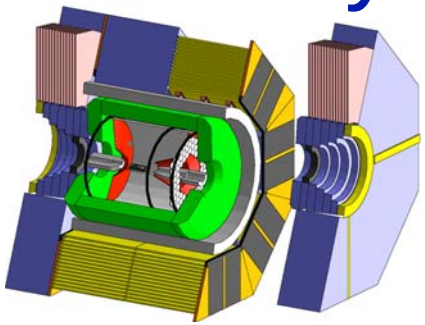
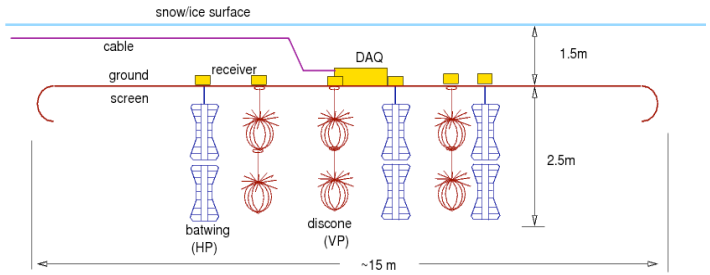
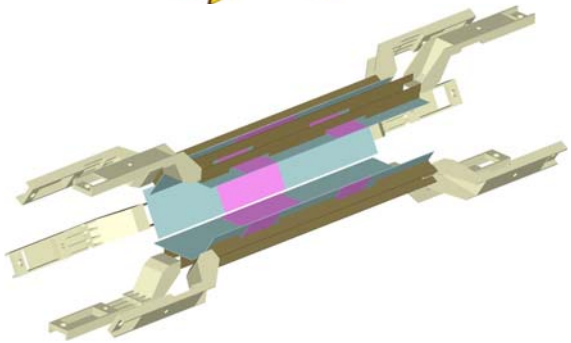
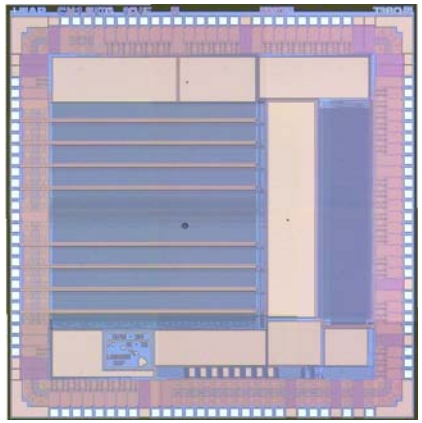
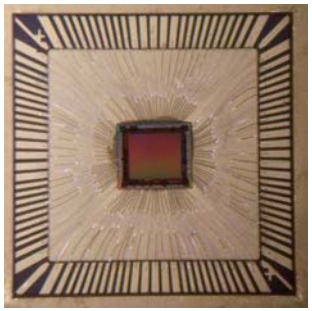
ASICs for Particle and Astroparticle Physics

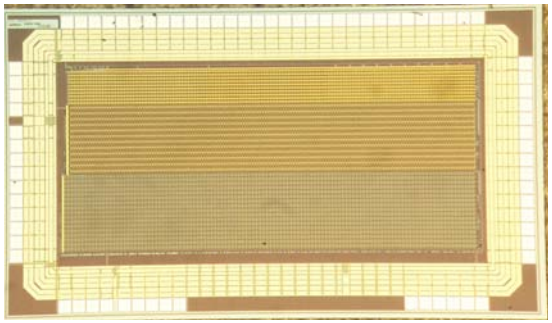


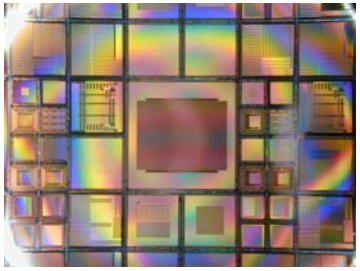


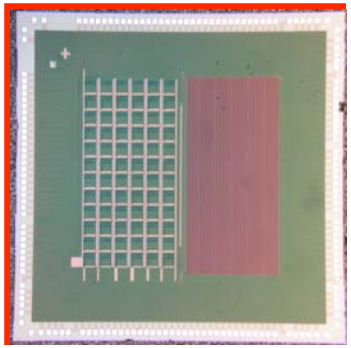










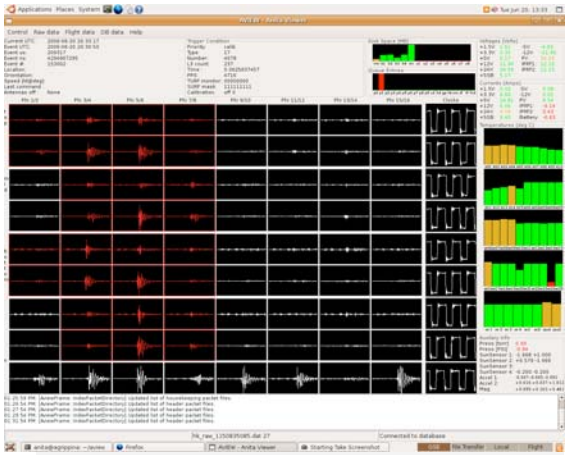


Gary S. Varner

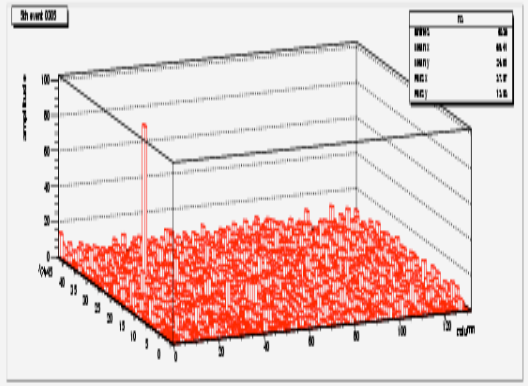
University of Hawai'i

SLAC Instrumentation Seminar 7/11/07

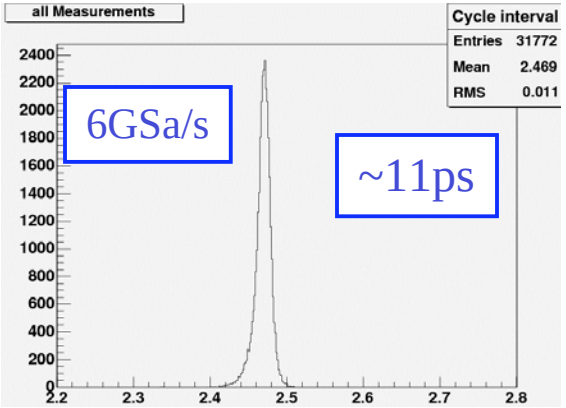
Topics



- RF Detection of UHE Neutrinos
  - Antarctic Impulsive Transient Antenna
  - IceRay (IceCube Radio)

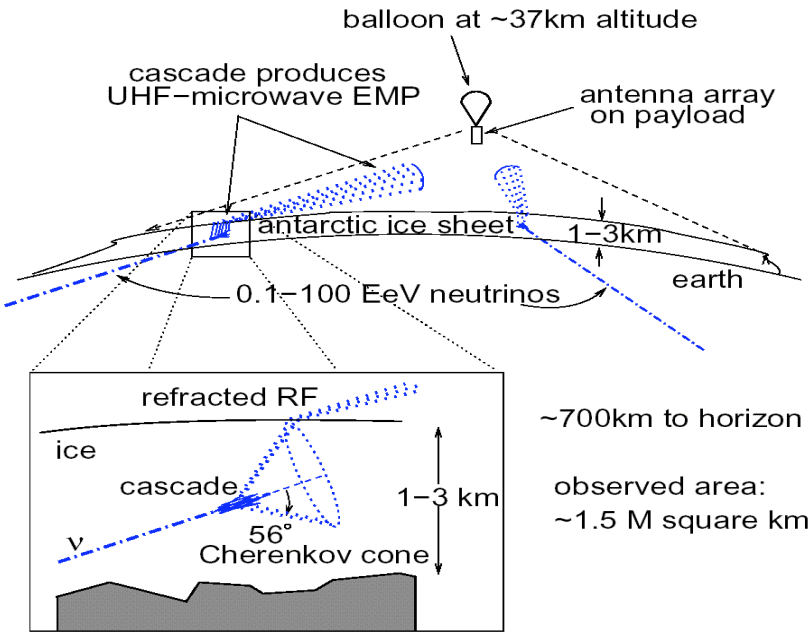


- Low momentum Precision Vertexer
  - Super B-factory pixel vertex detector
  - ILC vertex detector



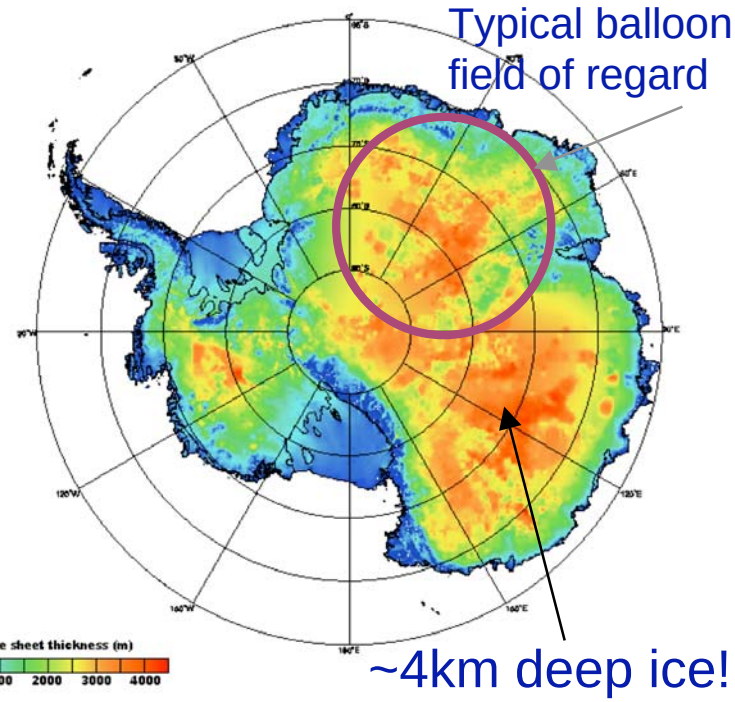
- High Precision Timing
  - High rate Particle Identification
  - Time-resolved laser ablation

The ANITA Concept

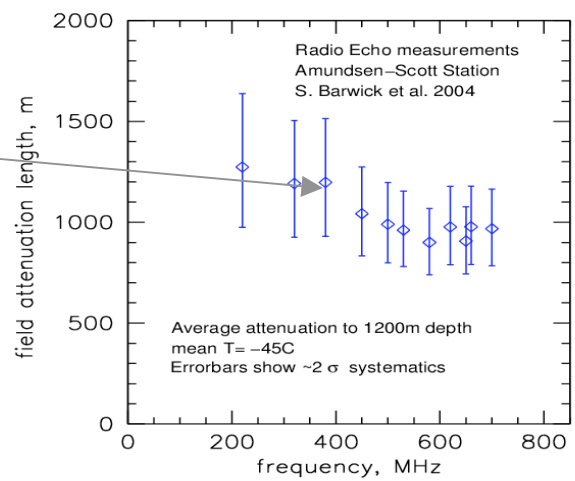


~700km to horizon

observed area:
~1.5 M square km



Ice RF clarity: 1.2 km(!) attenuation length

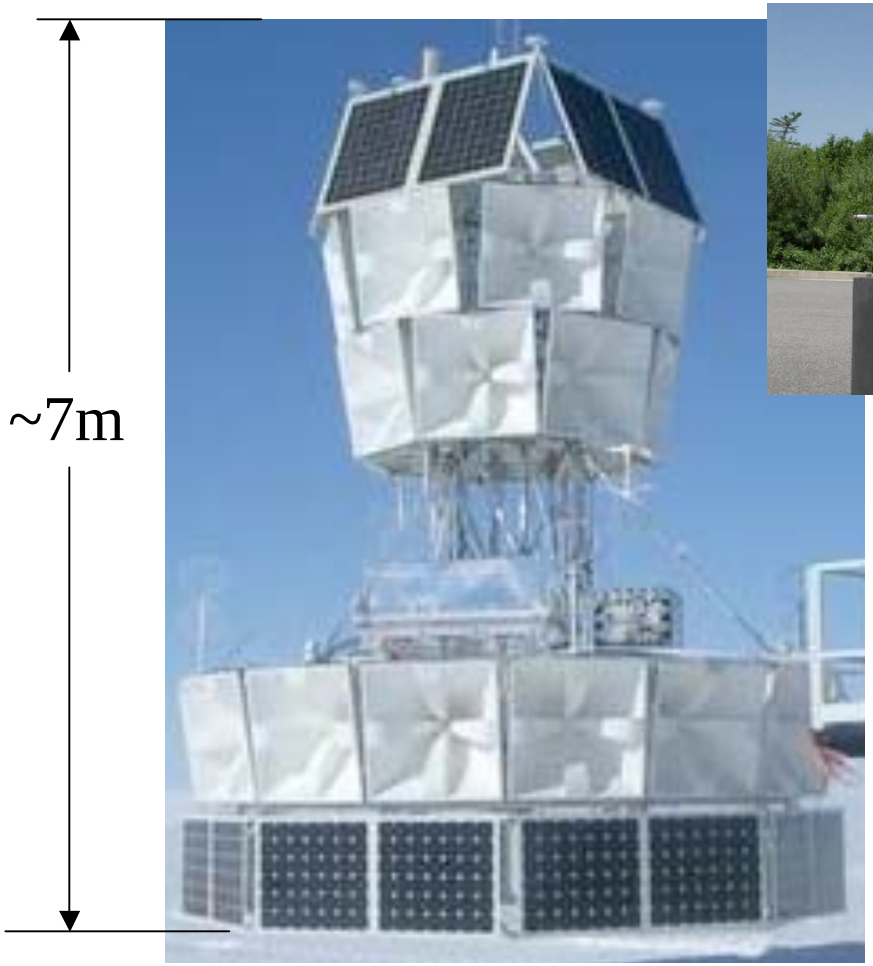


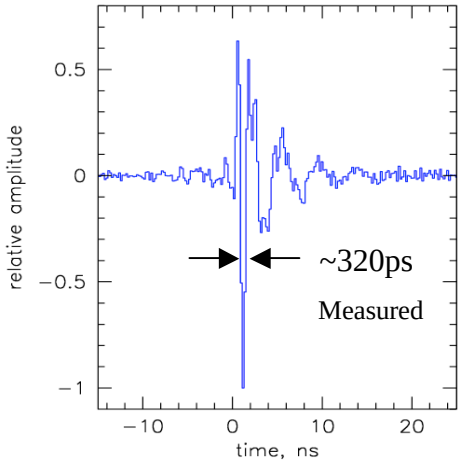
Effective "telescope" aperture:

- ~250 km^3 sr @ $10^{18.5}$ eV
- ~10^4 @ km^3 sr 10^{19} eV

(Area of Antarctica ~ area of Moon)

A demanding Application





Antarctic Impulsive Transient Antenna (ANITA)

- RF Transient (impulsive) Events (200-1200 MHz)
- Completely solar powered (tight demands on power, few hundred W total)
- 324 chan. @ 2.6GSa/s

Major Hurdles – these ν are elusive

- No commercial waveform recorder solution (power/resolution)
- 3σ thermal noise fluctuations occur at MHz rates (need ~2.3σ)

- Without being able to record or trigger efficiently, there is no experiment

STRAW2 Chip

Self-Triggered Recorder Analog Waveform (STRAW)

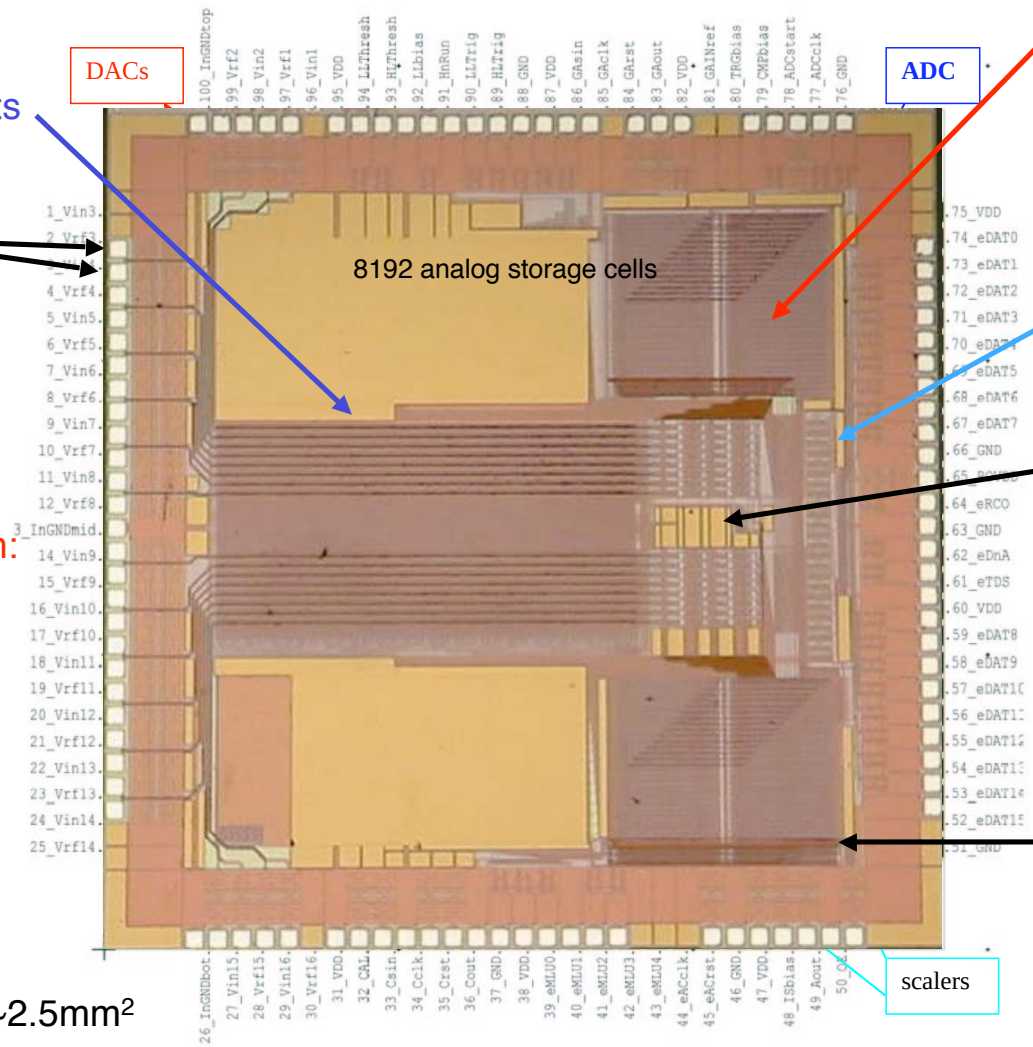
16 Channels of
256 deep SCA buckets

Optimized for RF input
Microstrip 50Ω

Target input Bandwidth:
>700MHz

Record length:
128-256ns

Die:~2.5mm²



Self-Triggering:

-LL and HL (adj.) for each channel

-Multiplicity trigger for LL hits

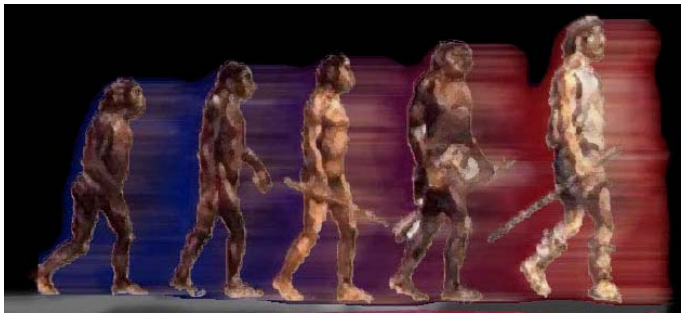
On-chip ADC:
12-bit, >2MSPS

Sampling Rate:
1-3GSa/s (adj.)

Sampling Rates
>~4GSa/s possible
w/ 0.25µm process

External option:
MUXed Analog out

A long,winding road...



STRAW1

STRAW2

STRAW3

SATURN

GLUE

SHORT2

LABRADOR

Trig

Comb.

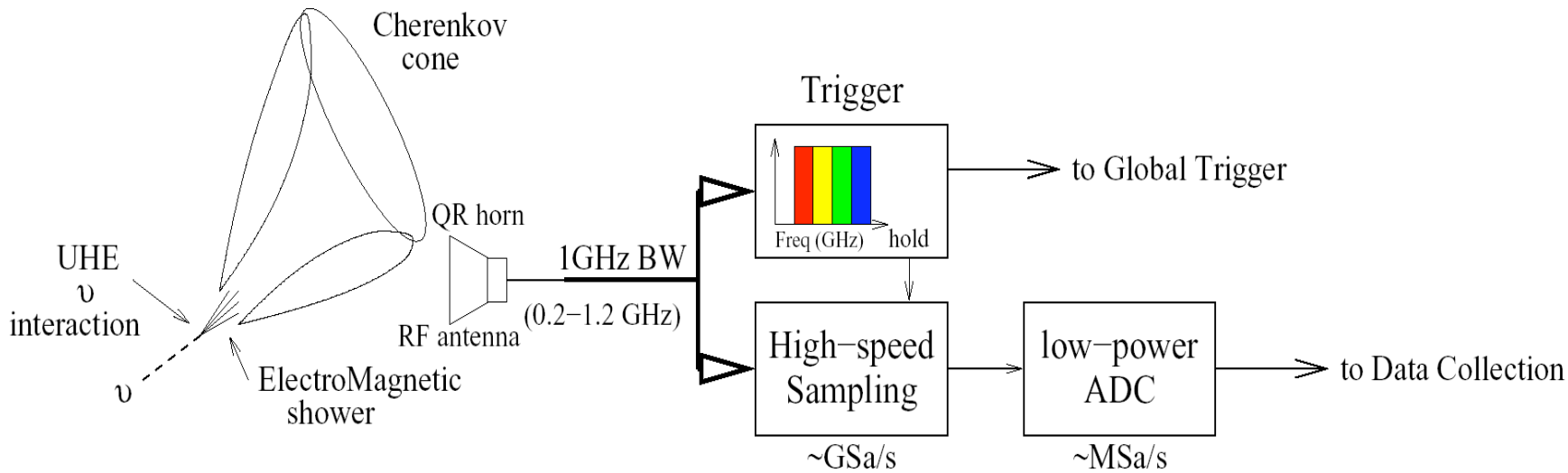
Sampling

LABRADOR2

LABRADOR3

"I've noticed a disturbing pattern Alice, the solution is always the LAST thing you try"
Dilbert's pointy-haired boss

Strategy: Divide and Conquer



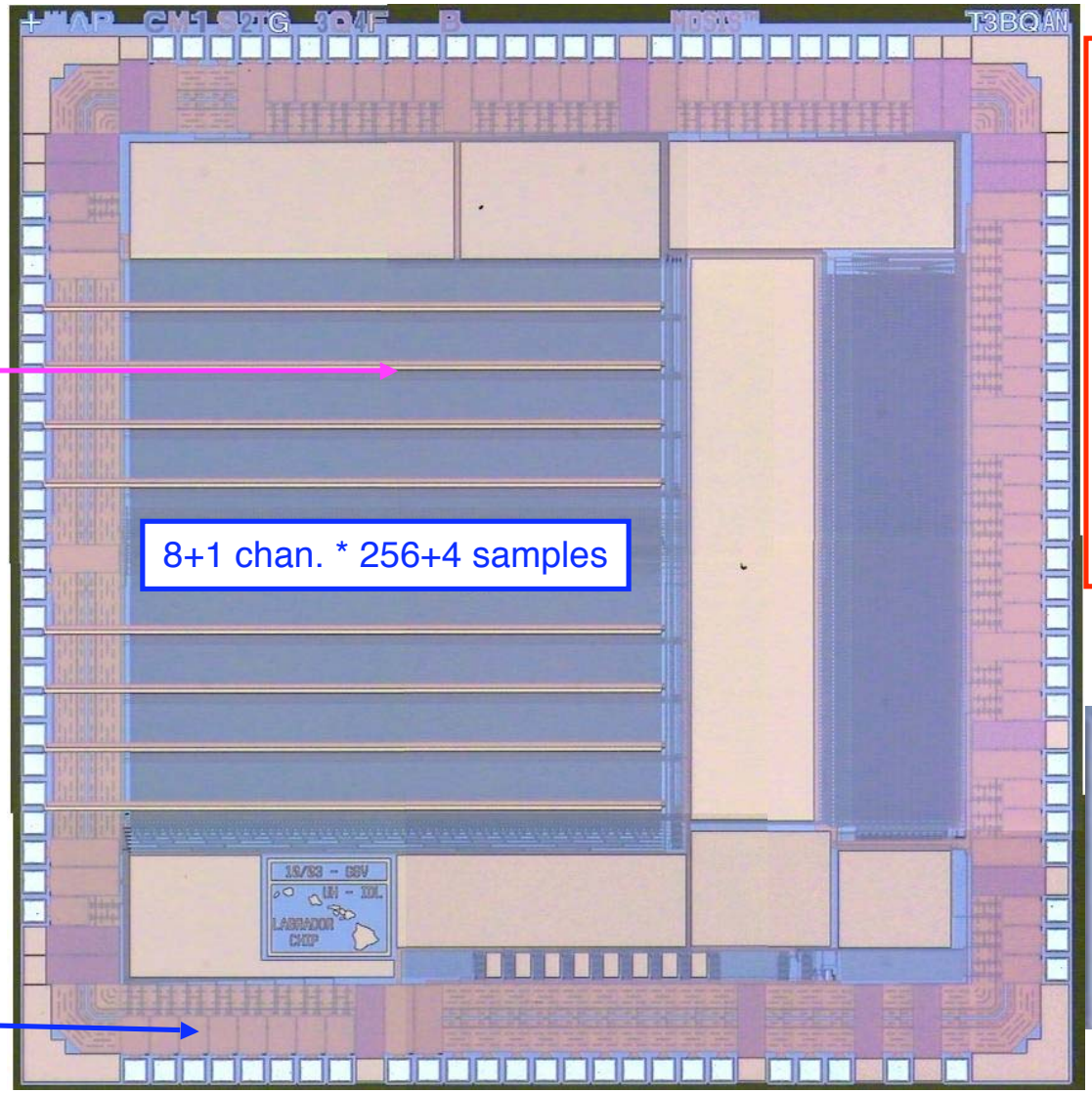
- Split signal: 1 path to trigger, 1 for digitizer
- Use multiple frequency bands for trigger
- Digitizer runs ONLY when triggered to save power

Large Analog Bandwidth Recorder and Digitizer with Ordered Readout [LABRADOR]

Straight Shot RF inputs

- Switched Capacitor Array (SCA)
- Massively parallel ADC array
- Similar to other WFS ASICs → analog bandwidth

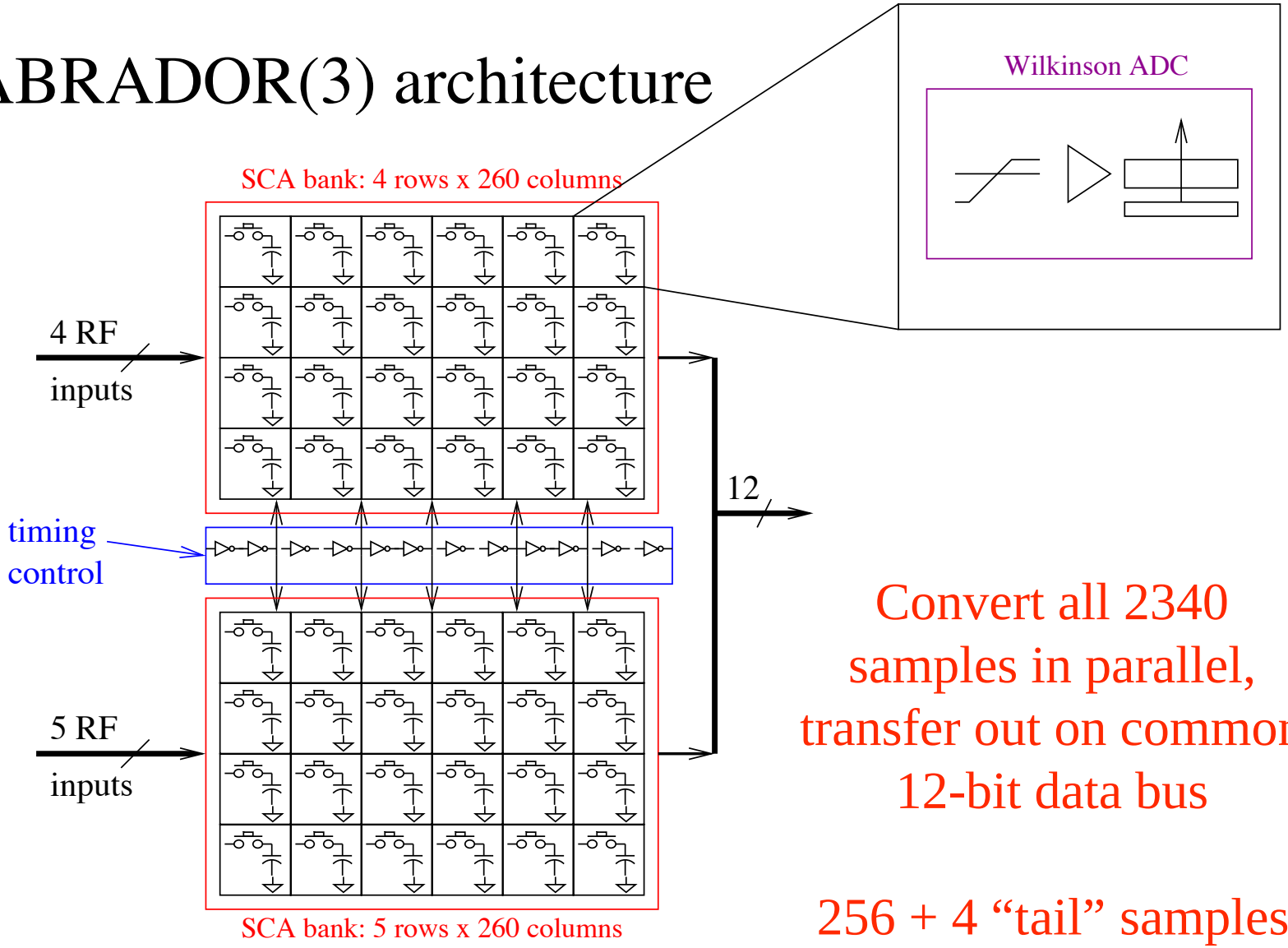
Random access:



- Common STOP acquisition
- 3.2 x 2.9 mm
- Conversion in 31µs (all 2340 samples)
- Data transfer takes 80µs
- Ready for next event in <150µs

9 x 260 samples = 2340 storage cells

LABRADOR(3) architecture



Convert all 2340 samples in parallel, transfer out on common 12-bit data bus

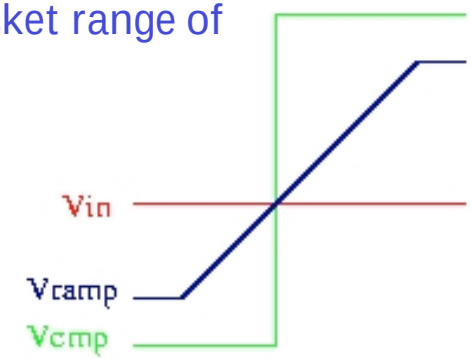
256 + 4 “tail” samples

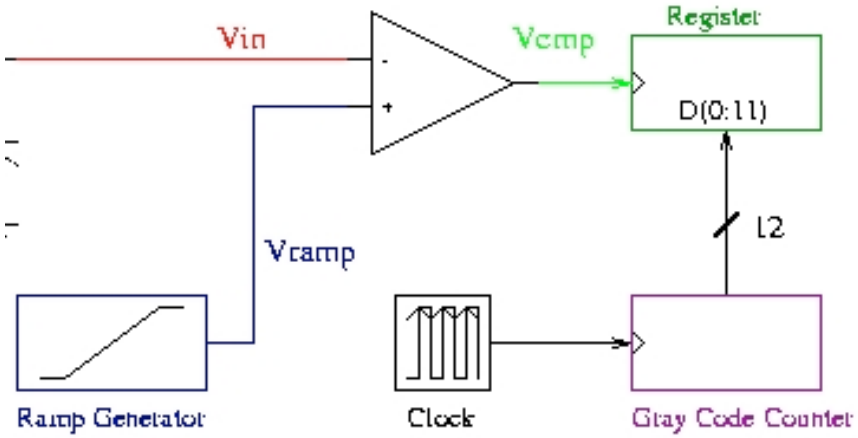
LABRADOR Digitization

Wilkinson ADC

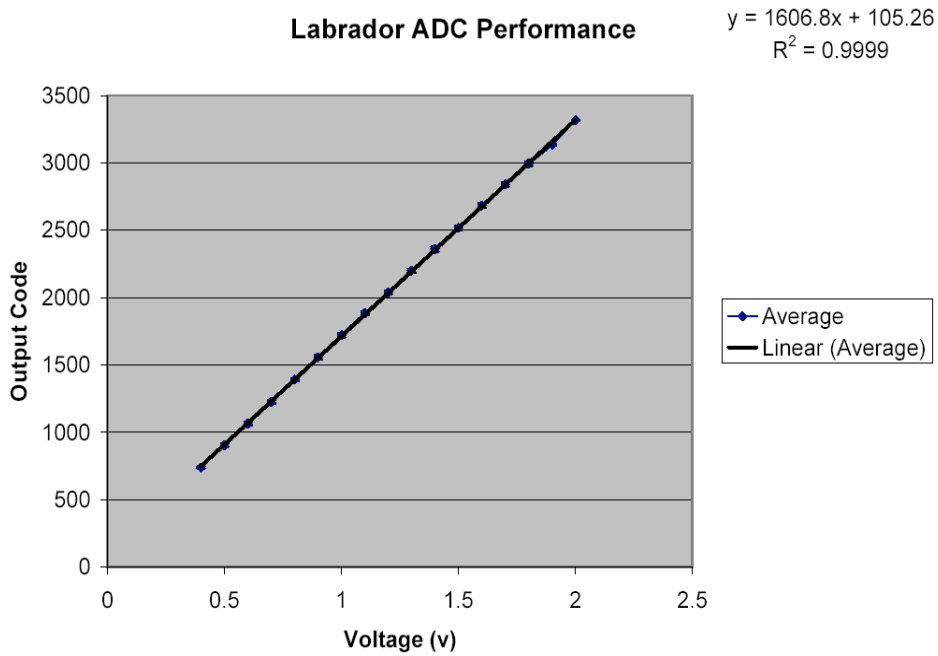
- No missing codes
- Linearity as good as can make ramp
- Can bracket range of interest

Run count during ramp



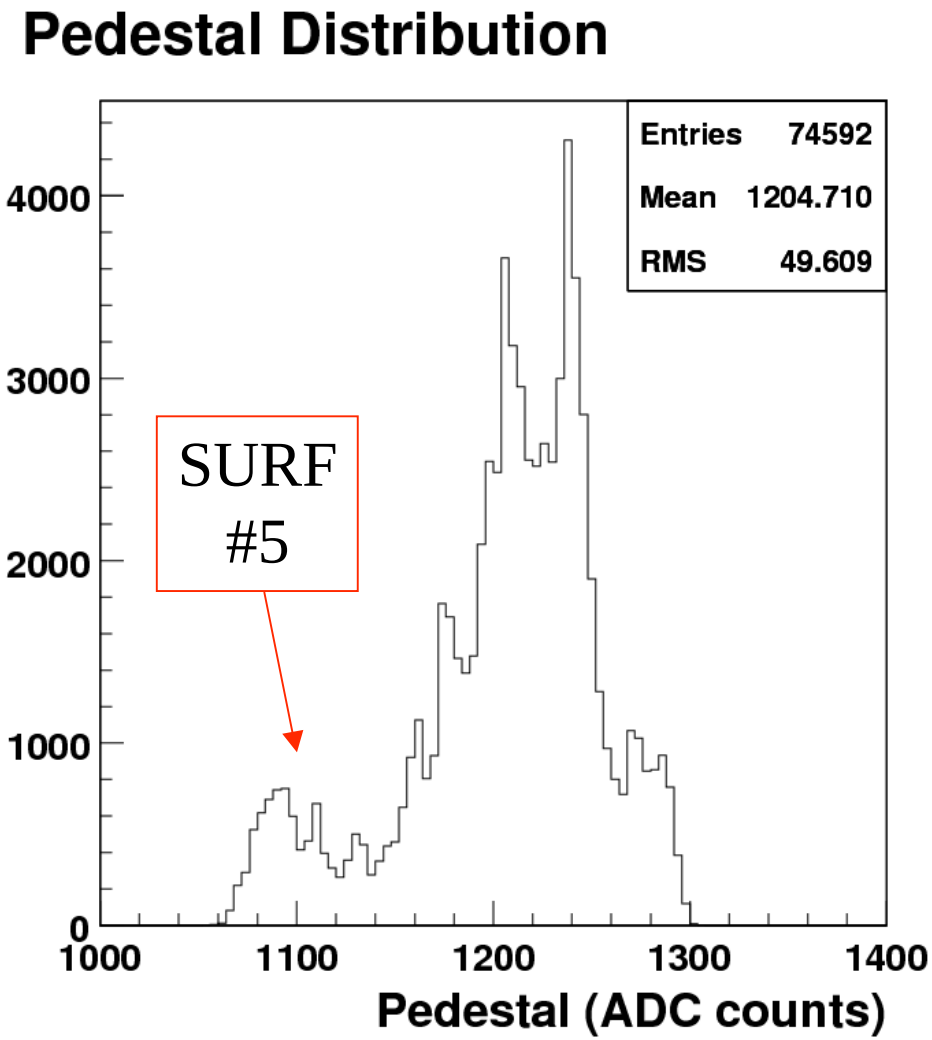


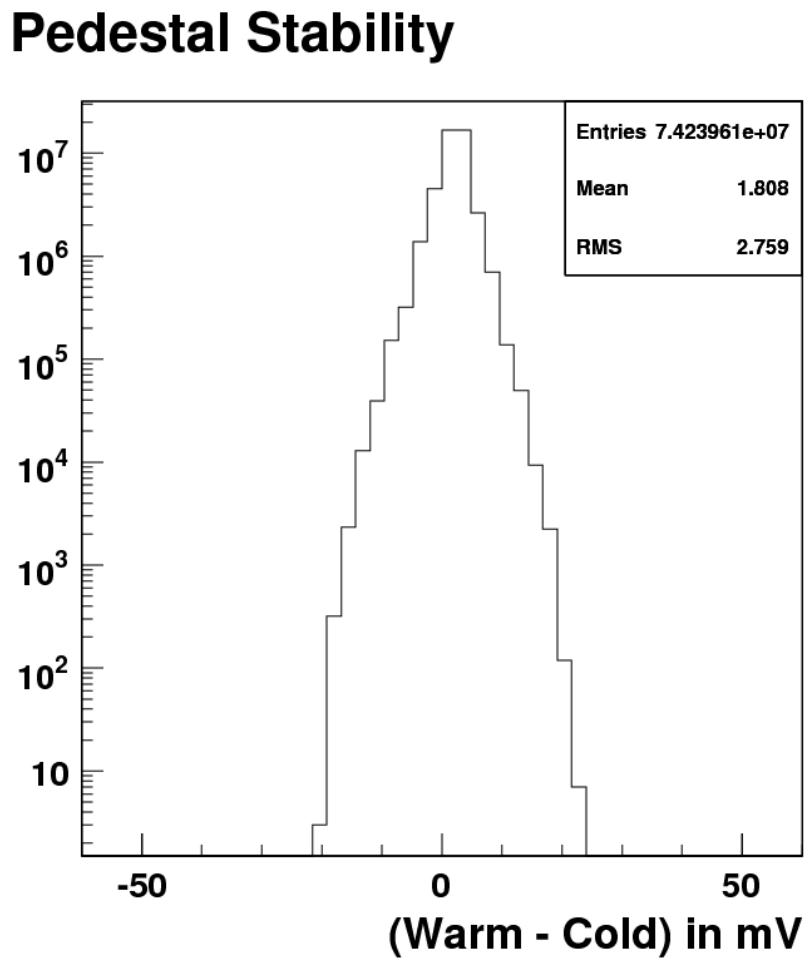
12-bit ADC



- Excellent linearity
- Basically as good as can make current source/comparator
- Comparator ~0.4 – 2.1V; 133MHz GCC max (~31us)

Pedestal and Pedestal Stability



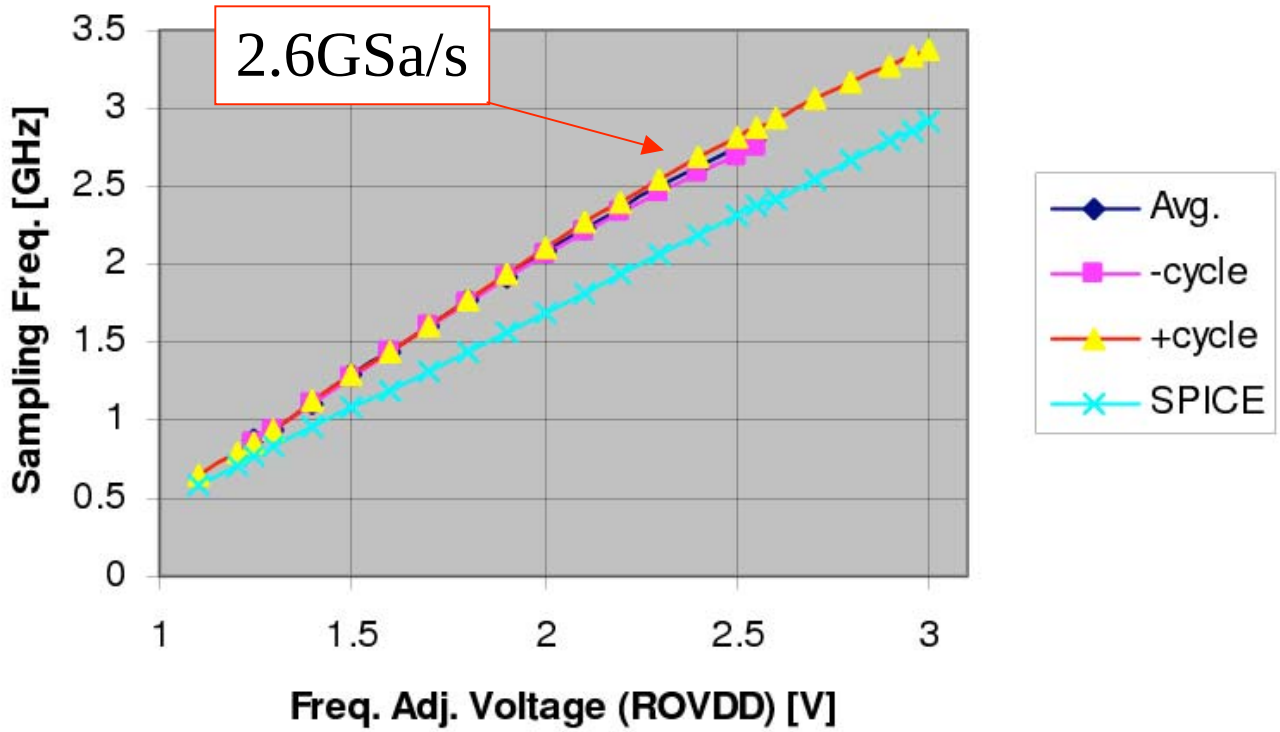


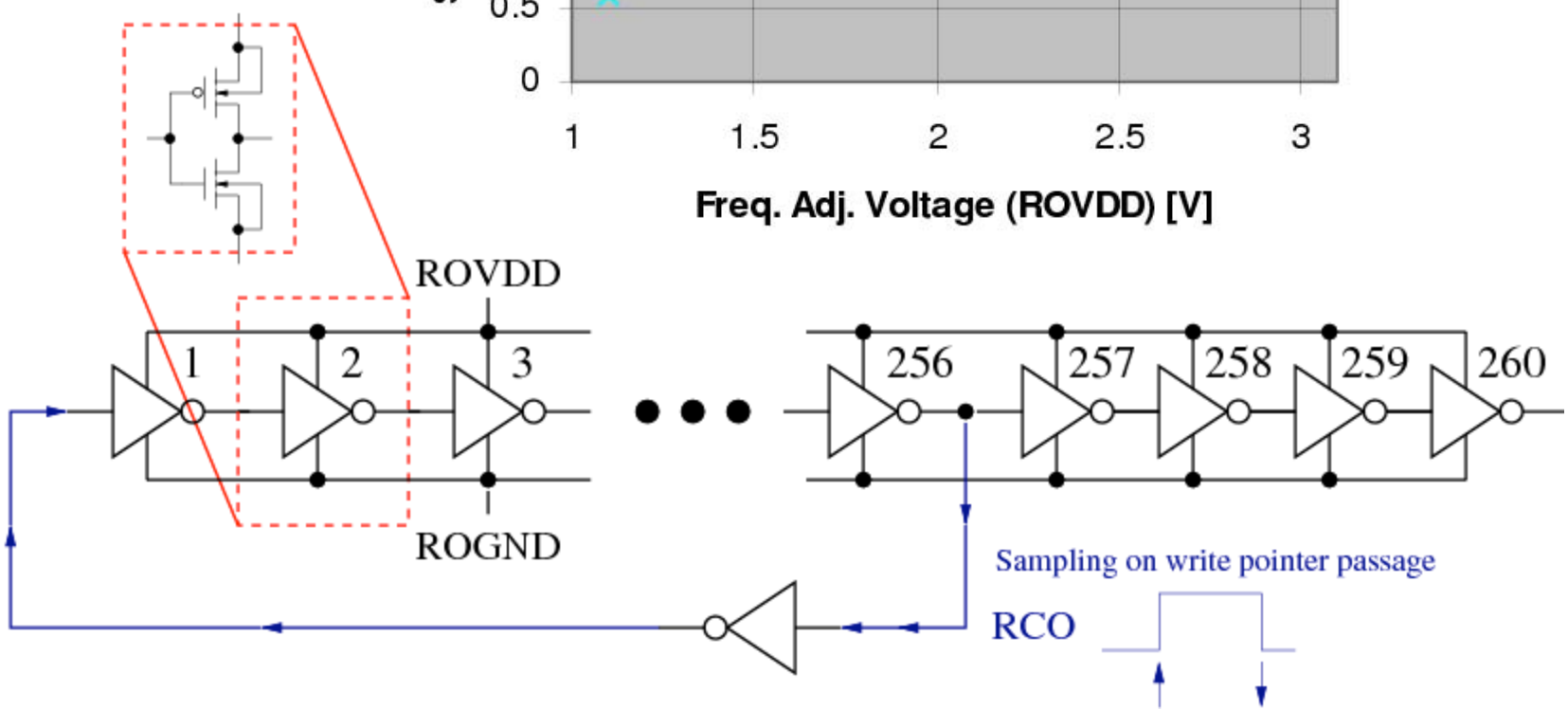
$\Delta T = 17C$ ($\delta t \sim 24$hours)
~ 0.052mV/C

- AC coupled input

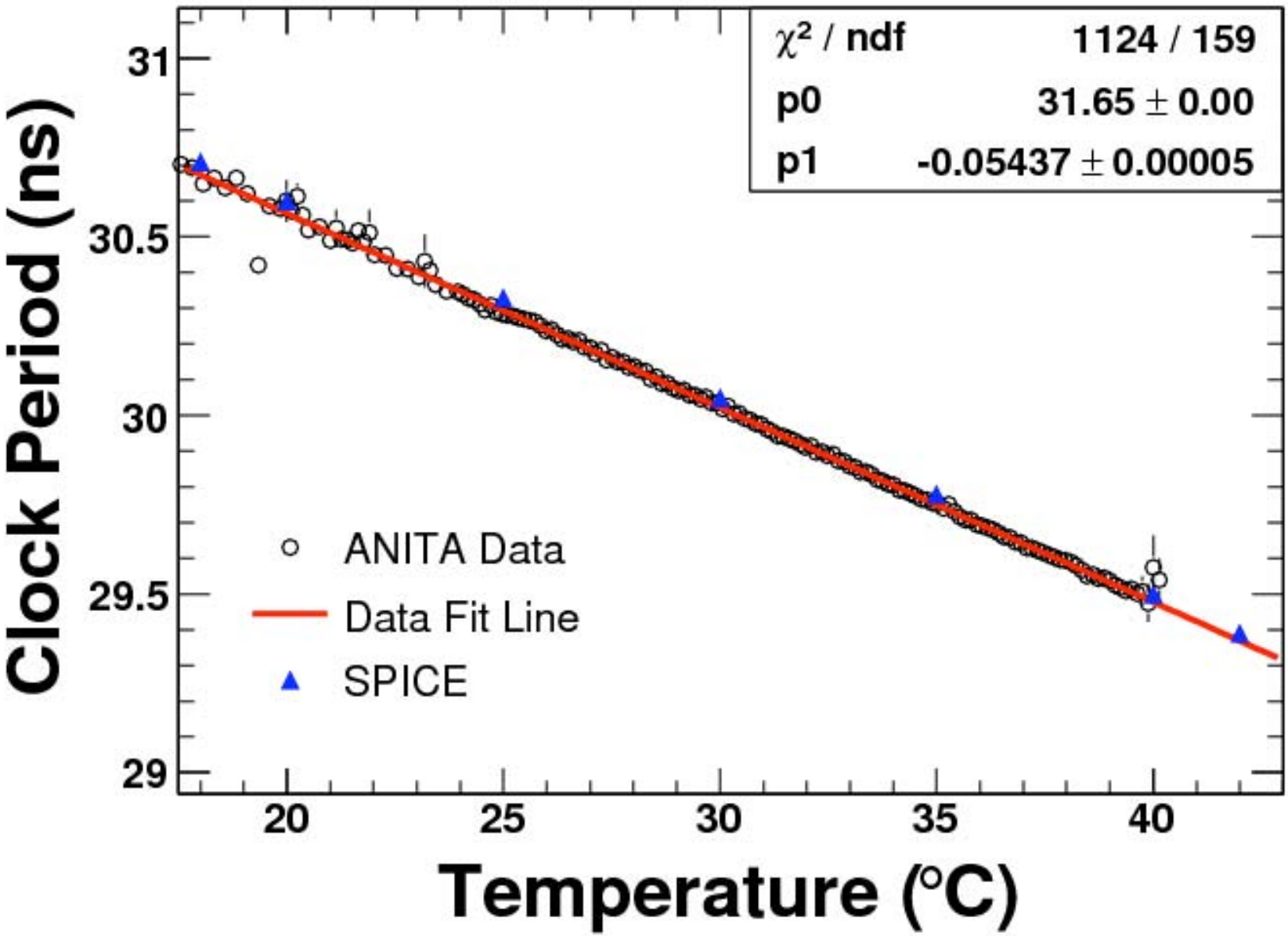
LABRADOR Sampling Speed

- XOR Look-ahead logic (sample on rising/falling edge)
- Sampling rates up to 4 GSa/s with voltage overdrive

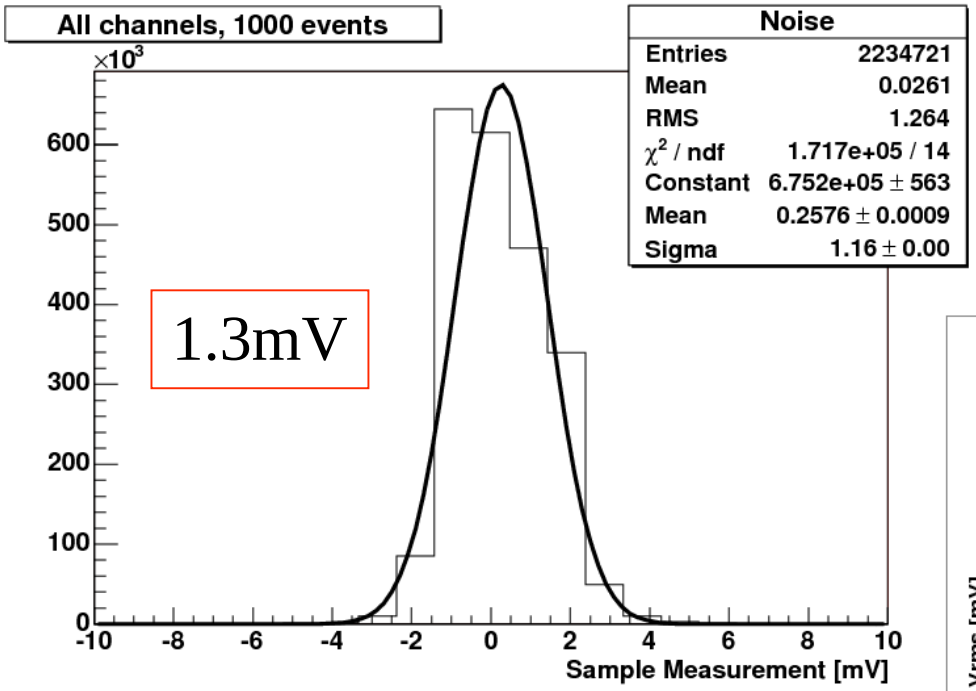


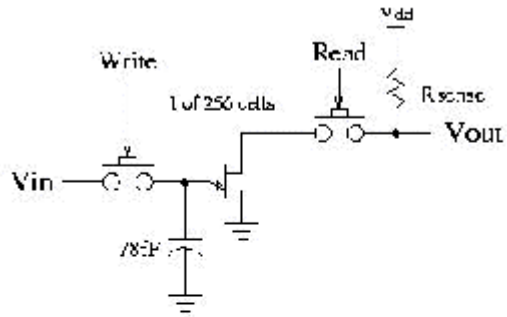


Sampling Rate Temperature Dependence



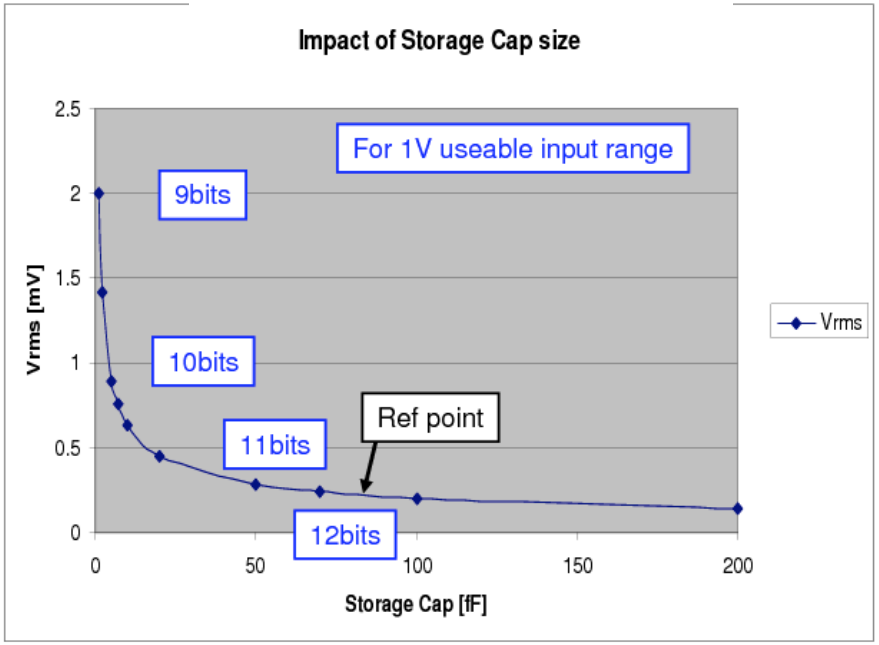
LABRADOR (SURF board) Noise





$$v_{rms} = \sqrt{\frac{kT}{C_{store}}} = 0.23mV$$

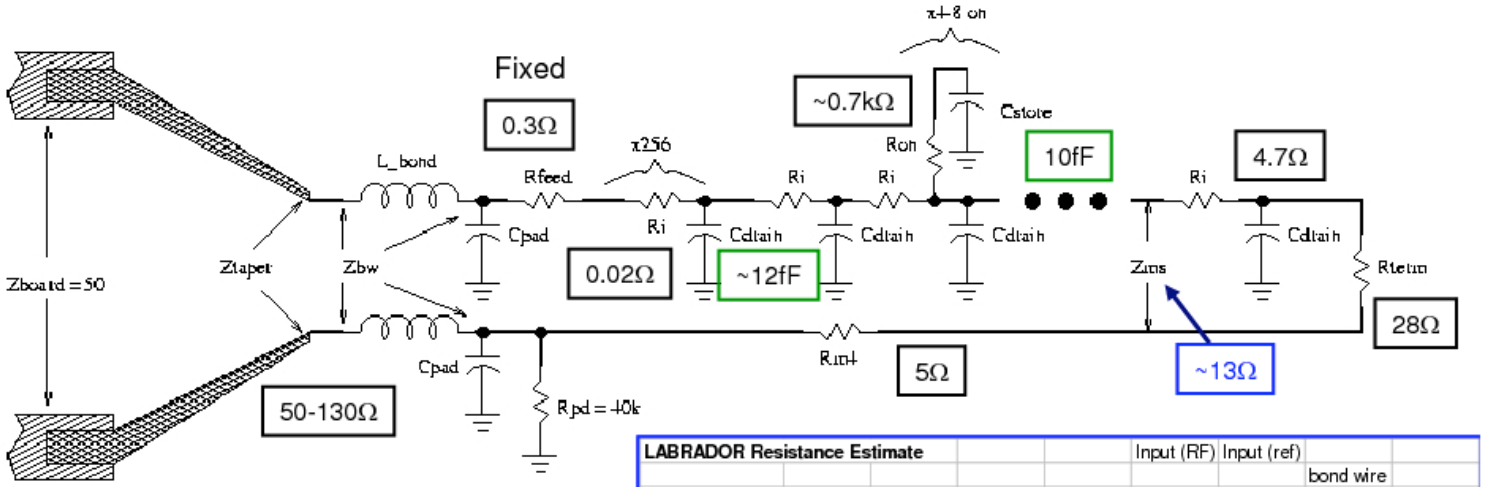
C_{store} = 78fF

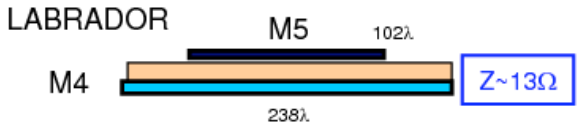


- 10 real bits (1.3V/1.3mV noise)

(2.5V VDD, rails smaller)

Bandwidth Limitations (LAB1 example)





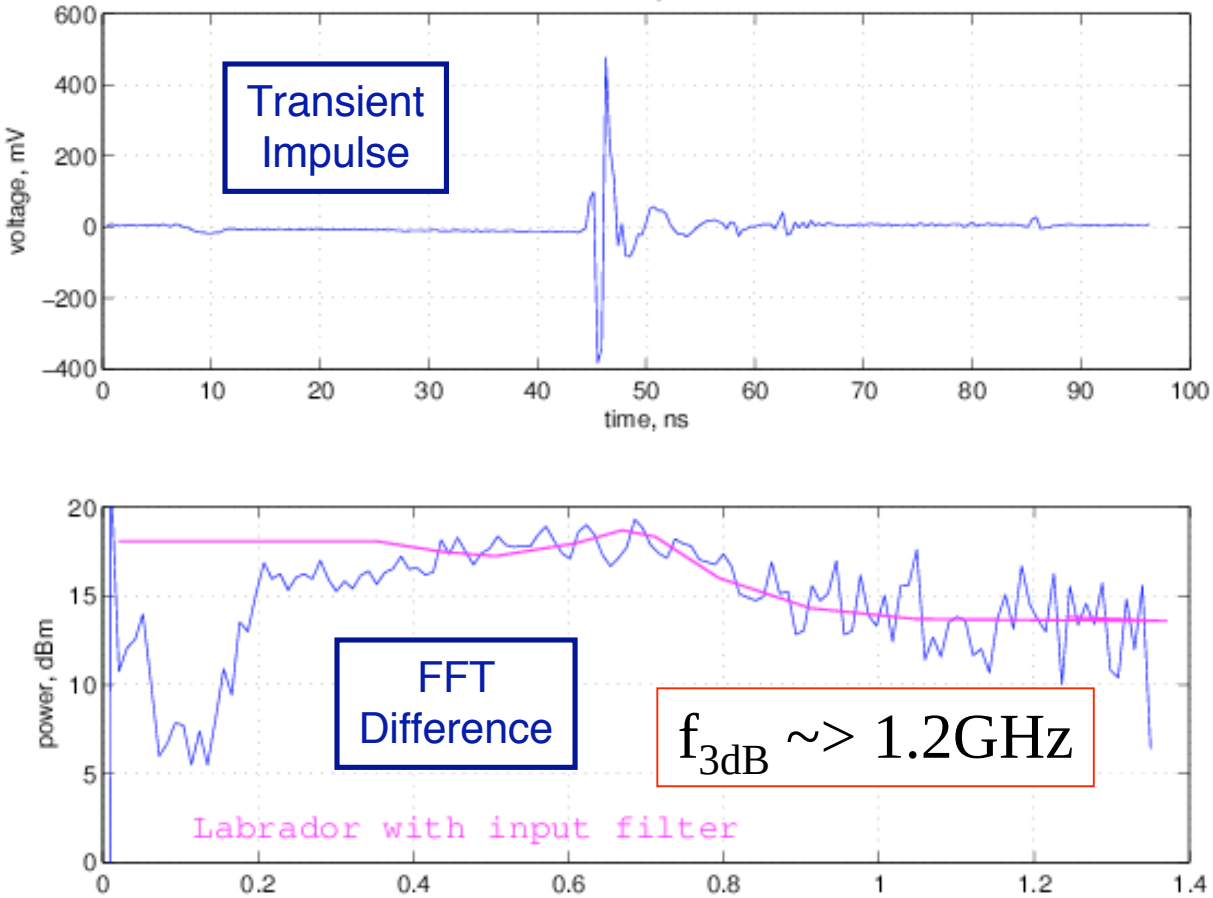
LABRADOR Resistance Estimate					Input (RF)	Input (ref)	
							bond wire
Length	17000	λ			0.0	0.1	pad
			70			0.2	M5-M4
Metal 4(sheet) =	0.07	Ohm/sq		71.42857		5.0	typ length (sq.)
Metal 5(sheet) =	0.03	Ohm/sq	166.6667		5.0		typ length (sq.)
Poly contact =	5.1	Ohm	6	6	0.9	0.9	
via 1=	2.7	Ohm	6	3	0.5	0.9	
via 2=	5.35	Ohm	6	3	0.9	1.8	
via 3=	8.26	Ohm	6	3	1.4	2.8	
via 4=	11.34	Ohm	6		1.9		
					10.5	11.5	Total per feed
						28	Rterminator
		Measured:		Ohm		**50.0**	Grand Total

$$f_{3dB} = 1/2\pi ZC$$

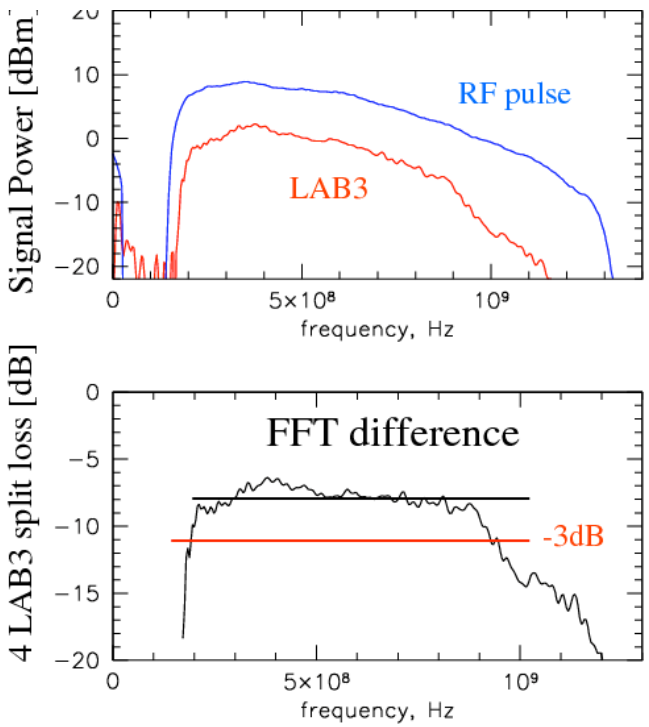
LAB3 → move R_{term} to front

- For 1.2GHz, C <~ 2pF (NB input protection diode ~10pF)
- Minimize C, (C_{drain} not negligible x260)

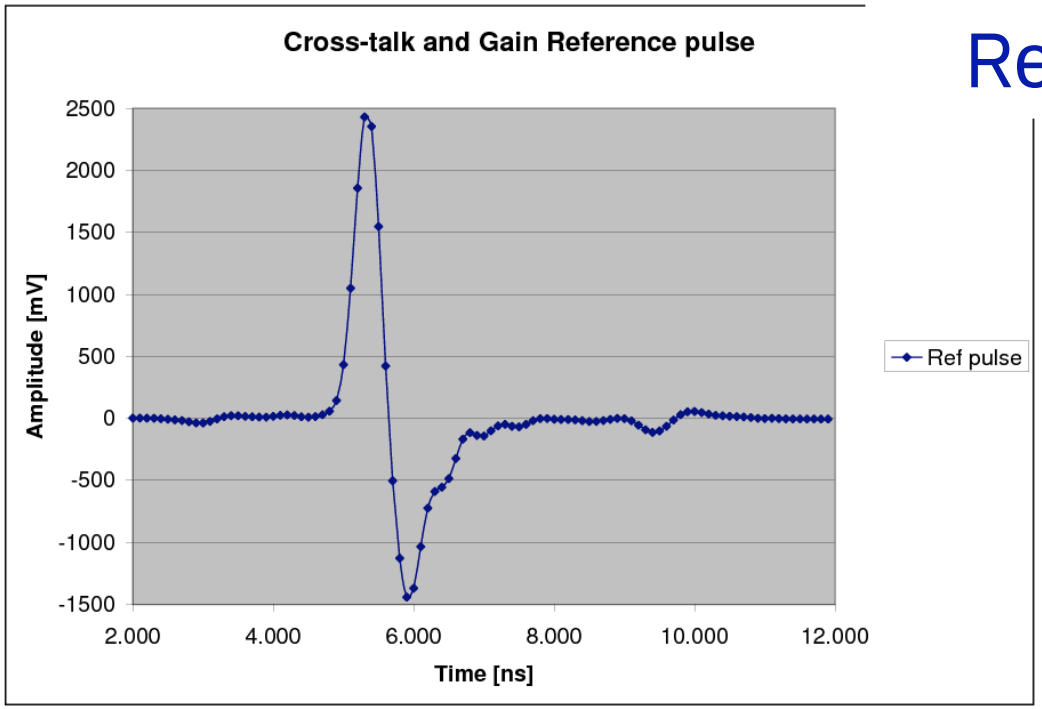
Bandwidth Evaluation



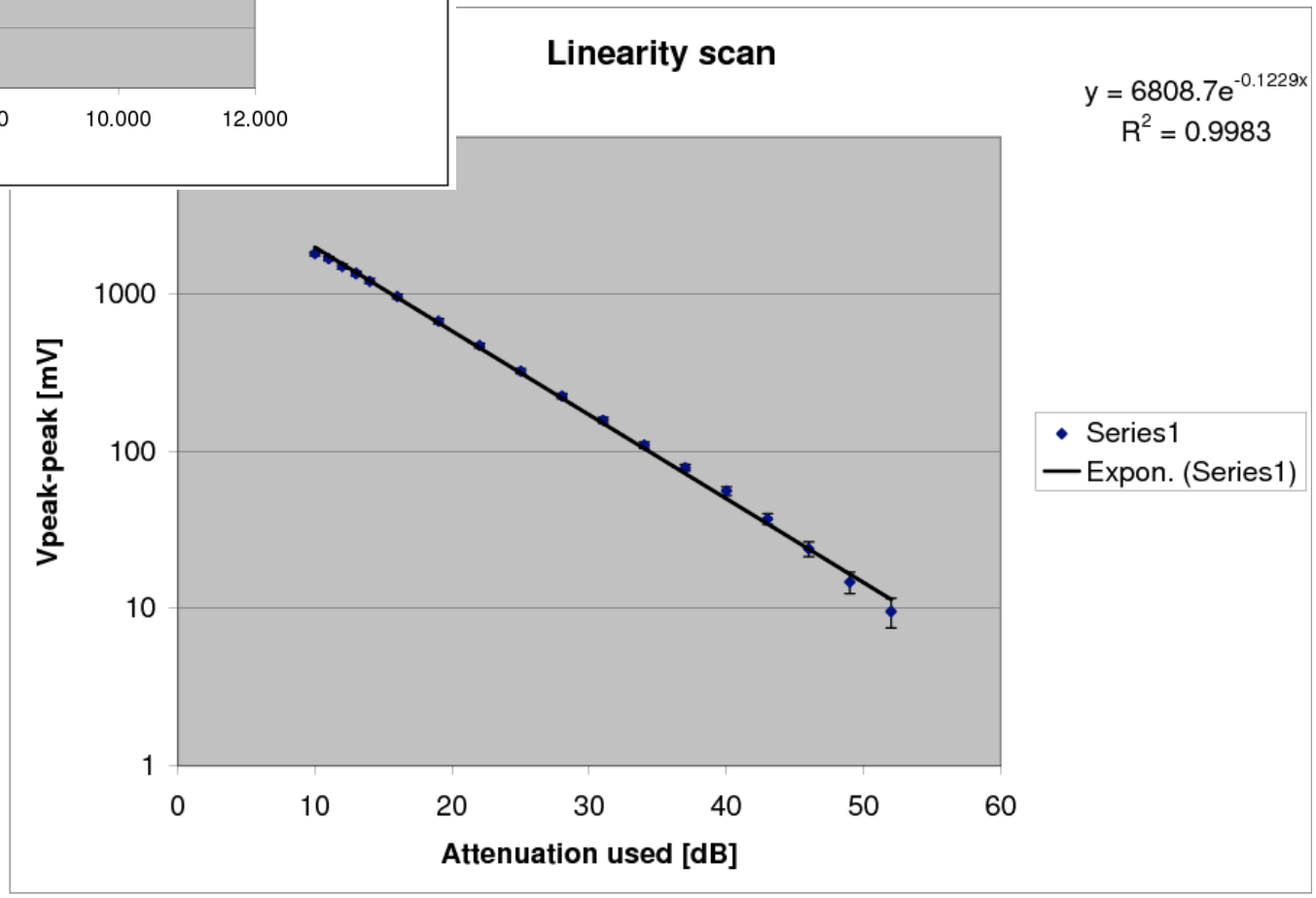
Frequency [GHz]



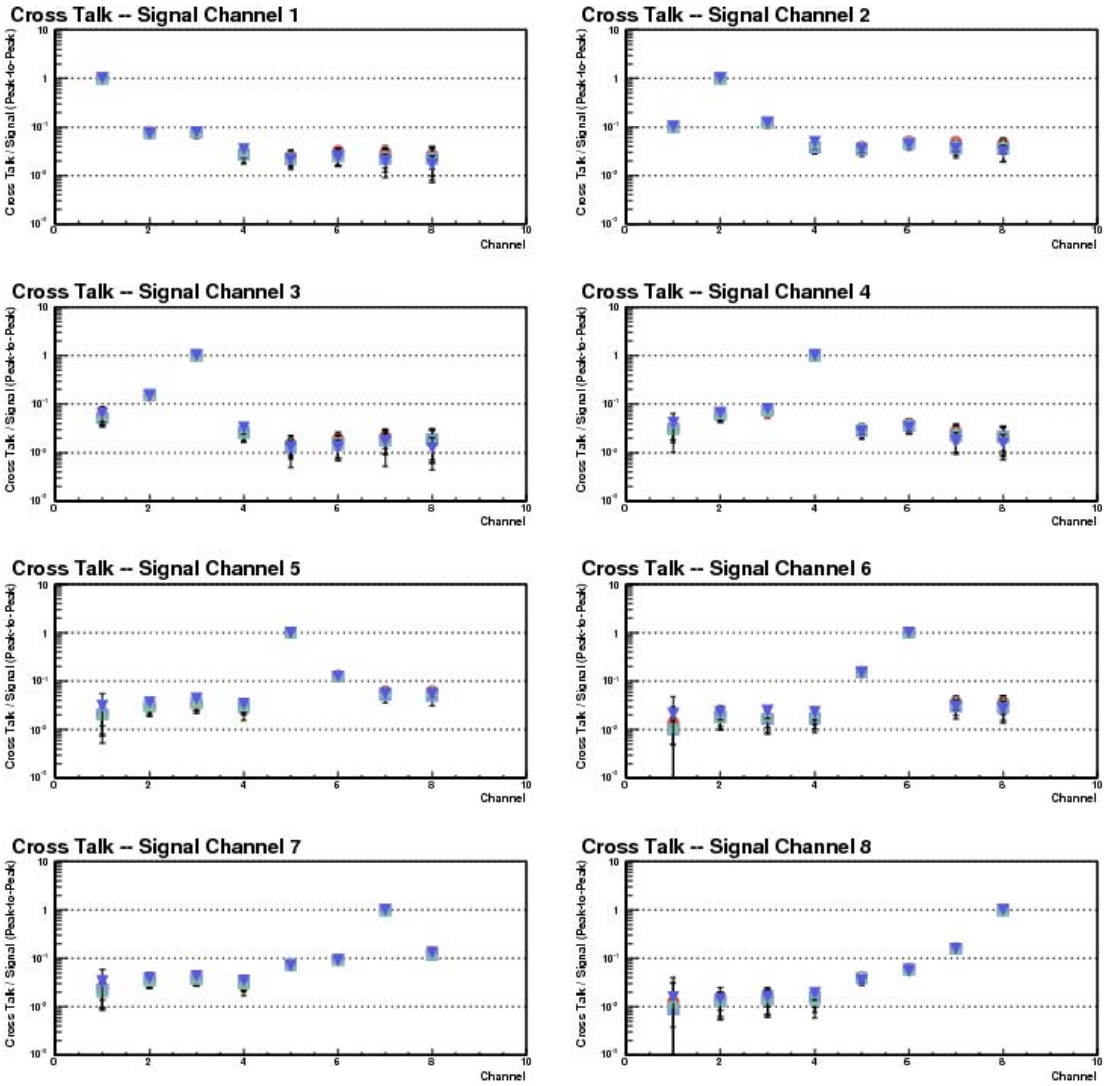
Response for RF Signals

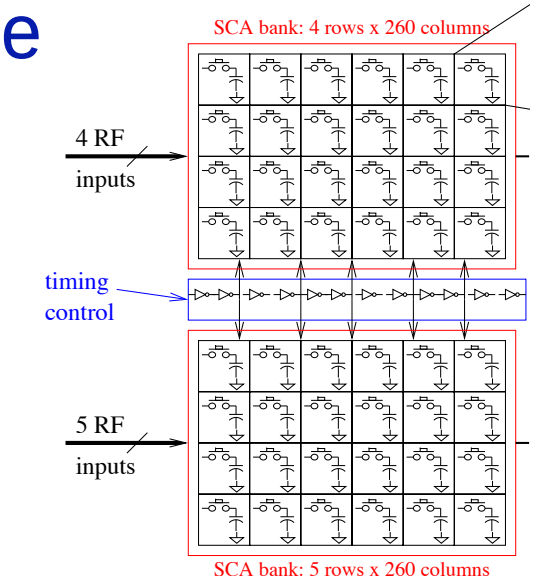


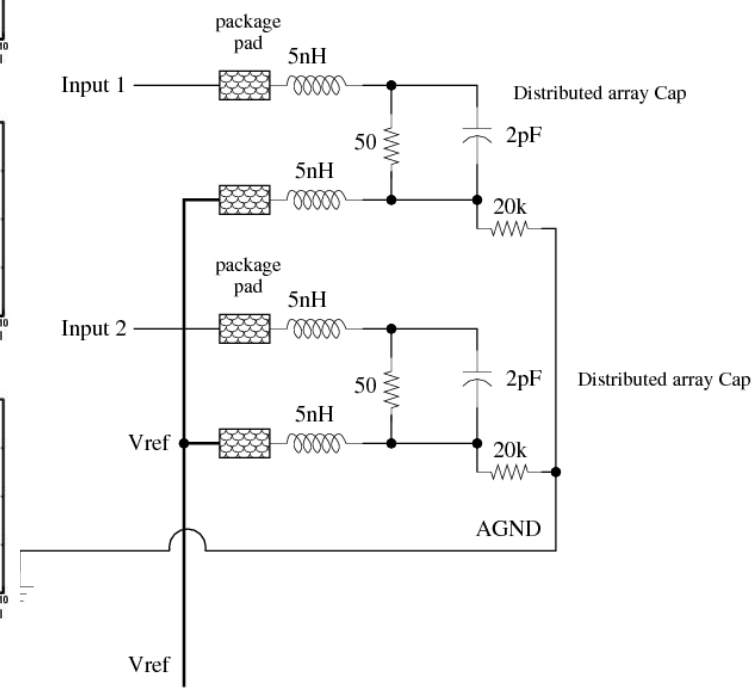
- 2.6 GSa/s, peak fit (@ board-level noise interference)



Cross-talk Amplitude

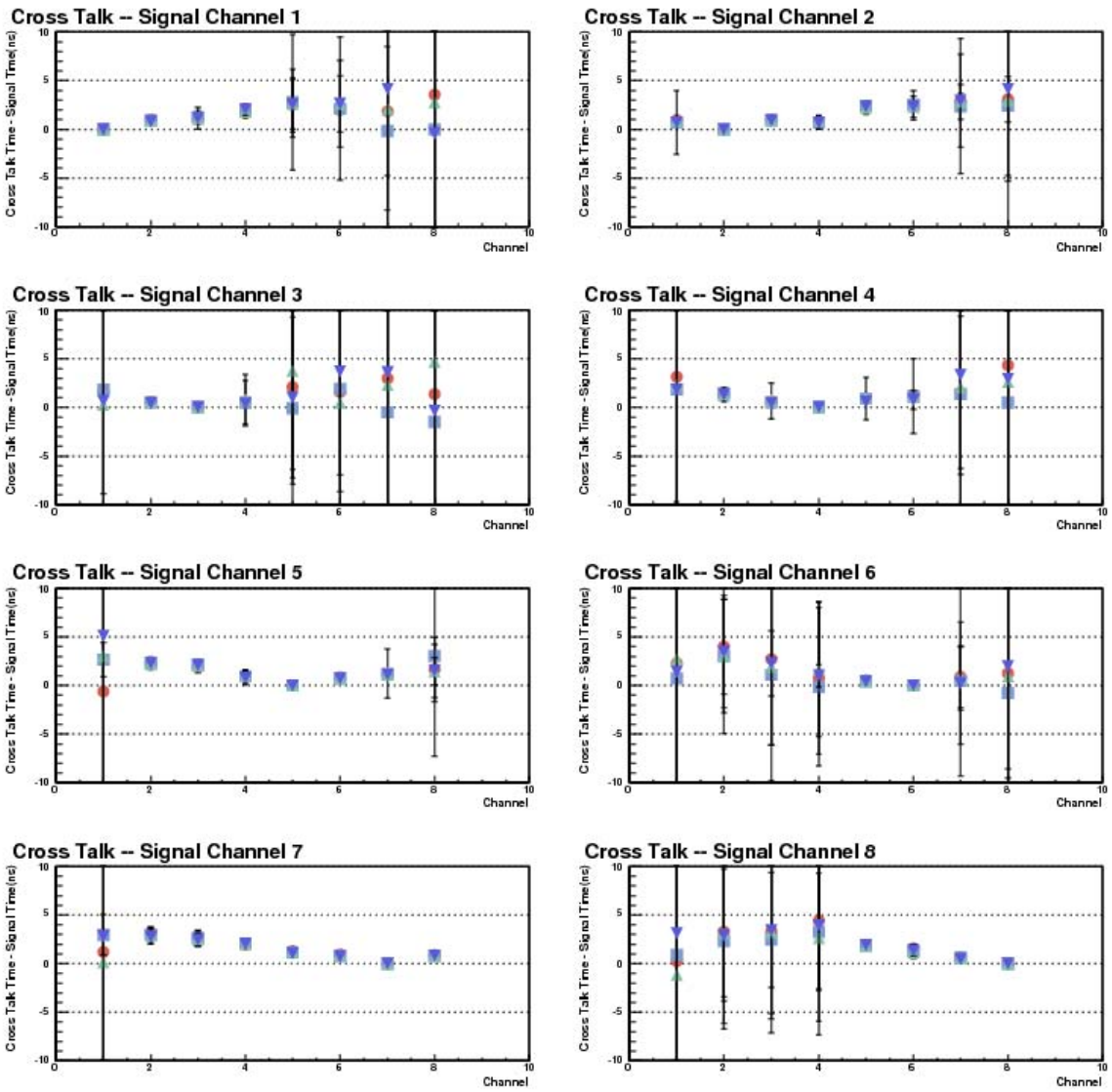


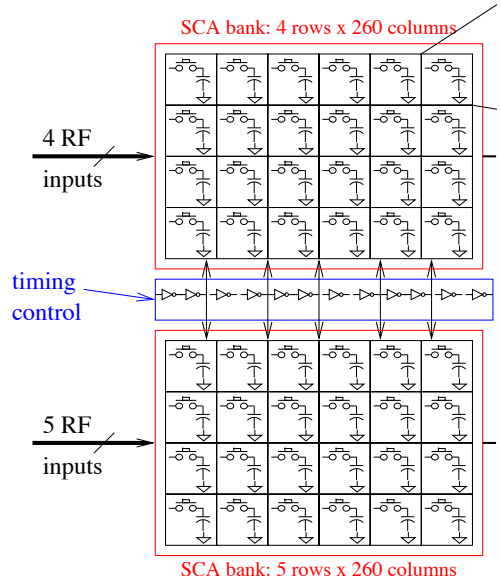


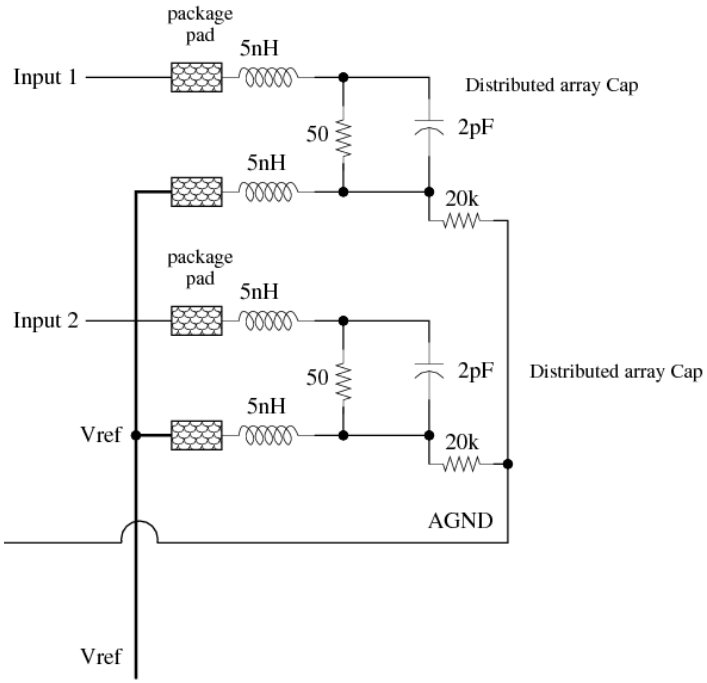


- Qualitative agreement obtained in SPICE

Cross-talk Phase

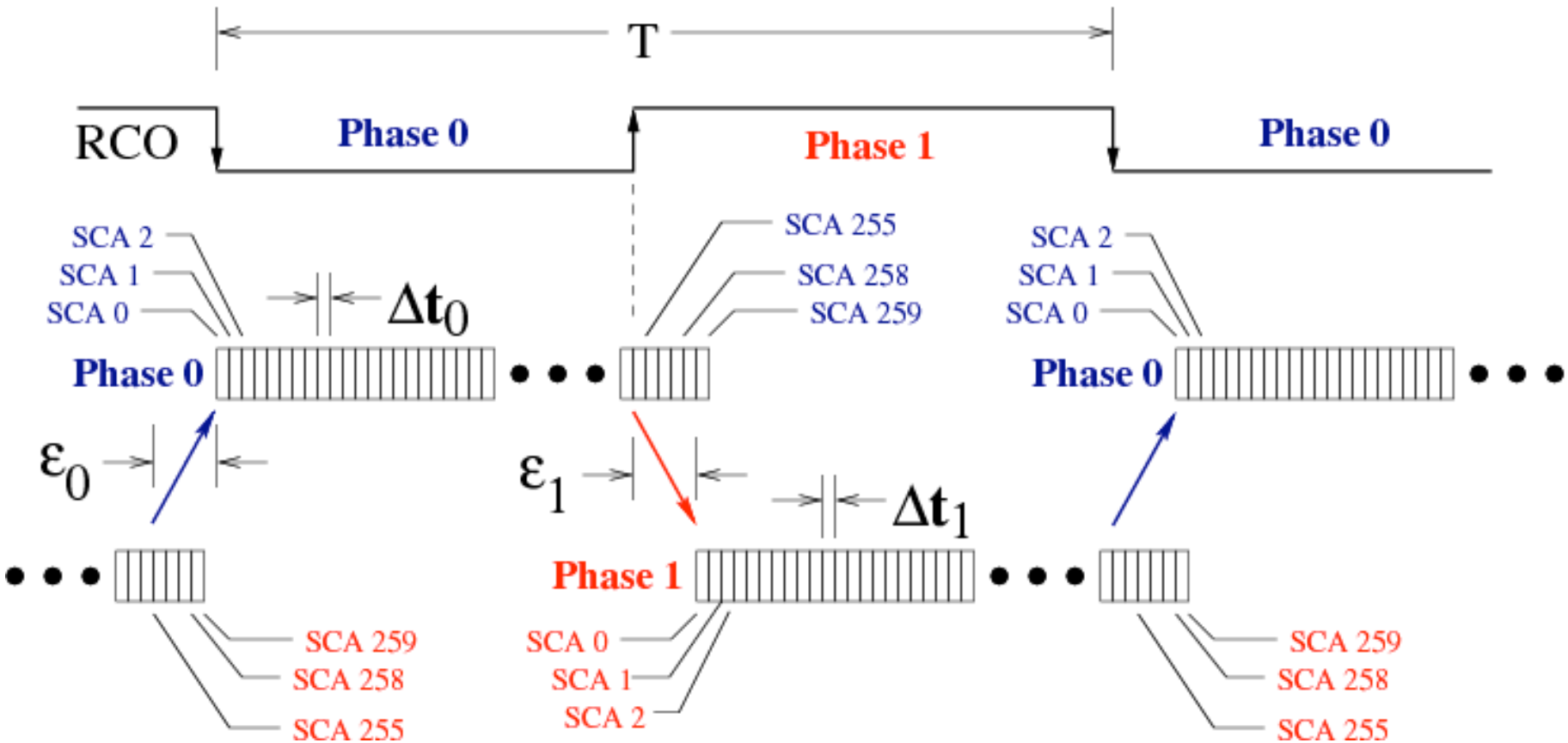






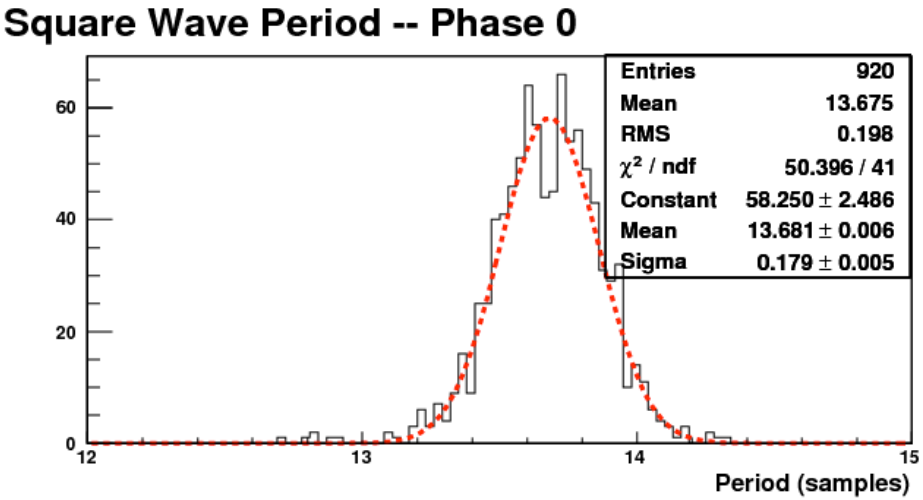
- Qualitative agreement obtained in SPICE

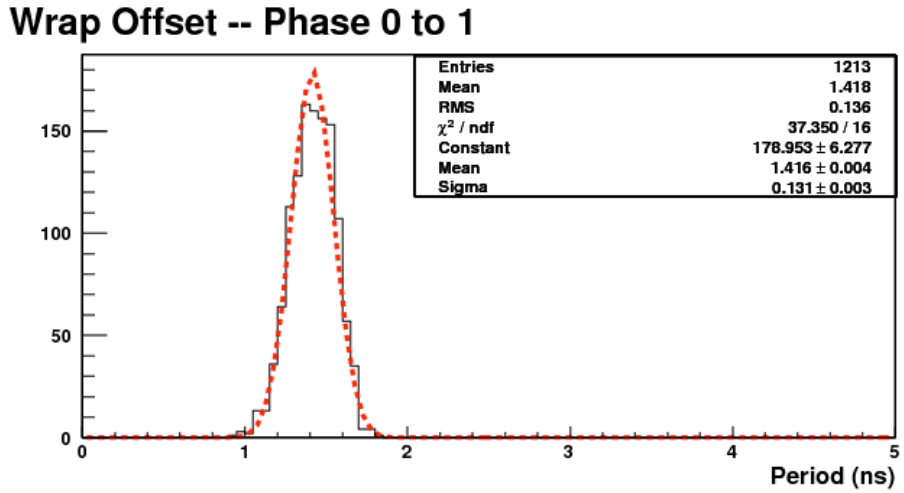
Timing Calibration Constants

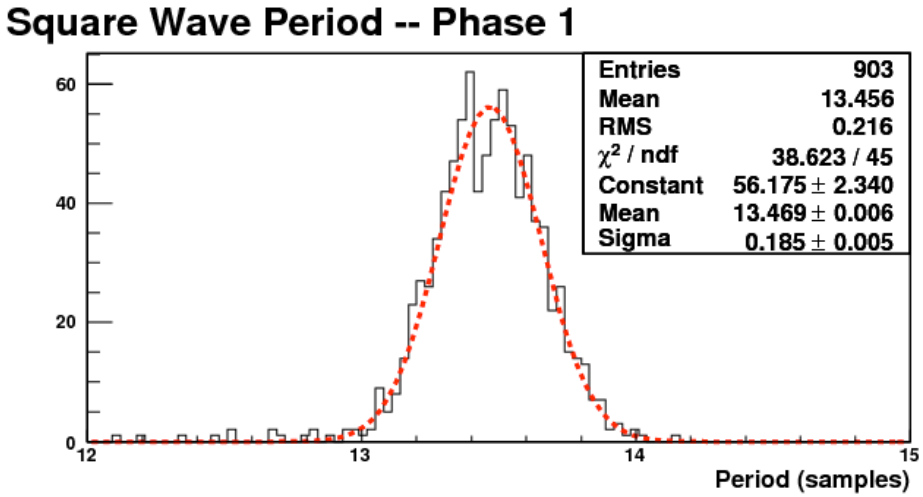


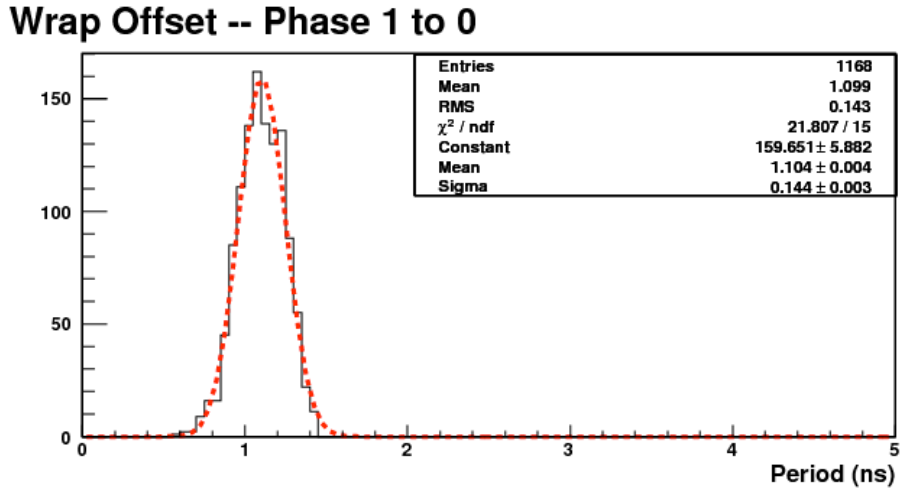
- T_0 != T_1 != ½ T
- Separate wrap time constants
- Need to determine Phase 0, 1 interleaving
- In general every Δt0, Δt1 different

Timing Calibrations (1)







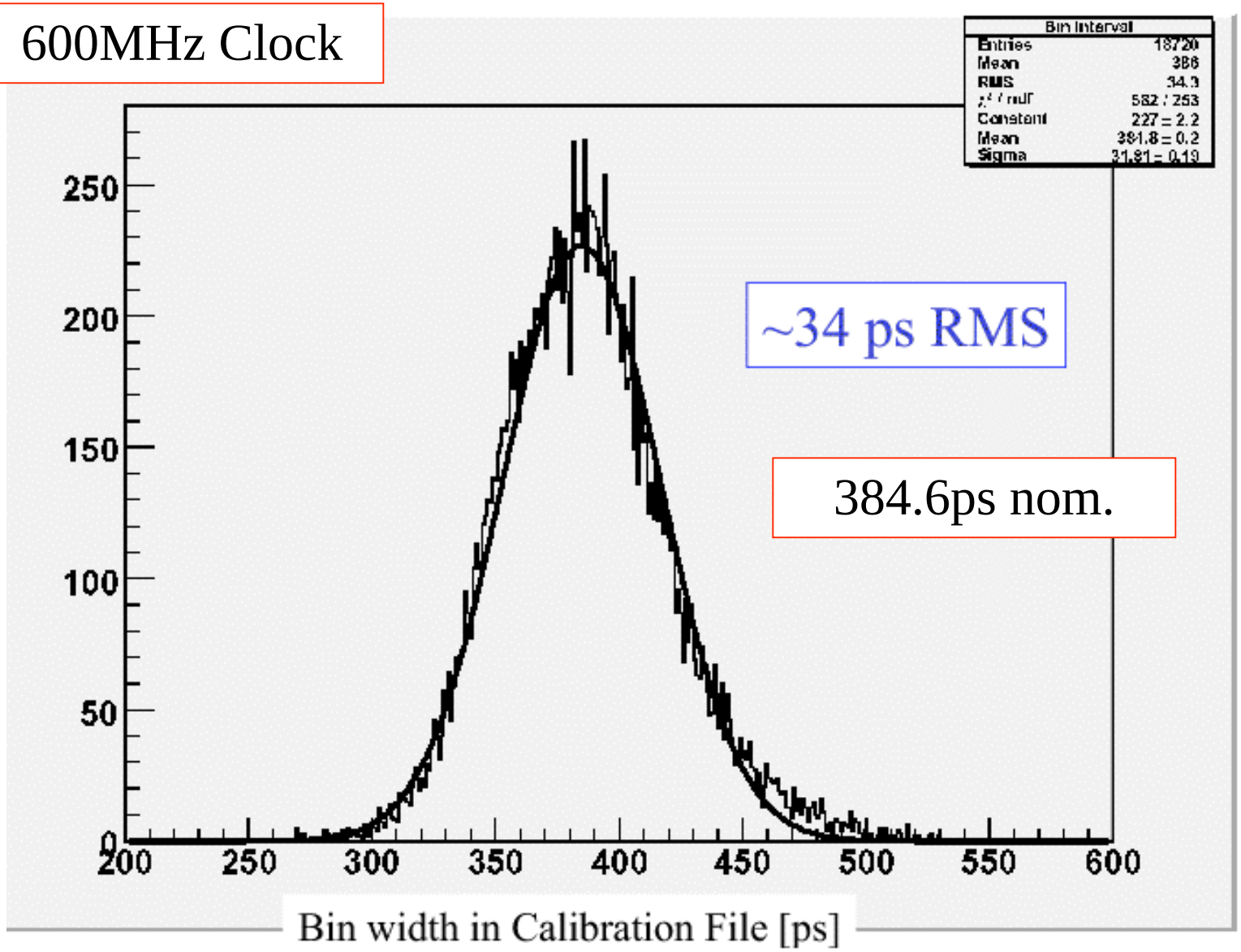


High-low != Low-high

Wrap-around time difference

Timing Calibrations (2)

600MHz Clock

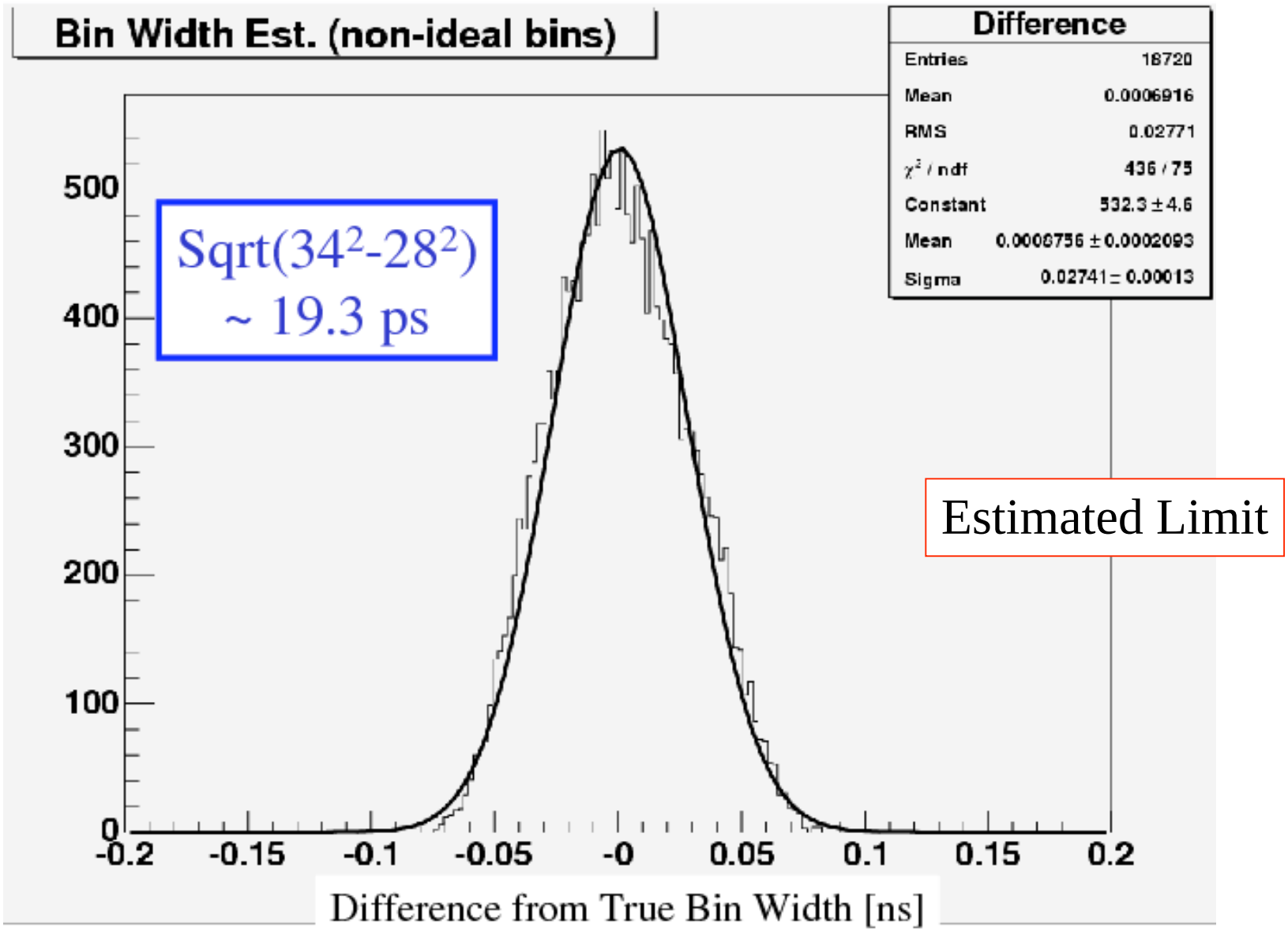


~34 ps RMS

384.6ps nom.

Bin-by-bin

MC study of Calibration Technique

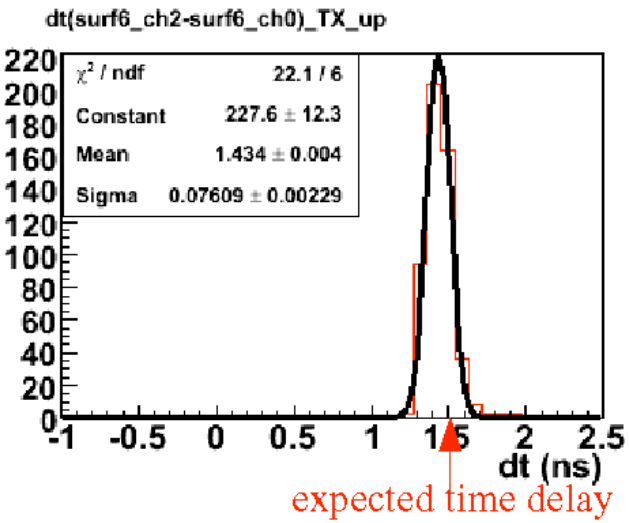


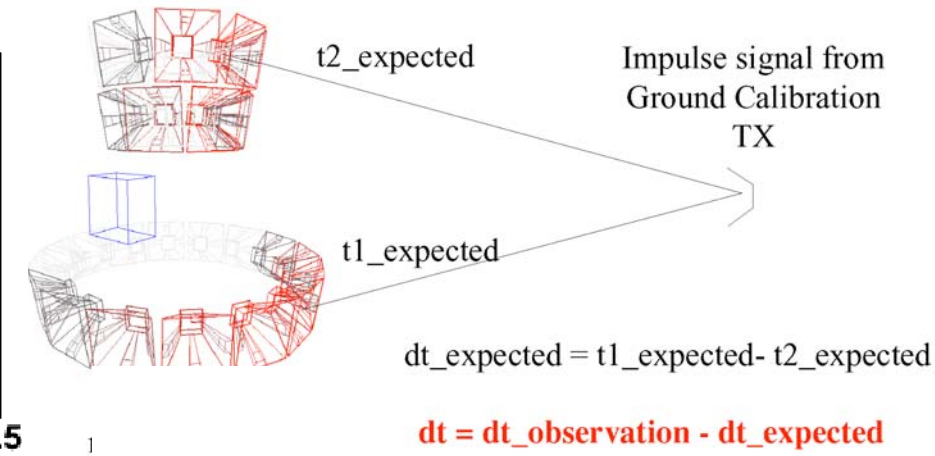
Timing vs Angle (with Impulse Calibration Radio Signal)

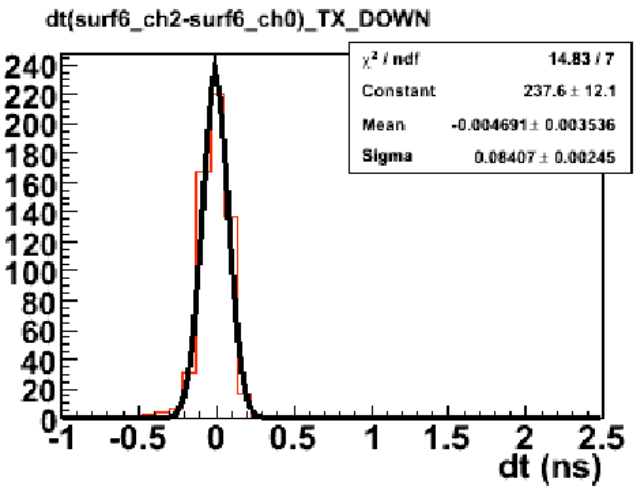
TX Up by 1.56 m

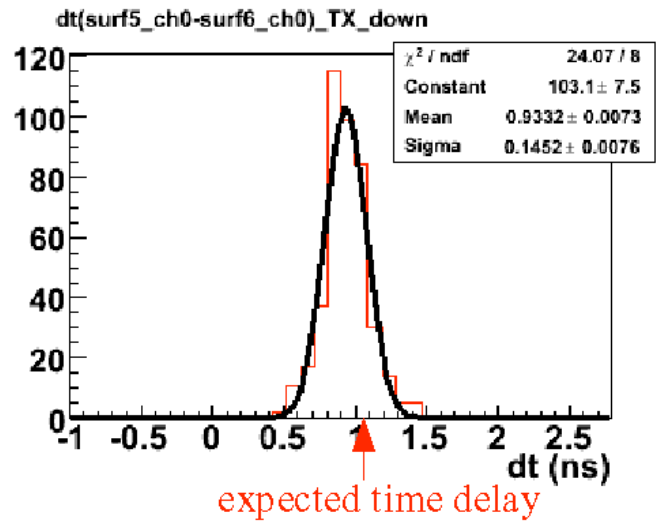
Vertical Angle Dependency

TX Down









Face to TX ← Horizontal Angle Dependency → Off by 1 Antenna

Jiwoo Nam
UC Irvine

Calibration with Realistic Signals

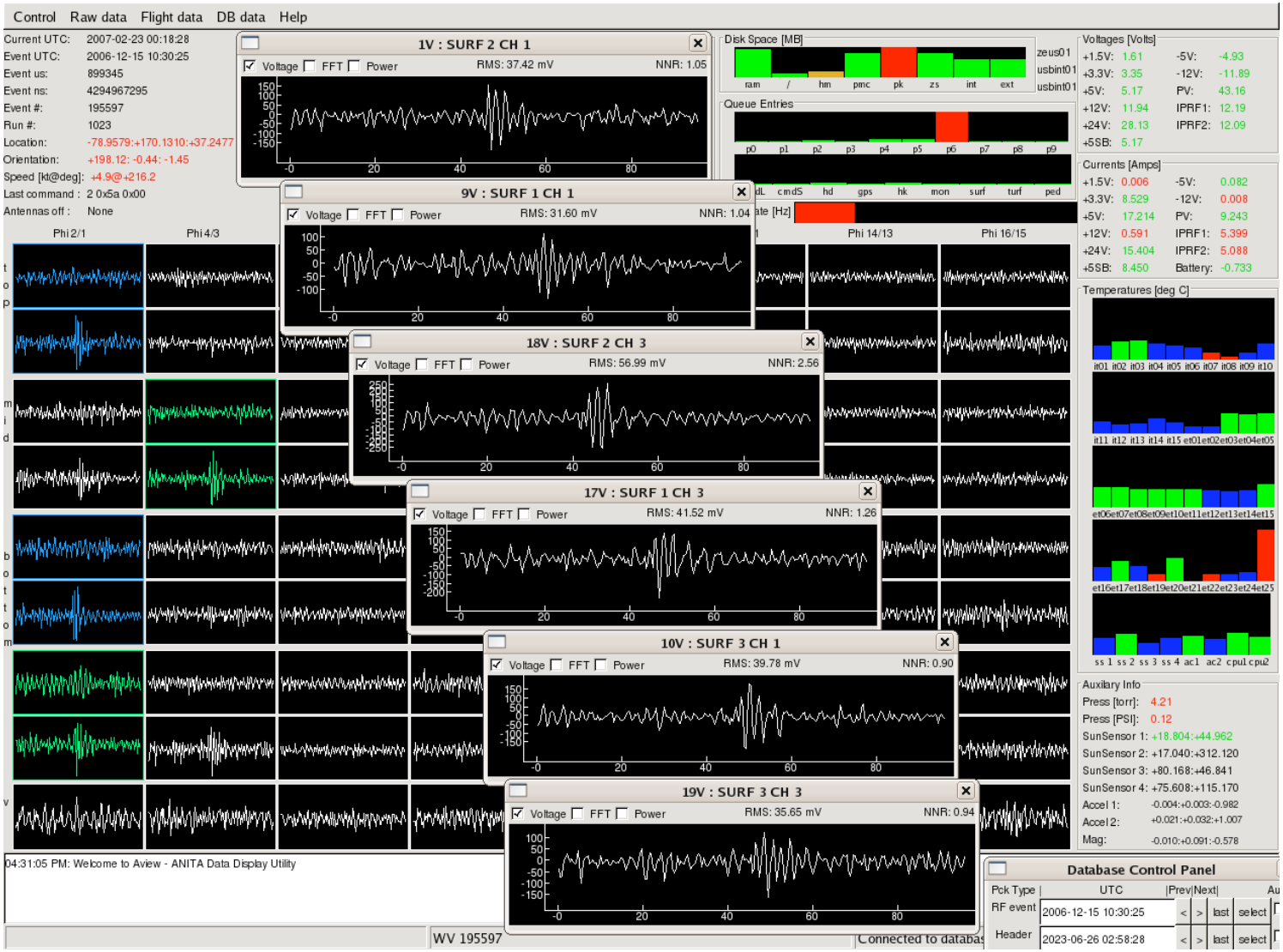
Ground pulser

Bore hole pulser

Dipole

- Ice 80m thick and messy

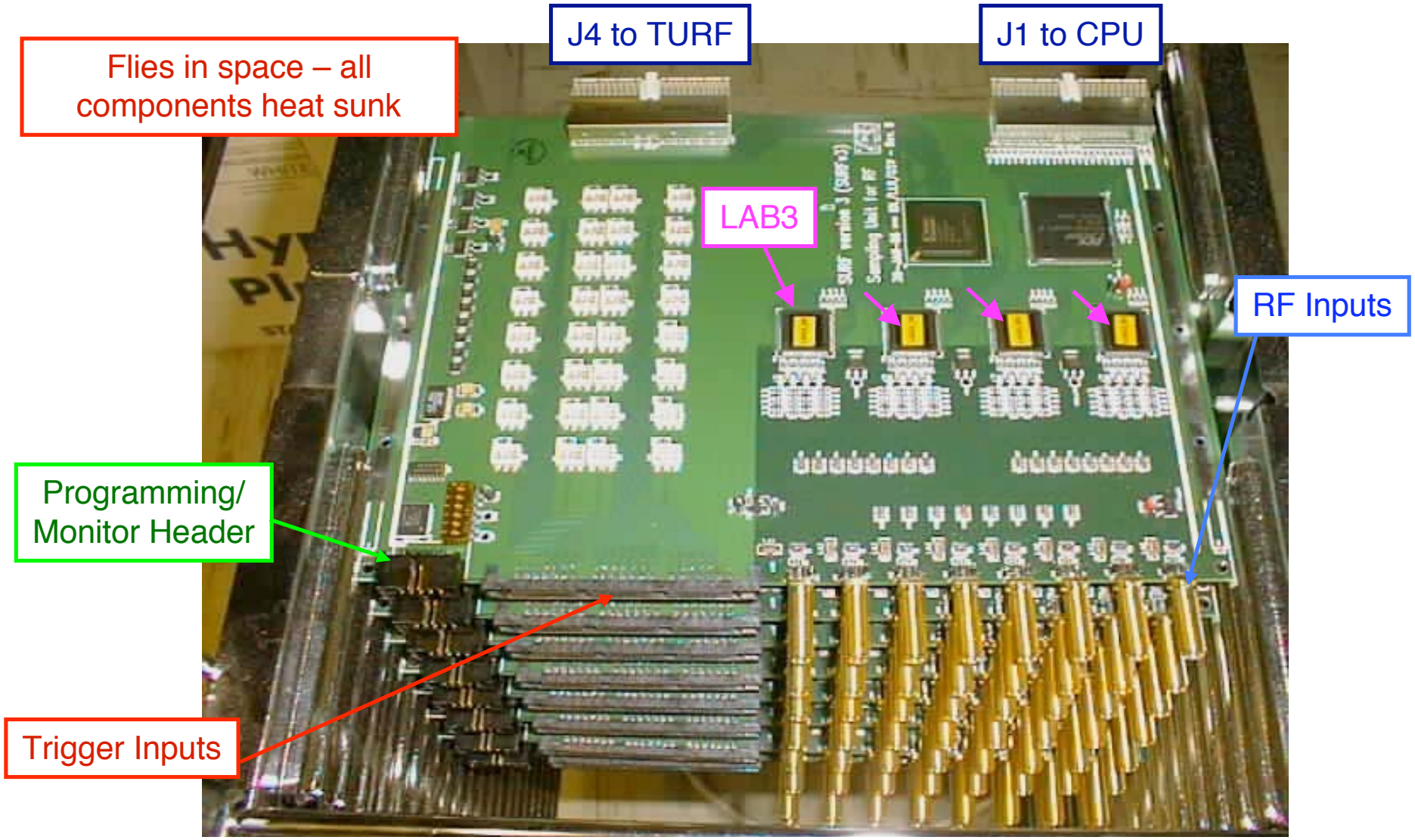
Validation data: borehole pulser



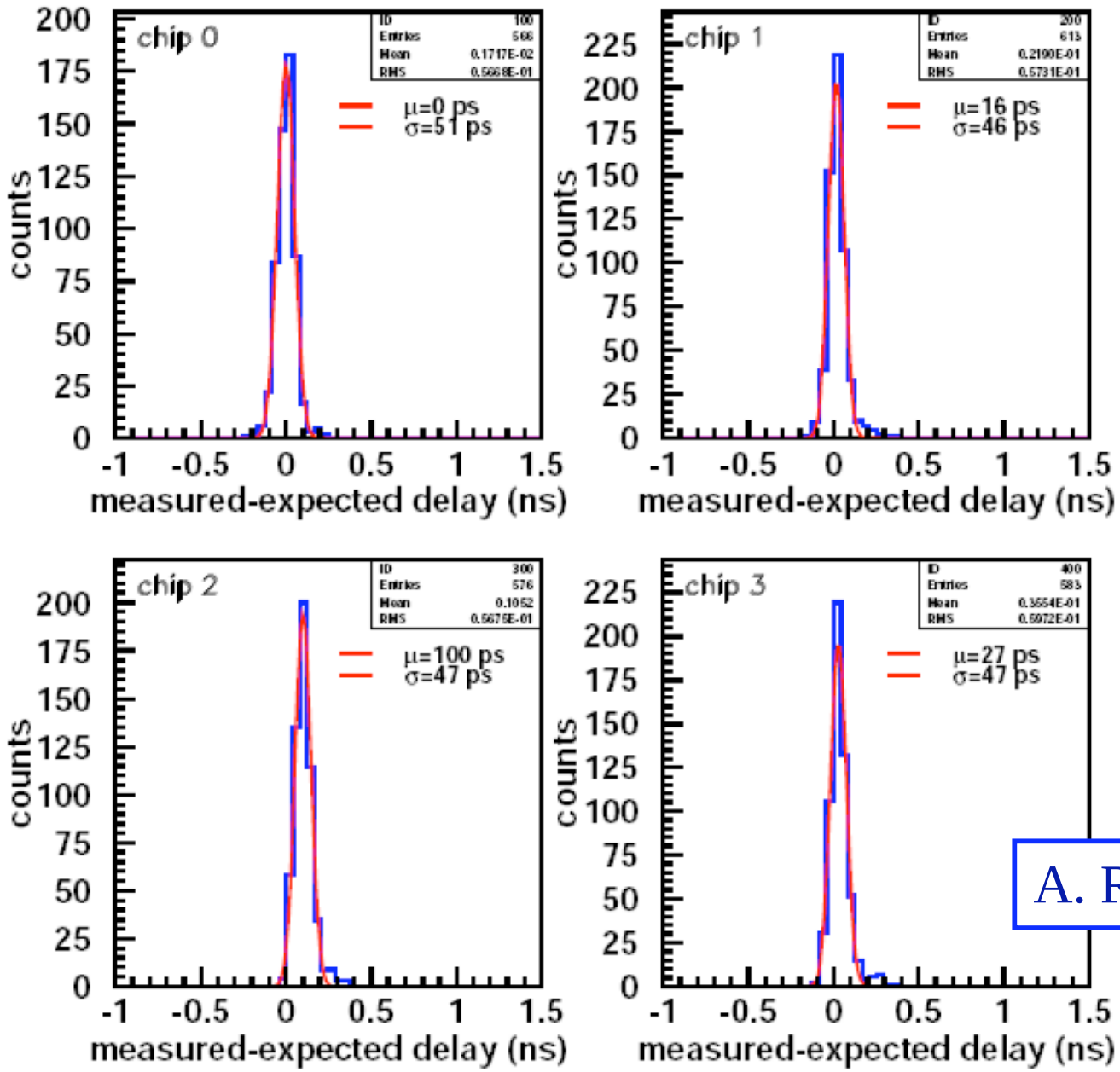
- RF Impulses from borehole antenna at Williams field
- Detected at payload out to 300-400 km, consistent with expected sensitivity
- Allows trigger & pointing calibration

SURFv3 Board

(SURF = Sampling Unit for RF)
(TURF = Trigger Unit for RF)

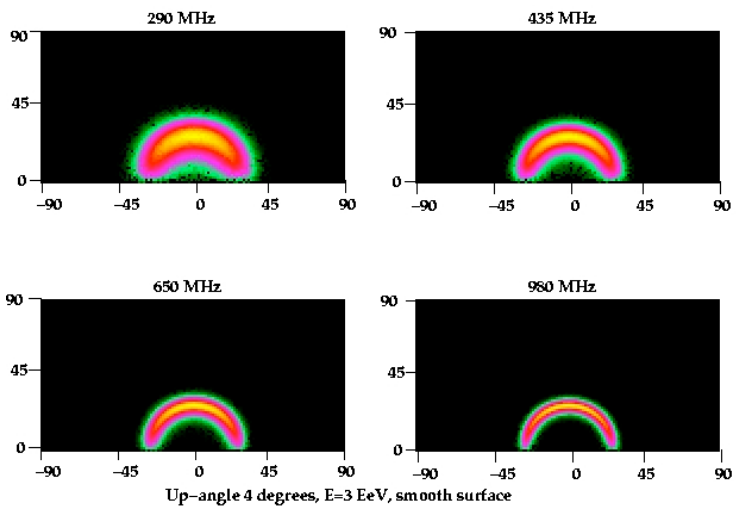


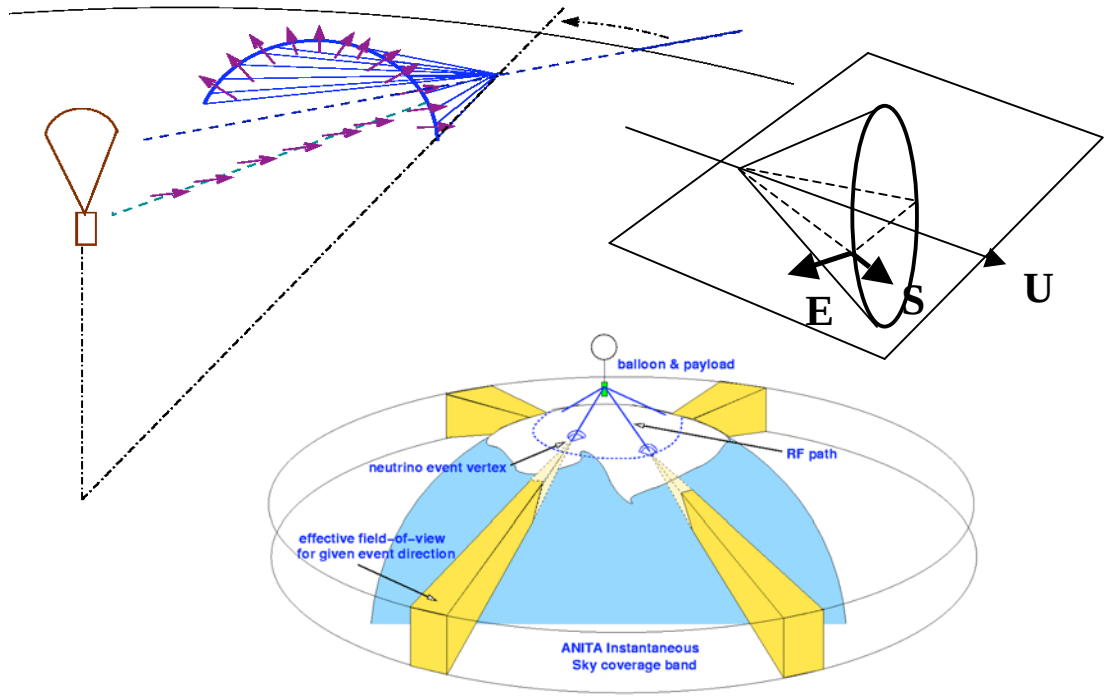
After full calibration – 250 km downrange

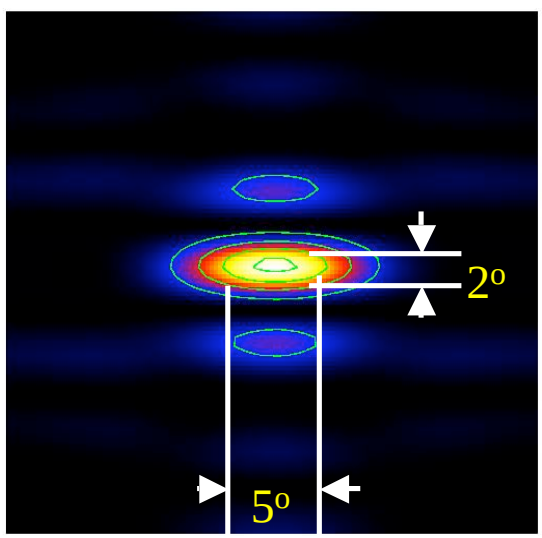


A. Romero-Wolf

ANITA as a neutrino telescope
-- Initial Guesstimates

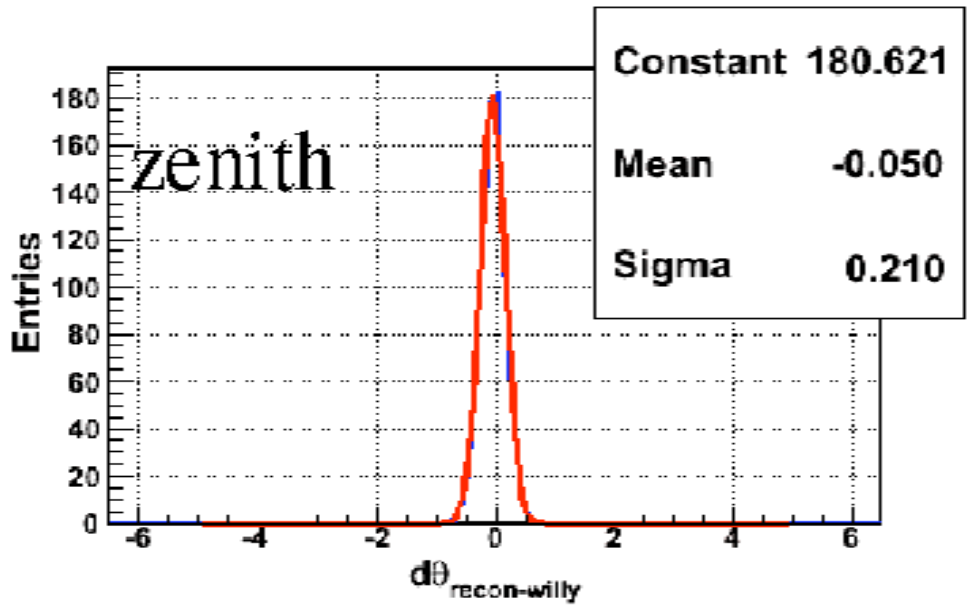


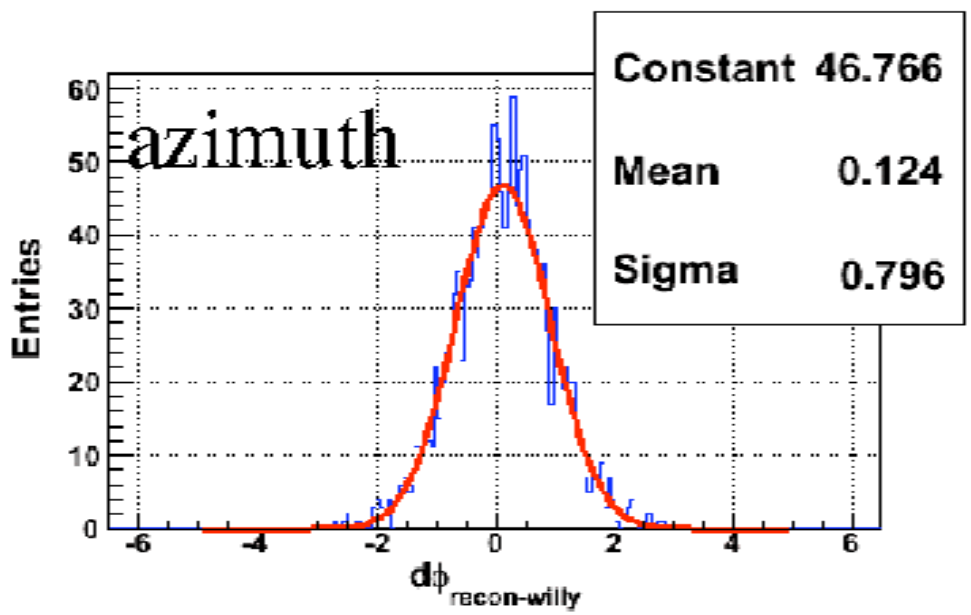




- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival direction** of radio pulse
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

Event Resolution – Borehore Pulser Reconstruction

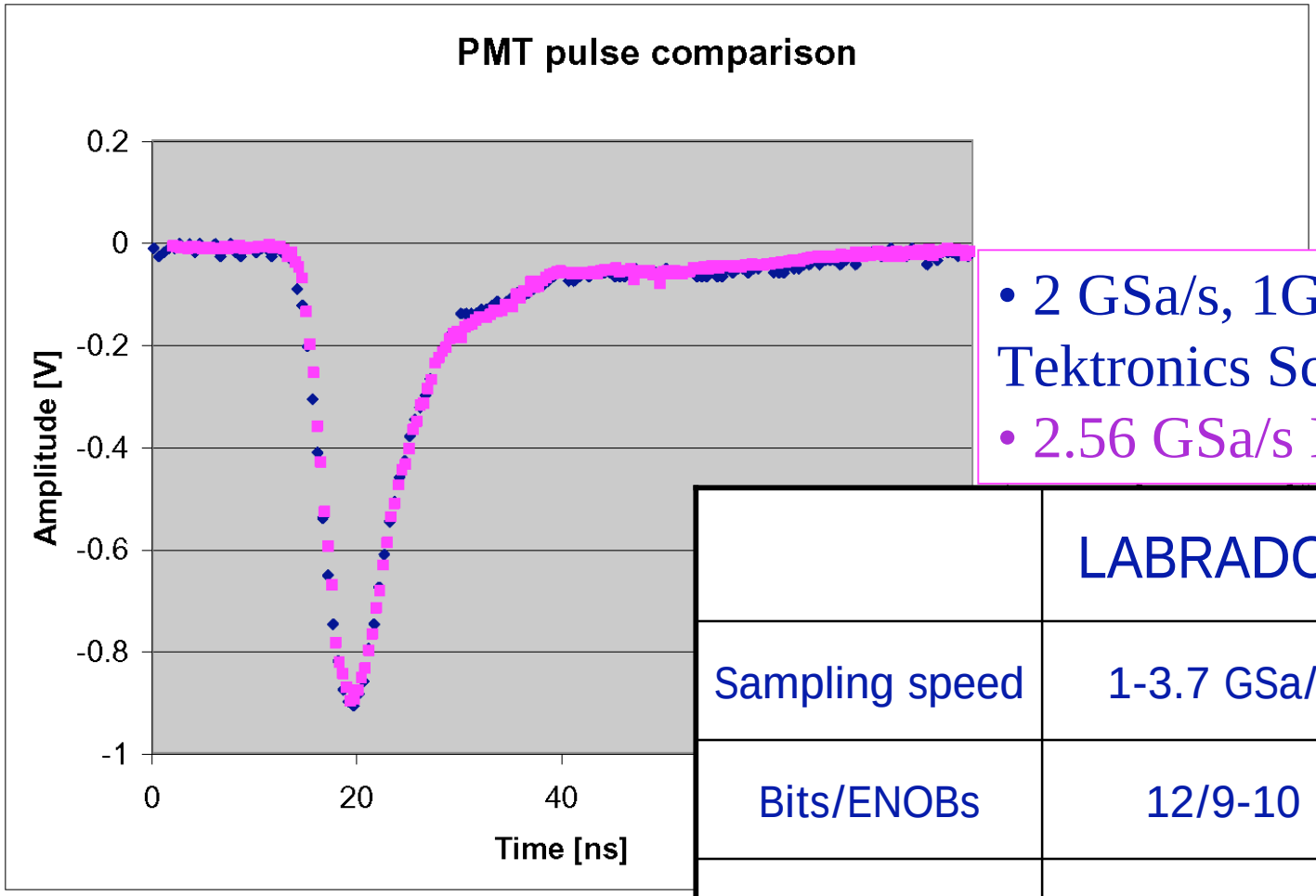




- Better than design specification
- << 1 degree inclination angle
- < 1 degree azimuth
- Likely to be physics (not electronics) limited

[J. Nam – UCI]

High Speed sampling – Other Applications

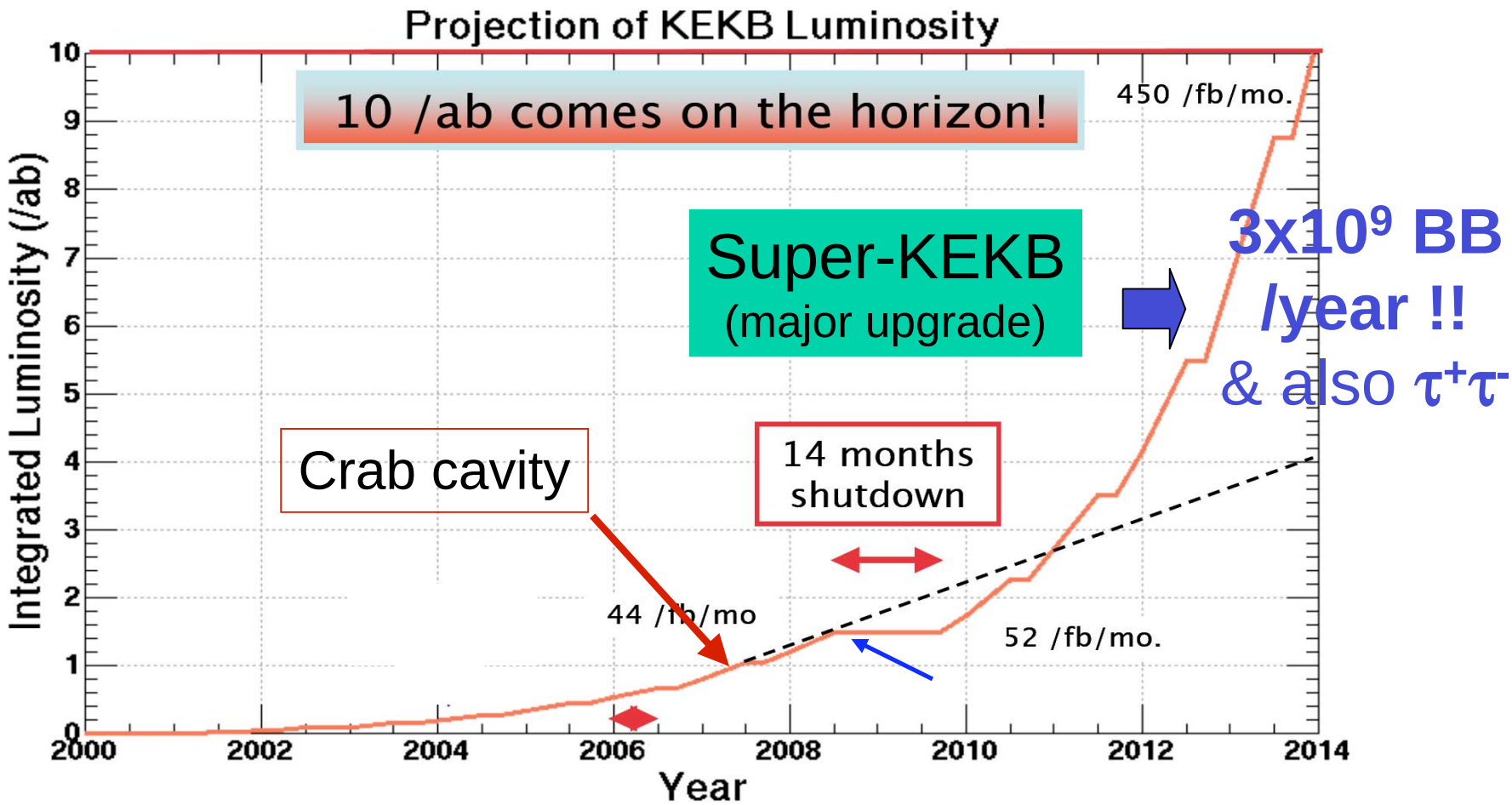


- 2 GSa/s, 1GHz ABW Tektronics Scope
- 2.56 GSa/s LAB

	LABRADOR	Commercial
Sampling speed	1-3.7 GSa/s	2 GSa/s
Bits/ENOBs	12/9-10	8/7.4
Power/Chan.	<= 0.05W	5-10W
Cost/Ch.	$10	> 1k$

KEKB Upgrade Scenario

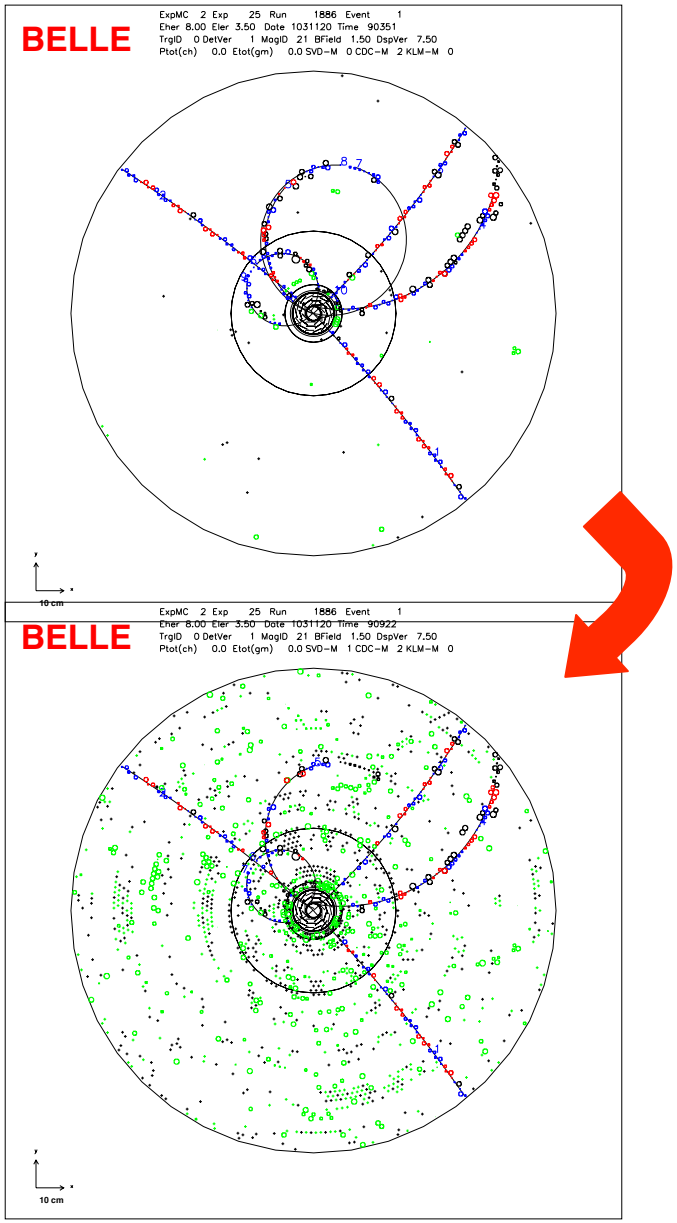
L_{peak} ($cm^{-2}s^{-1}$)	1.6×10^{34}	5×10^{34}	5×10^{35}
L_{int}	467 fb^{-1}	1 ab^{-1}	10 ab^{-1}



Requirements for the detector

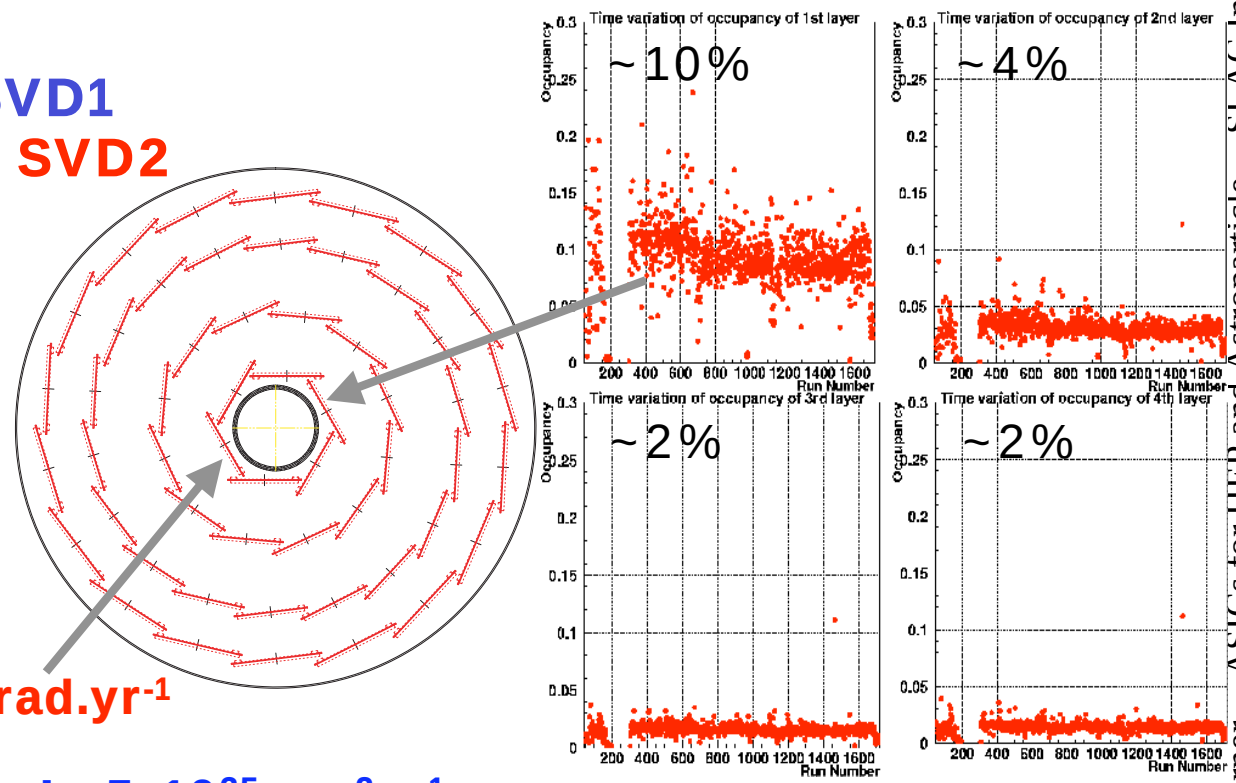
Issues

- **Higher background (×20-50)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low p μ identification ← sμμ recon. eff.
  - hermeticity ← ν "reconstruction"



Occupancy in Silicon Vertex Detector

152M $B\bar{B}$ pairs with SVD1
+ ~550M $B\bar{B}$ pairs with SVD2



Present : layer 1 of SVD

~10% occupancy / 200 Krad.yr^{-1}

Upgrade: L~1.7x10^{34} → L~5x10^{35} cm^{-2}.s^{-1}

Background increase typ. X20-50, w/large uncertainties → Occupancy / dose

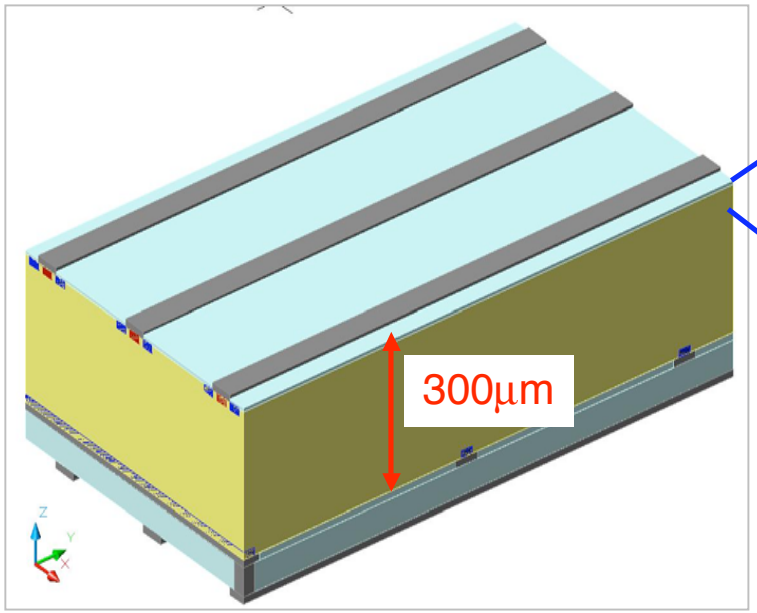
Conventional solutions (Si strips) do not work

Pixel Occupancy Scaling

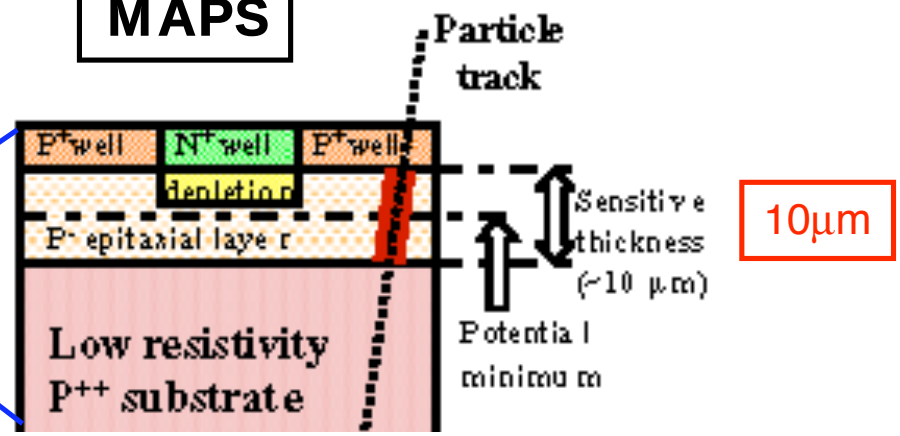
- Work from following assumptions:
  - Super-B canonical x20 background increase
    - Assume 10% Layer 1 occupancy as "current"
    - Strip area (L1) = 85mm x 50μm = 4.25M μm^2
  - Pixel spatial reduction:
    - Pixel area = 22.5μm x 22.5μm = 506 μm^2
    - Reduction factor ~8400
    - Low E γ, reduced cross-section (~3% active thickness)
  - Pixel temporal loss:
    - 0.8μs SVD vs. 10μs PVD (could be improved)
    - Increase factor ~ 12.5
  - Grand total:
    - 10% * 20 * 8400^{-1} * 12.5
    - Can expect ~ 0.3% occupancy (no ghosting)

Monolithic Active Pixel Sensor

Current DSSD



MAPS

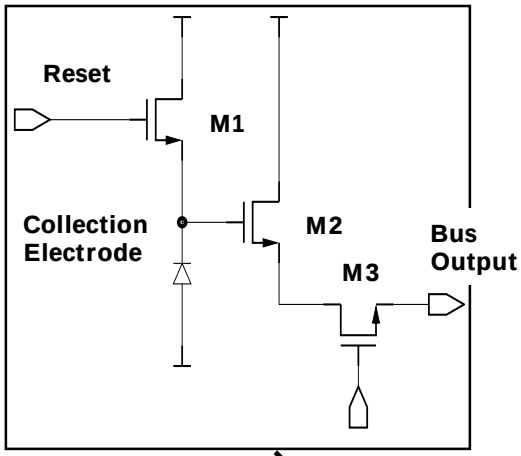


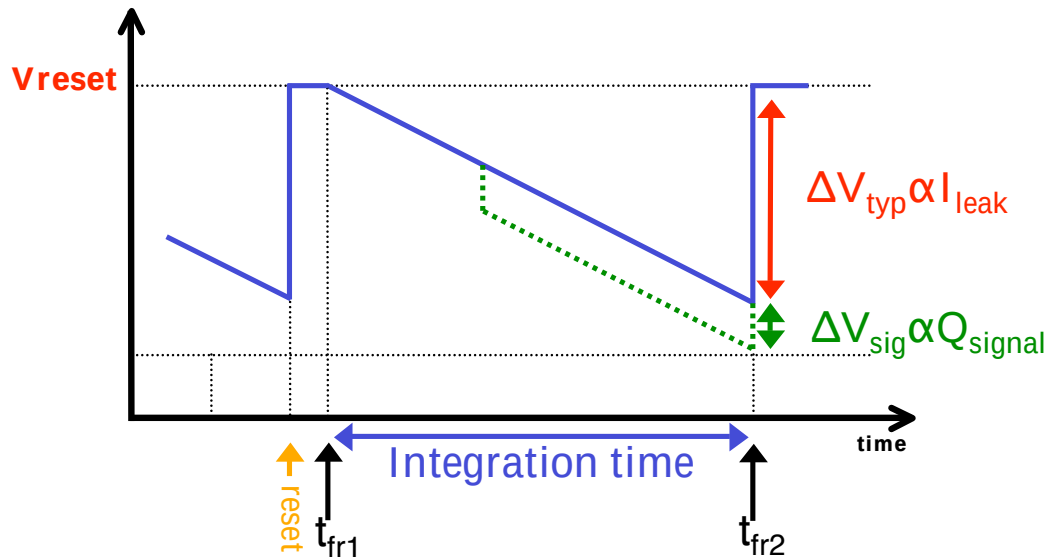
Because of large Capacitance, need Thick DSSDs -- APS can be VERY Thin

Key Features:

- Thin
  - **reduced multiple-scattering, γ conversion, background γ target**
- **NO bump bonding – fine pitch possible (8000x reduction)**
- **Standard CMOS process "System on Chip" possible**

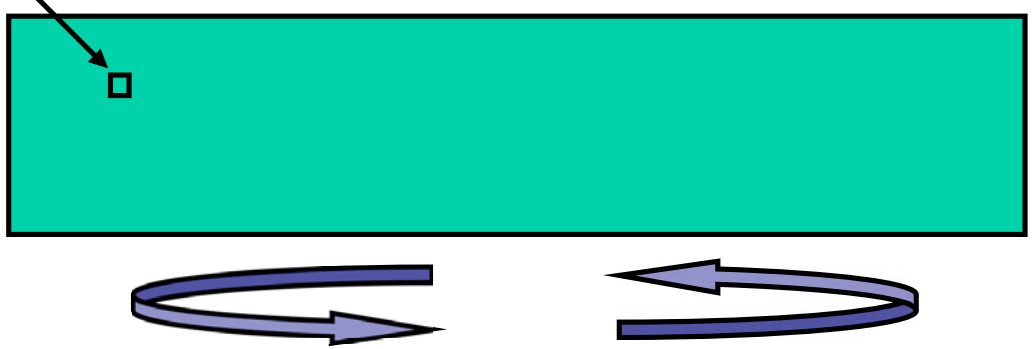
Continuous Acquisition Pixel (CAP)





Pixel

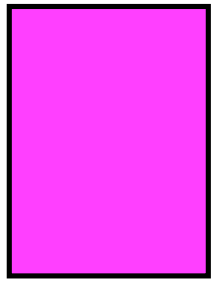
Array of 132x48 pixels



High-speed

analog

ADC



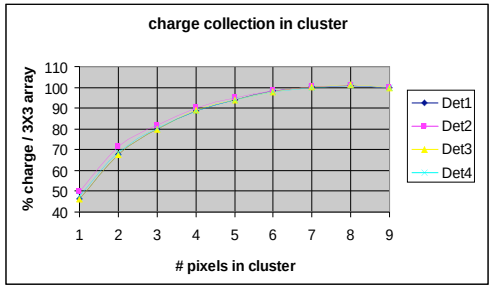
& storage

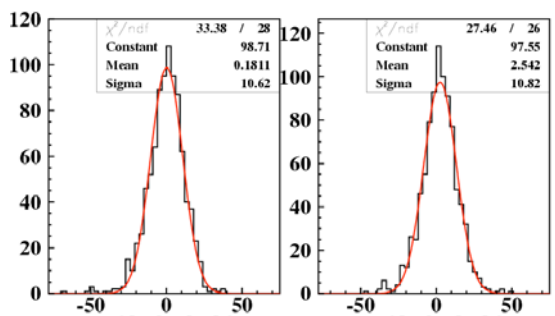
Pixel Array: Column select – ganged row read

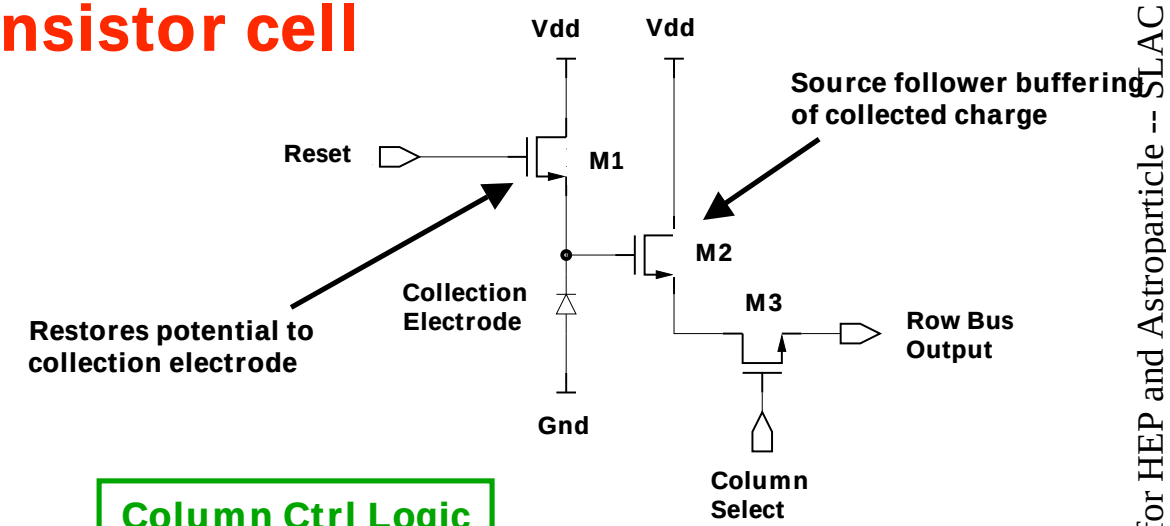
Low power – only significant draw at readout edge

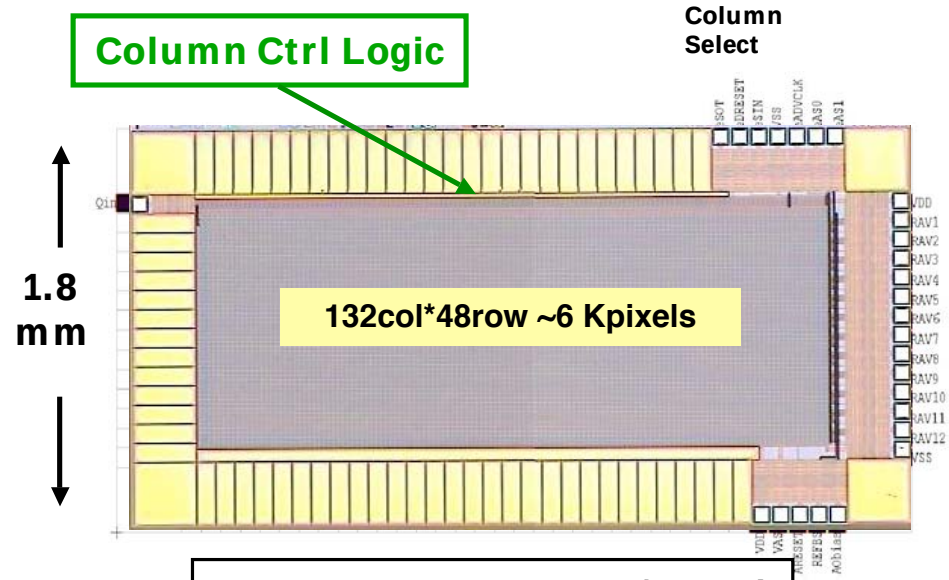
Cont. Acq. Pixels (CAP) 1 Prototype

CAP1: simple 3-transistor cell









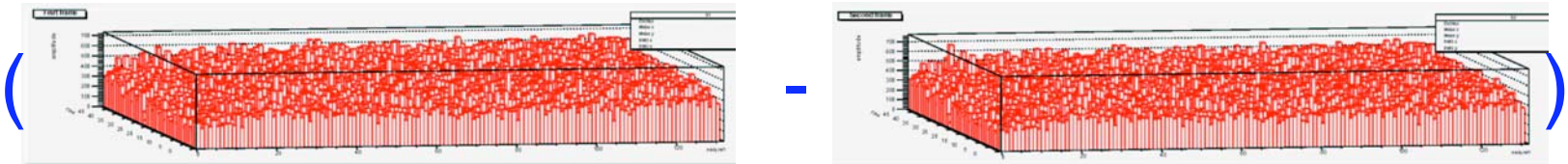
Pixel size:

22.5 μm x 22.5 μm

CAPs sample tested: all detectors (>15) function.

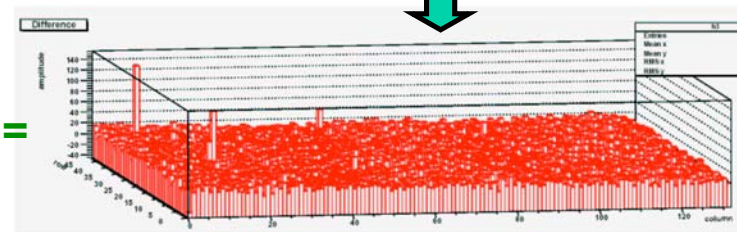
NIM A541:166-171 (2005)

Correlated Double Sampling (CDS)

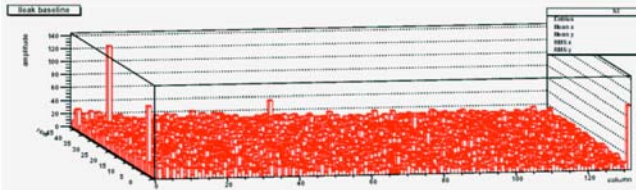


8ms integration

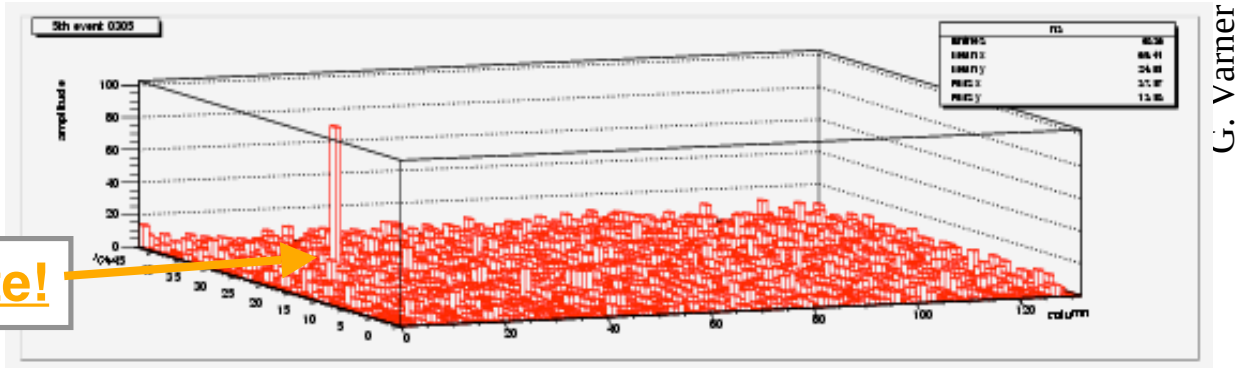
Frame 1 - Frame 2 =



- Leakage current Correction



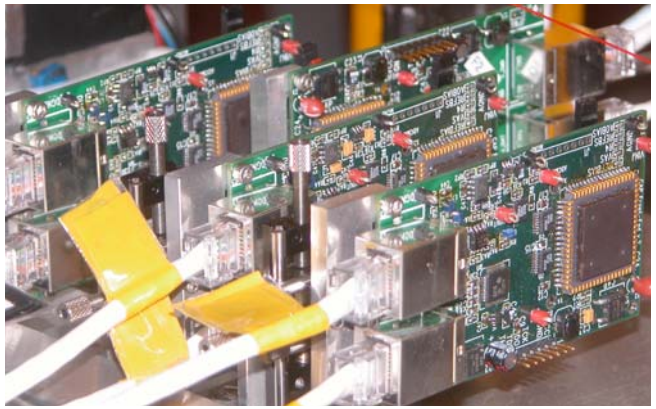
~fA leakage current (typ)
~18fA for hottest pixel shown

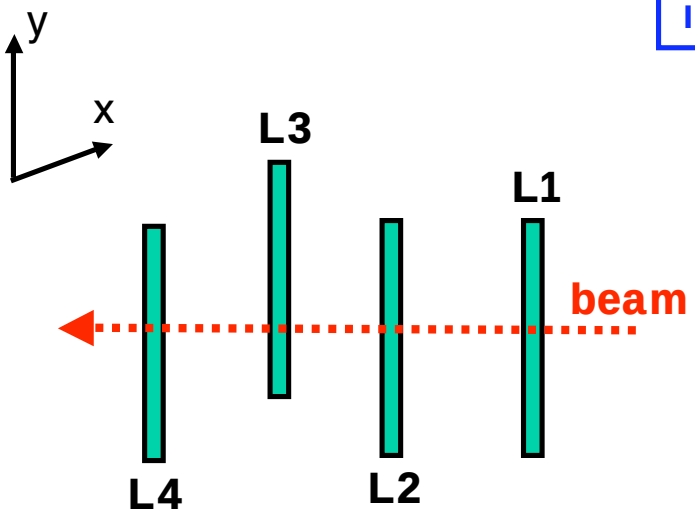


Hit candidate!

Mechanical alignment

~1mm x 3mm "rice grain"

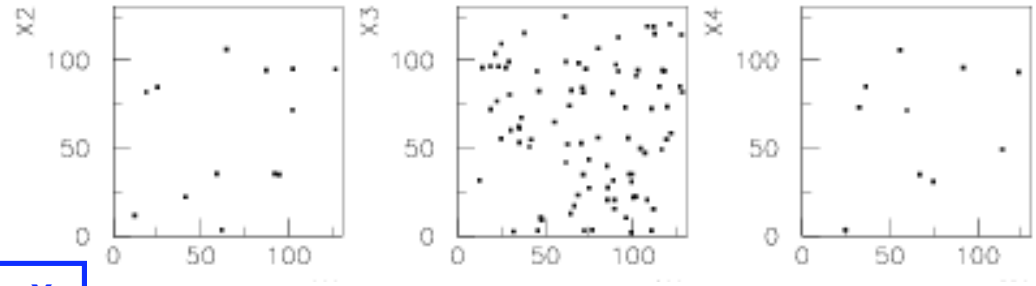




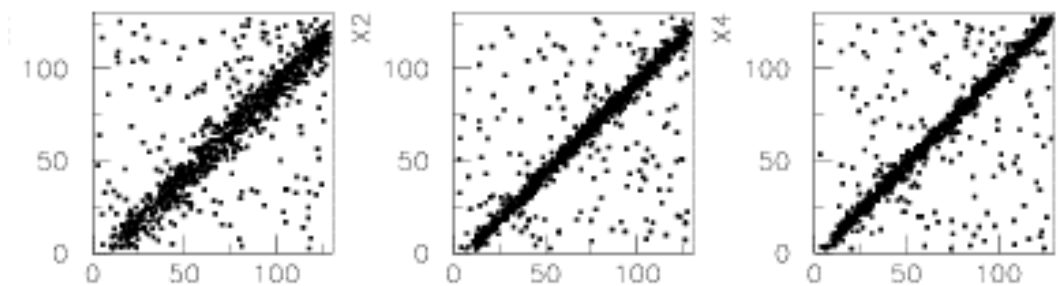
Initial Det. /Det. correlations

Det.3 vs. Det.1 **Det.3 vs. Det.2** **Det.3 vs. Det.4**

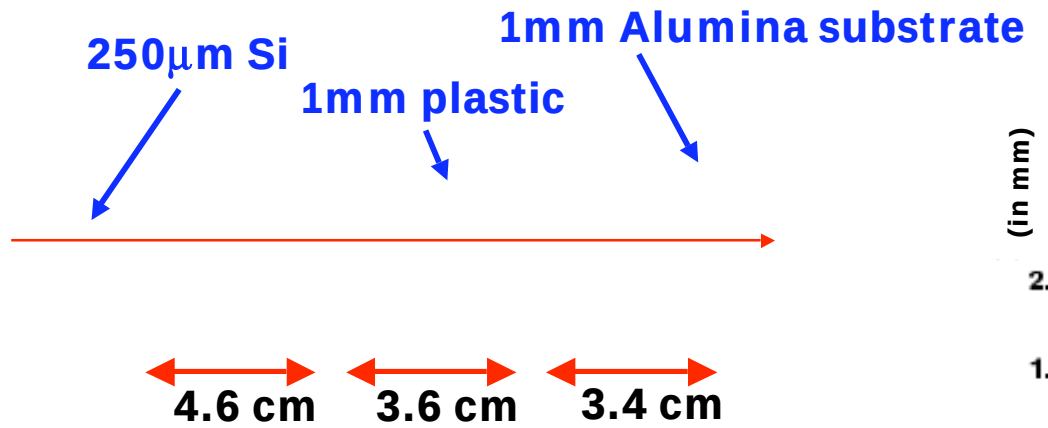
In X

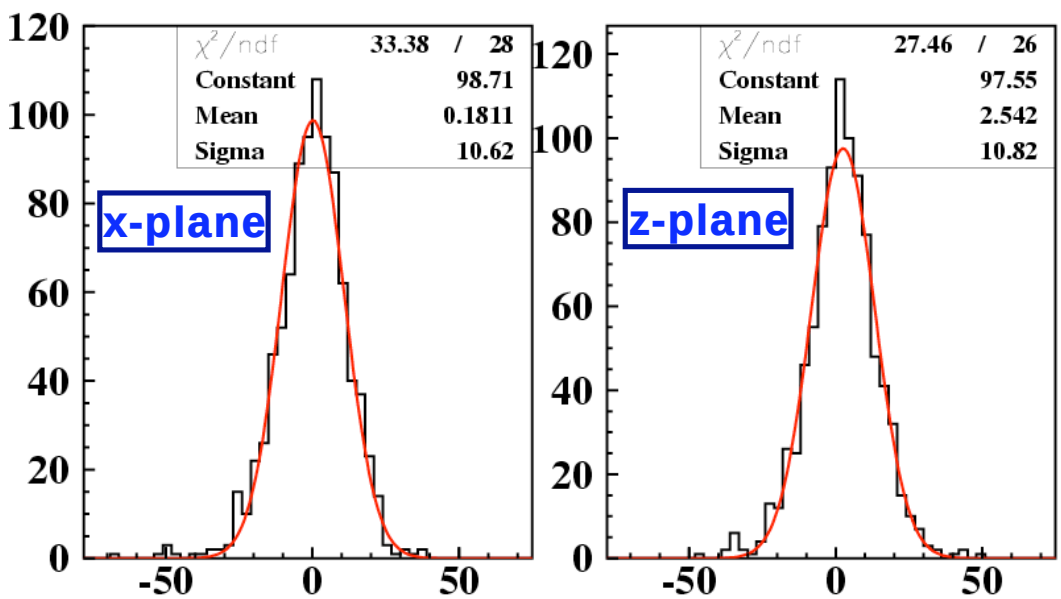


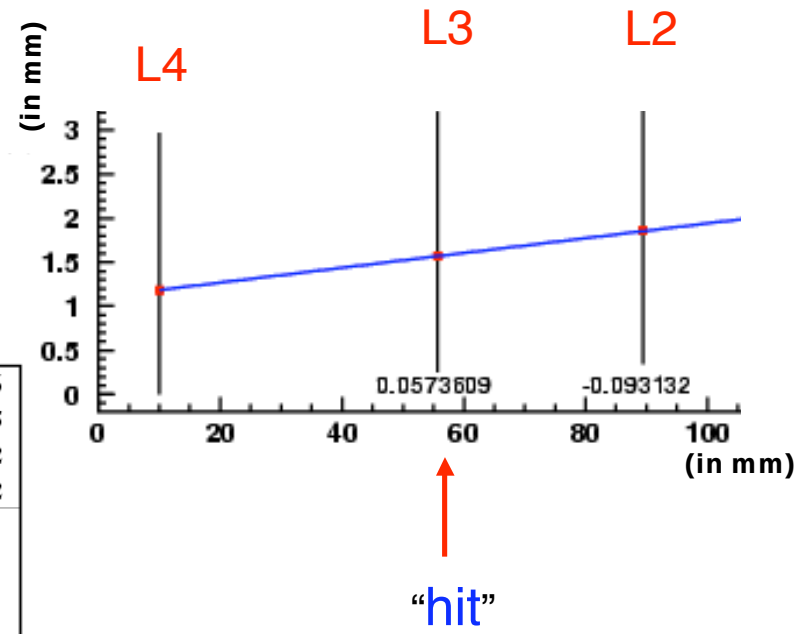
Improved correlations



Hit resolution measurement

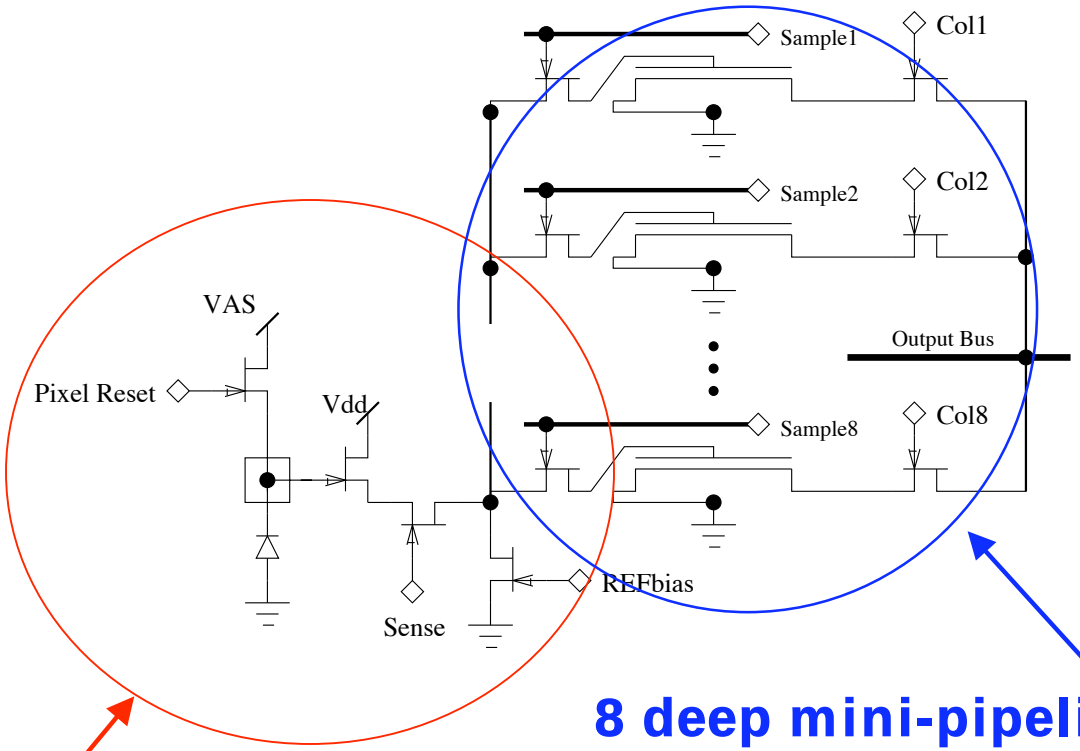






Residuals for 4GeV/c pions:
- **<11μm (in both planes)**

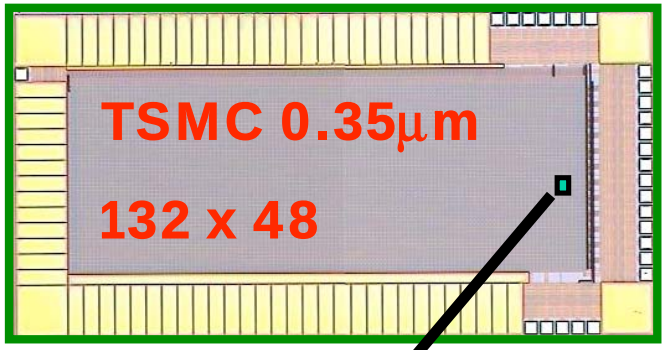
CAP2 – Pipelined operation

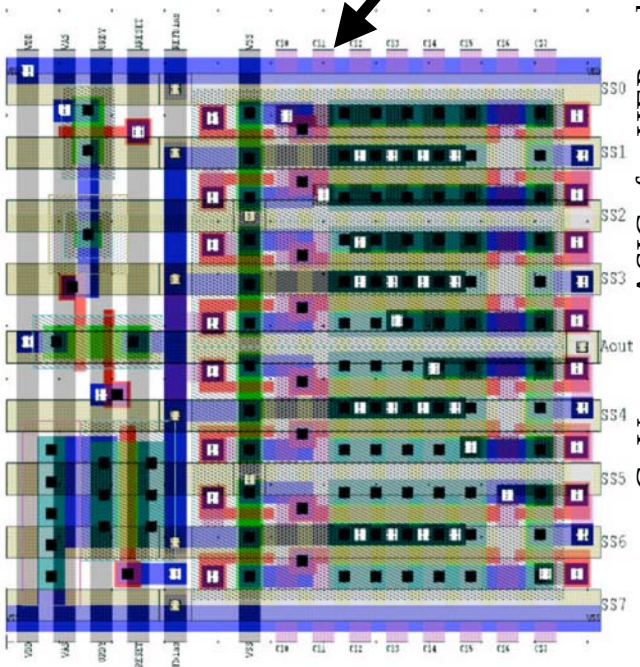


3-transistor cell

8 deep mini-pipeline in each cell

132x48=6336 channels 50688 samples





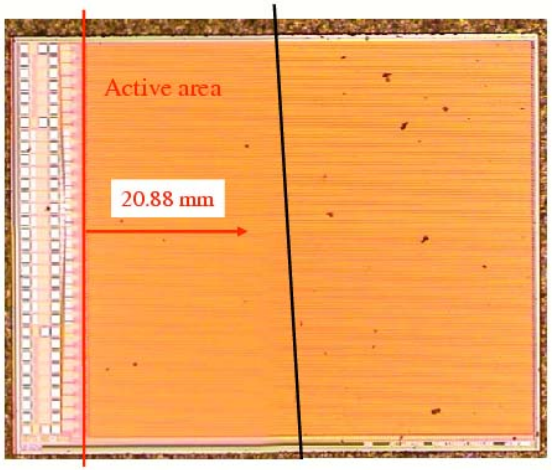
Pixel size 22.5 µm x 22.5 µm

10µs frame acquisition speed achieved!

[IEEE Trans.Nucl.Sci.**52** (2005) 1187]

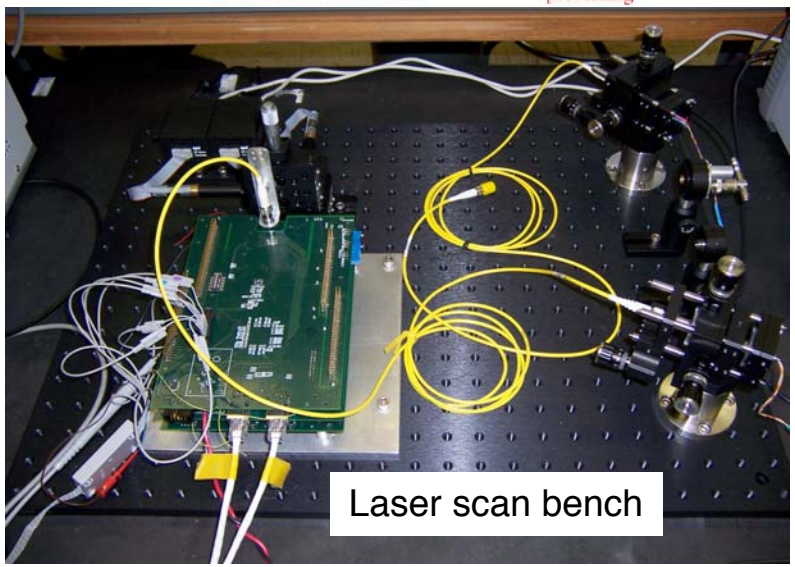
CAP3: Full-size Detector Test/Lessons learned

928 x 128 pixels = 118,784

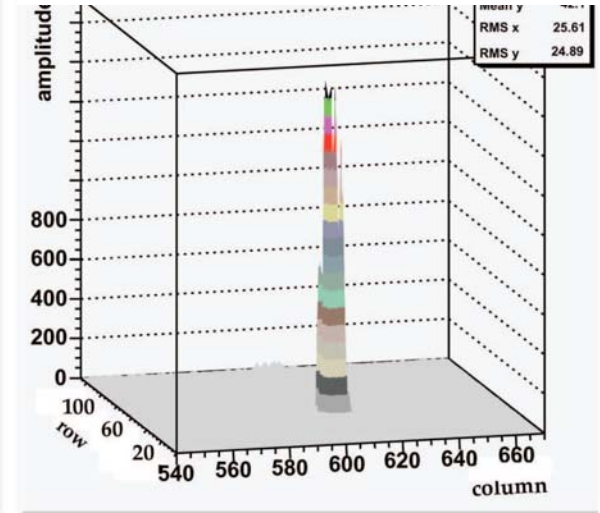


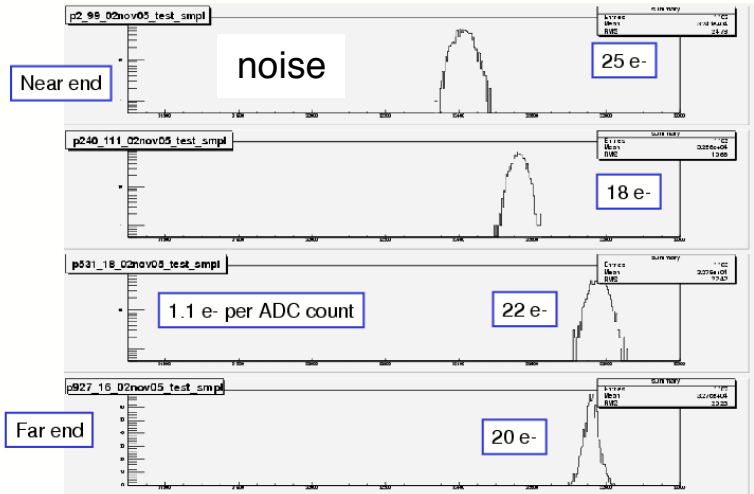
~4.3M transistors

>93% active without active edge processing



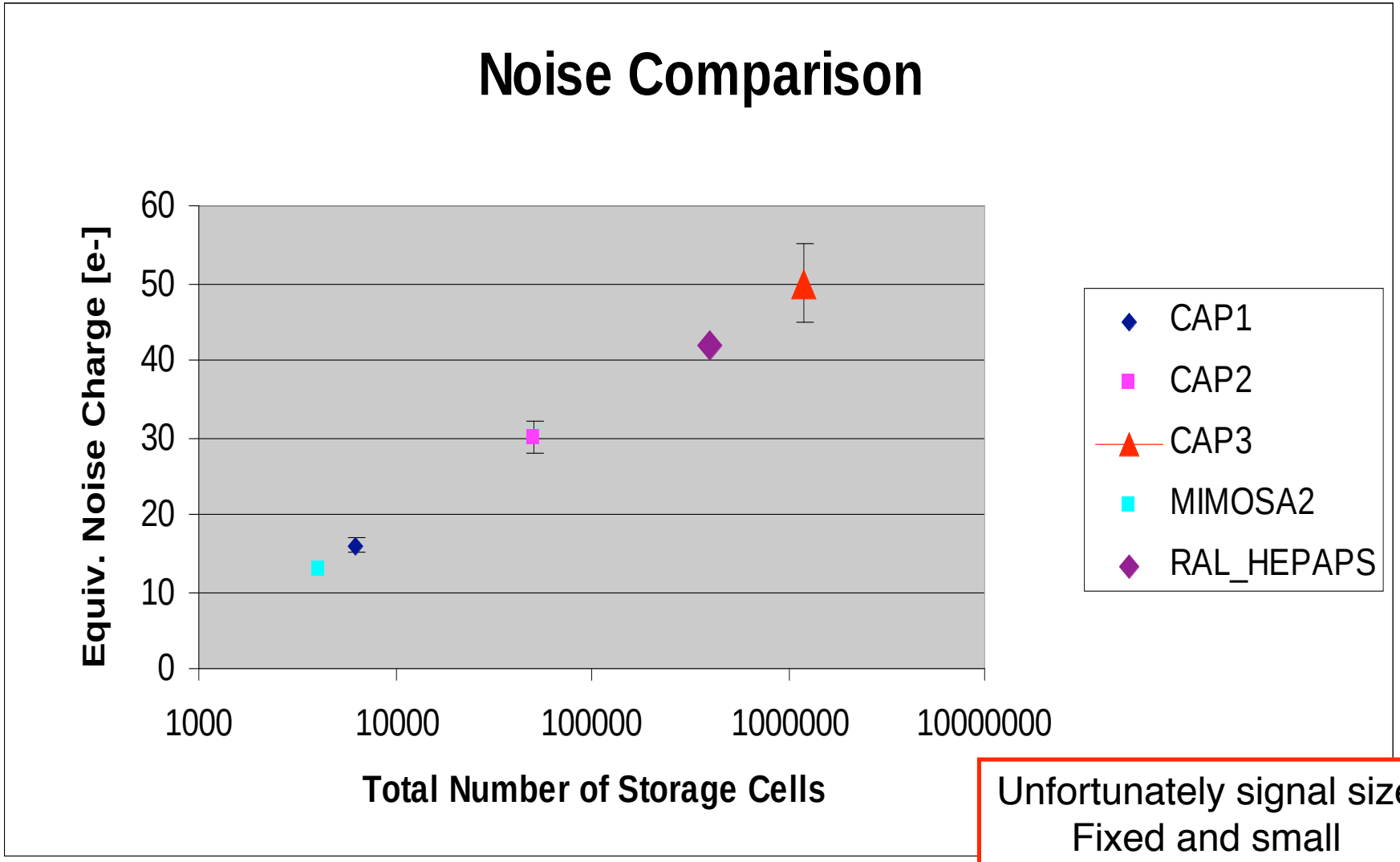
Laser spot (backside illumination)





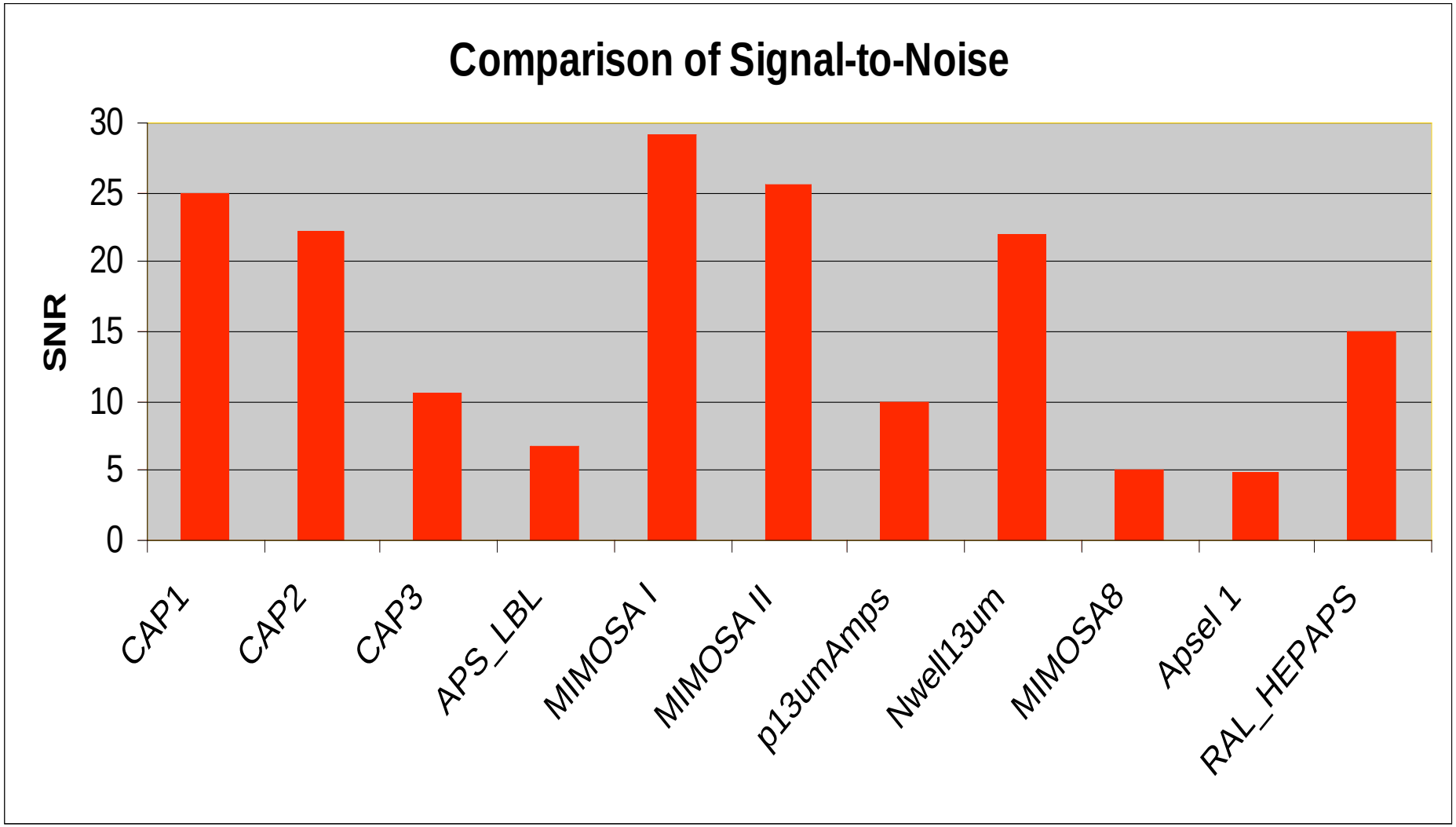
CAP3: Laser Scan

Noise (ENC): Summary of MAPS



Unfortunately signal size
Fixed and small

SNR: Summary of Efforts



CMOS Pixel Back-thinning (Battaglia *et al* LBL)

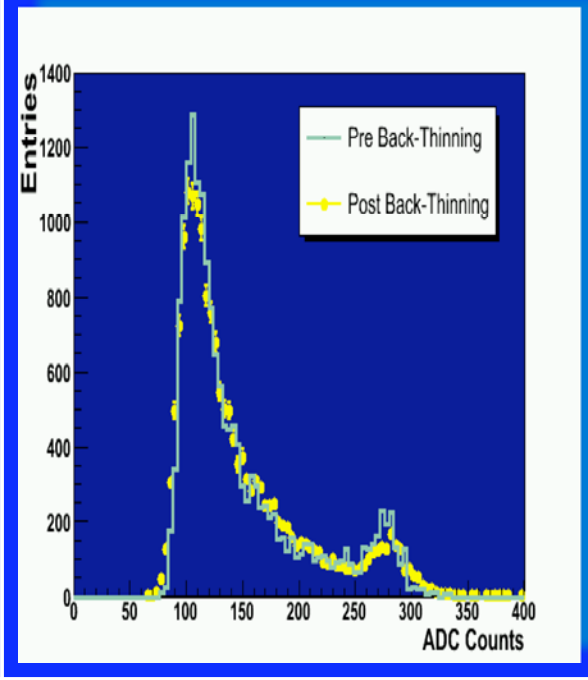
Program of back-thinning of diced chips using grinding process by APTEK;

Thinned over 15 chips,
yield of functional chips~90%,
Process reliable down to 40 μm
Measured thickness of chips:

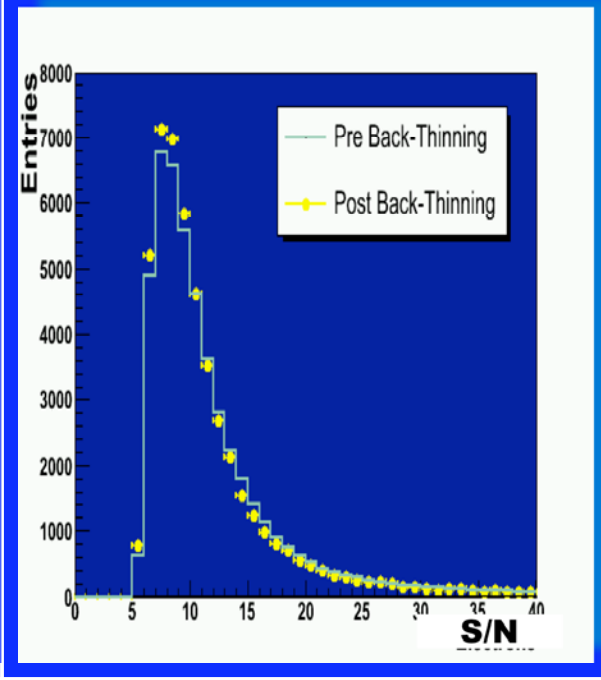
Before	550 ± 0.5
"50 μm"	50 ± 7
"40 μm"	41 ± 6

Study change in charge collection and S/N before/after back-thinning: MIMOSA 5 sensors (1 M pixels, 17 μm, 18x18 mm² surface, AMS 0.6)

^{55}Fe
Determine chip gain and S/N for 5.9 keV X rays

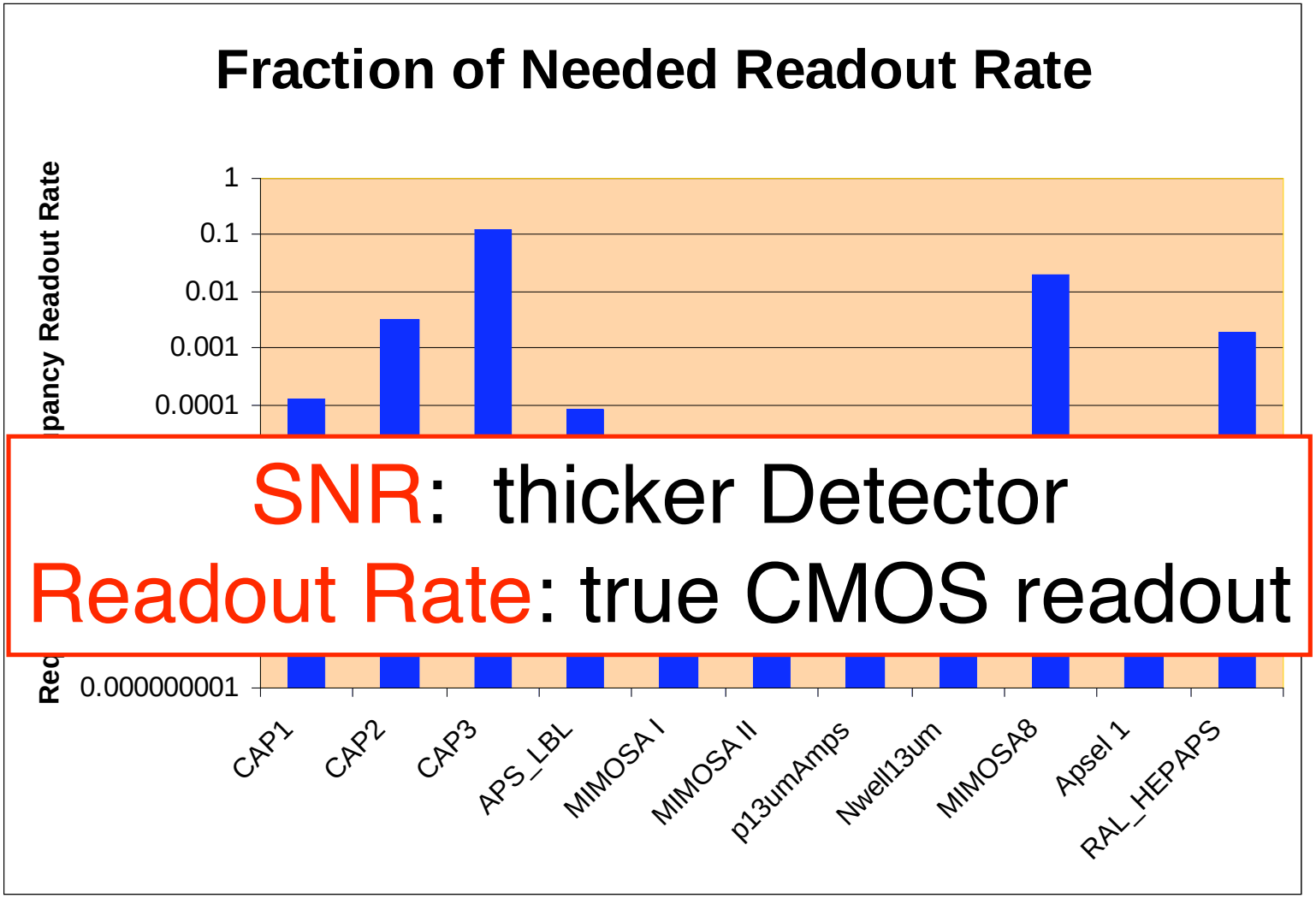


1.5 GeV e⁻ beam
Determine S/N and cluster size for m.i.p.



Feasibility of Back-thinning CMOS sensors demonstrated

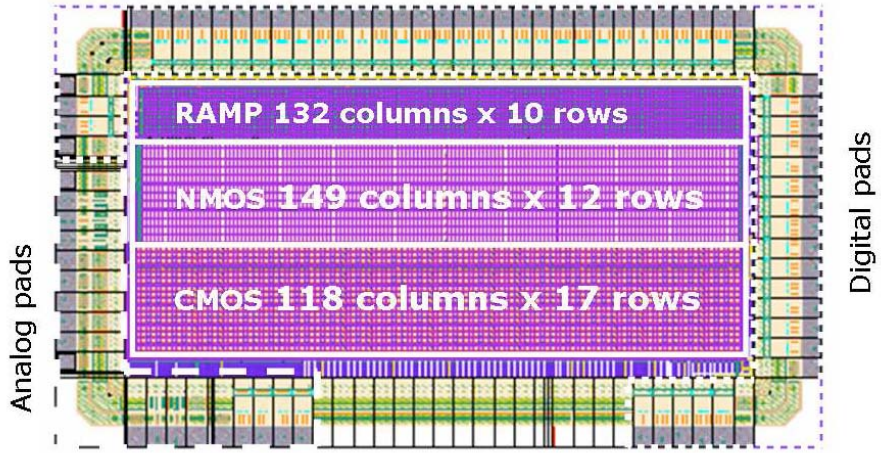
Readout Rate: Summary of Efforts

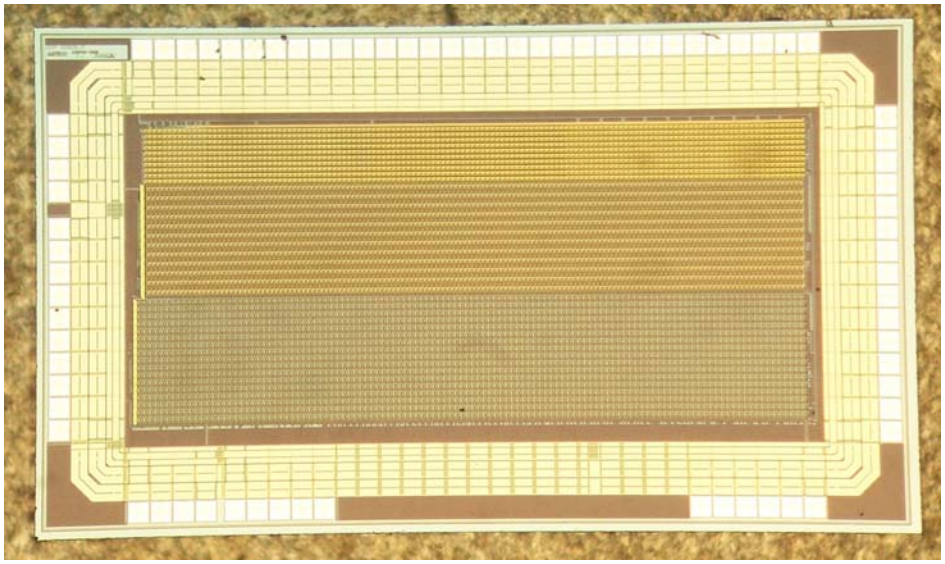


SNR: thicker Detector

Readout Rate: true CMOS readout

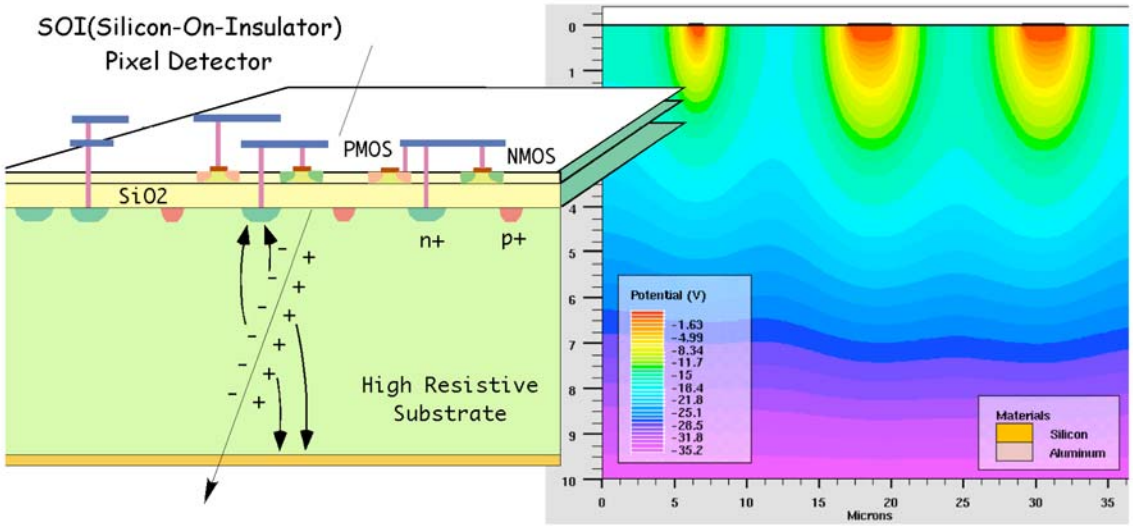
CAP4: 3 architectures in AMS 0.35um Opto

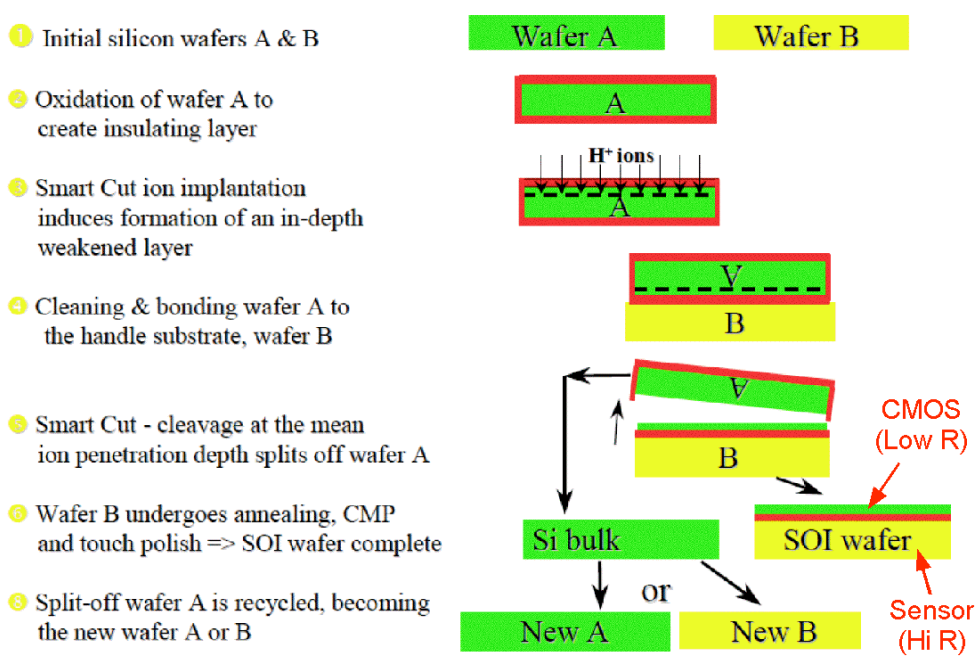




- Four different architectures
  - Wilkinson Ramp transfer encoding
  - Mostly NMOS space-time encoding scheme (modest charge collection loss)
  - CMOS space-time encoding scheme (large collection efficiency loss)
- Evaluations
  - Speed
  - Uniformity
  - Evaluate space-time technique
- Will apply lessons learned
  - Next SOI run (CAP6/LCAP1)

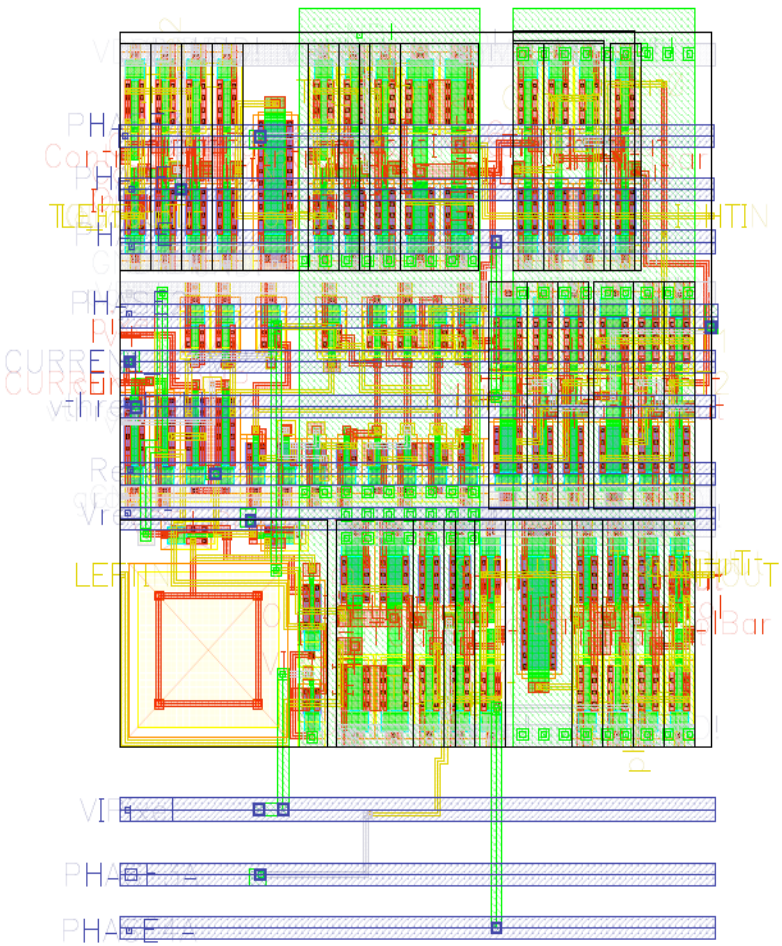
OKI 0.15um SOI



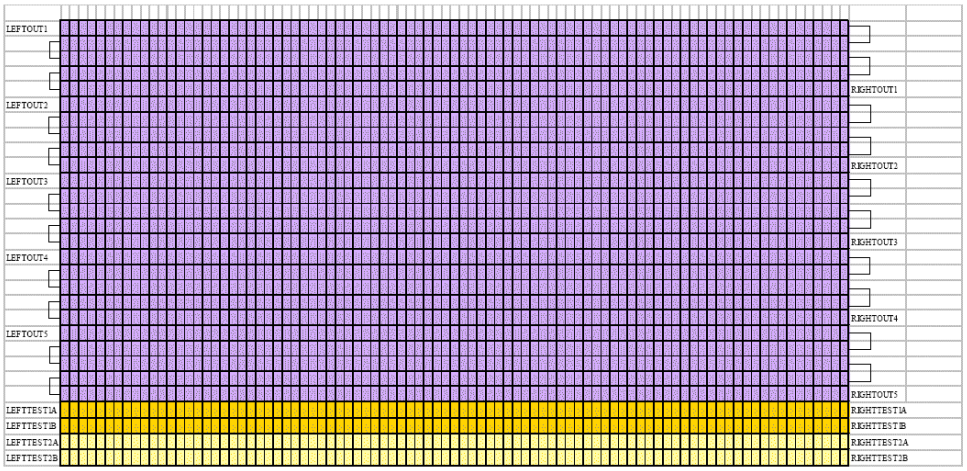


- Best of both worlds
  - High resistivity, fully depleted detector (large signal)
  - Excellent deep submicron CMOS
- Wafer bonding
  - No bump bonding interconnects
  - Very low collection electrode capacitance
- Rad hardness
  - SOI known to be rad-hard

CAP5



- 108 x 34 pixels total structure (28.7 μm by 32.5 μm)
- 6 row testing structures introduced
- Use of CMOS circuits for all structures

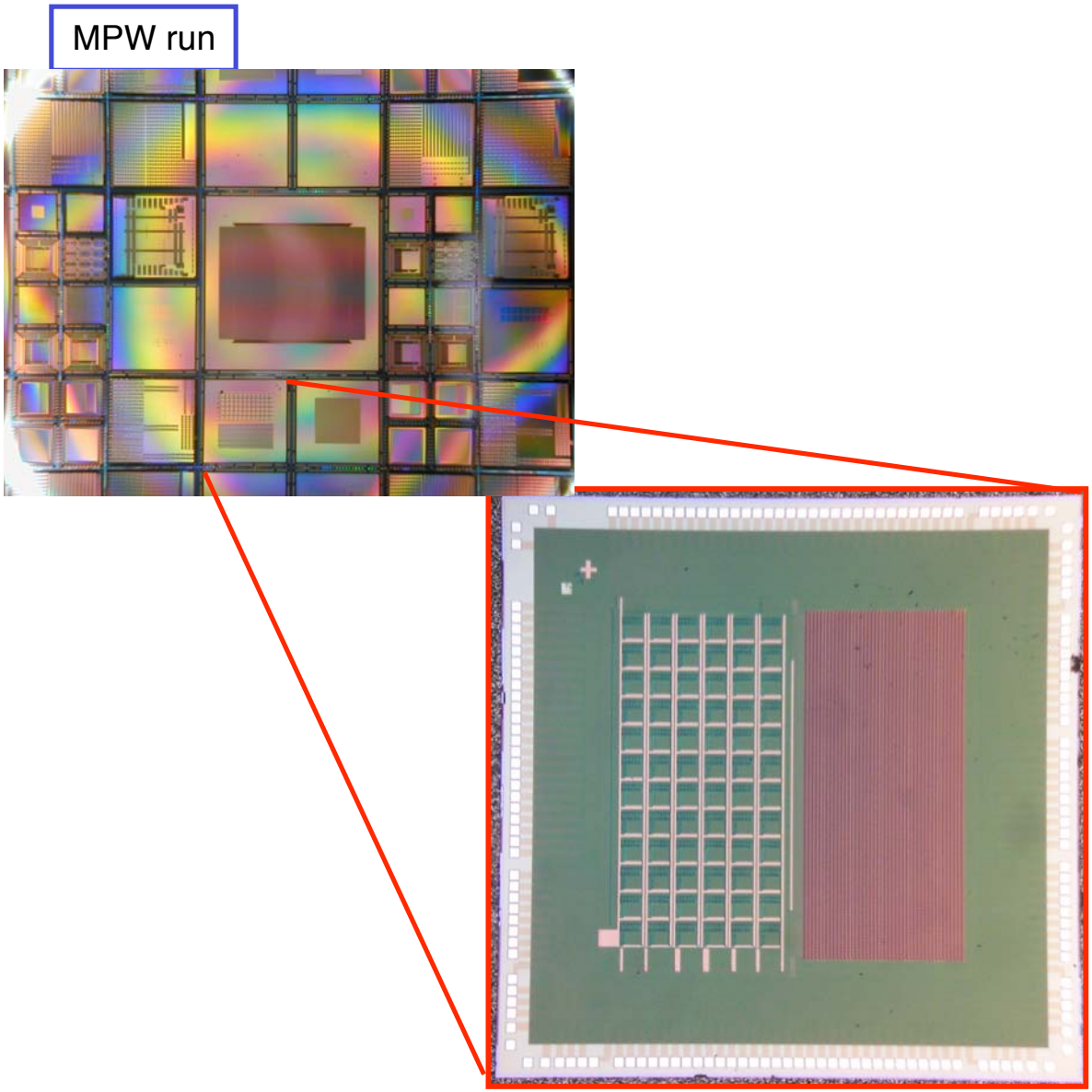


$$v_{noise} = \sqrt{\frac{kT}{C}}$$

$$v_{noise\_Electrode} = 0.822mV$$

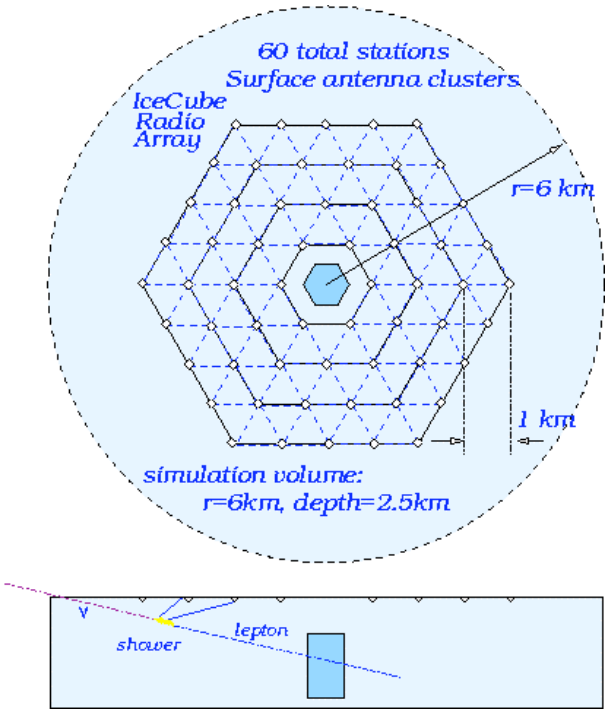
$$\Delta V = \frac{\Delta Q(1\mu s)}{C} = 0.151V$$

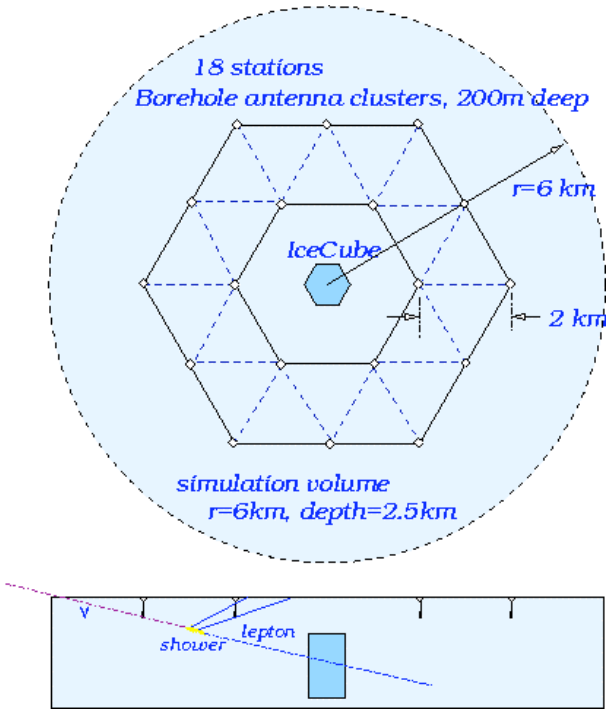
CAP5: 2nd iteration in OKI 0.15um SOI



- First submission
  - Promise of better S, same N → better SNR
  - Many other groups (FNAL/BNL & LBL) subsequently join
- Second submission
  - 4x larger die
  - Study process spread
  - Evaluate space-time correlation
- Will apply lessons learned
  - Next SOI run (0.2um)
  - Thin devices to be proven

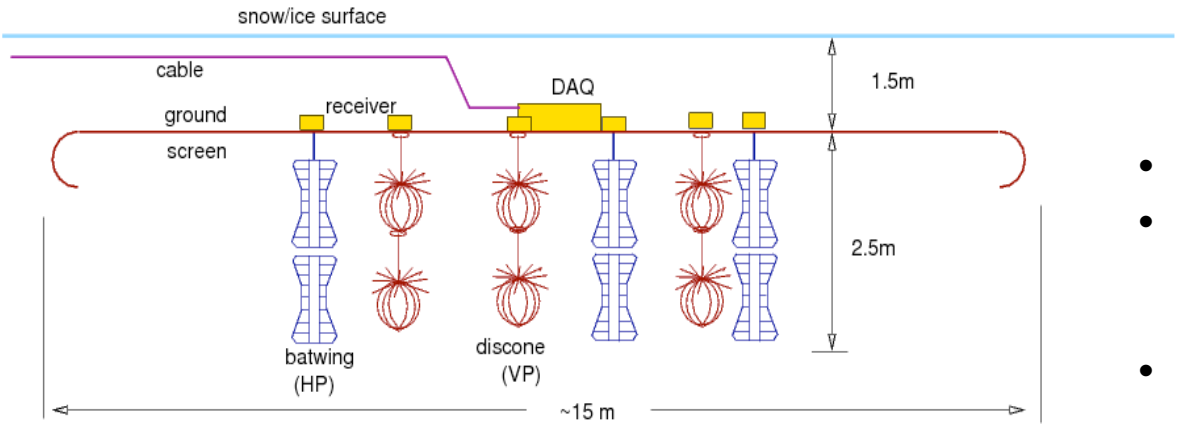
An IceCube UHE Radio Augmentation

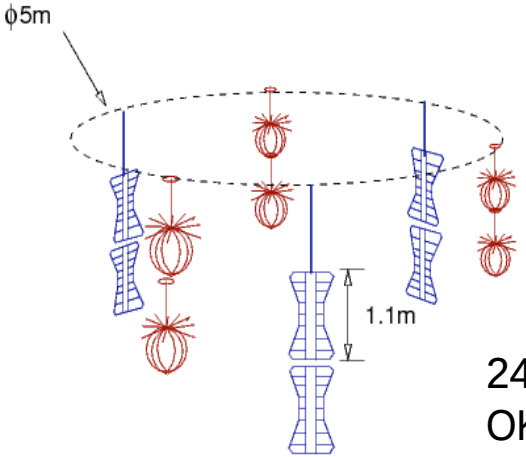




- GZK neutrinos ($10^{17\text{-}19.5}$ eV), at lowest possible cost
  - Surface or shallow submerged array (60 or ~20, costs similar?)
  - sparse, give up resolution for volume
- Hybrid events with IceCube
  - Primary vertex calorimetry in radio, HE muon or tau secondary in IceCube

Surface Station geometry
"mini ANITA" in ice

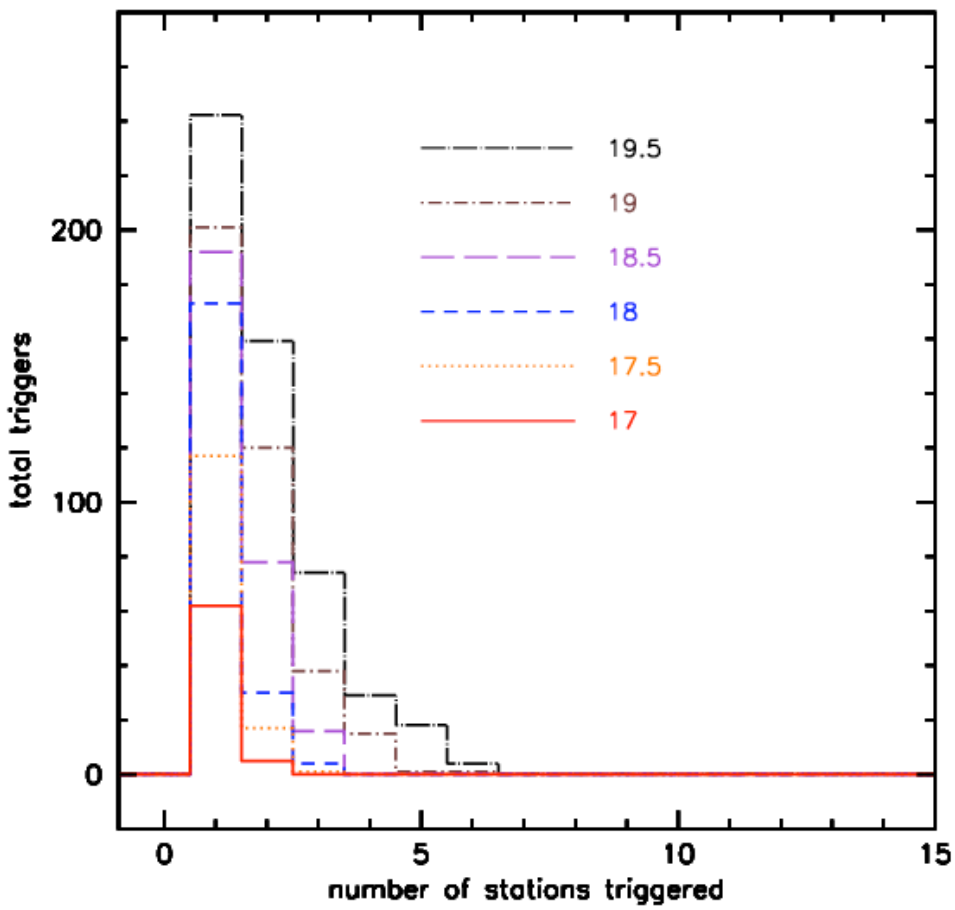




24" diam holes
OK for both antennas

- Propose 12+2 antennas
  - 6 V pol 6 Hpol
  - Discones for Vpol
  - Batwings for Hpol
  - 5 m circle
  - 2.5m depth below gnd screen
  - Stacked in pairs for vertical resolution
- 15m Cu mesh ground screen
- DAQ & receivers in shielded boxes ~1.5m depth just above screen
- Also:
  - 1 monitor antenna above screen, but ~1m deep still
  - Pulser bicone at ~15m away, in 24" augered hole, 2.5-3m deep

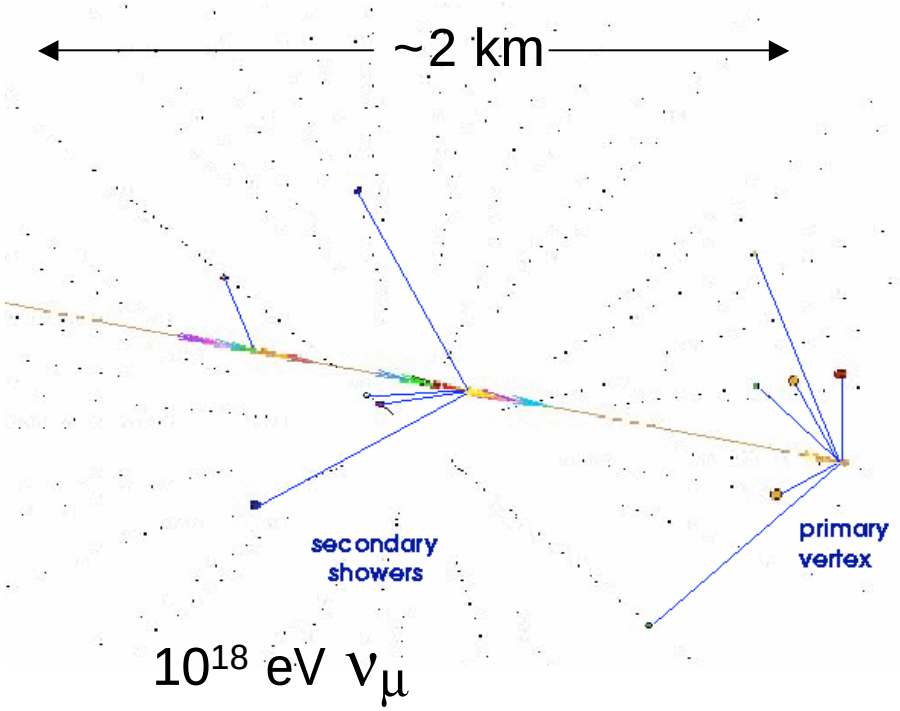
Station trigger multiplicity: IceRay



[P. Gorham – UH]

- At lower energies (<10^{18} eV) single station triggers dominate
  - ~10% 2-station hits for 10^{17}eV
  - ~60% by 3 x 10^{18}eV
- Higher energies, multiple stations triggers are common
  - Good stereo reconstruction on a subset of GZK neutrino events
- Actual 2nd station hits will be higher if all stations are latched on each trigger
  - Can look deeper into noise

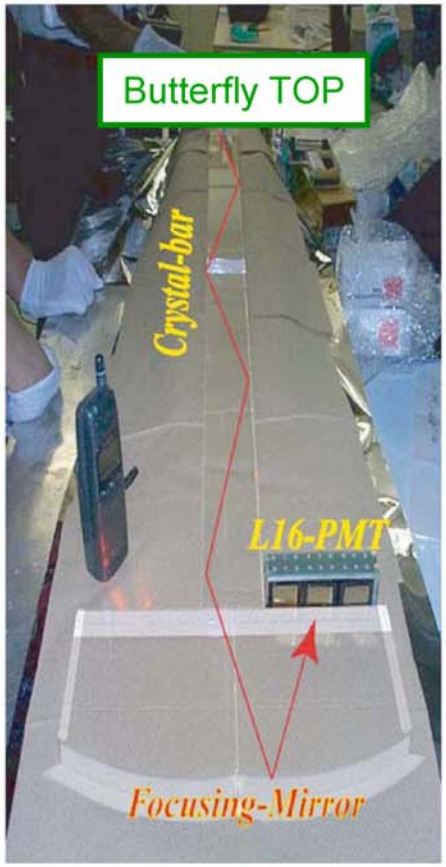
Particle ID – subthreshold detection

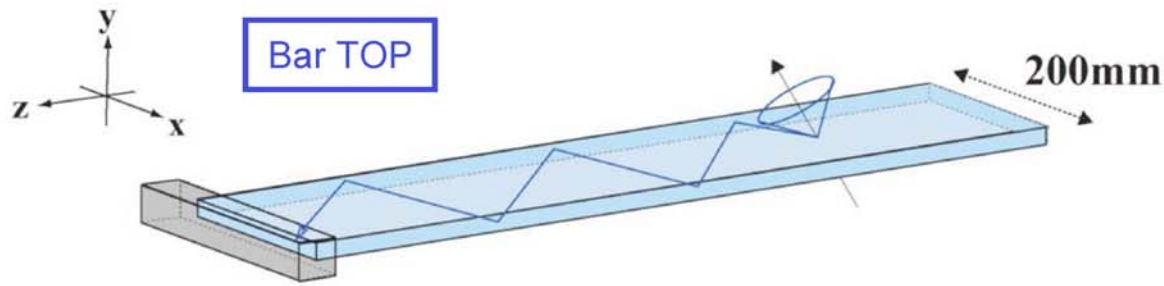


	Charged current (SM: 80%)	Neutral current (SM: 20%)
e	25% hadronic + 75% EM shower at primary vertex; LPM on EM shower	Single hadronic shower at vertex
μ	25% hadronic at primary, 2ndary lepton showers, mainly EM	Single hadronic shower at vertex
τ	25% hadronic at vertex, 2ndary lepton showers, mainly hadronic	Single hadronic shower at vertex

- Charged/neutral current & flavor ID enhanced with subthreshold samples
- Coincidence with optical (lower E threshold [PeV])
- Phased array – can push well down into the noise
- Challenge: for multi-k antenna array, multi-Terasamples/s

SuperB Barrel PID Upgrade





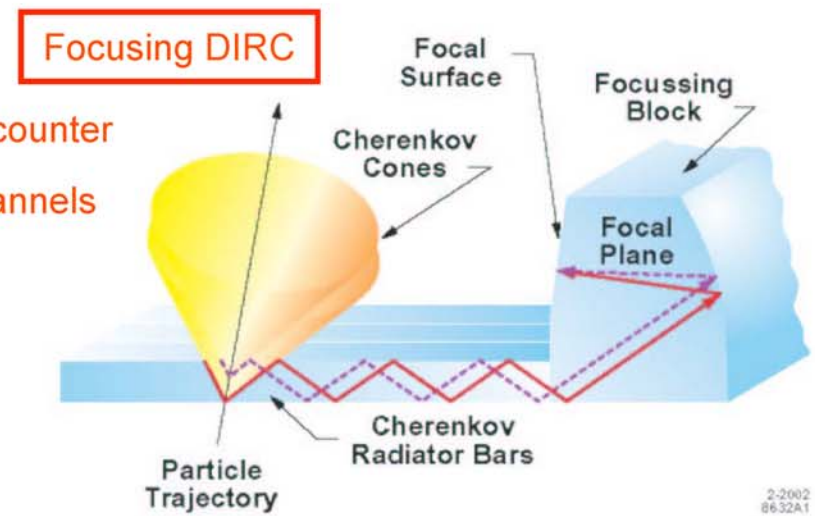
~5mm pos. resolution: 40 Ch/counter

*200 counters = 1440 channels

Multi-hit (hidden cost) >1440 channels

~few mm x few mm: few kCh/counter

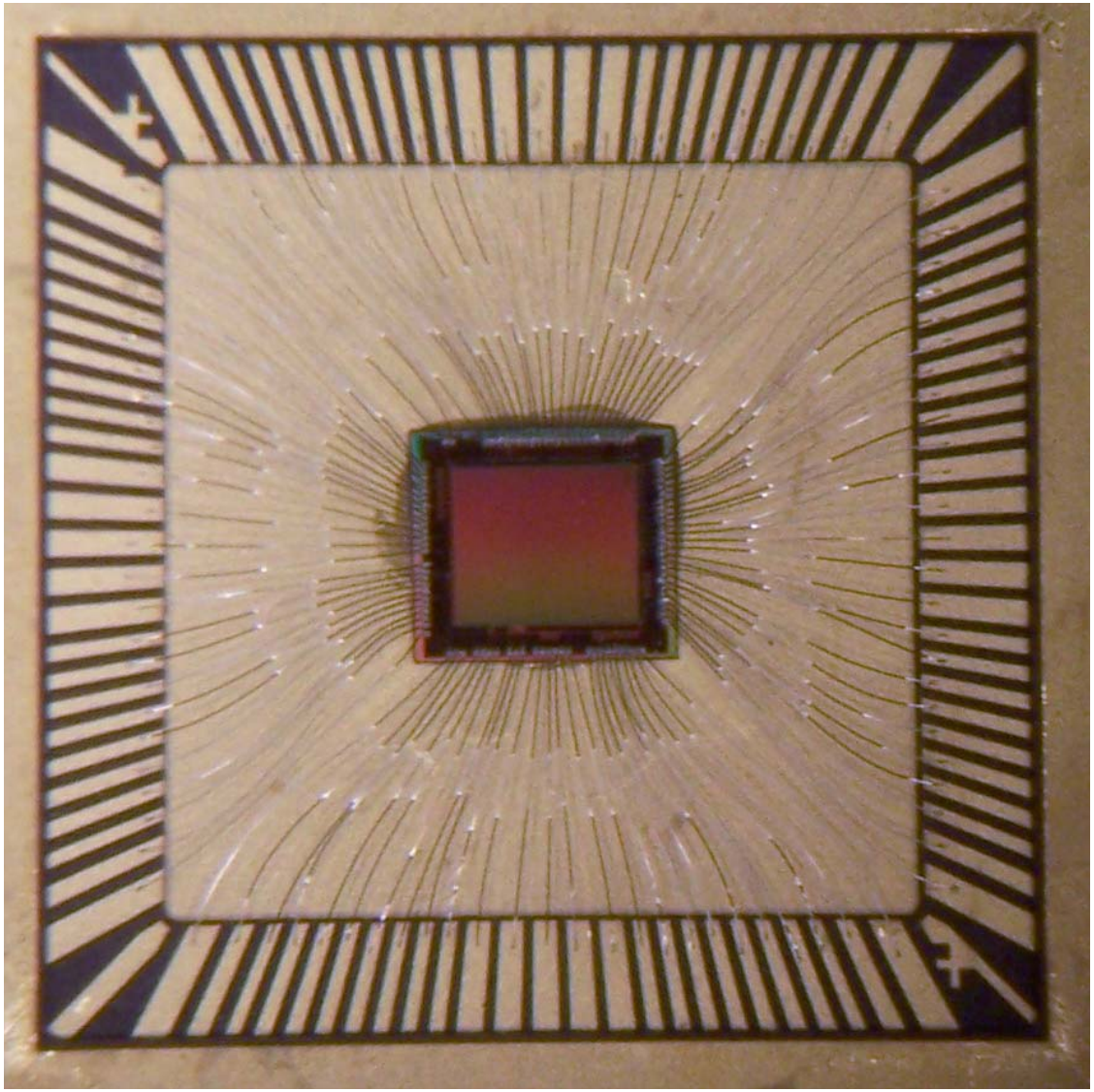
*~100 counters: few 100k channels



~1mm pos. resolution: 200 Ch/counter

*180 counters = 36,000 channels

Buffered LABRADOR (BLAB1) ASIC



3mm x 2.8mm, TSMC 0.25um

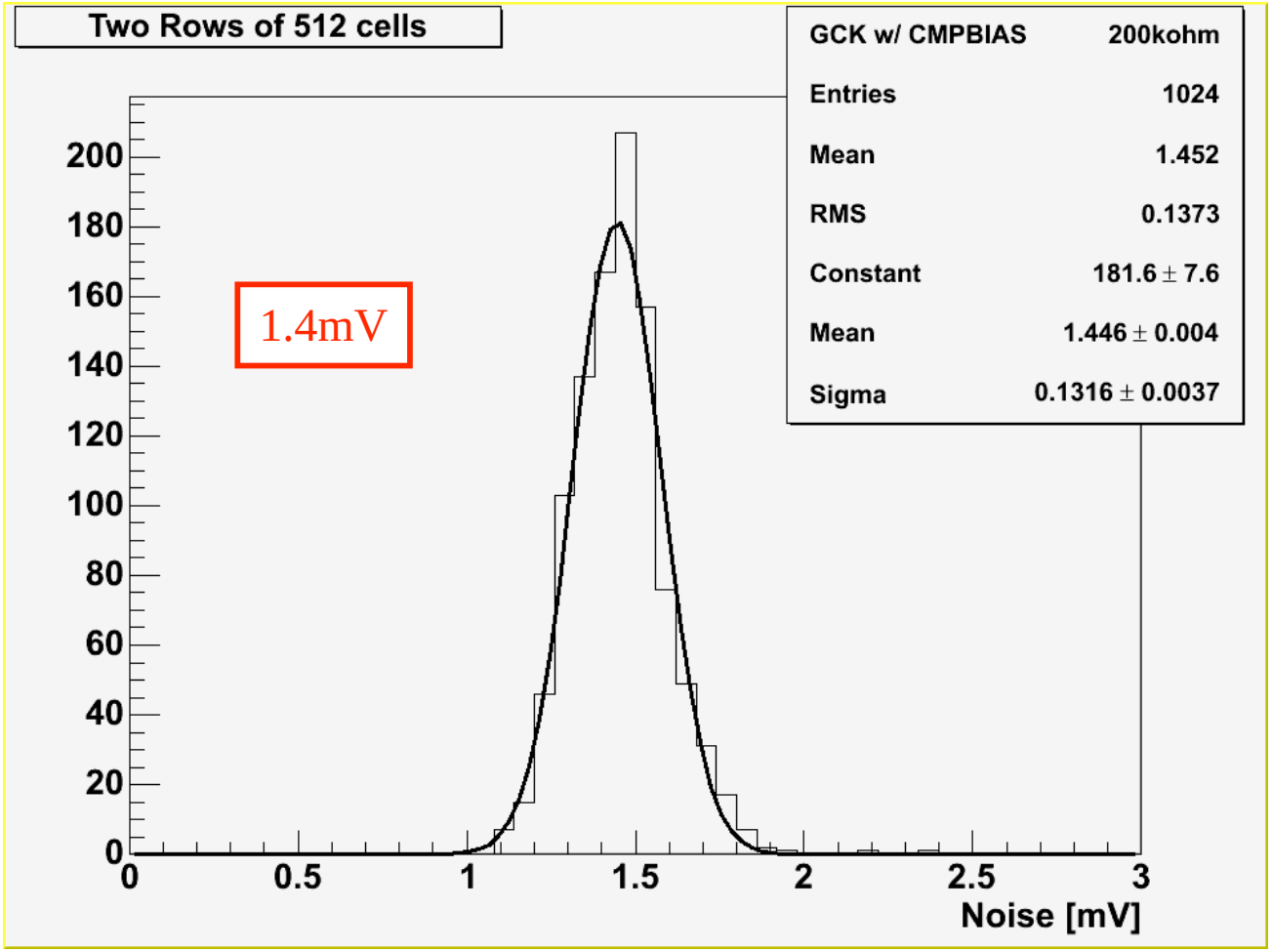
- 64k samples deep
- Multi-MSa/s to Multi-GSa/s
- 12-64us to form Global trigger
- Depth can be expanded

Buffered LABRADOR (BLAB1) ASIC

- 10 real bits of dynamic range

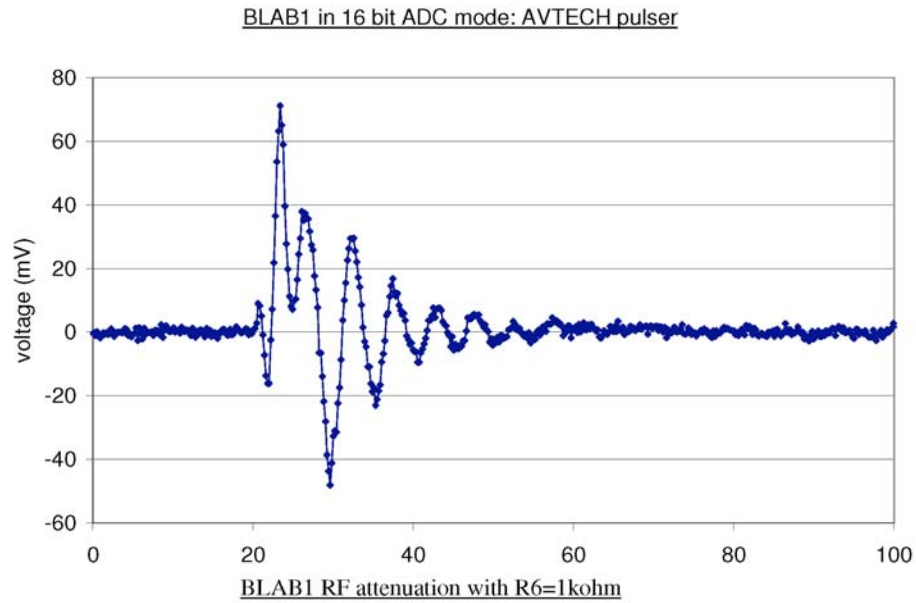
Measured Noise

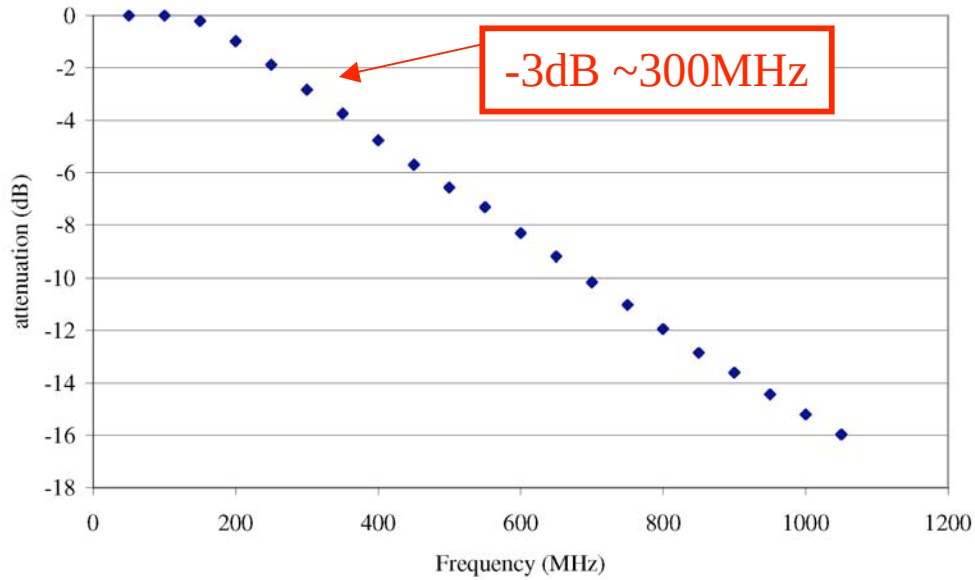
1.8V dynamic range



BLAB1 Analog Bandwidth

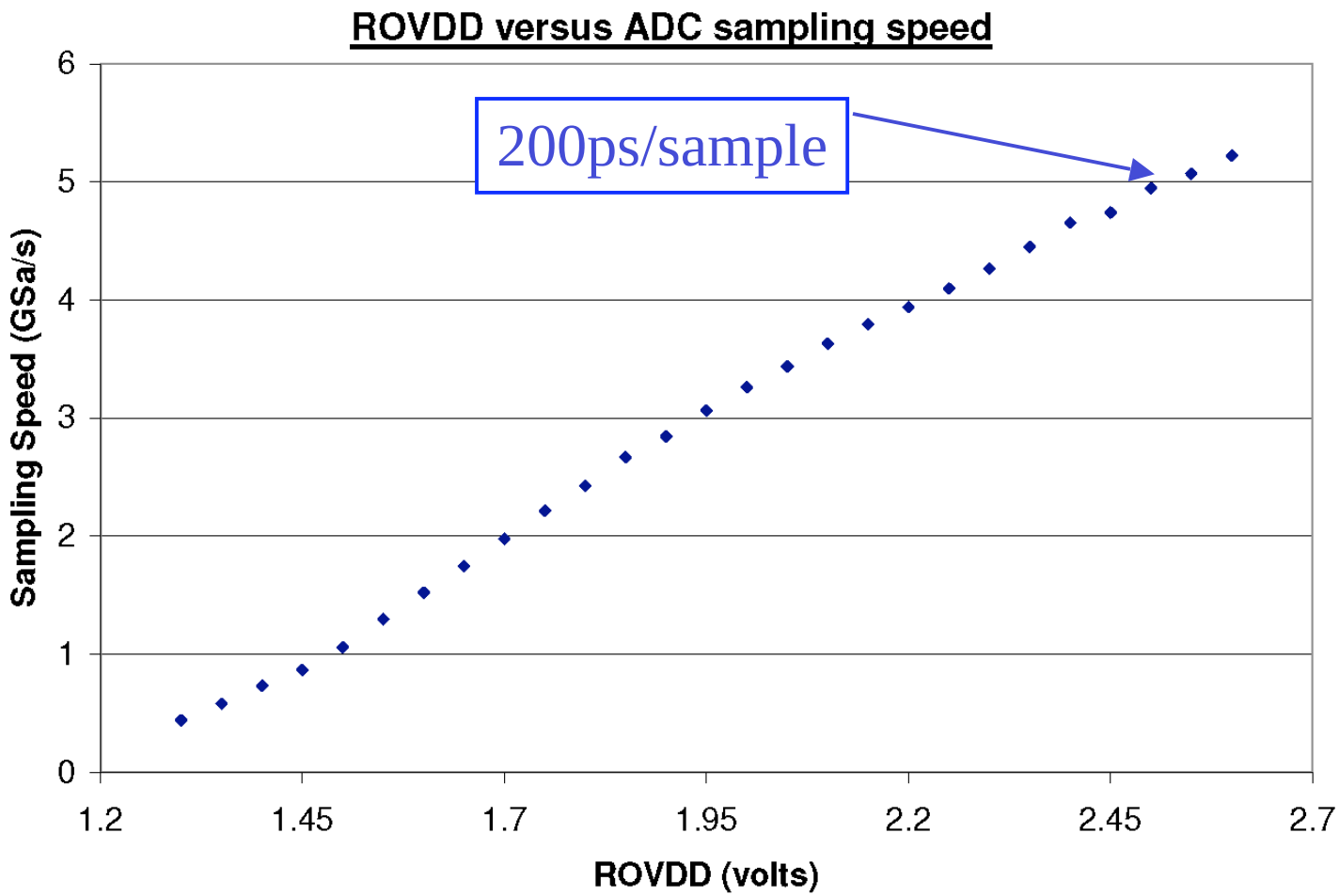
- A few fixes (lower power, higher BW)
- BLAB2 [when find support]





BLAB1 Sampling Speed

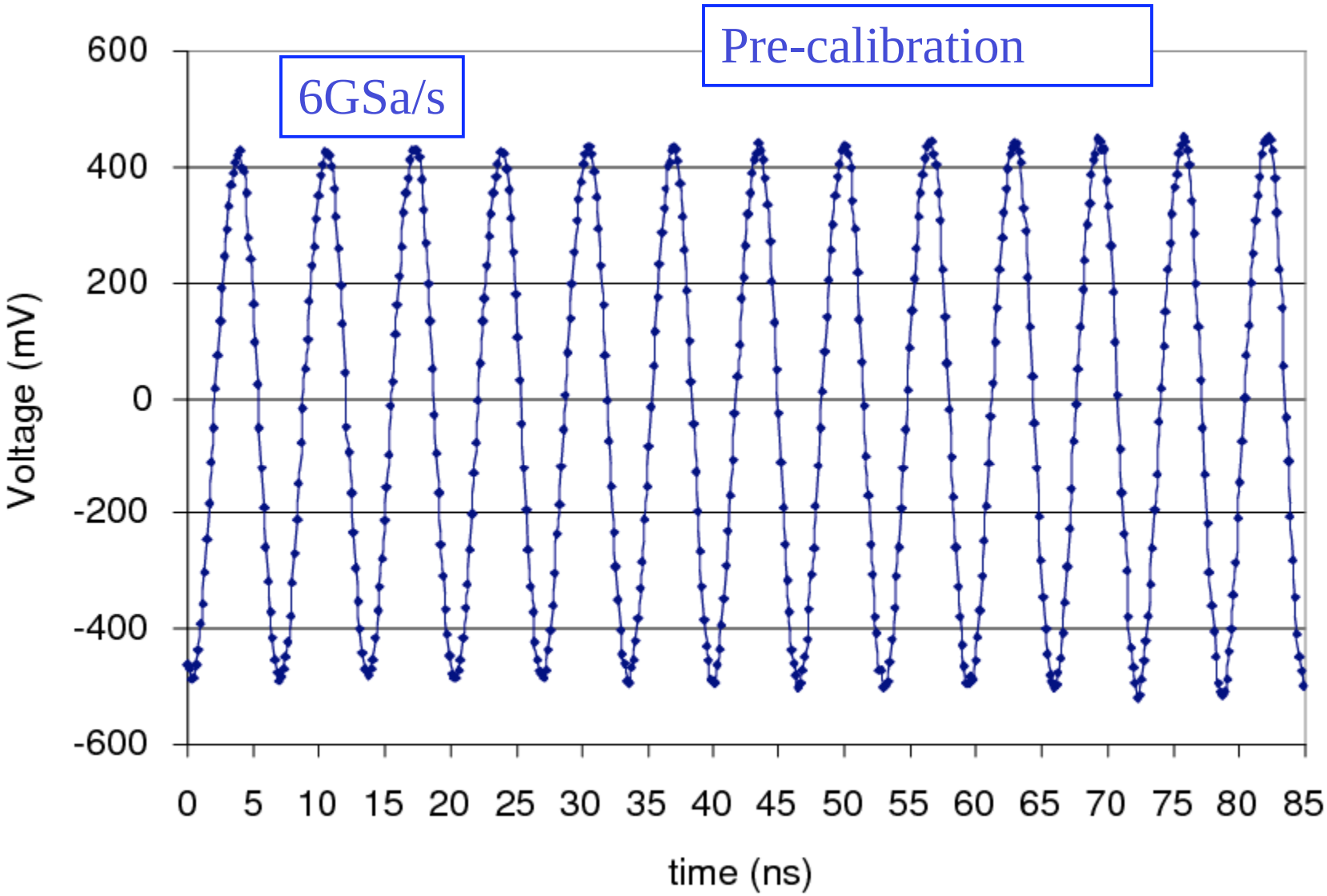
Can store 13us at 5GSa/s (before wrapping around)



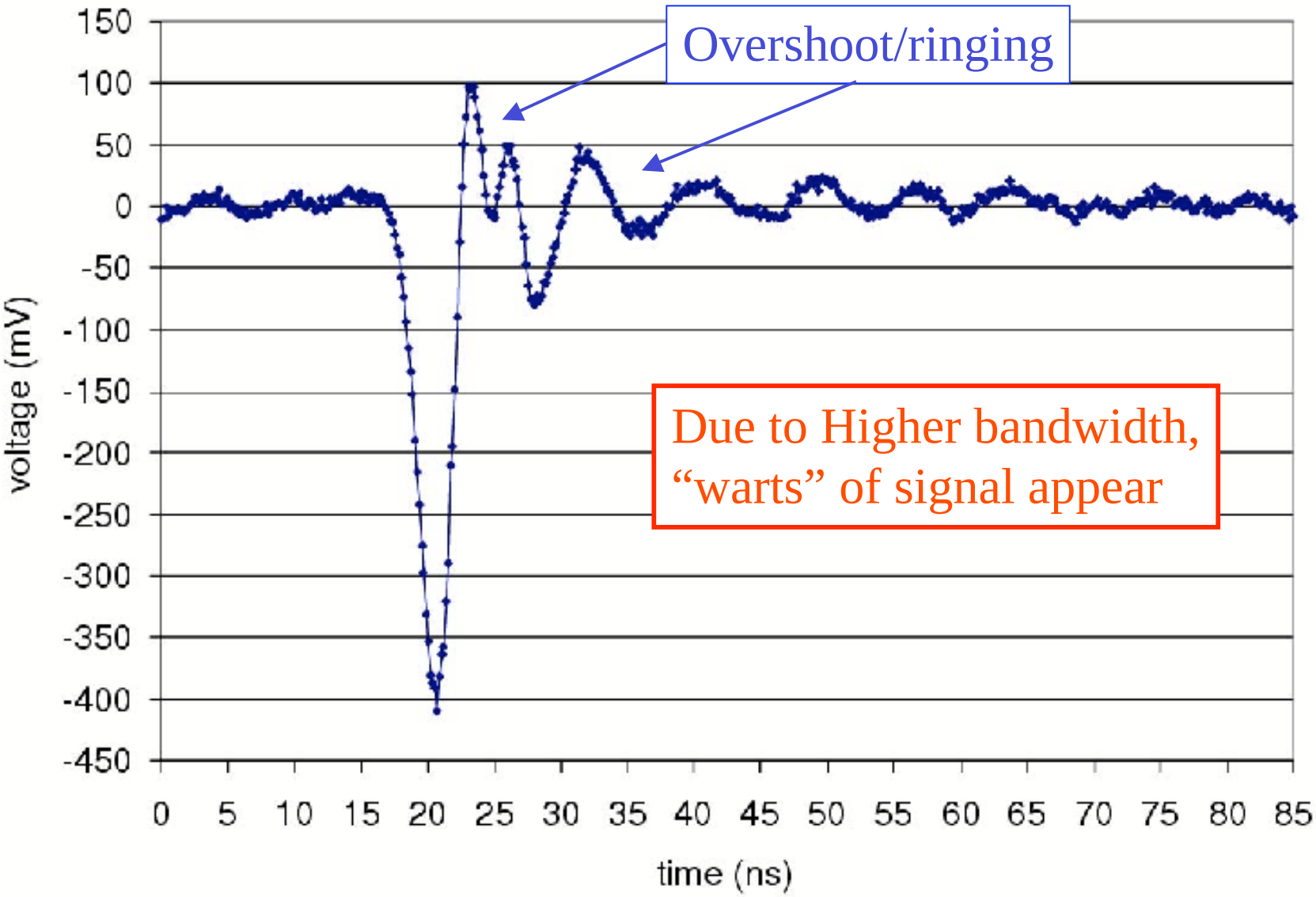
Single sample:
200/SQRT(12)
~ 58ps

But, have Complete Waveform Information

125MHz sine wave

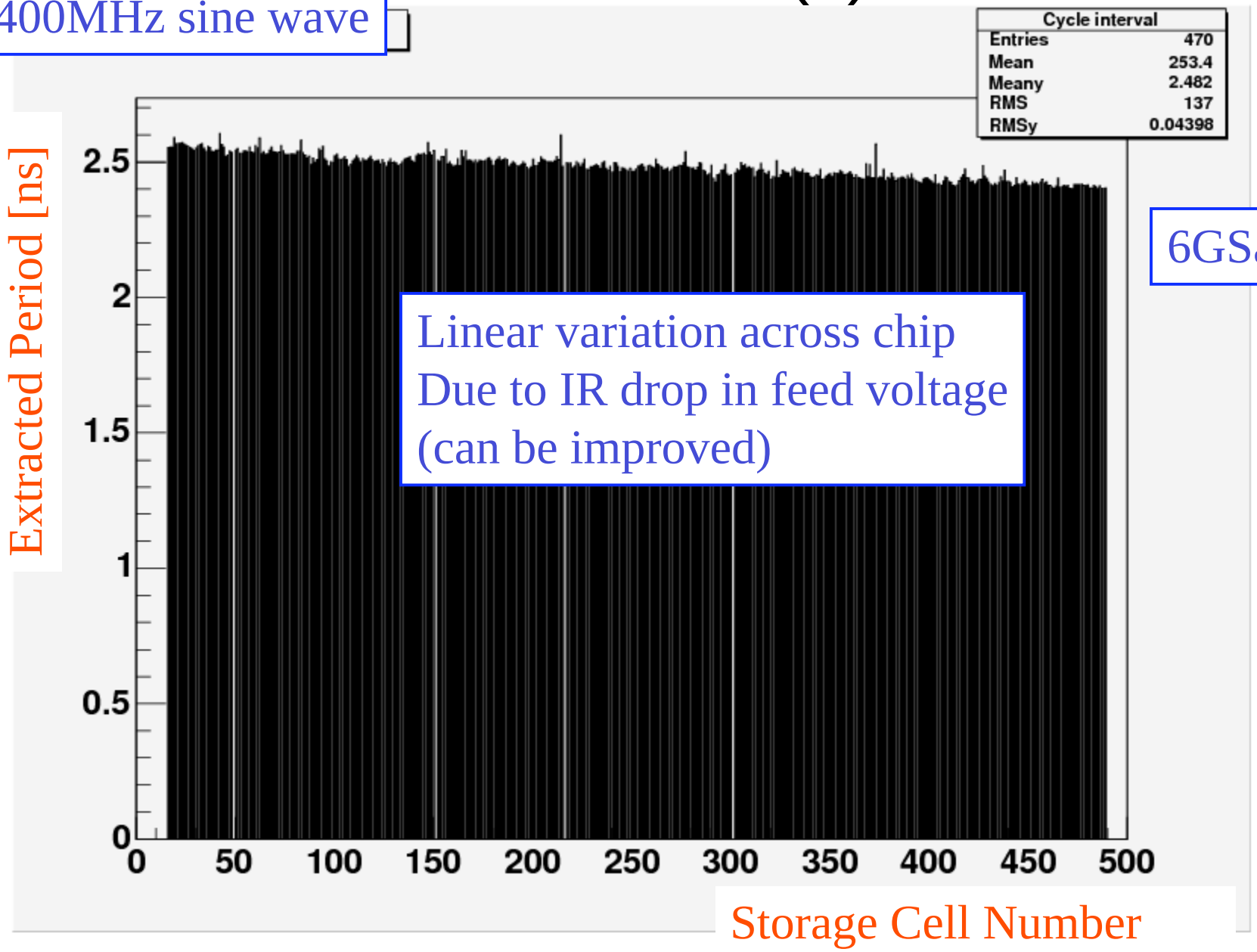


Typical single p.e. signal [Burle]



Calibration (1)

400MHz sine wave



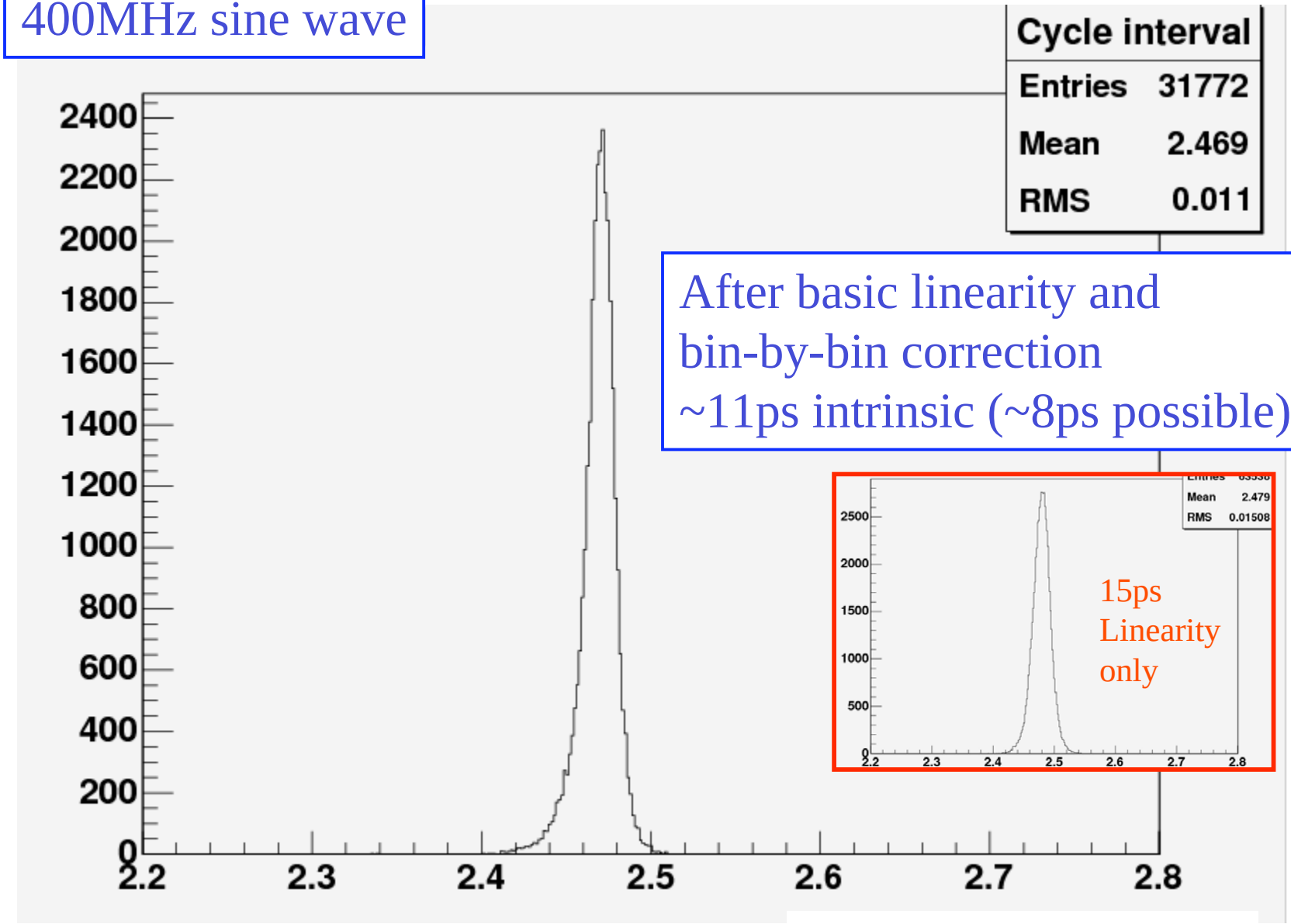
6GSa/s

Linear variation across chip
Due to IR drop in feed voltage
(can be improved)

Calibration (2)

6GSa/s

400MHz sine wave

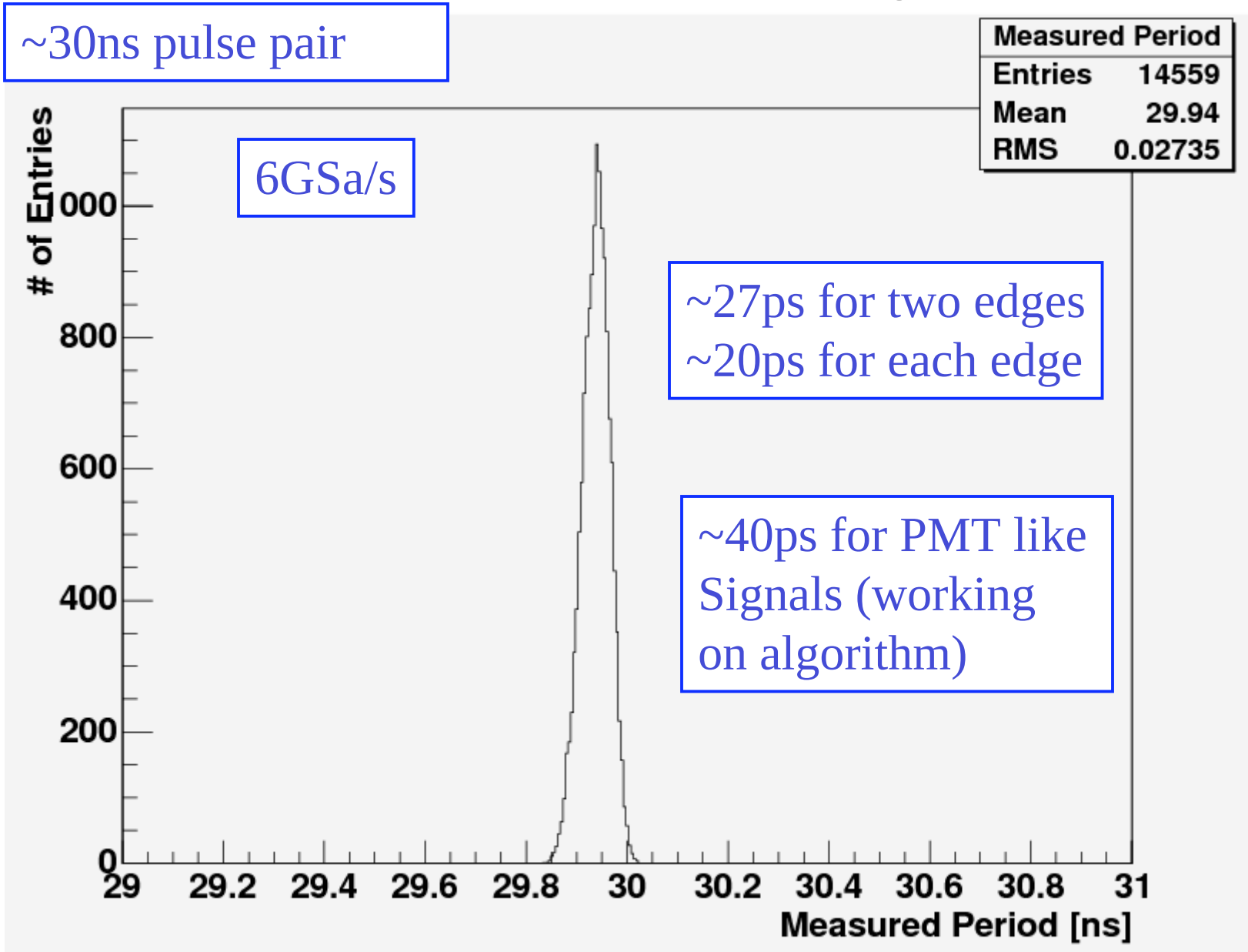


After basic linearity and
bin-by-bin correction
~11ps intrinsic (~8ps possible)

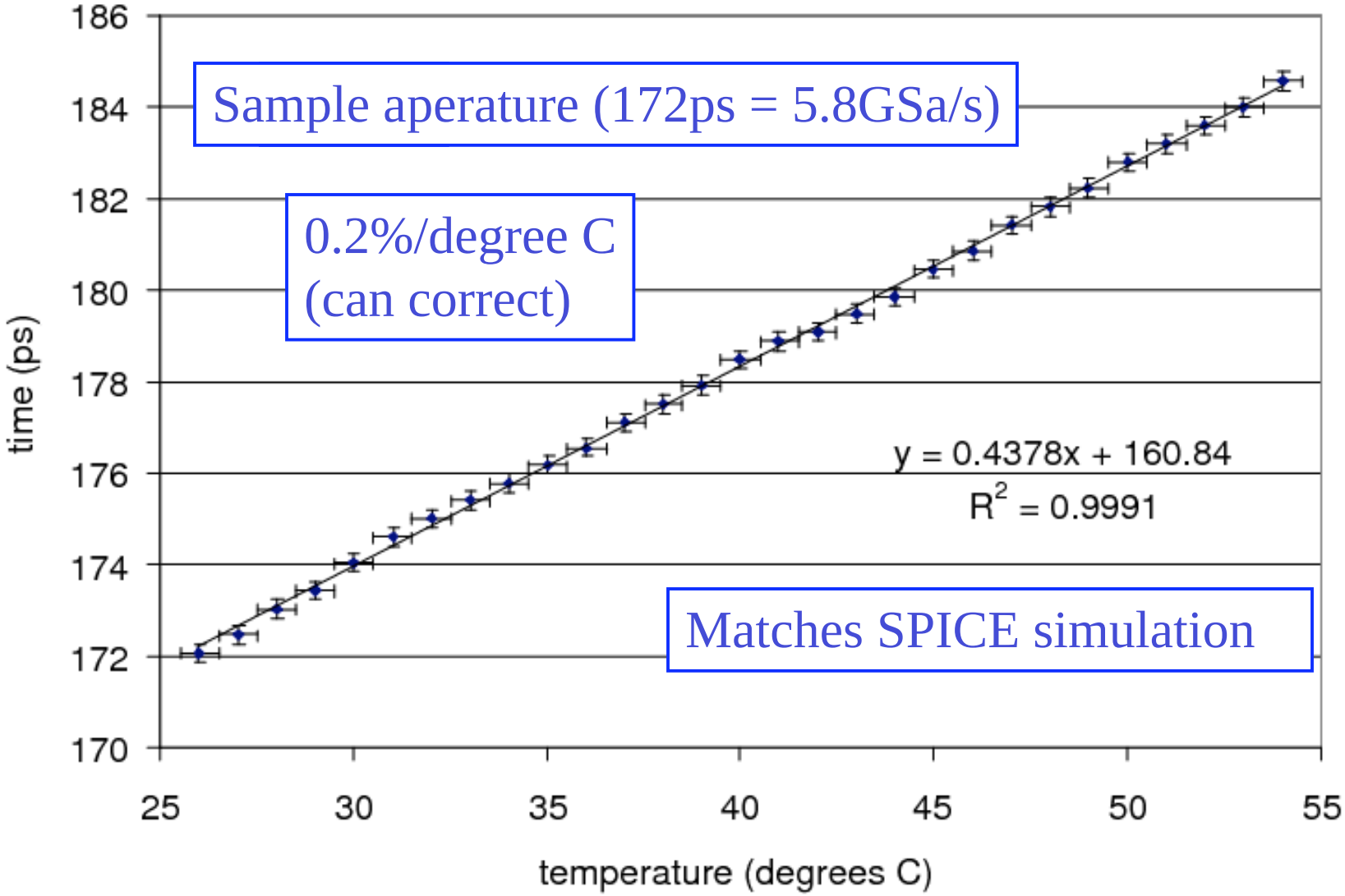
Extracted Period [ns]

Bench Test timing

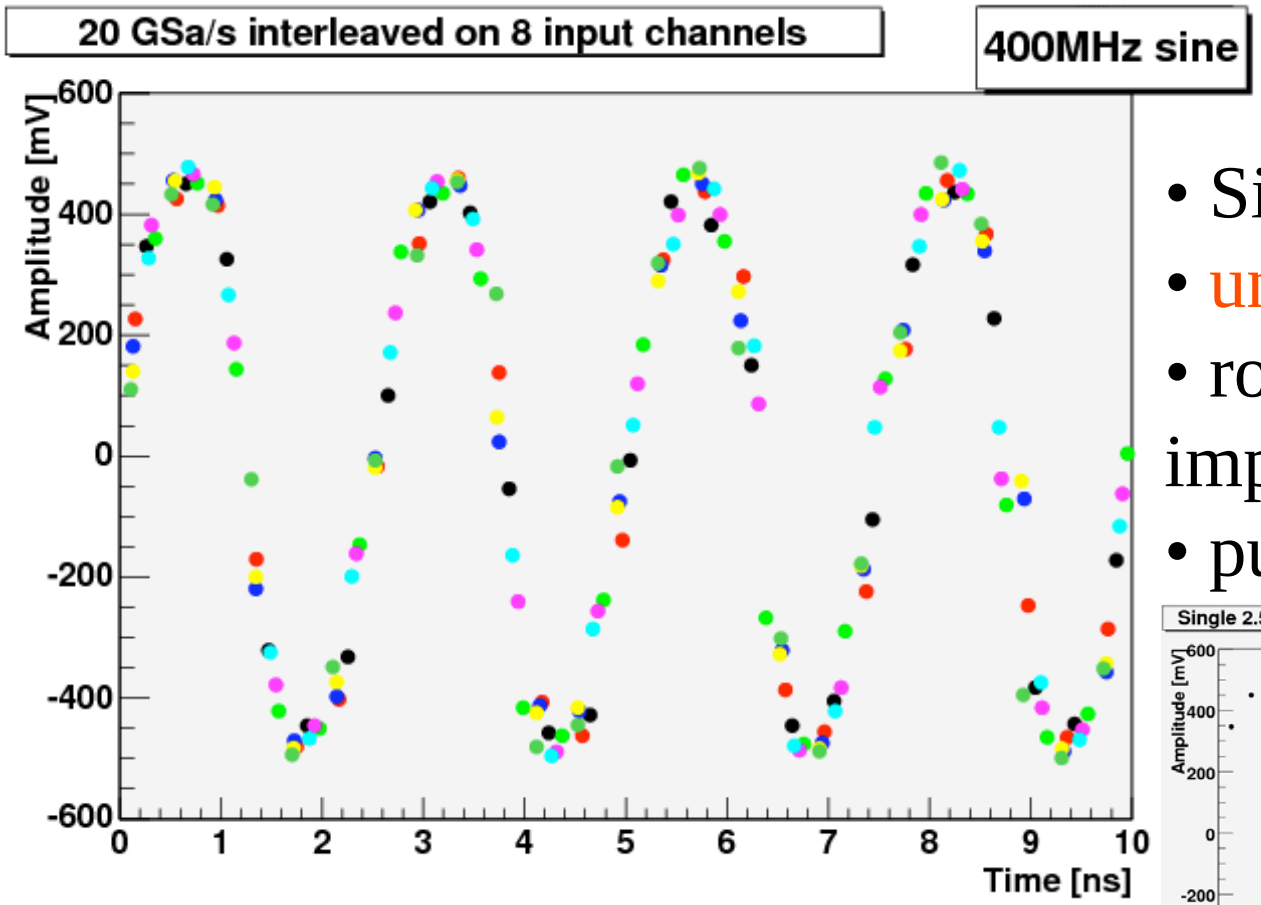
~30ns pulse pair



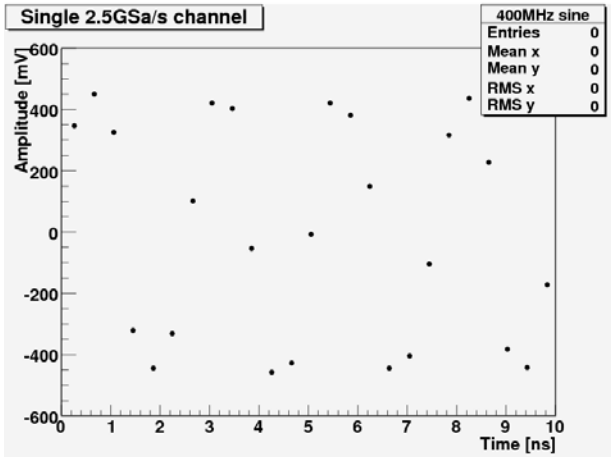
Temperature Dependence



Interleaved Operation



- Single shot!
- uncalibrated
- room for improvement
- push BW higher

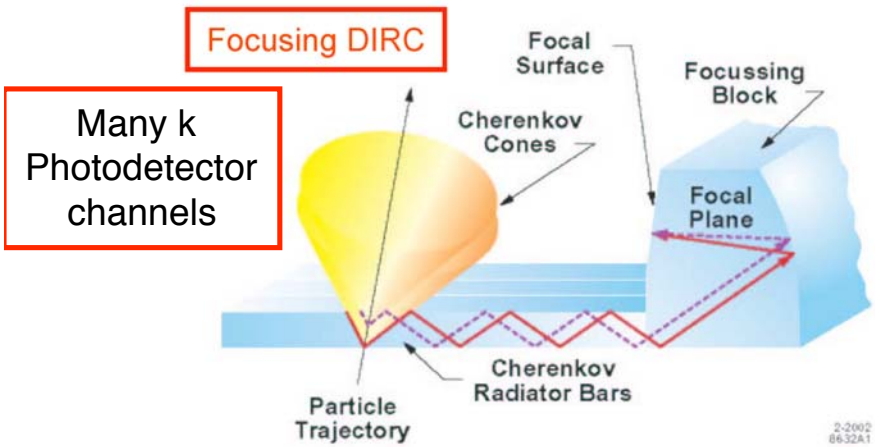


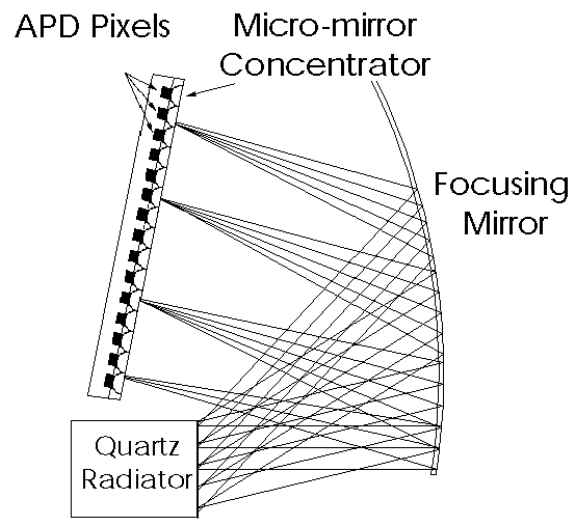
LARC ASIC:

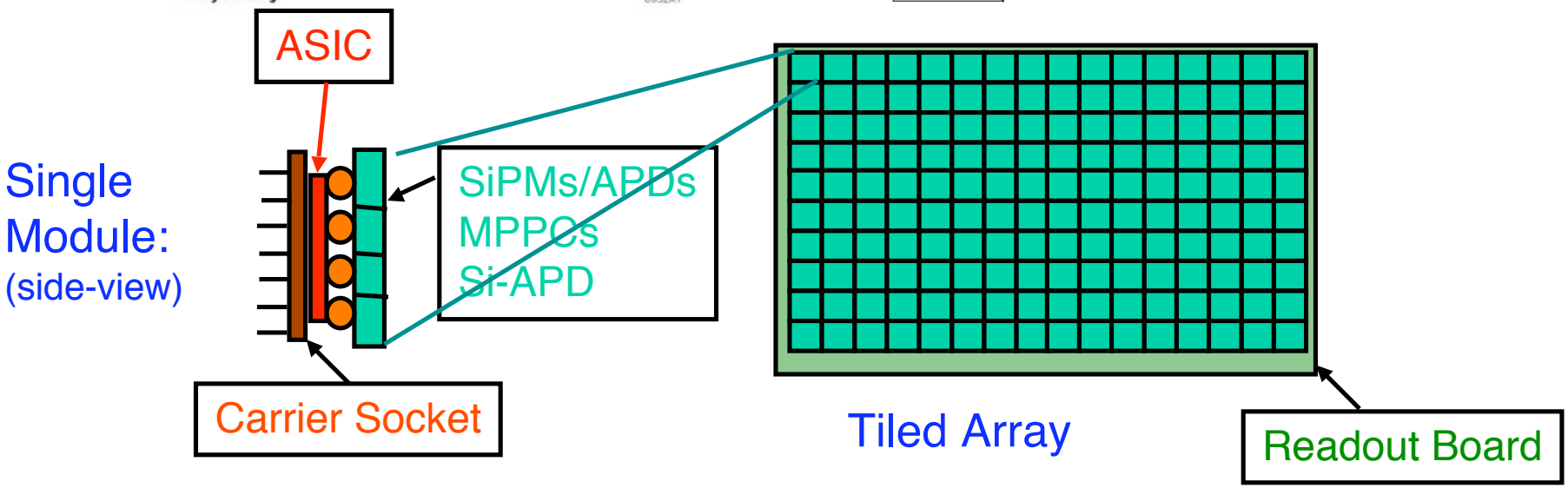
64 chan @ 5 GSa/s = 384GSa/s

→Streak camera type applications – ps timing

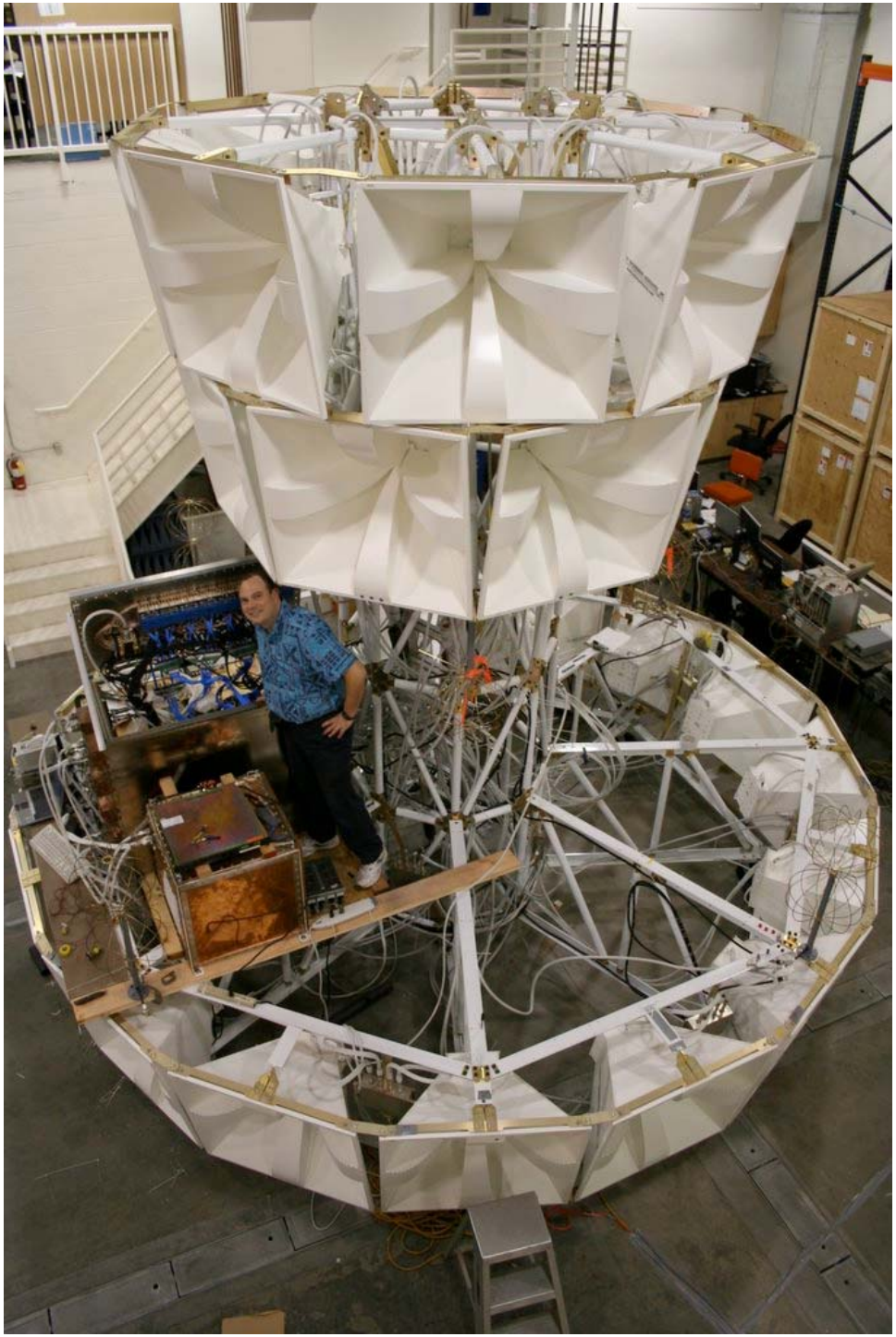
f-DIRC Array Concept







SBIR Phase 2 to develop 1k channel (Si-APD) readout

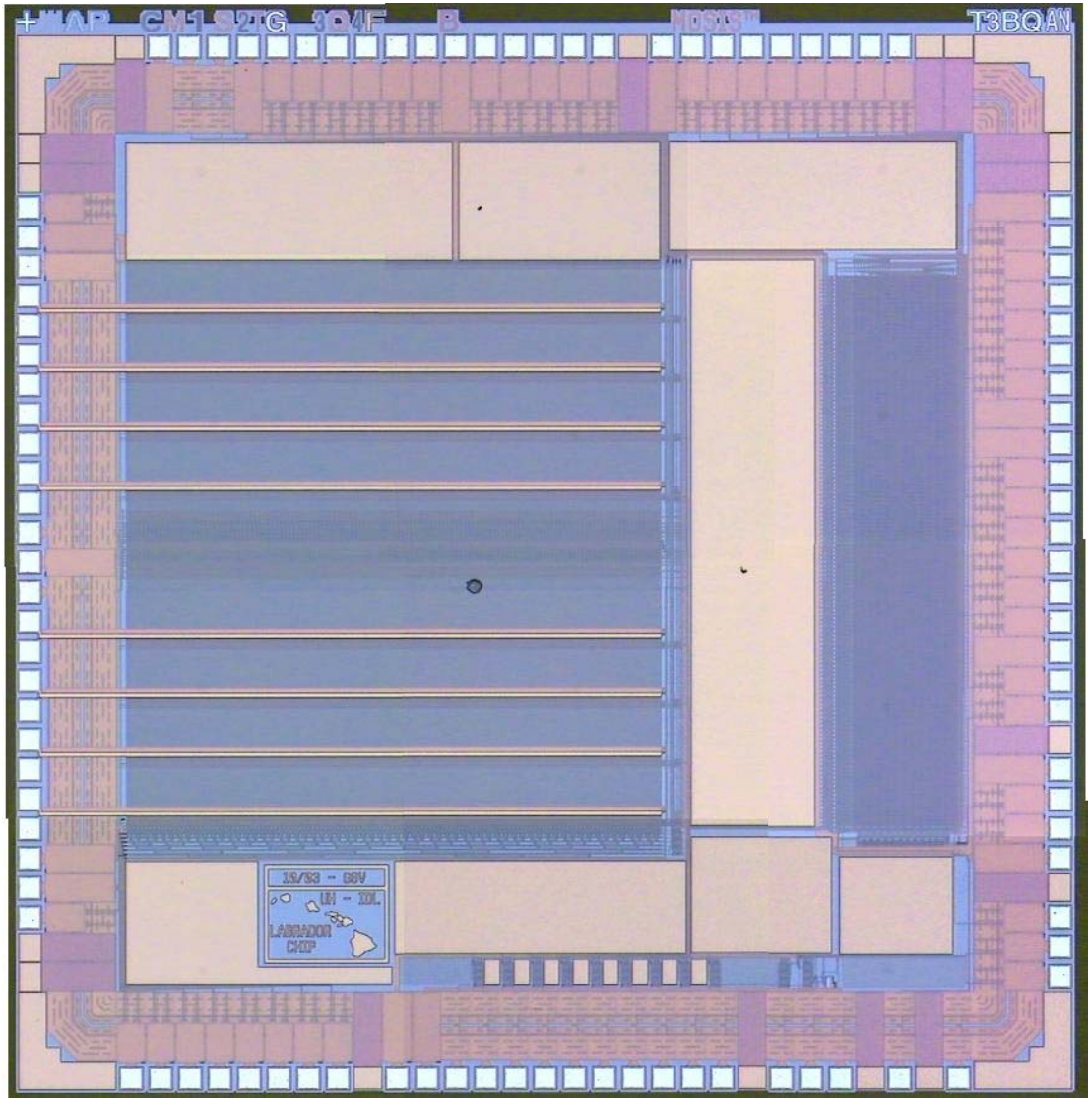


Summary

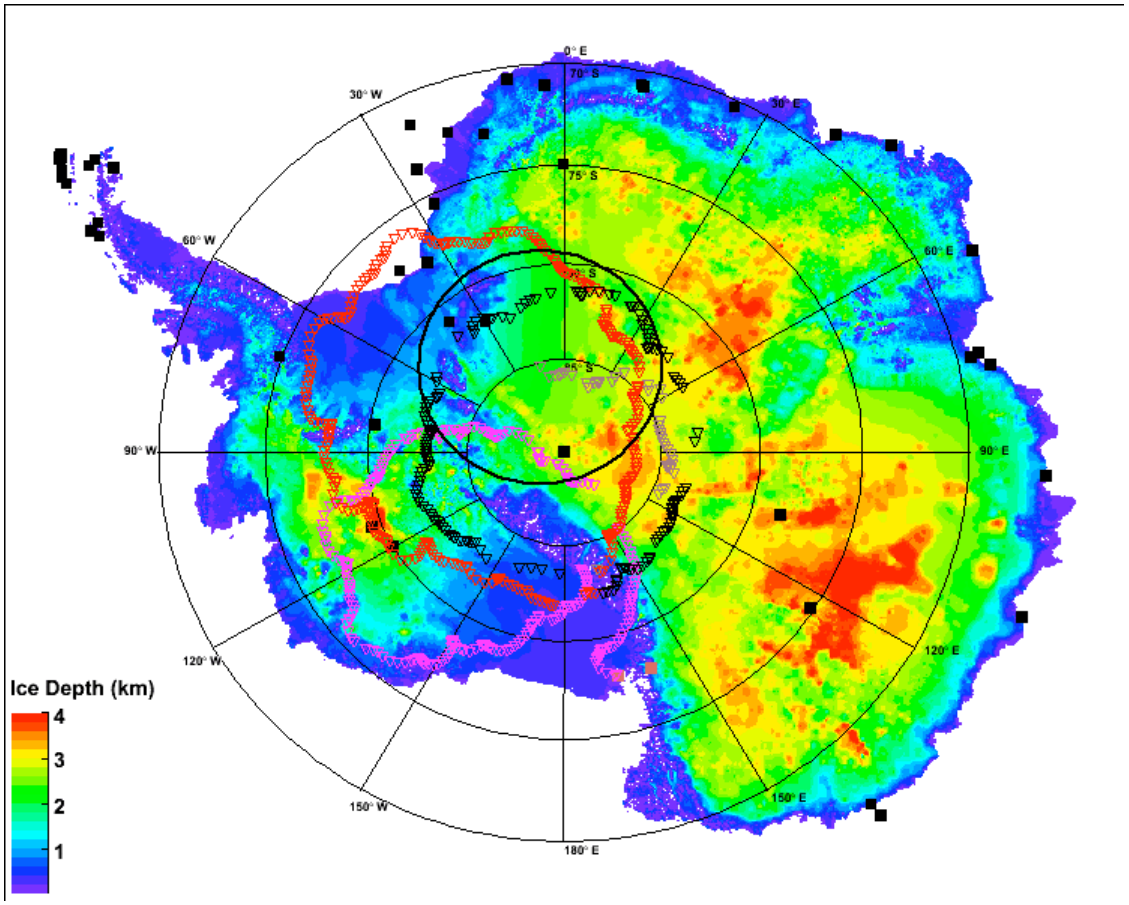
Exciting ASIC developments enabling next generation HEP and Astroparticle Experiments

- Tera-ton GZK neutrino detector
- Pixel detector for Super-B and ILC
- Time resolved single photon detection (deep storage, PET, LIBS)

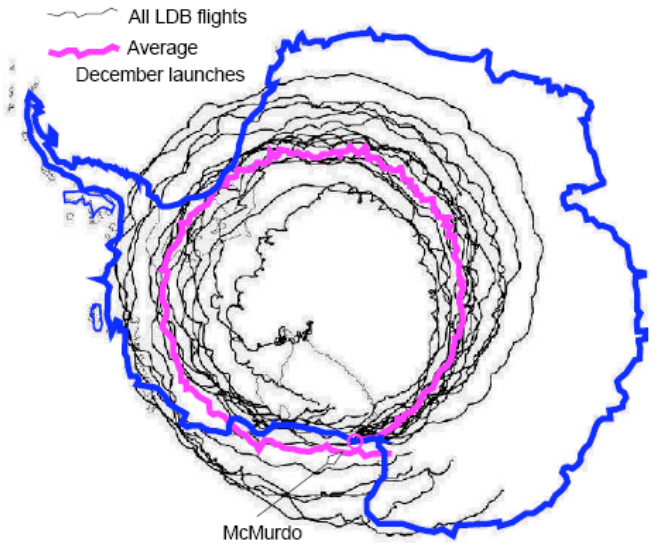
Back-up slides



ANITA flight path

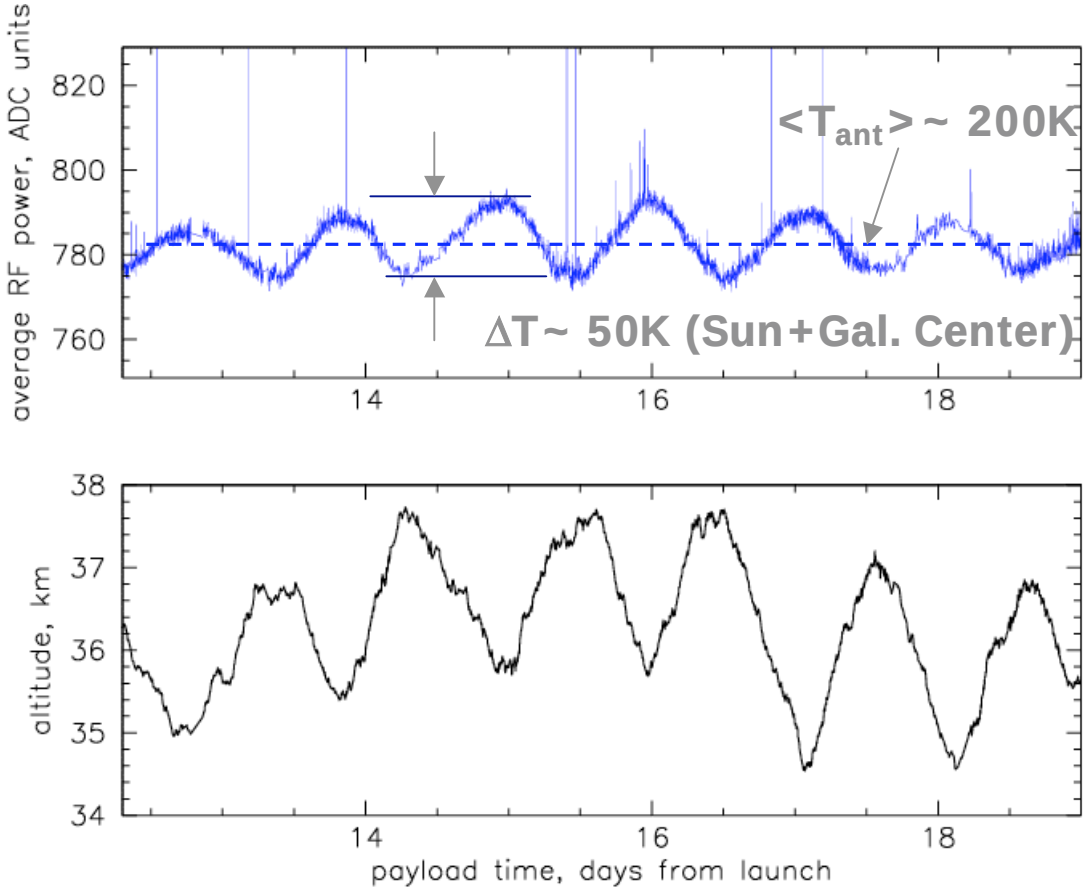


- 35 days, 3.5 orbits
- Anomalous Polar Vortex conditions
- Stayed much further "west" than average
- In view of stations (Pole & MCM) ~30% of time



About 8.2M Triggered Events logged

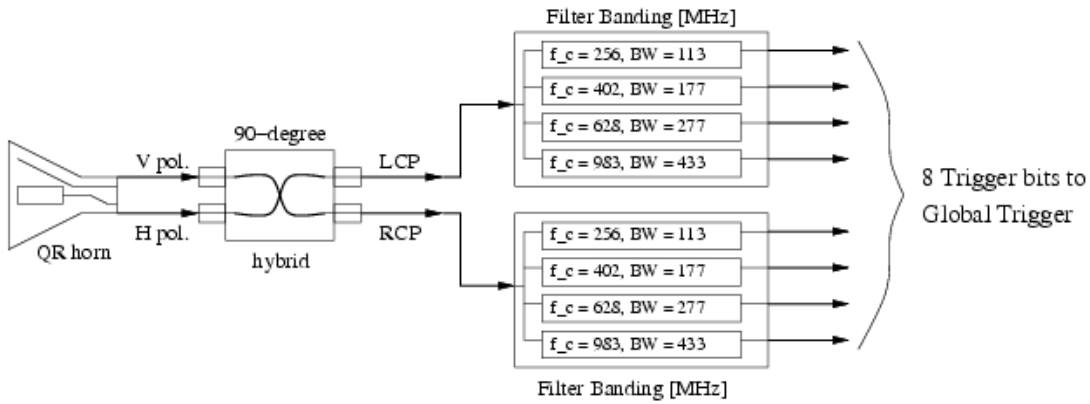
Flight sensitivity snapshot (preliminary)

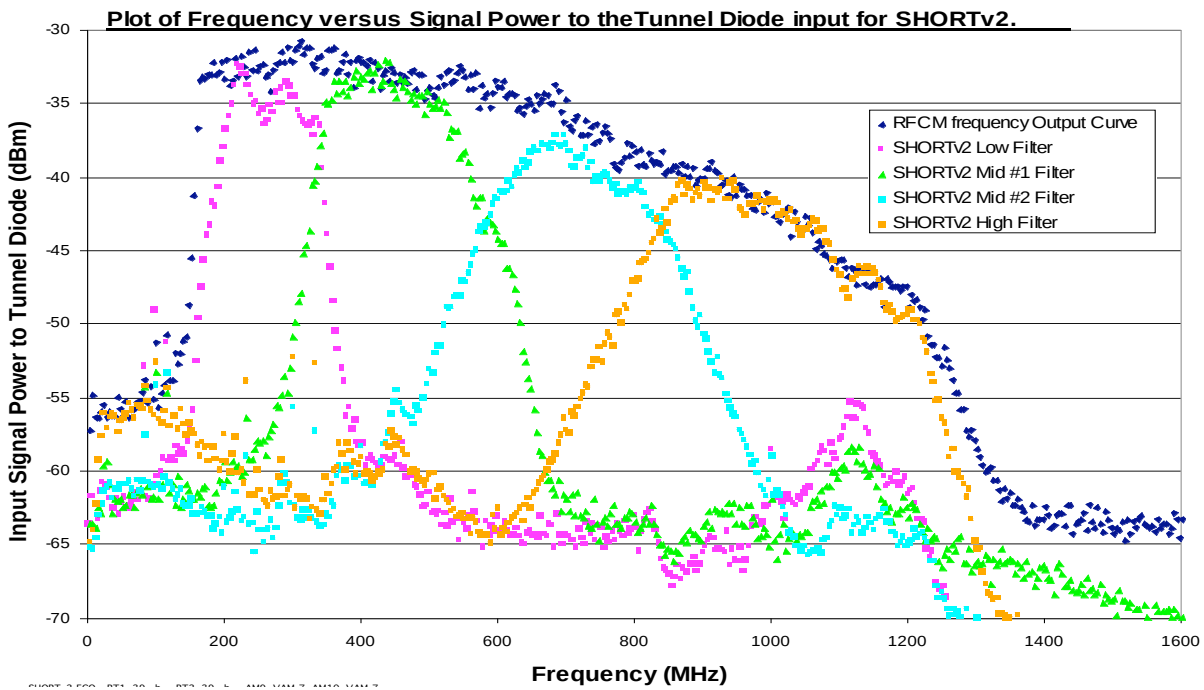


- ANITA sensitivity floor defined by thermal (kT) noise from ice + sky
- Thermal noise floor seen throughout most of flight—but punctuated by station & satellite noise
- Significant fraction (>40%) of time with pristine conditions

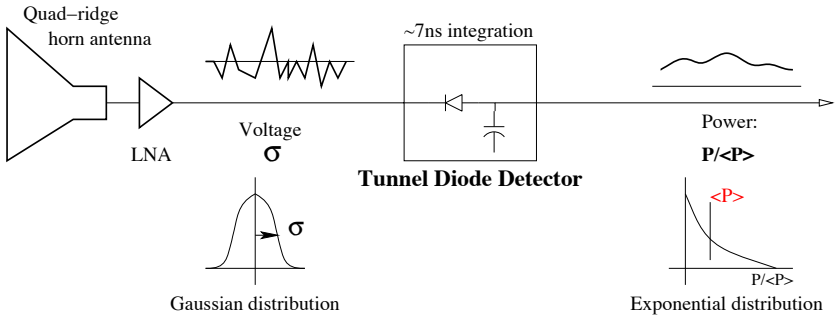
- T anti-correlated to altitude:
  - higher altitude at higher sun angle
  - sun+GC higher ➔ farther off main antenna beam

ANITA Level 1 – 3 of 8 Antenna

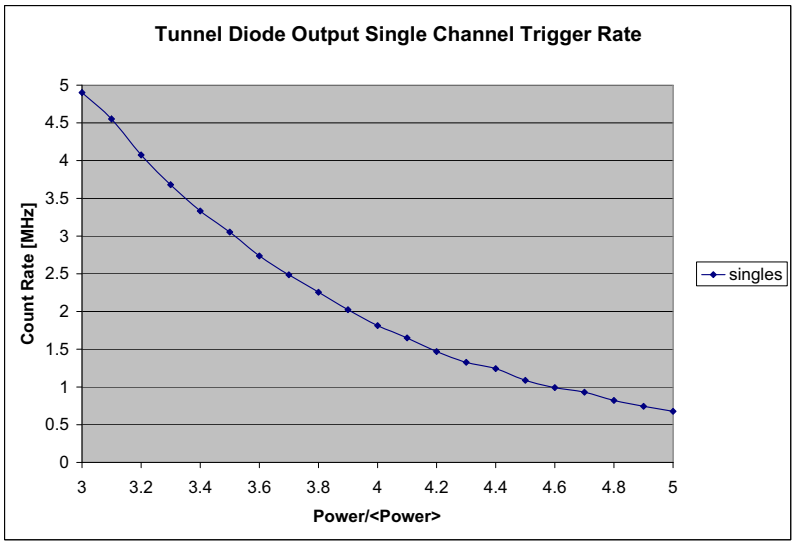


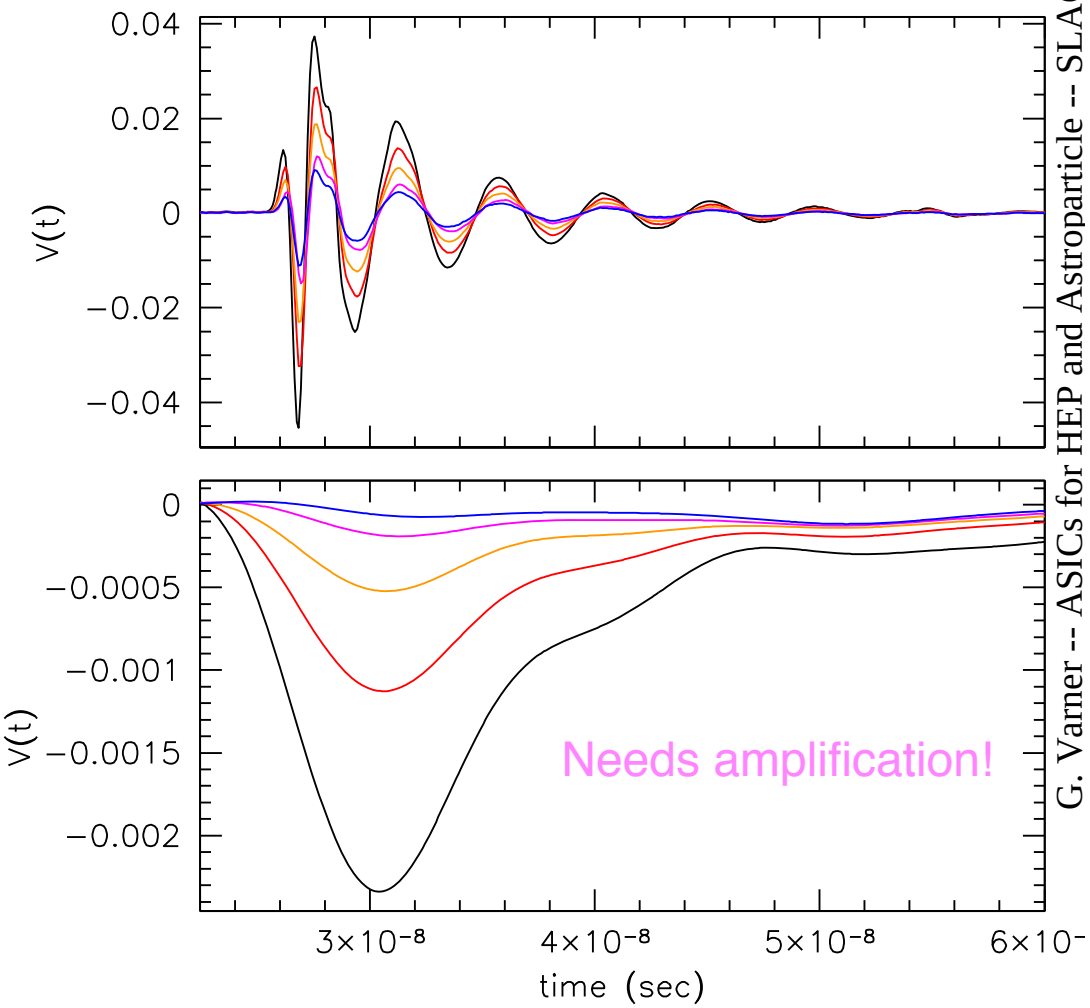


Diode detector Response

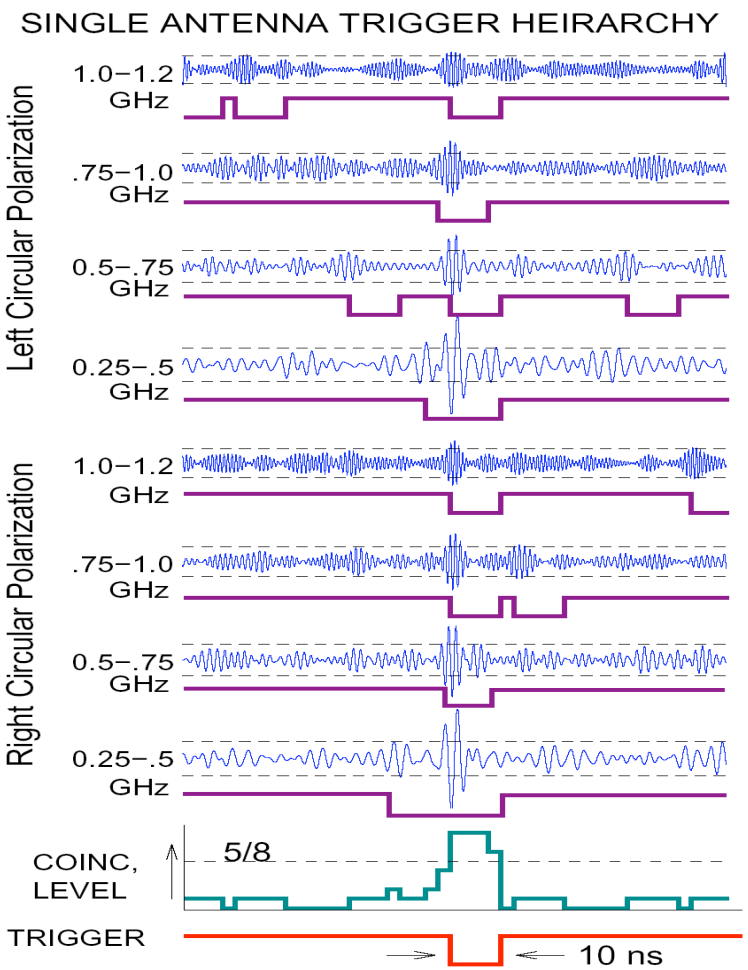


2.3σ ~= 3.9 P/<P>



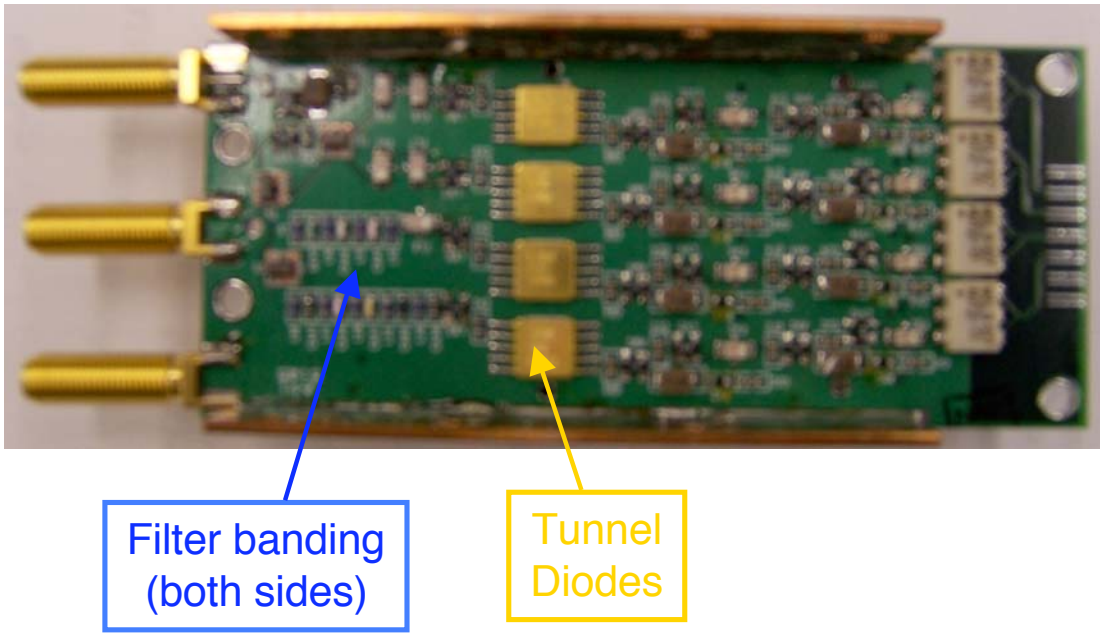


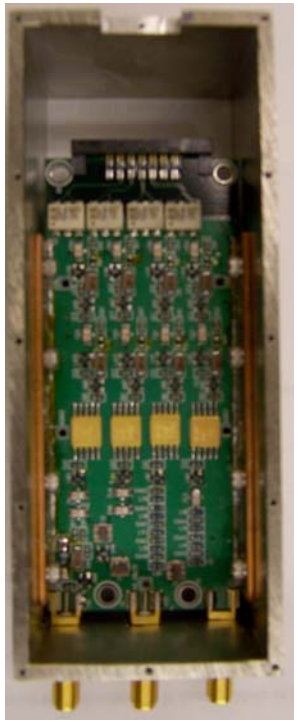
ANITA local trigger



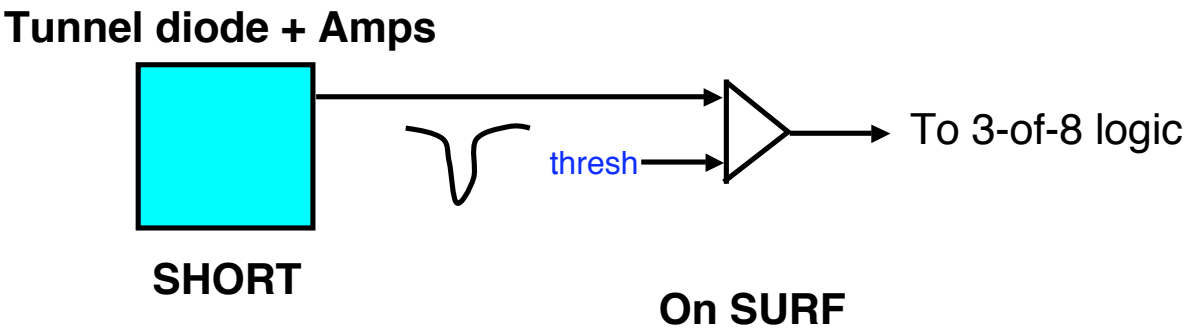
- Multi-band triggering essential to ANITA sensitivity
- Methods proven by FORTE, GLUE experiments
- Exploits statistical properties of thermal noise vs. linear polarization for signal
- Signal: most or all bands;
- noise: random
- all 8 shown here -- 3 of 8 is found to be enough

SURF High Occupancy RF Trig (SHORT)





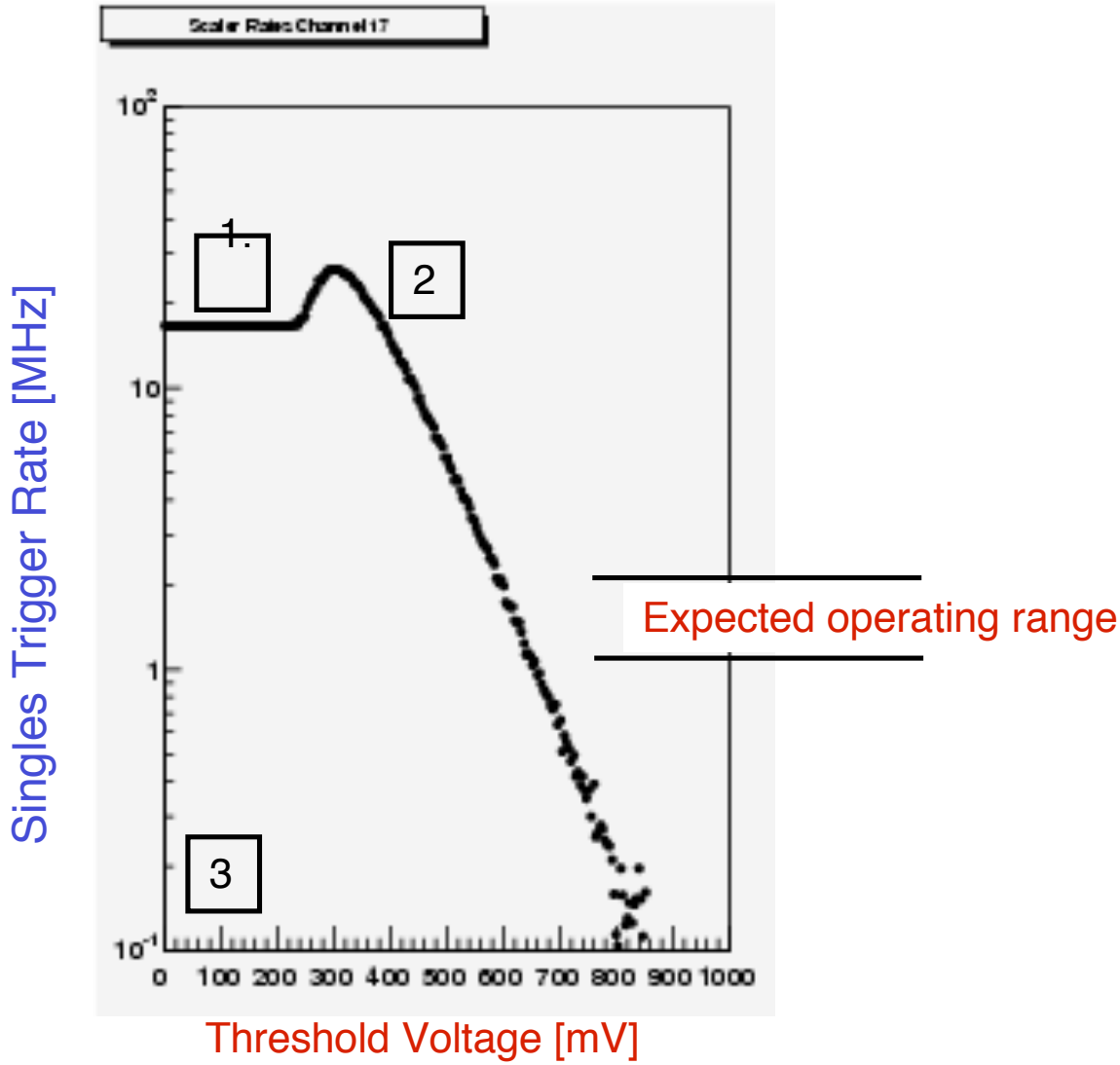
For each band:



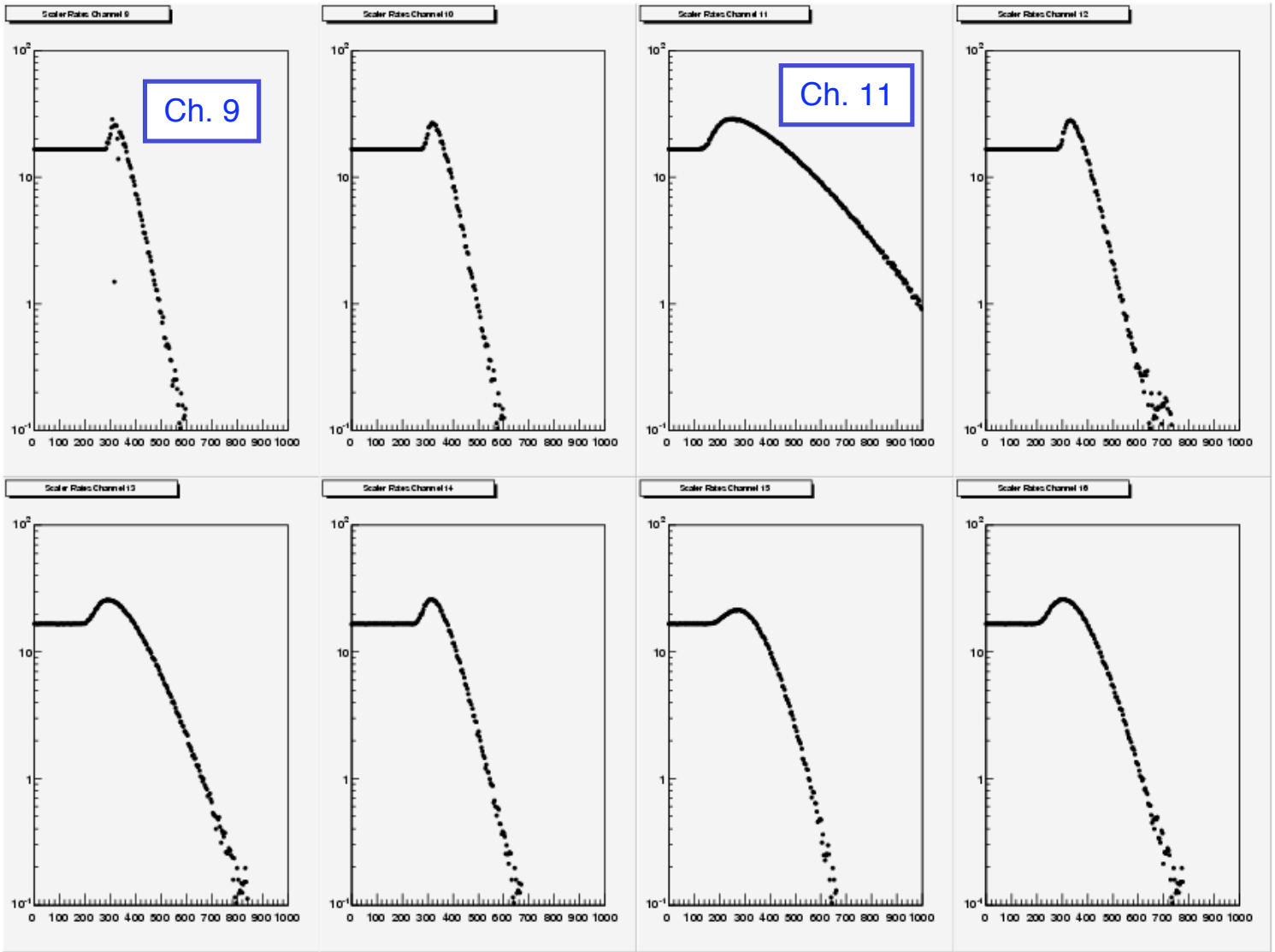
Threshold Scan

Notes:

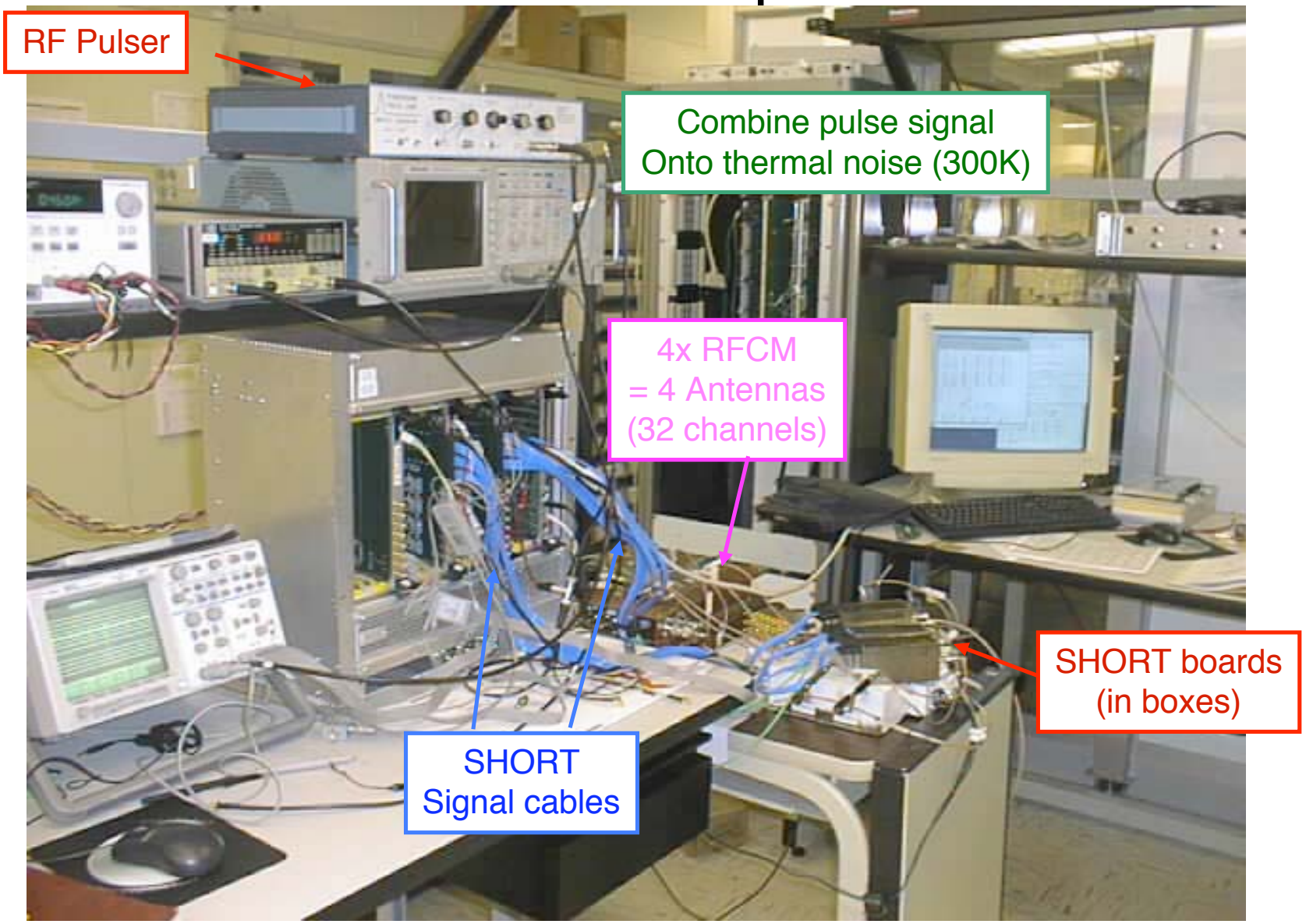
1. Due to Stuck-on detect circuit
2. Deadtime for 1/f !<< 12ns
3. Threshold zero is arbitrary



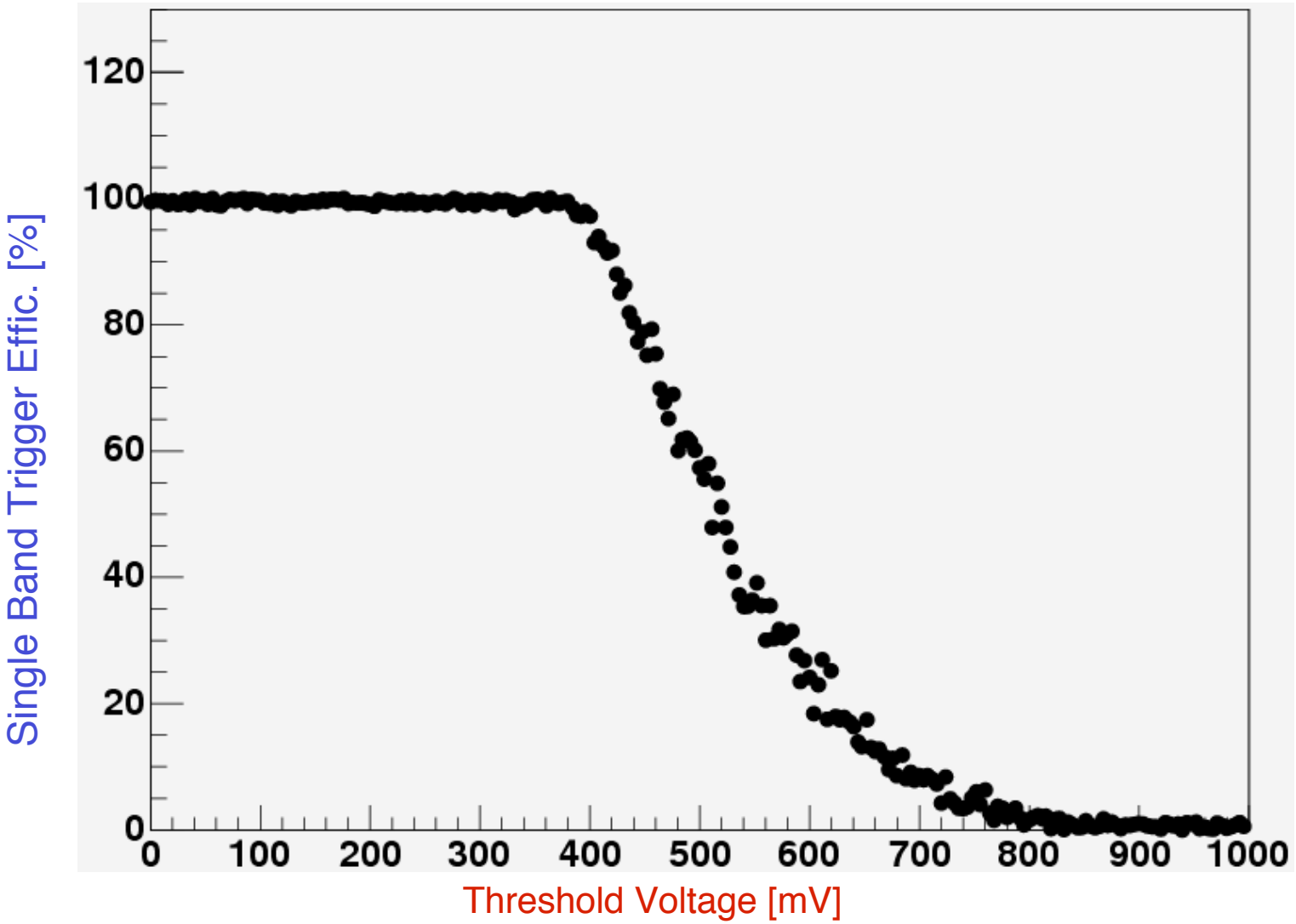
Some Channel-channel variation



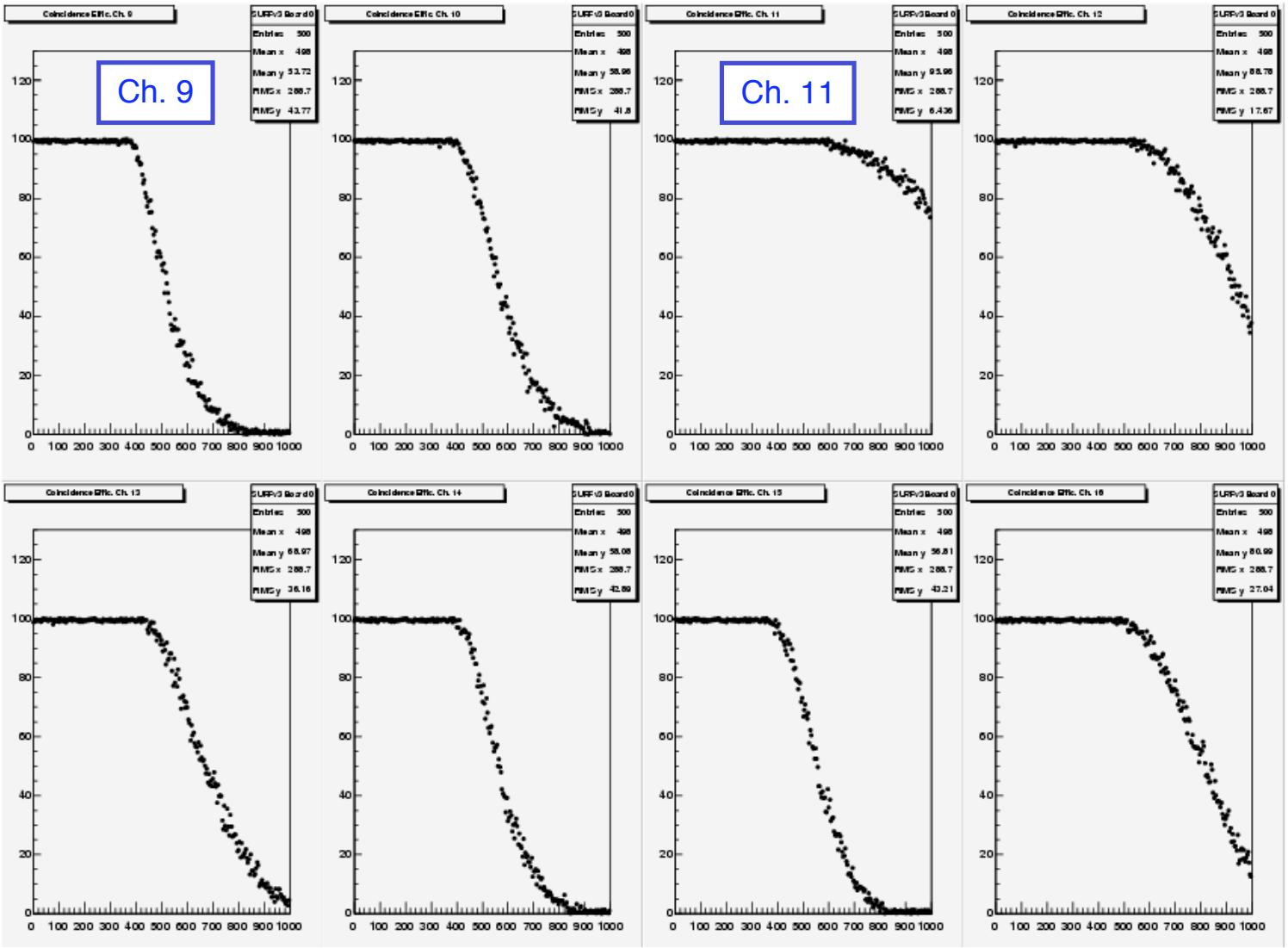
Test Set-up


RF Pulser
Combine pulse signal
Onto thermal noise (300K)
4x RFCM
= 4 Antennas
(32 channels)
SHORT boards
(in boxes)
SHORT
Signal cables

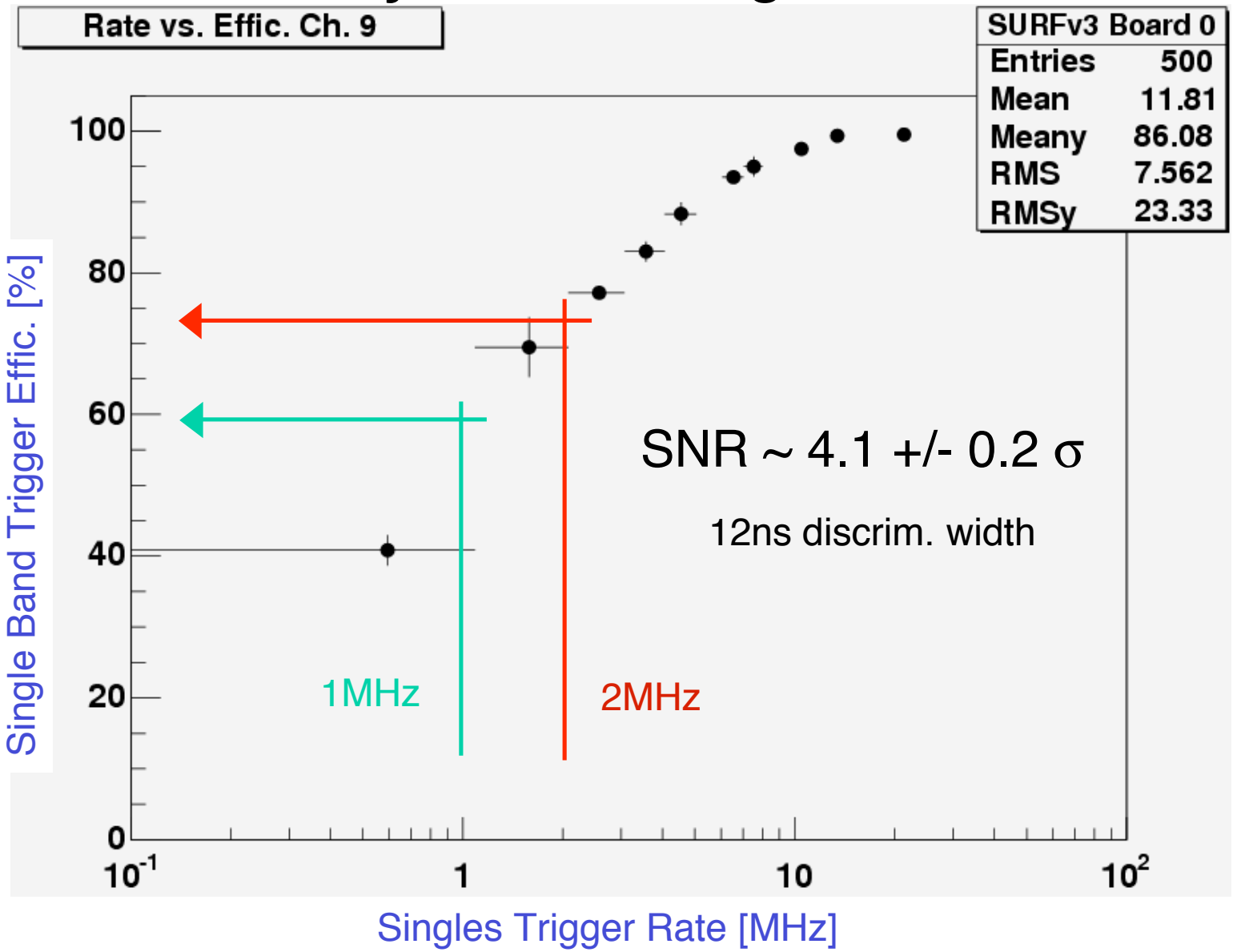
Single-band efficiency



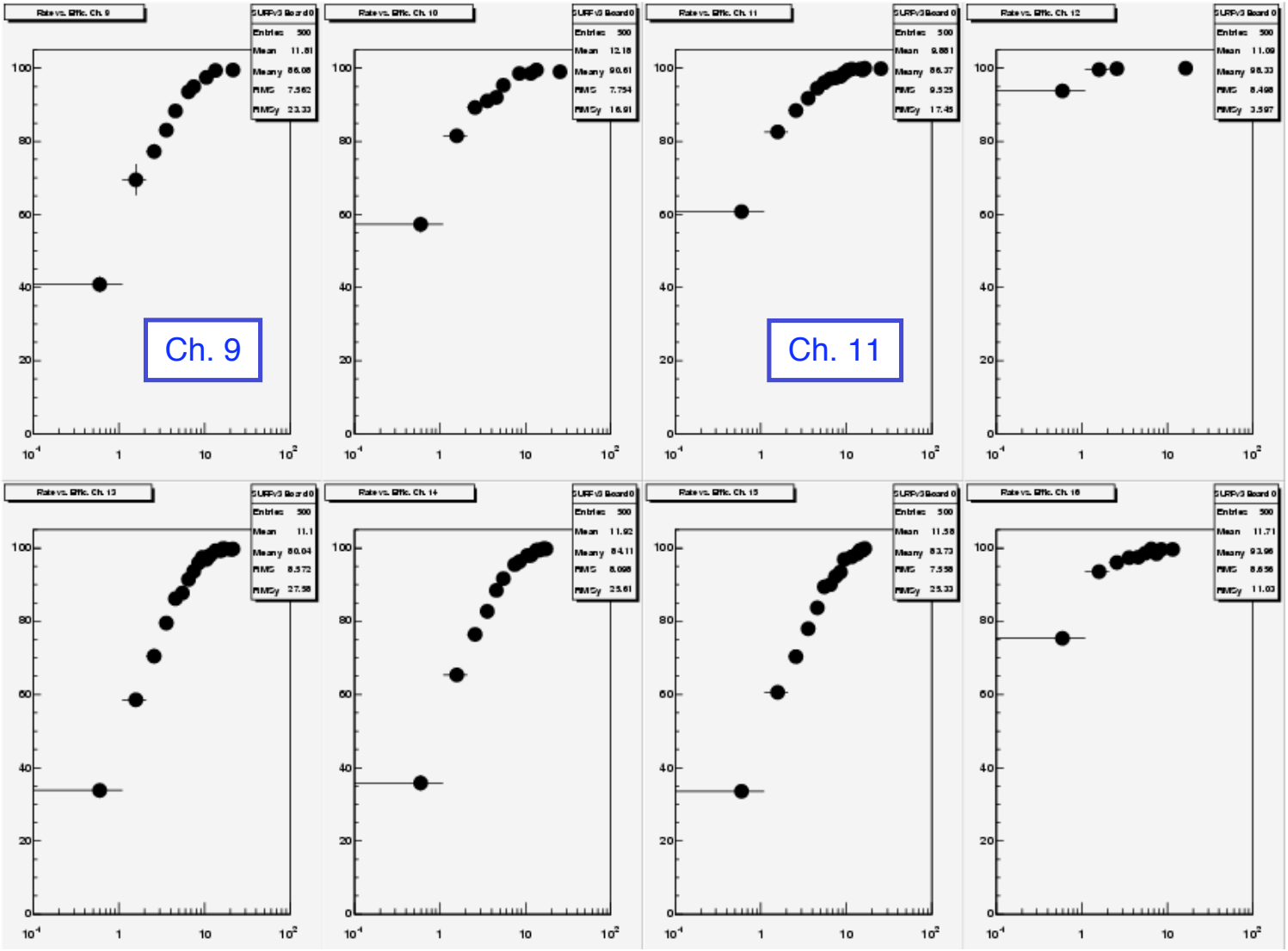
Single-band efficiencies



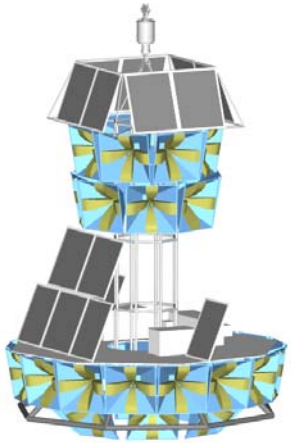
Efficiency versus Singles Rate

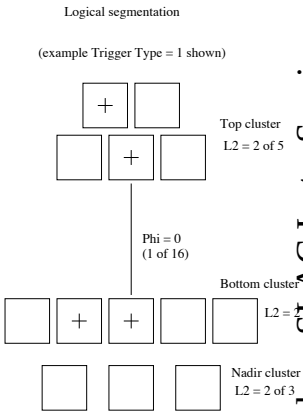


Efficiency versus Singles Rate



Trigger Reduction





Raw Signals

Level-1

Antenna

3-of-8

Level-2

Cluster

2-of-5

Level-3

Phi

2-of-2

Prioritizer (+compress)

Few events/min TDRSS

80 RF channels @ 1.5By * 2.6GSa/s = 312 Gbytes/s

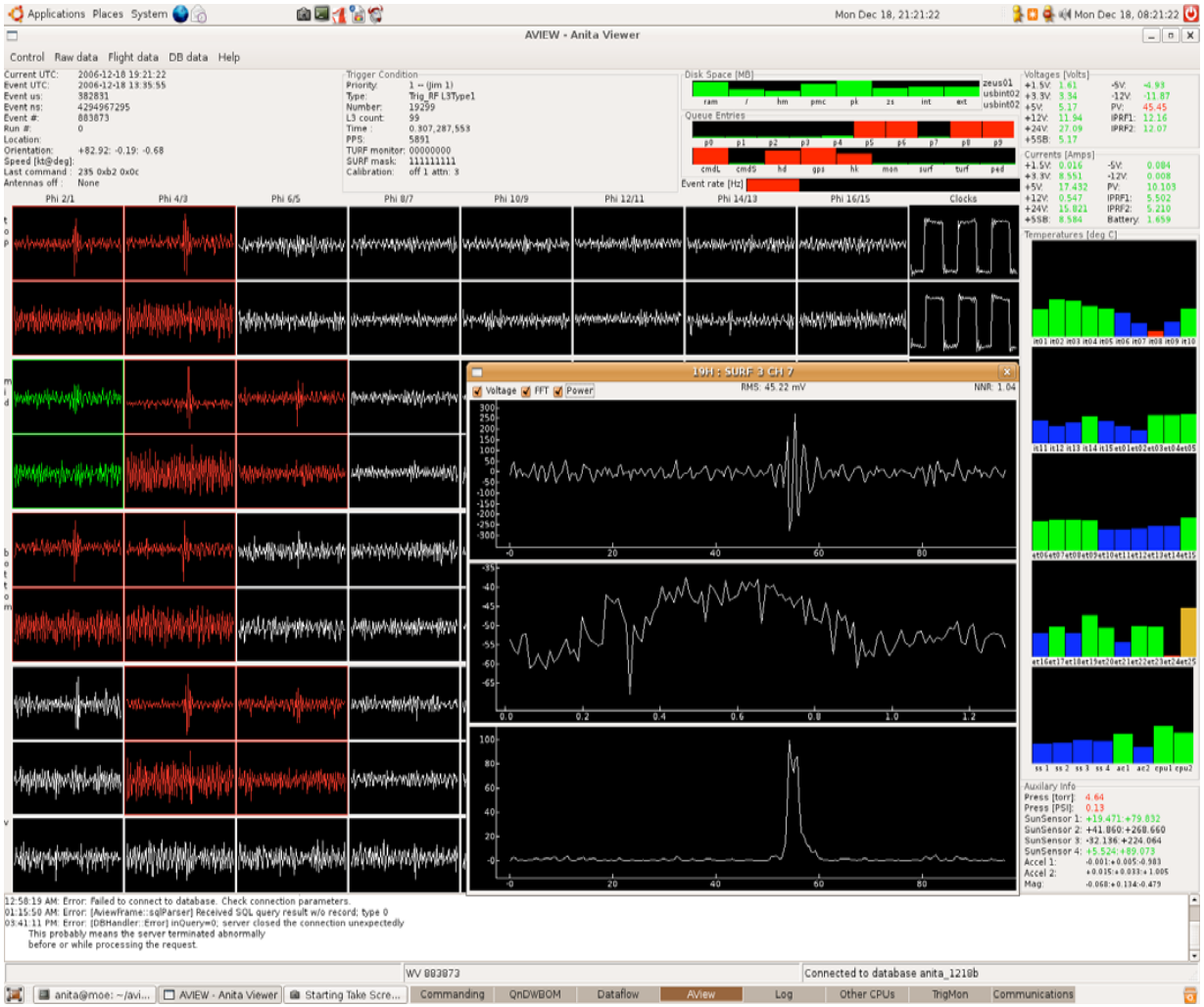
100-200kHz @ 36kBy/evt = 3.6-7.2Gby/s

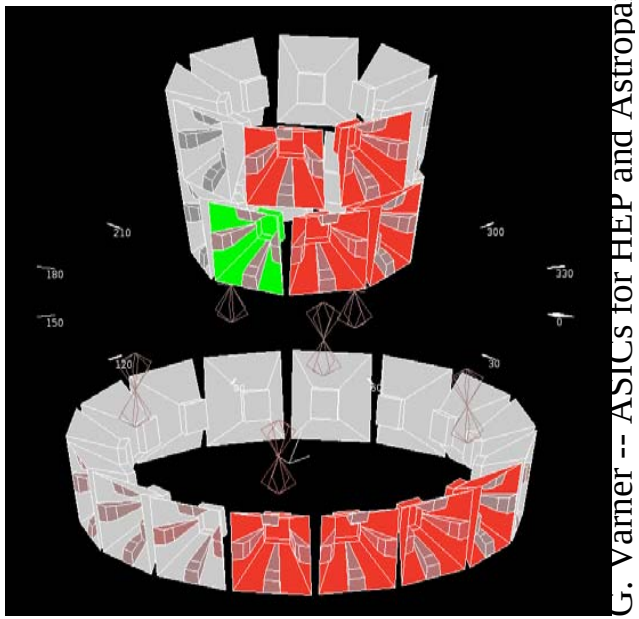
Few kHz @ 36kBy/evt = 36-72Mby/s

5-10Hz @ 36kBy/evt = 180-360kBy/s

To disk

Viewing Impulsive Events with ANITA Viewer

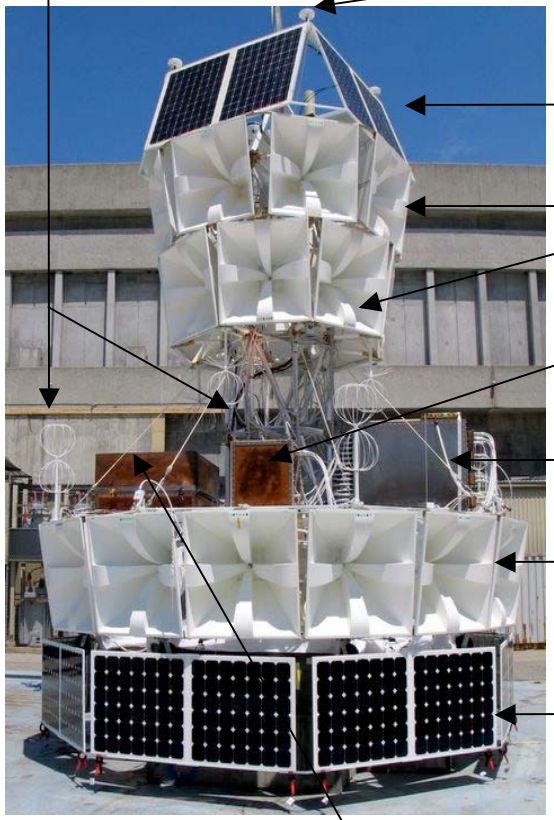




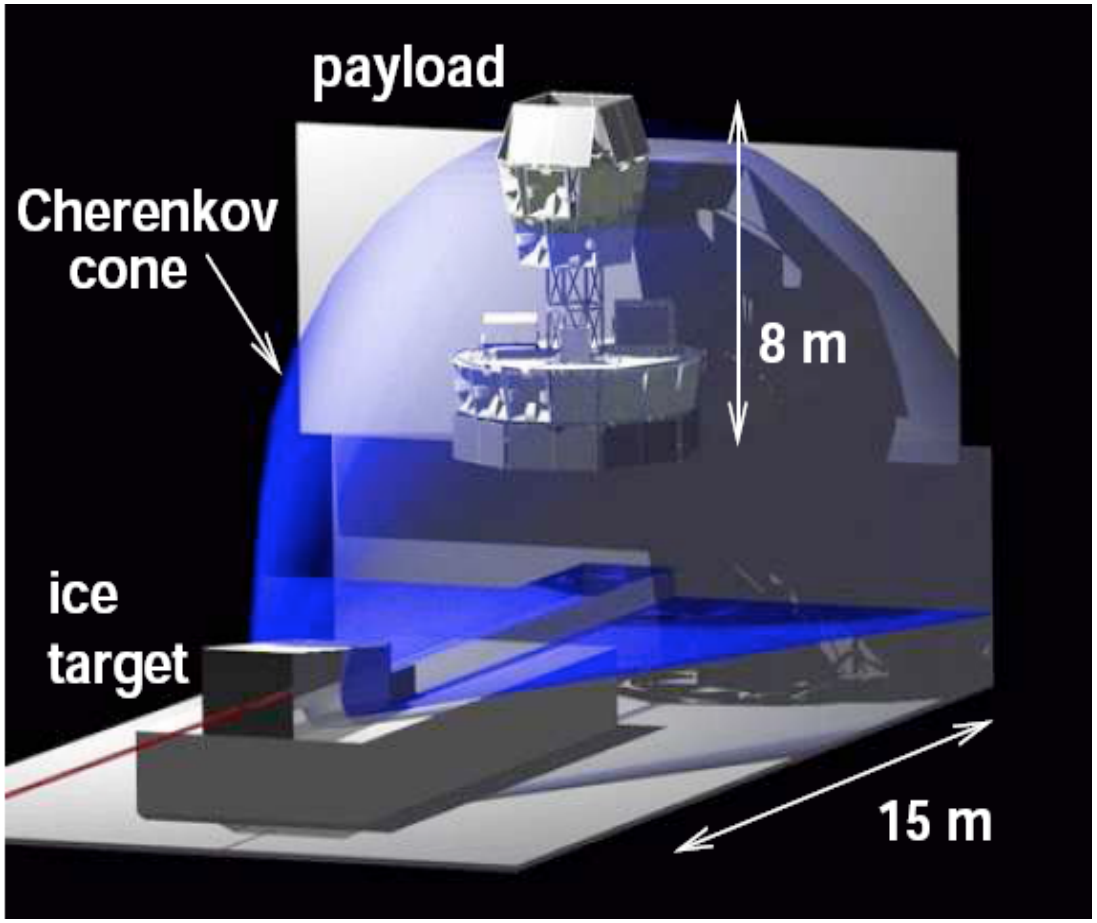
T-486 [Ice!] ANITA on the End Station A beamline (June 2006)

- 32 QR horns
- 4 discones
- 4 bicones
- 8 monitor antennas
- 72 (288) channels RF digitizer & 256 channels trigger (self-triggered)
- Ethernet/LOS Tx only

The ANITA Payload

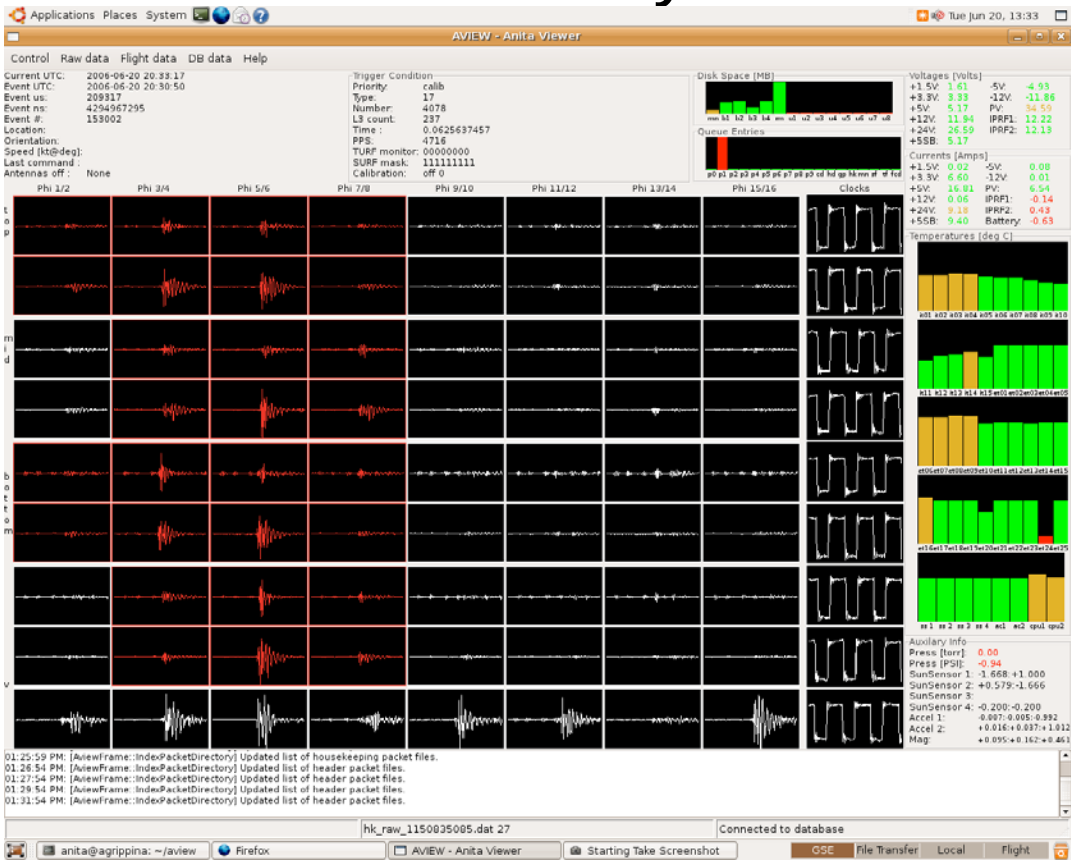


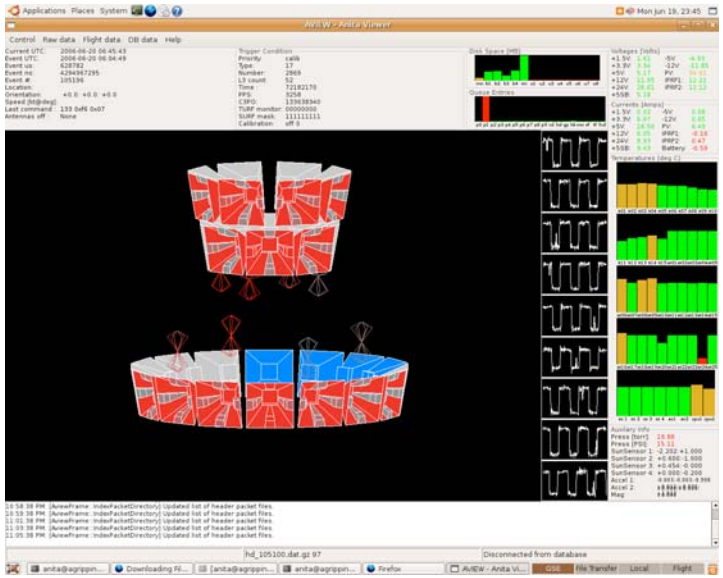
SLAC T486

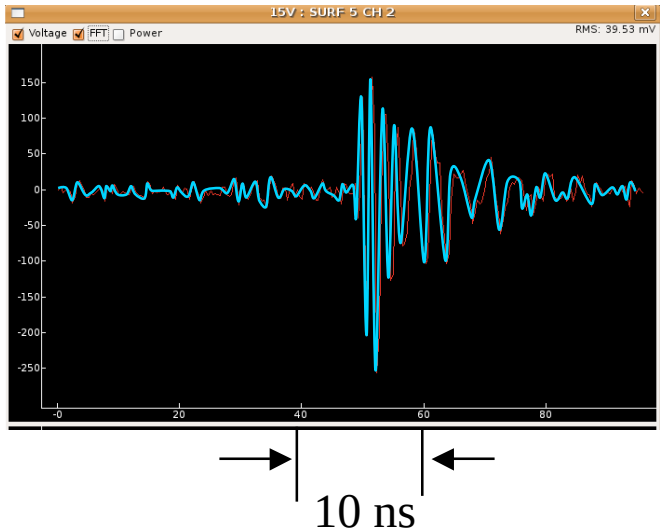


- 1st measurement of the Askaryan Effect in Ice
- Calibration of the ANITA experiment with 28.5 GeV electrons
- EM shower max ~ 2m inside 7 tonne ice target
- Examine effects of surface roughness
- 1 week of live-time

Askaryan effect in ice



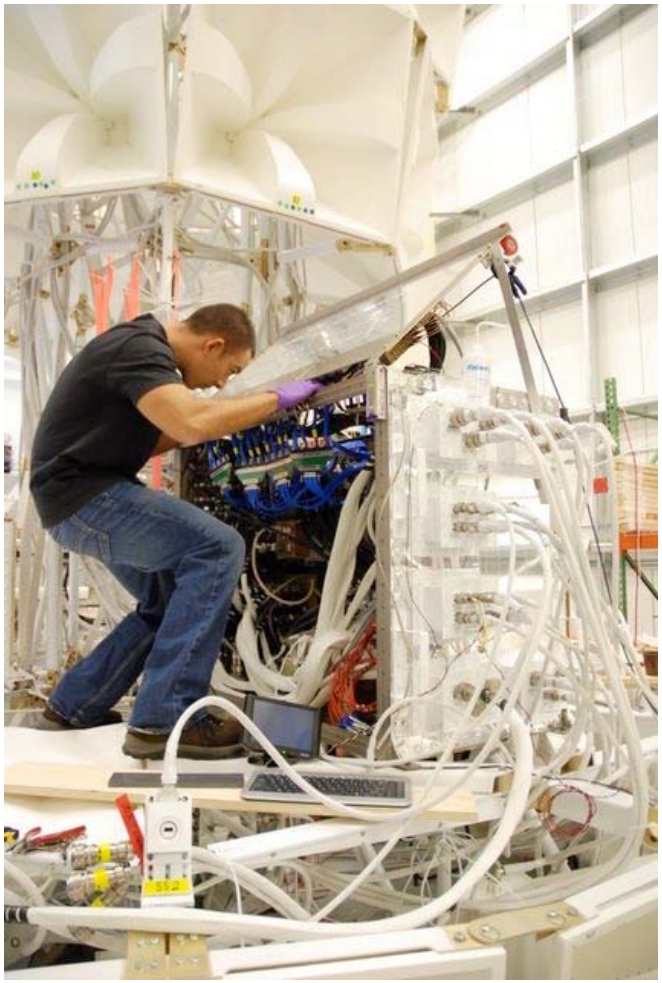




- **Impulses are band-limited, highly polarized, as expected**

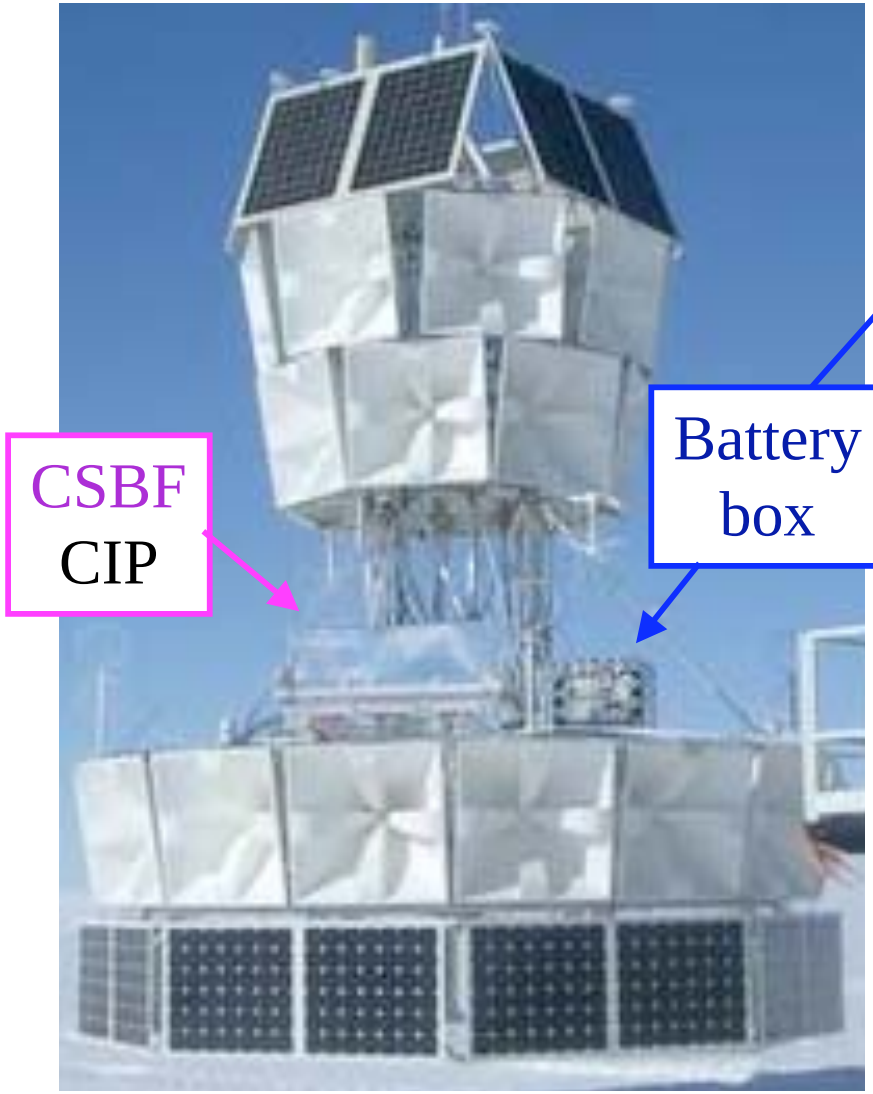
- **Very strong--need 20dB 'pads' on inputs--signals are +95dB compared to Antarctic neutrino signals, since we are much closer**

Life in Payload Bay 1

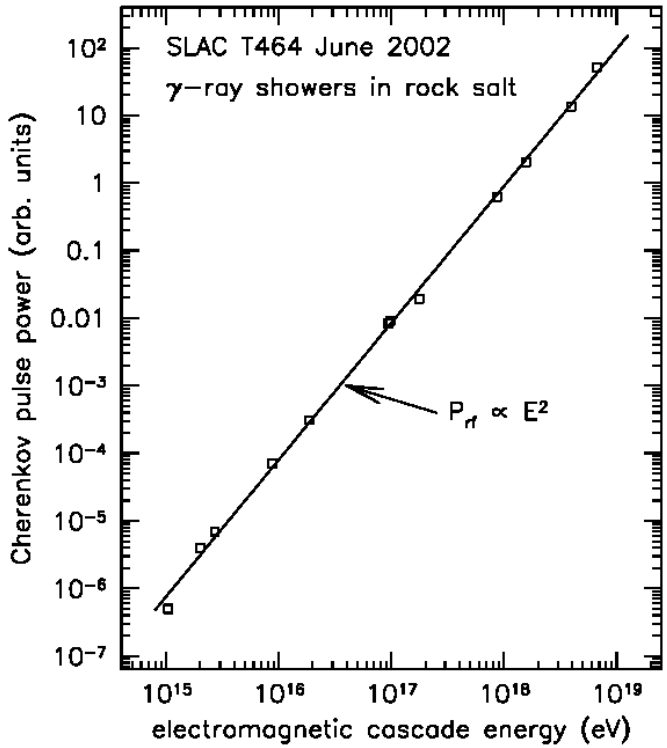


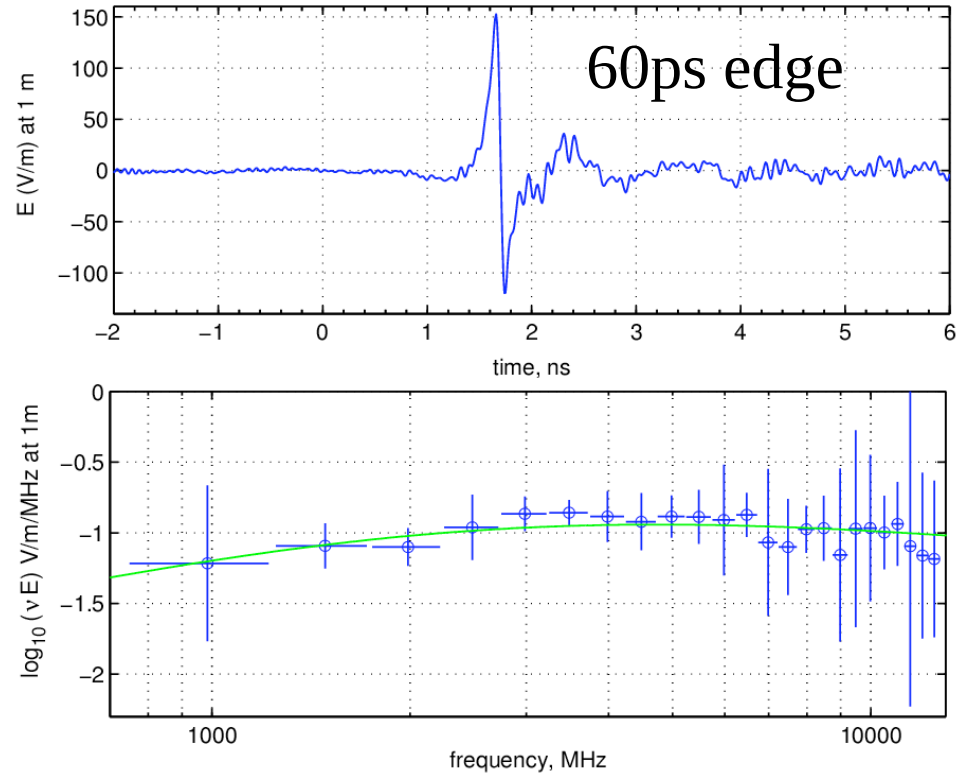
- Barely fit out door
- Room dropped 45C in 30 s
- 4-5 hours to recharge
- Go outside to warm up

Key Instrument pieces



RF Coherence vs. energy & frequency

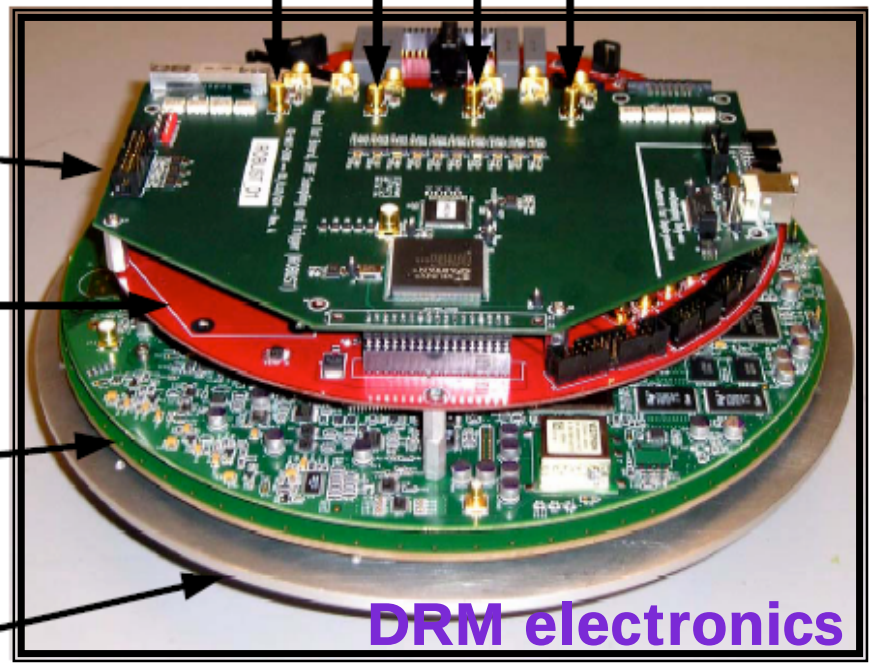


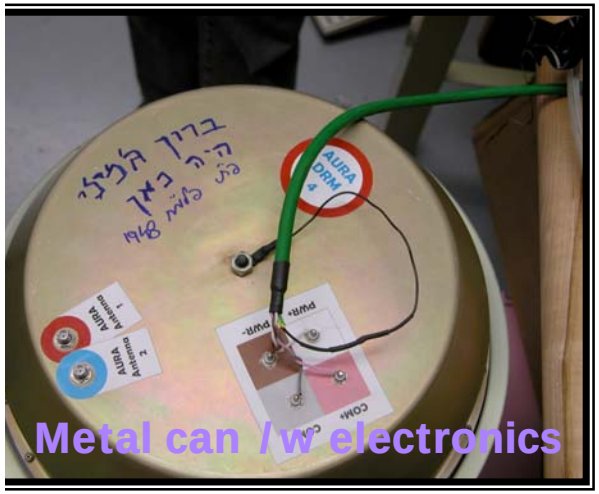


- **Much wider energy range covered than previously: 1PeV up to 10 EeV**
- **Coherence (quadratic rise of pulse power with shower energy) observed over 8 orders of magnitude in radio pulse power**
- **Differs from actual EeV showers only in leading interactions==> radio emission almost unaffected**

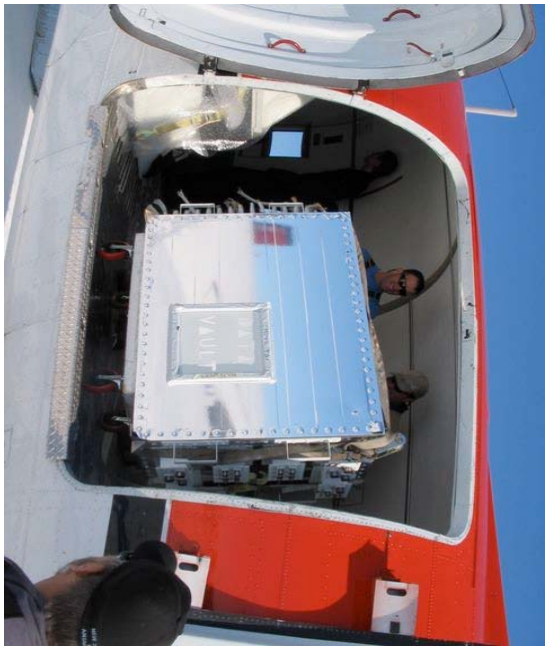

Sealing the DRM

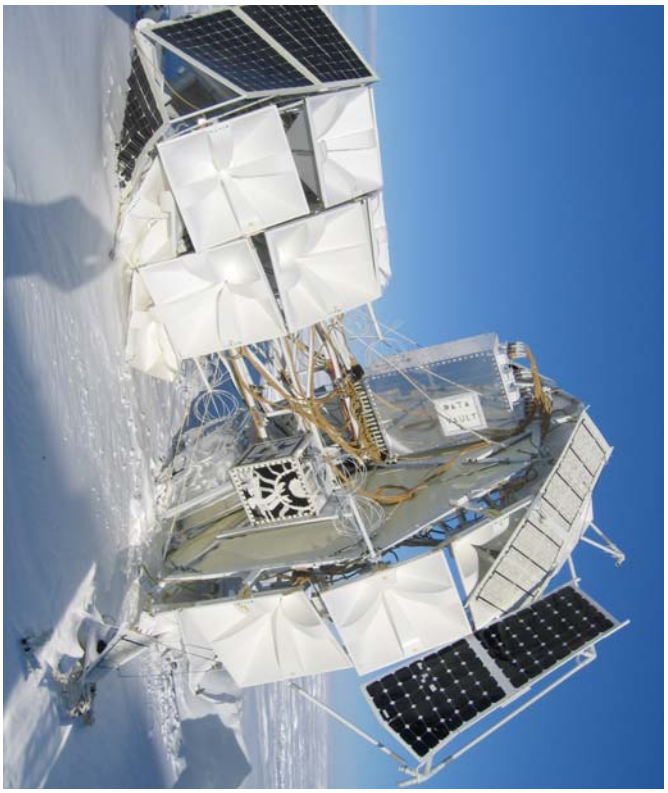

EXIT
Surface Test


Antennas
ROBUST
TRACR
DOM-MB
Metal Plate
DRM electronics


AURA
DRM
4
Metal can / w electronics

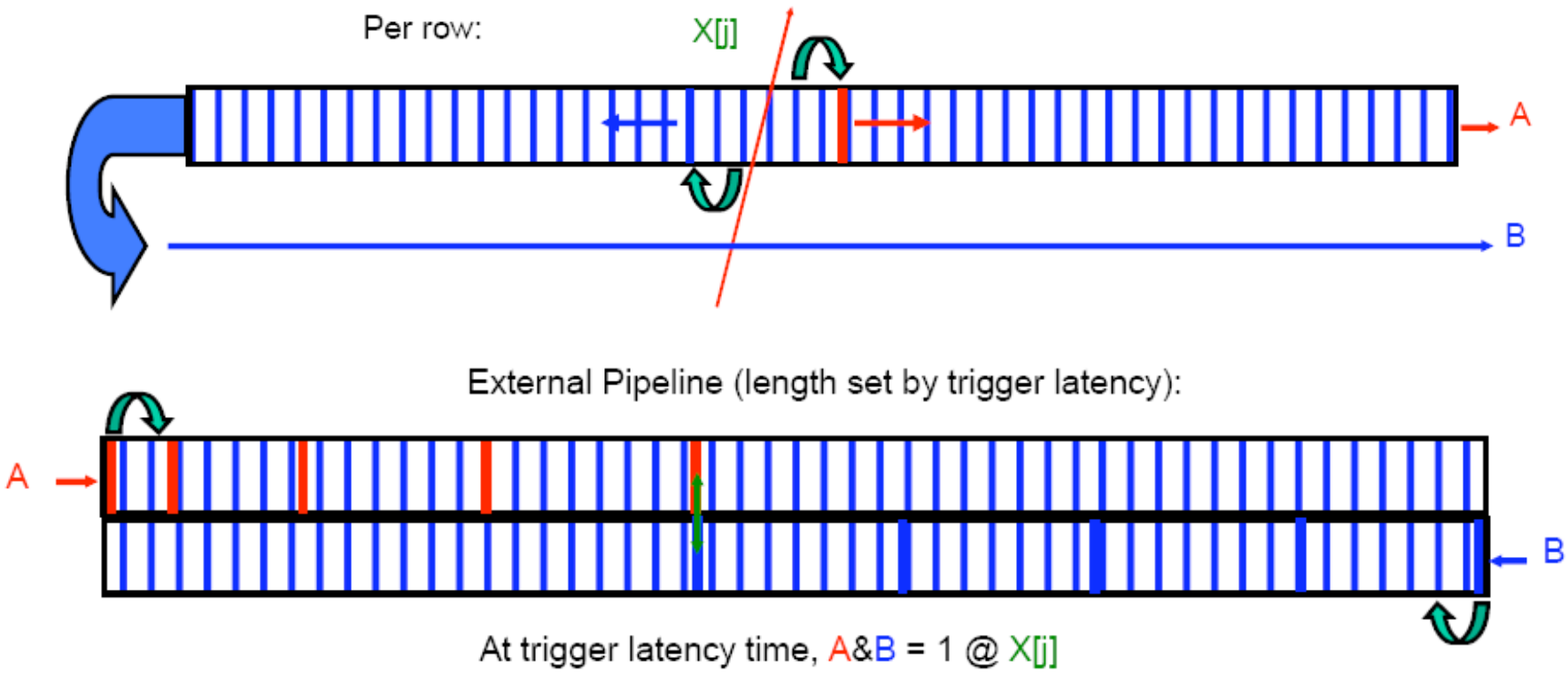

095





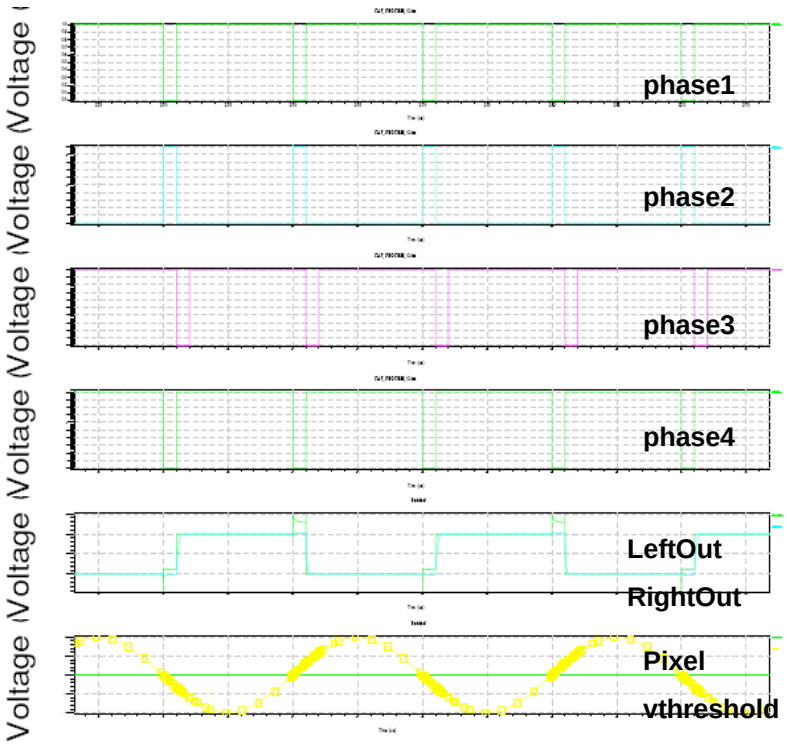
CAP5

BINARY READ OUT

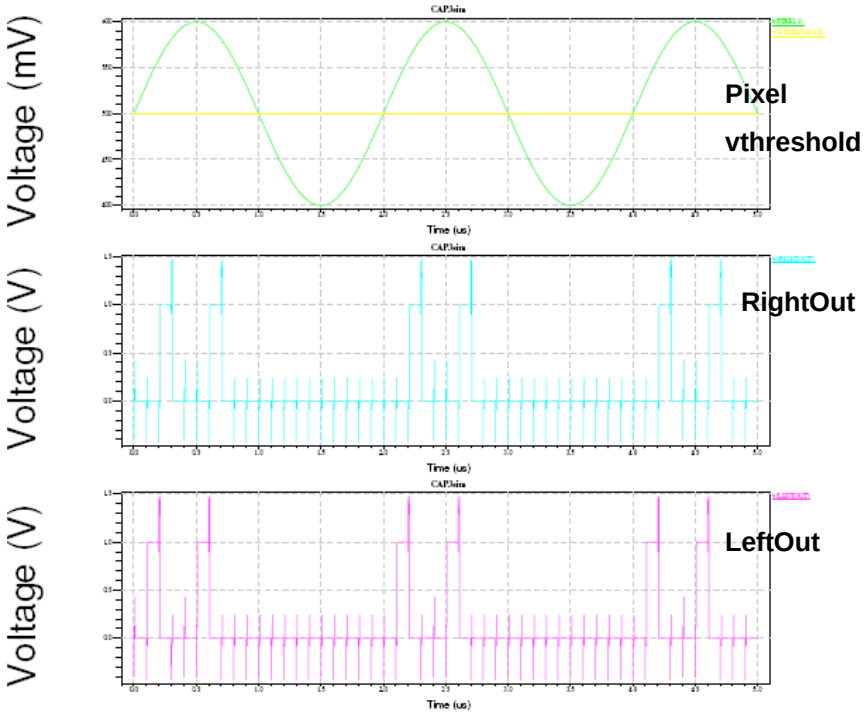


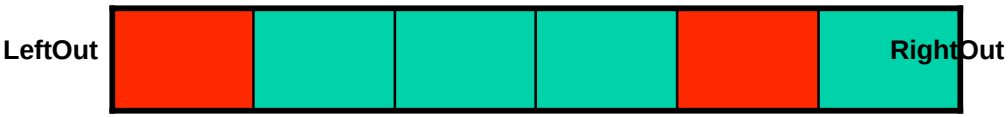
CAP5

1pixel simulation



6pixel simulation





Vacuum MCP-PMT Issues

- lower Q.E., fill factor
- High voltage operation, longevity
- High density packing
- Magnetic field effects
- Irreducible Manufacturing Costs

How to get to a large system?

- SBIR with LightSpin Technologies
  - Proprietary Solid-State MCP demonstrator (1 x 1024)
  - No HV, high Q.E. (200 – 900nm!!)
  - Lower dark count rate than Si-PM
  - Mate with BLAB variant, determine timing resolution