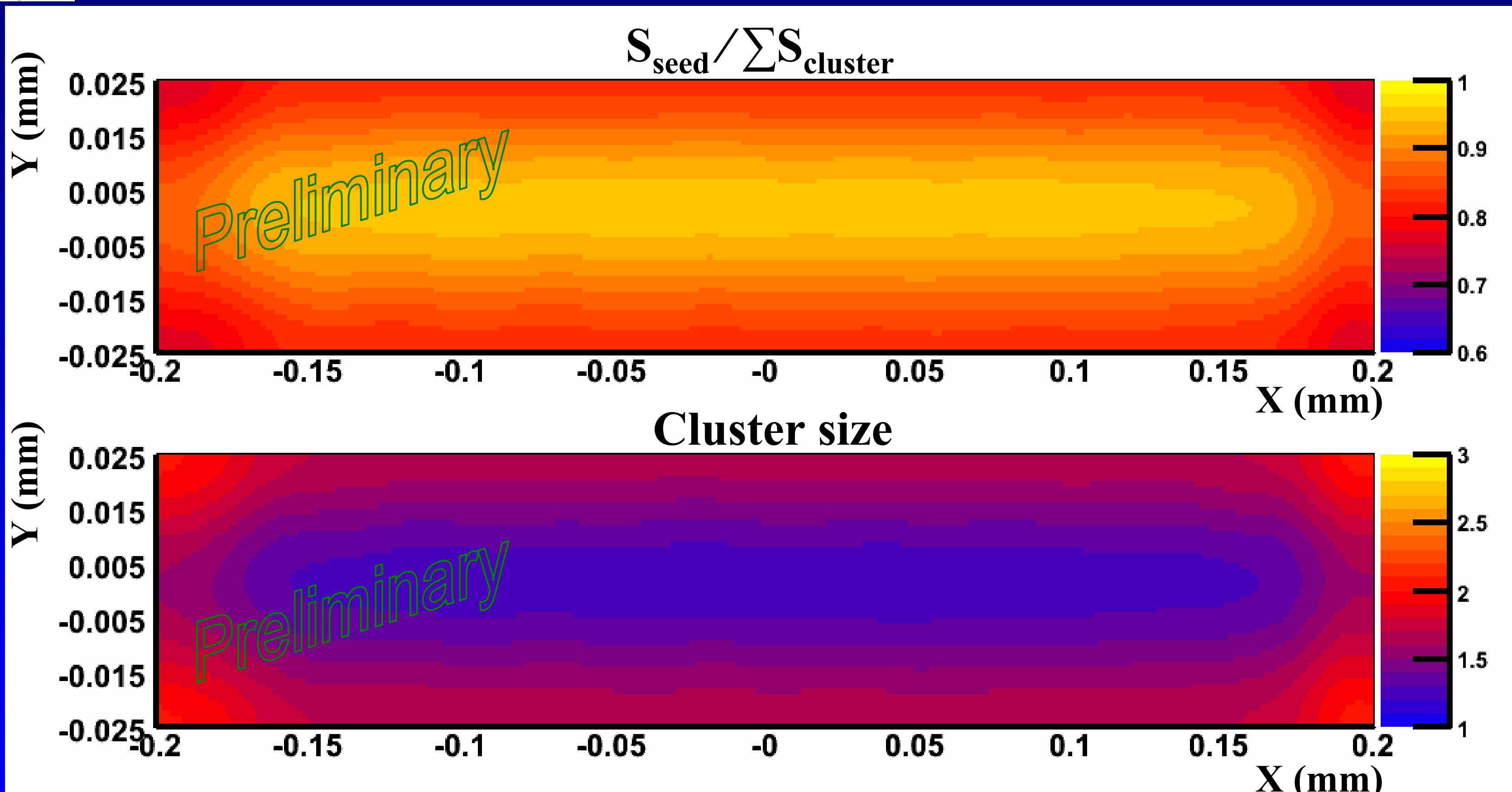


Charge division



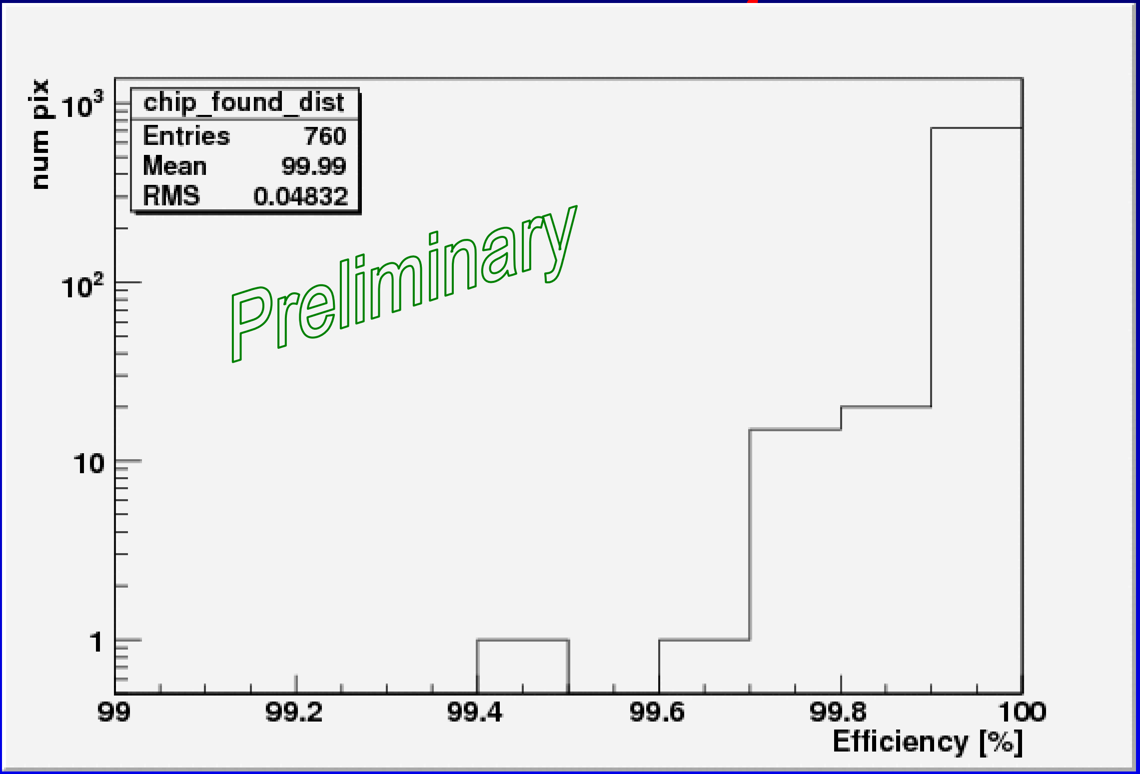
- Quasi-analog readout allows signal measurement in e^-

Charge division

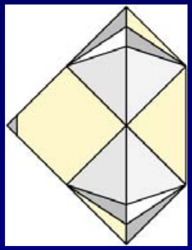


- Most charge collected in seed
- Small clusters

Efficiency

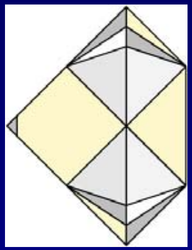


- Efficiency=99.989±0.002% @ E=1 V/μm and Efficiency=99.992±0.002% @ E=0.25 V/μm
  - Still investigating misses (tracking, scattering, …)
- Single crystal diamond performs really well!



Summary

- Diamond very radiation hard material (ok for sLHC)
- A fullsized ATLAS pixel module CVD diamond was produced and performs well in beam tests
  - Efficiency >97% (ineff. still includes multiple scattering & tracking errors)
  - No problem producing CVD diamond B-layer
- Large size (~1cm^2) single crystal CVD diamond available
  - Spectroscopic grade material
  - Pixel detector: efficiency=99.992±0.002% @E=0.25 V/μm



Outlook

- Will build 5 more ATLAS pixel modules
  - More beam tests to get module statistics
- Characterize new highest quality single crystal diamonds
- Irradiations of pCVD and scCVD samples up to 20×10^{15} p/cm^2

- Diamonds are forever… even at the sLHC !