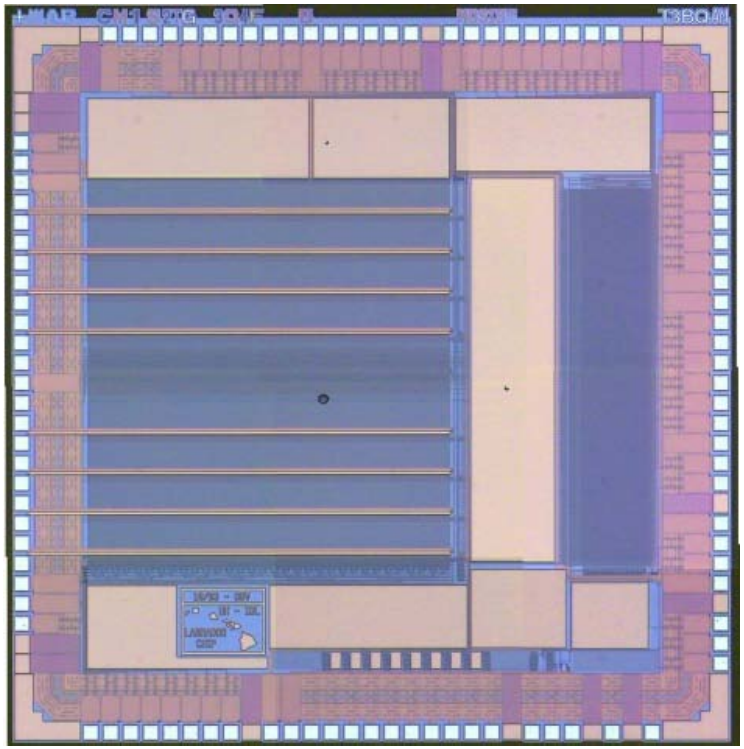
The “Giga” Era of Instrumentation at the Discovery Frontier



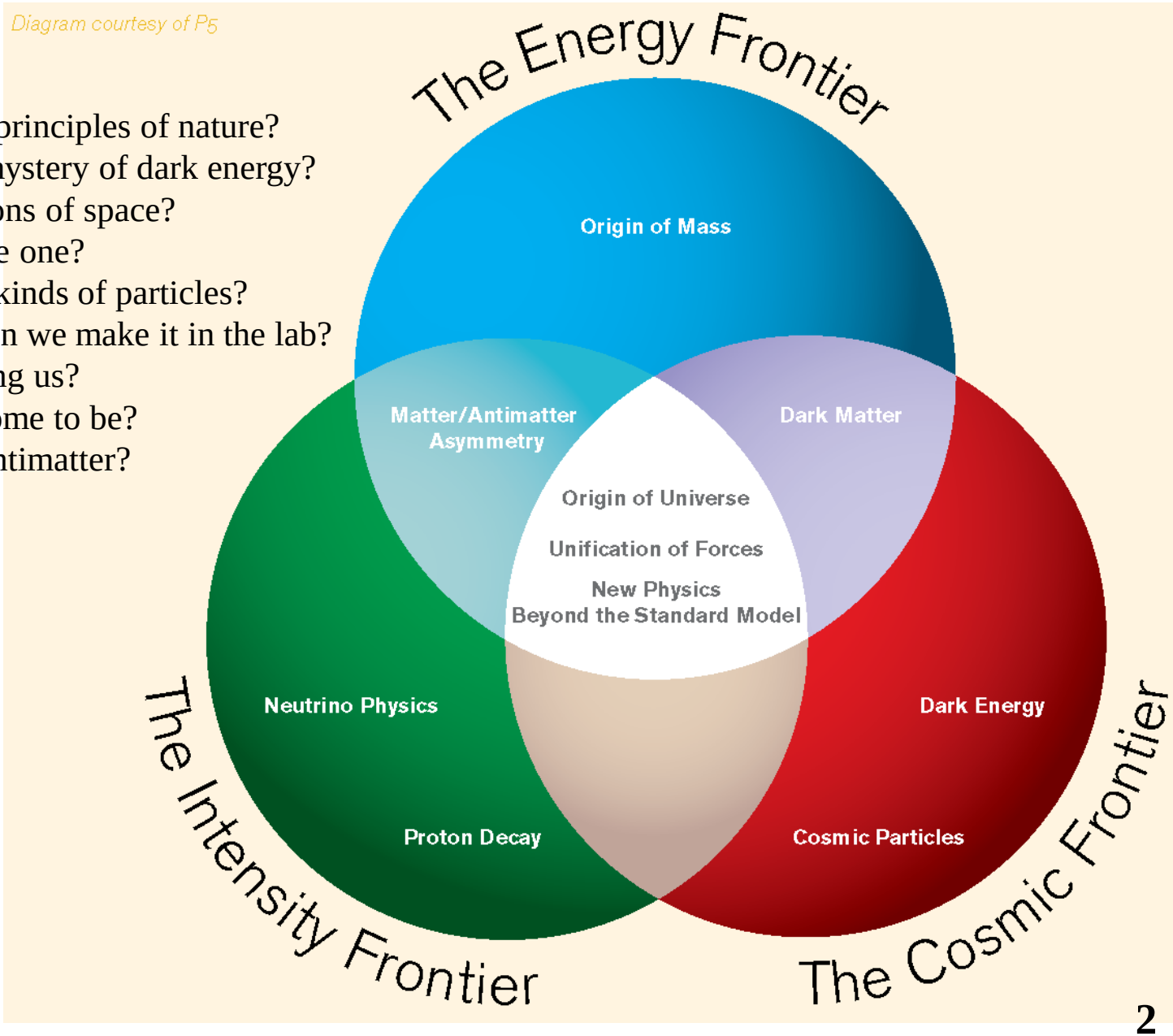
Gary S. Varner

University of Hawai’i

KMI Seminar, Nov. 9, 2012

The big Questions

1. Are there undiscovered principles of nature?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? Can we make it in the lab?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?



The (Particle Physics) Discovery Frontier

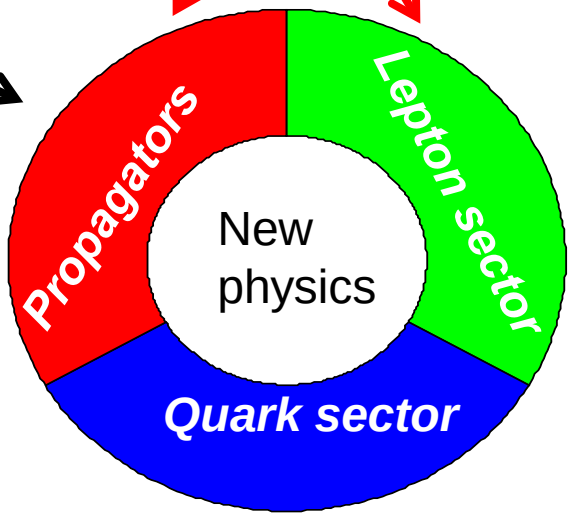
LHC, ILC

Higgs boson mass and couplings. New particle searches

UHE neutrinos

ν expts accel, reactor, g_μ-2, $\mu \to e\gamma$, etc.

ν mass and mixing, CPV, and LFV



τ LFV, τ CPV

Flavor mixing, CPV phases

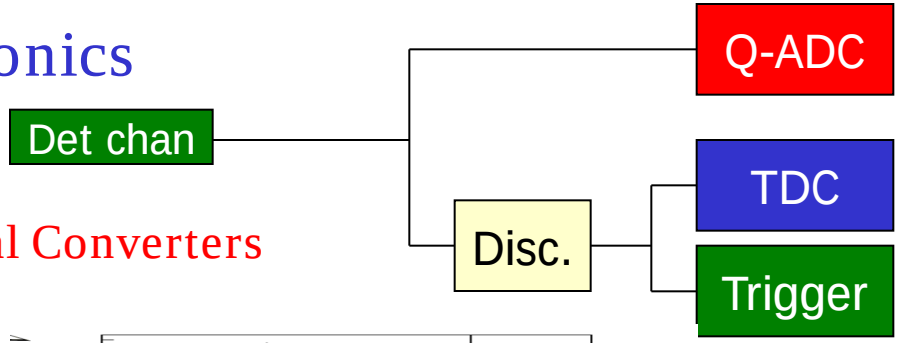
Super B Factory, LHCb, BESIII, Rare *K* expts, …

Overview

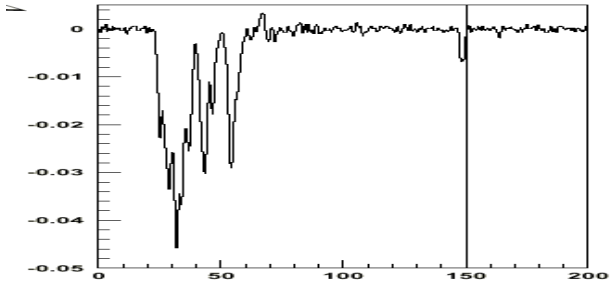
- Further advances at the Discovery Frontier
  - Depends upon developing new instruments and techniques
  - Exploit commodity resources
- The "easy" experiments are being completed
  - Can't necessarily scale up ($$$, $T > N * t_{gradstudent}$)
  - Innovation fuels new opportunities
- What I hope to convey:
  1. What the "Giga" Era means
  2. Key elements
  3. An example where this has been fundamentally enabling
  4. The Belle II (Time Of Propagation) Particle Detector

Detector Instrumentation Evolution

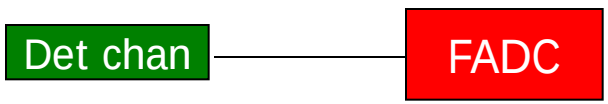
- Traditional "crate based" electronics
  - Gated Analog-to-Digital Converters
  - Referenced "triggered" Time-to-Digital Converters



- High-rate applications
  - "pipelined operation"
  - Low-speed, low-resolution sampling



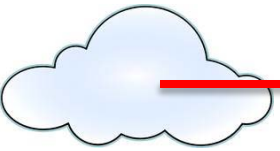
- High channel counts
  - Motivation to reduce cabling
  - Integrate electronics onto detector elements



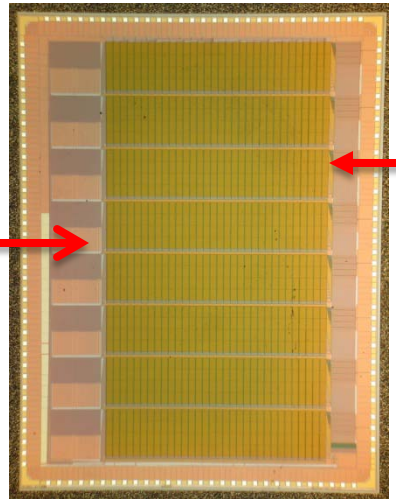
Issues: cost, power, resolution, data volume

A “Giga” Overview (Modern Readout)

Physical

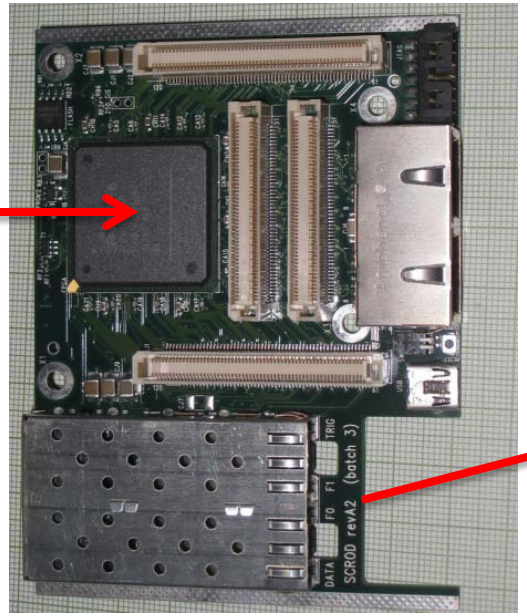


Measurement



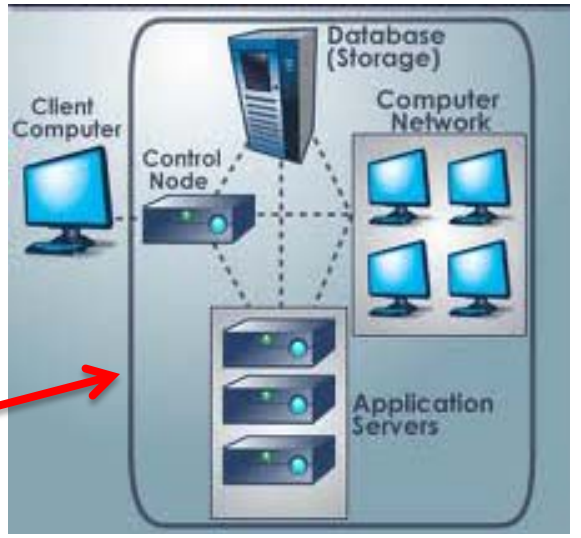
1. **Giga**sample/s “digital oscilloscope on a chip”

2. 100’s of **Giga**flops per Field-Programmable Gate Array



3. Inexpensive **Giga**-bit/s fiber link interconnect; **Giga**-bit ethernet

4. Commodity Servers running at **Giga**-Hz rates, 1000’s of **Giga**flops



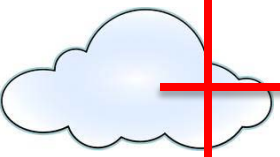
Technology advances ➔ high rate, high-precision experiments

Focus on the first of these

2. 100's of Gigaflops per Field-Programmable Gate Array

4. Commodity Servers running at Giga-Hz rates, 1000's of Gigaflops

Physical



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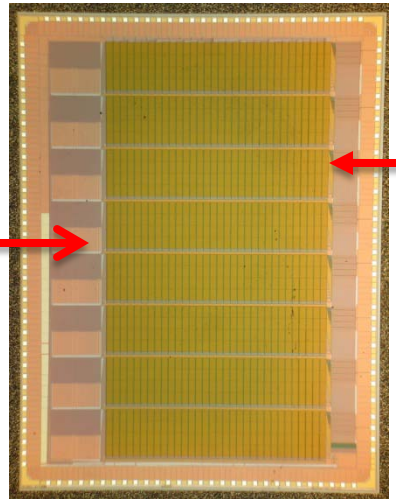
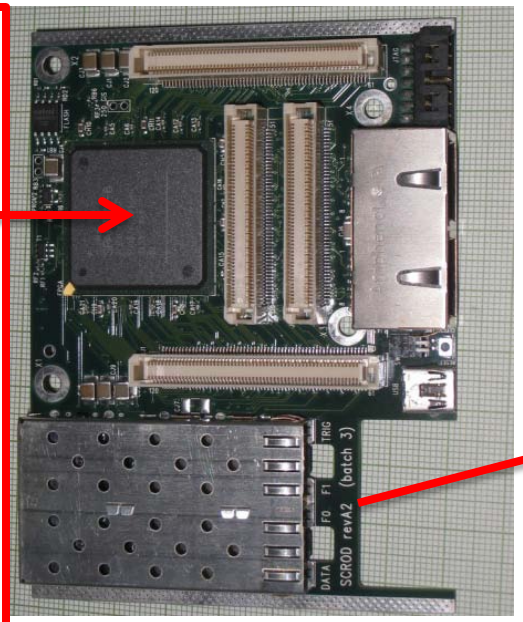
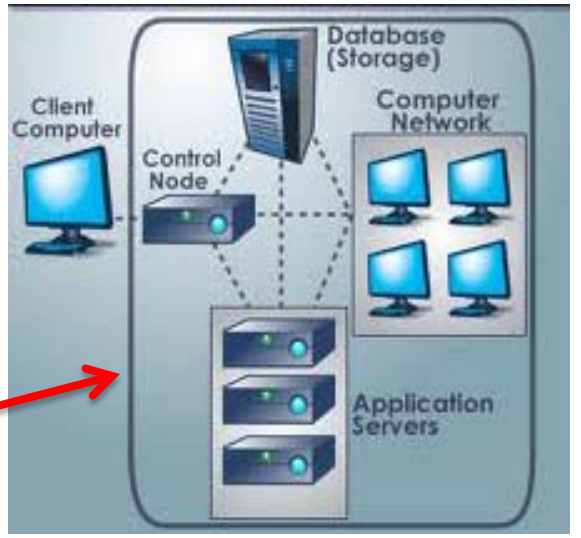






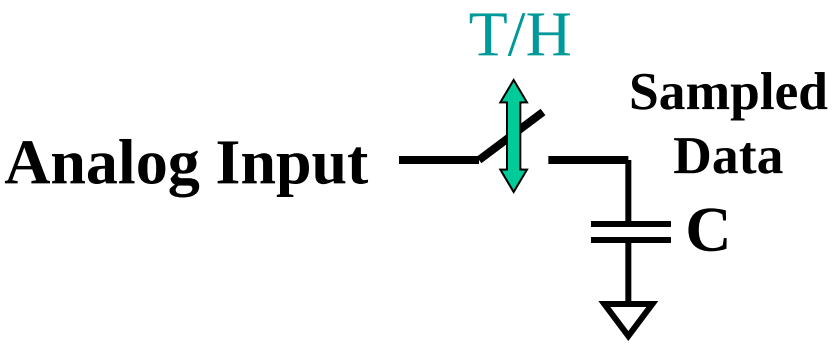
1. Gigasample/s "digital oscilloscope on a chip"

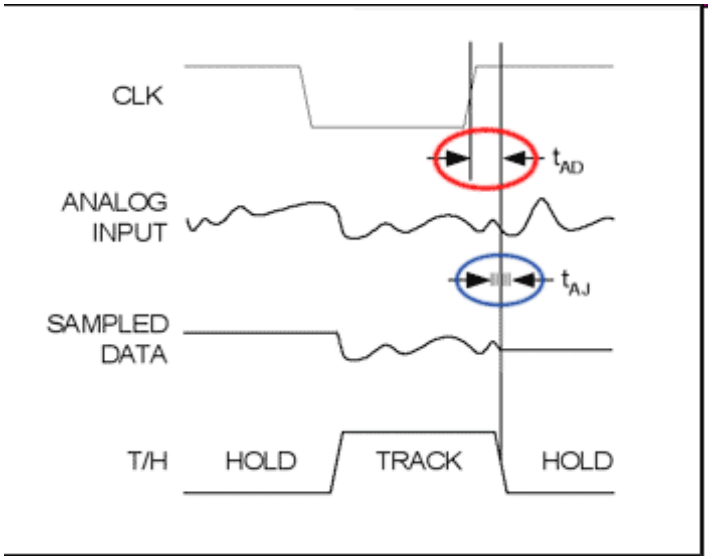
3. Inexpensive Giga-bit/s fiber link interconnect; Giga-bit ethernet

- Defines limit of the physical measurement
- What Instrumentation Physicists contribute

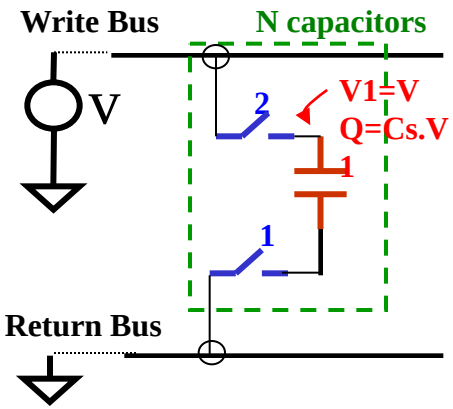
Underlying Technology

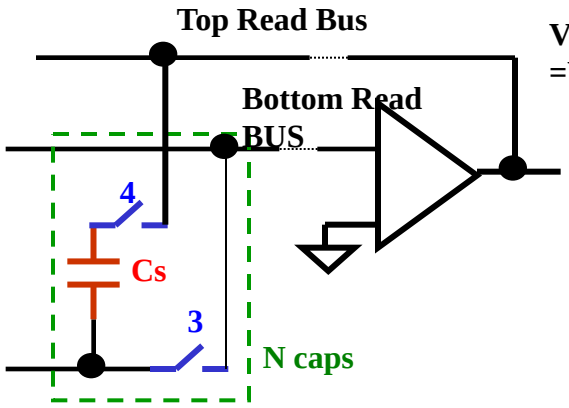
- Track and Hold (T/H)





- Pipelined storage = array of T/H elements, with output buffering

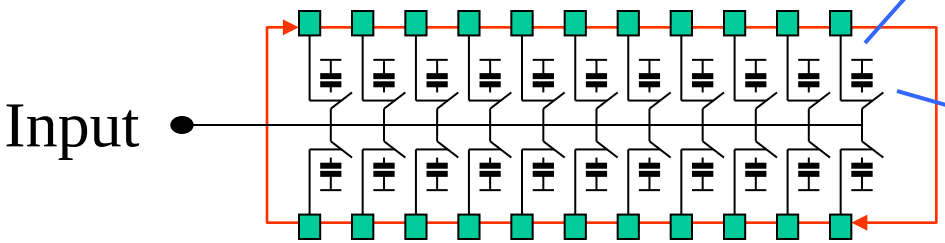


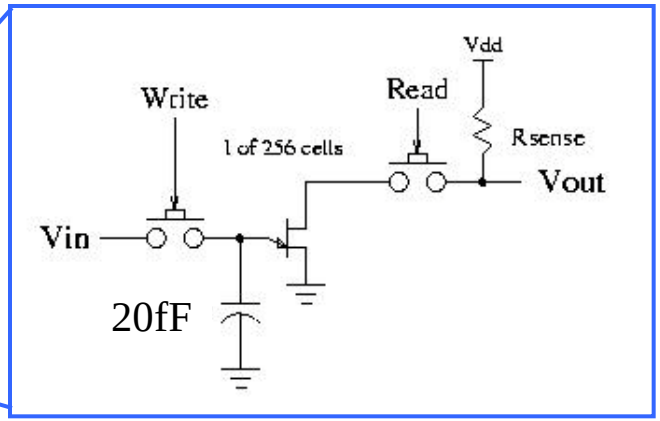


Vout=A / (1+A) * Q/Cs
=V1 * A/(1+A)

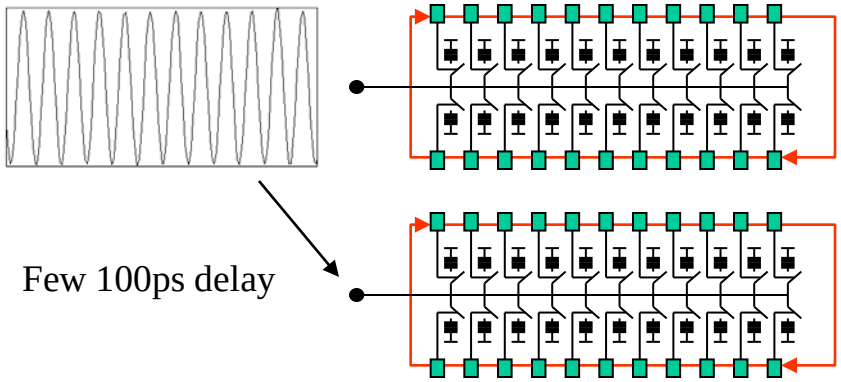
Switched Capacitor Array Sampling

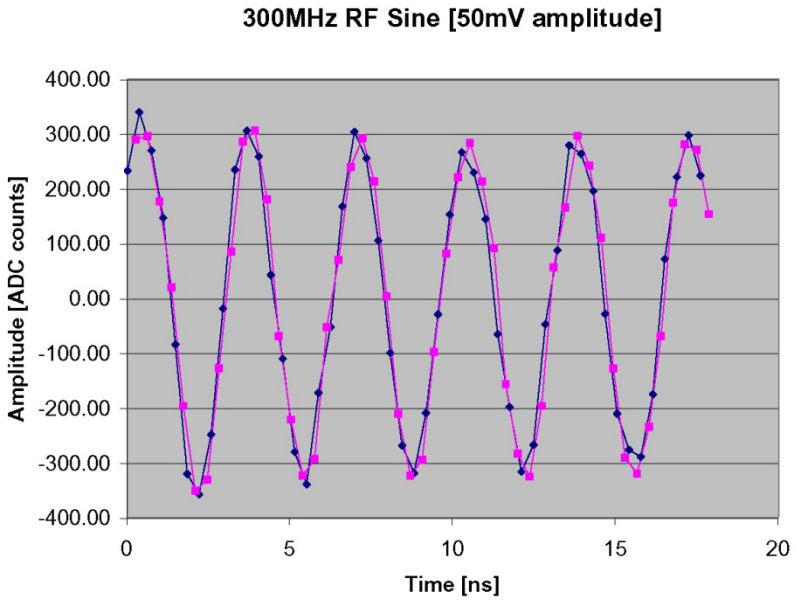
- Write pointer is ~few switches closed @ once



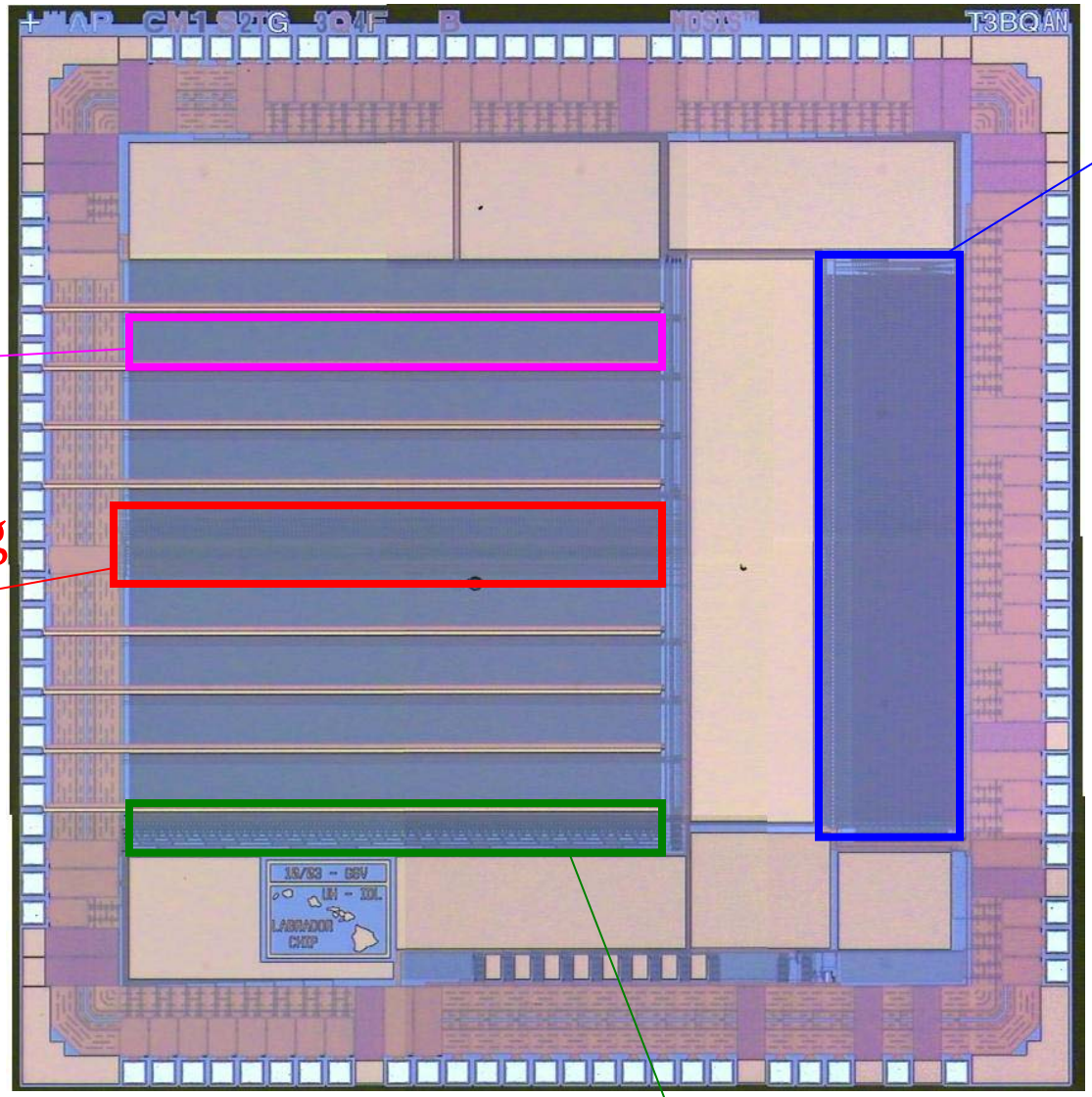


Tiny charge: 1mV ~ 100e$^-$

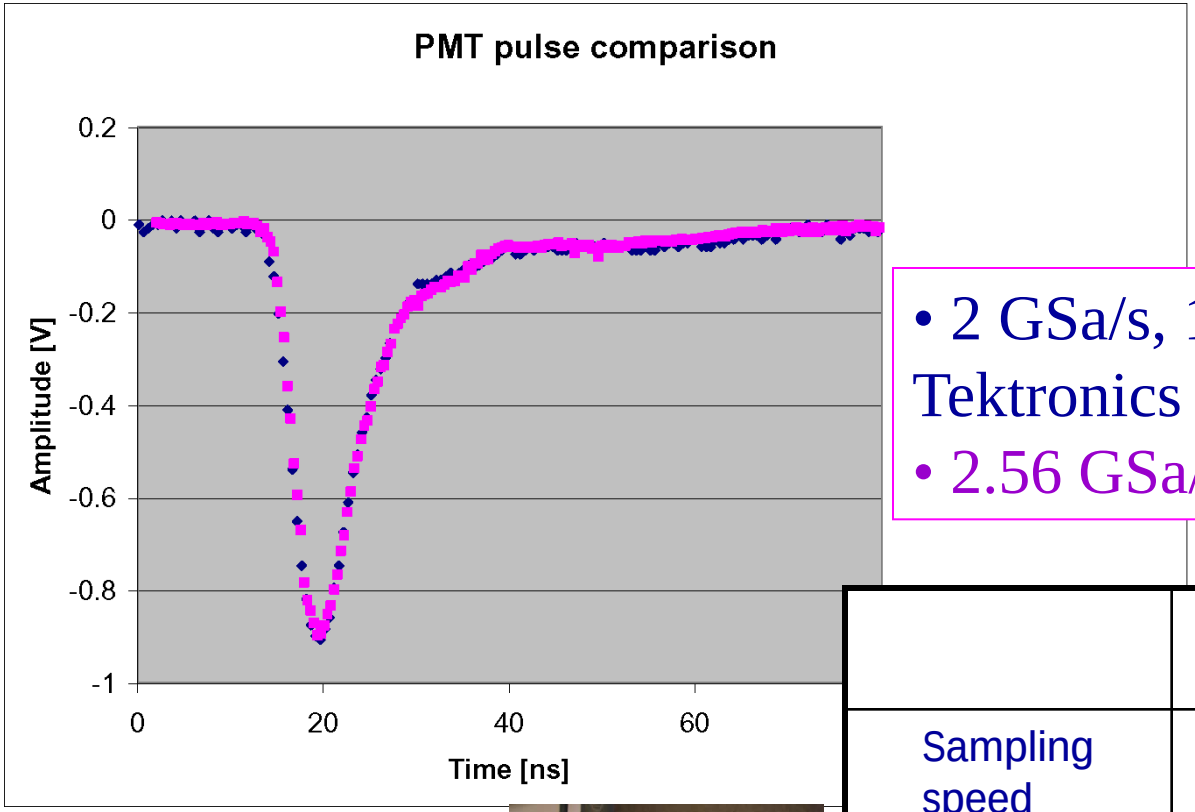


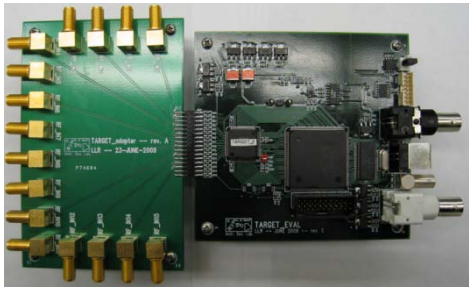


Basic Functional components



The Giga Package

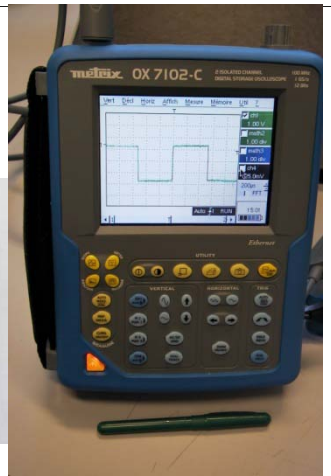




- 2 GSa/s, 1GHz ABW Tektronics Scope
- 2.56 GSa/s LAB

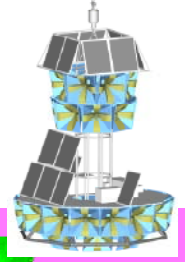
	WFS ASIC	Commercial
Sampling speed	0.1-6 GSa/s	2 GSa/s
Bits/ENOBs	16/9-13+	8/7.4
Power/Chan.	<= 0.05W	Few W
Cost/Ch.	< $10 (vol)	> 100$

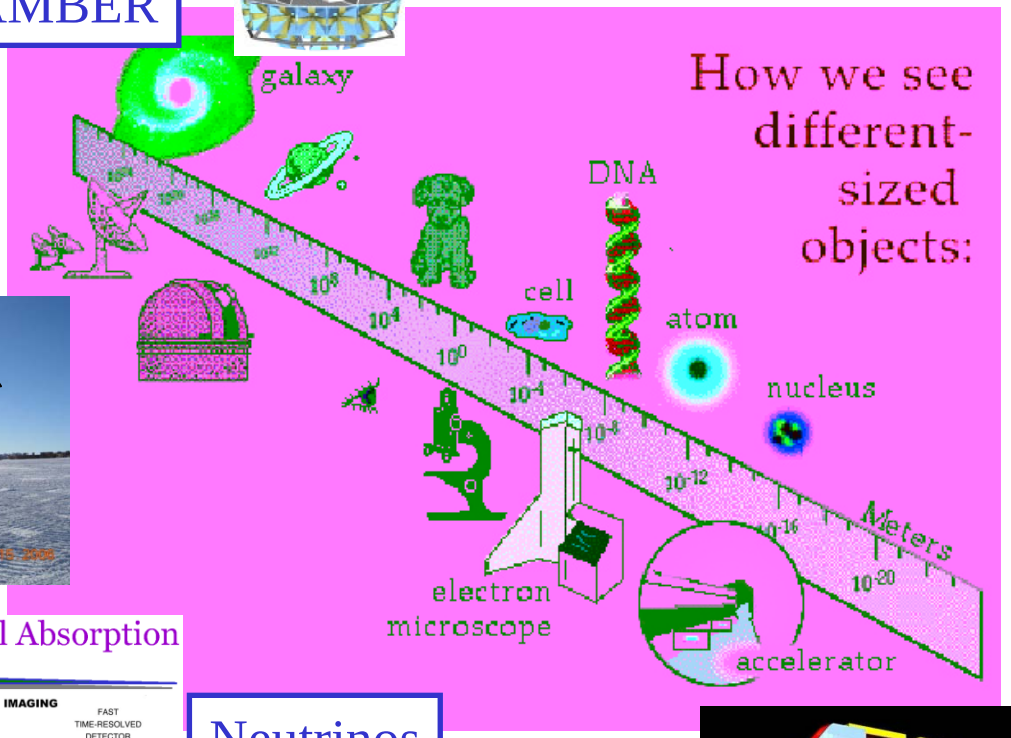
"oscilloscope on a chip"

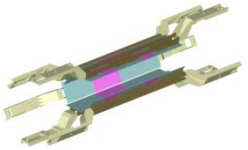


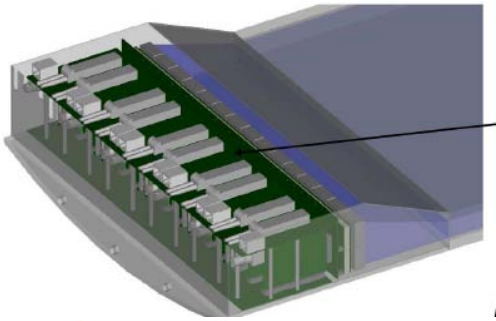
Very broad Impact

AMBER

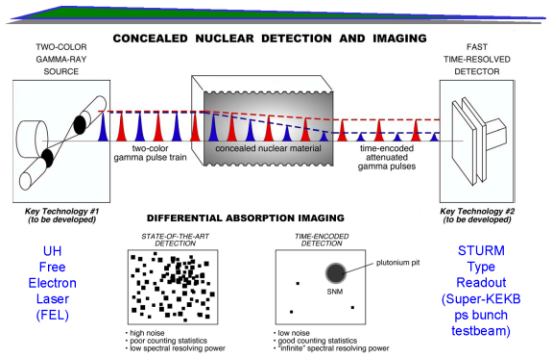




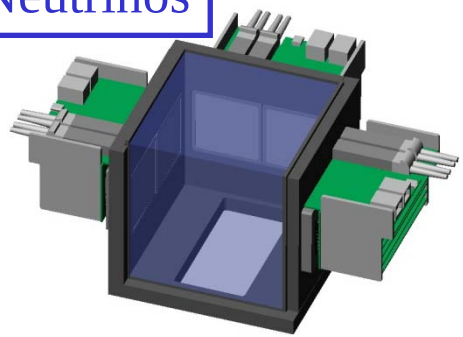


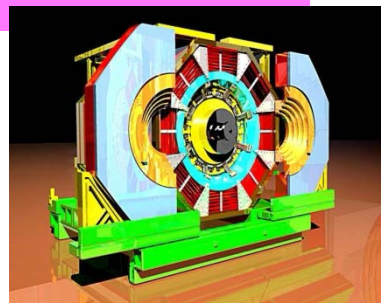


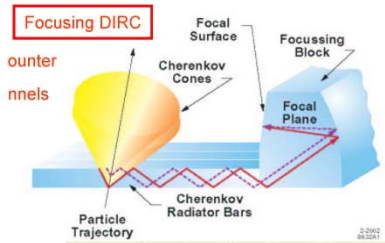
Time-Encoded Differential Absorption



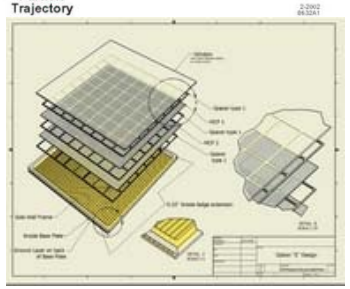
Neutrinos





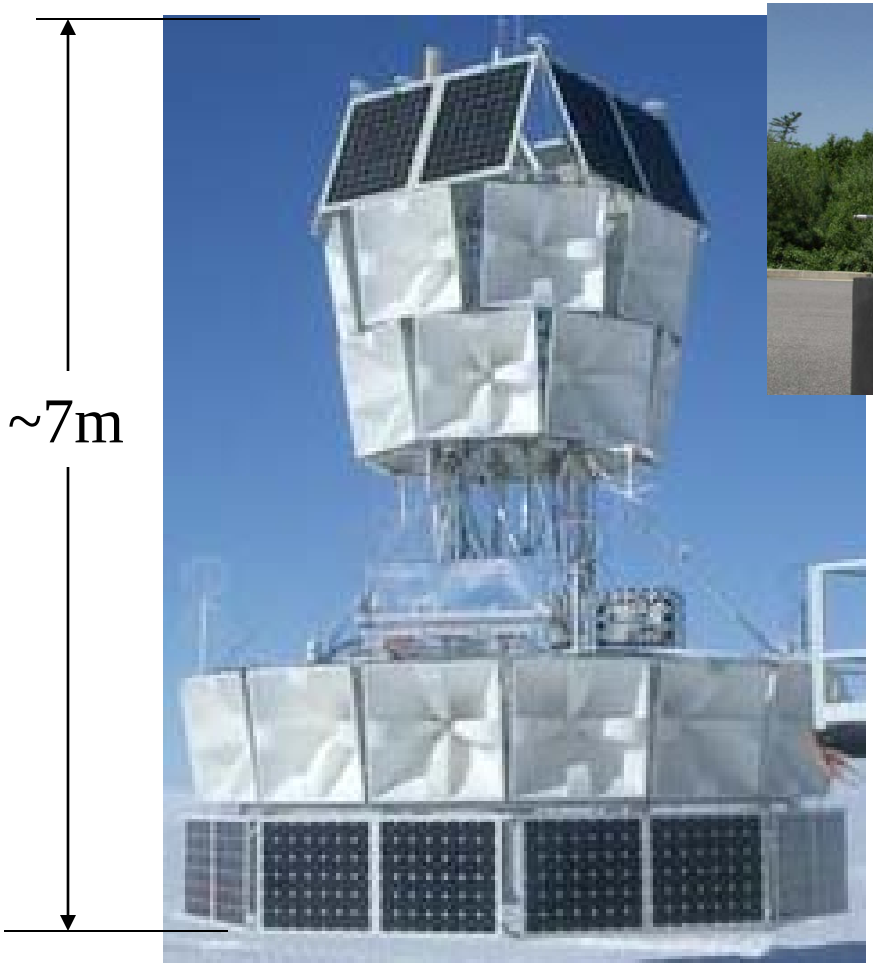


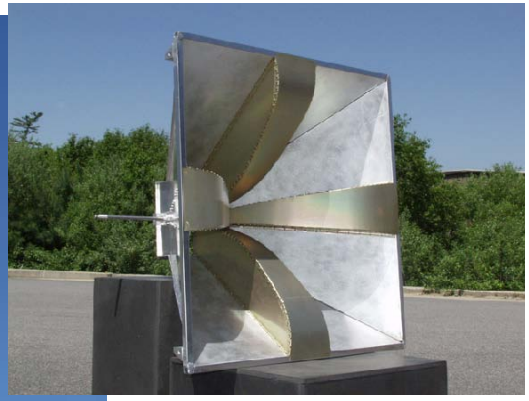
LAPPD→

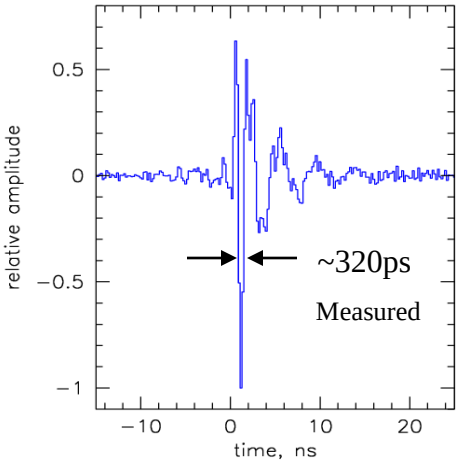


Fundamental enabling technology (all current Hawaii activities)

To be explicit, a demanding Application



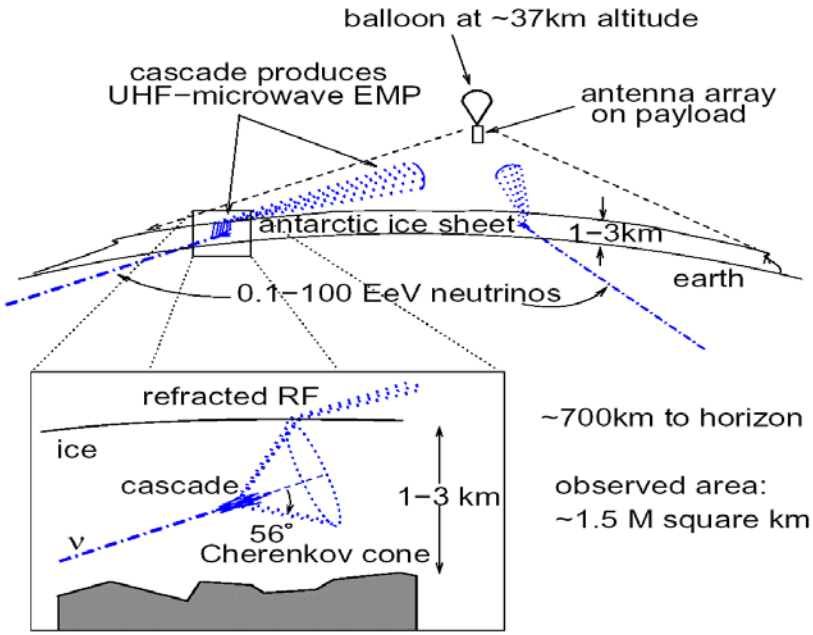


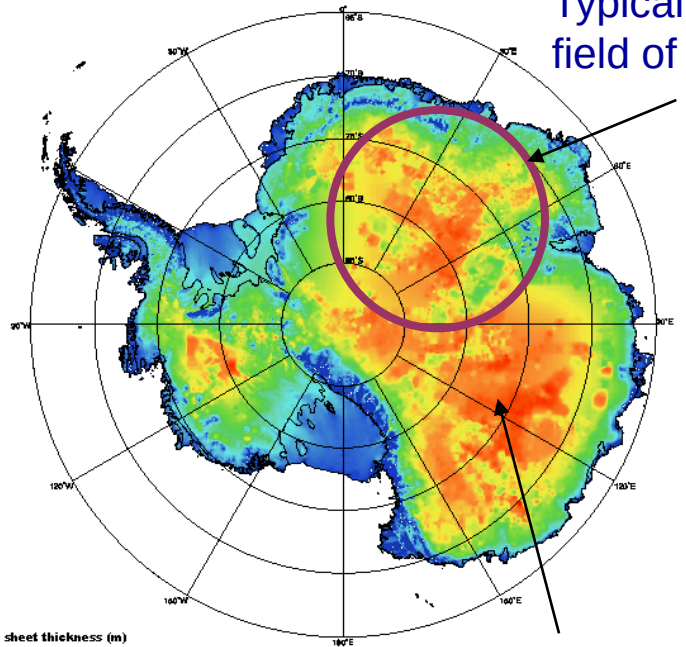


Antarctic Impulsive Transient Antenna (ANITA-I)

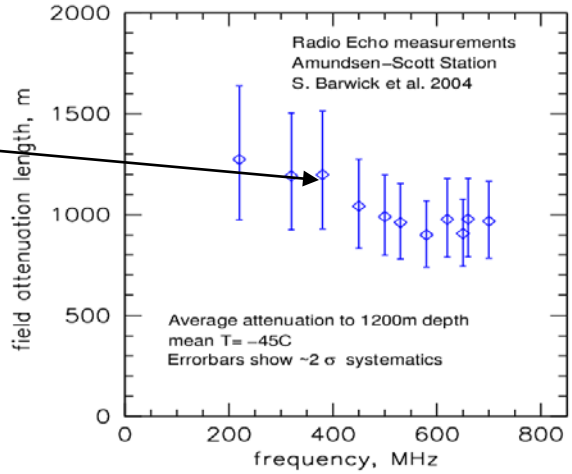
- RF Transient (impulsive) Events (200-1200 MHz)
- 324 chan. @ 2.6GSa/s
- Completely solar powered (tight demands on power, few hundred W total)
- Need full waveforms

ANITA concept





Ice RF clarity: ~1.2km(!) attenuation length



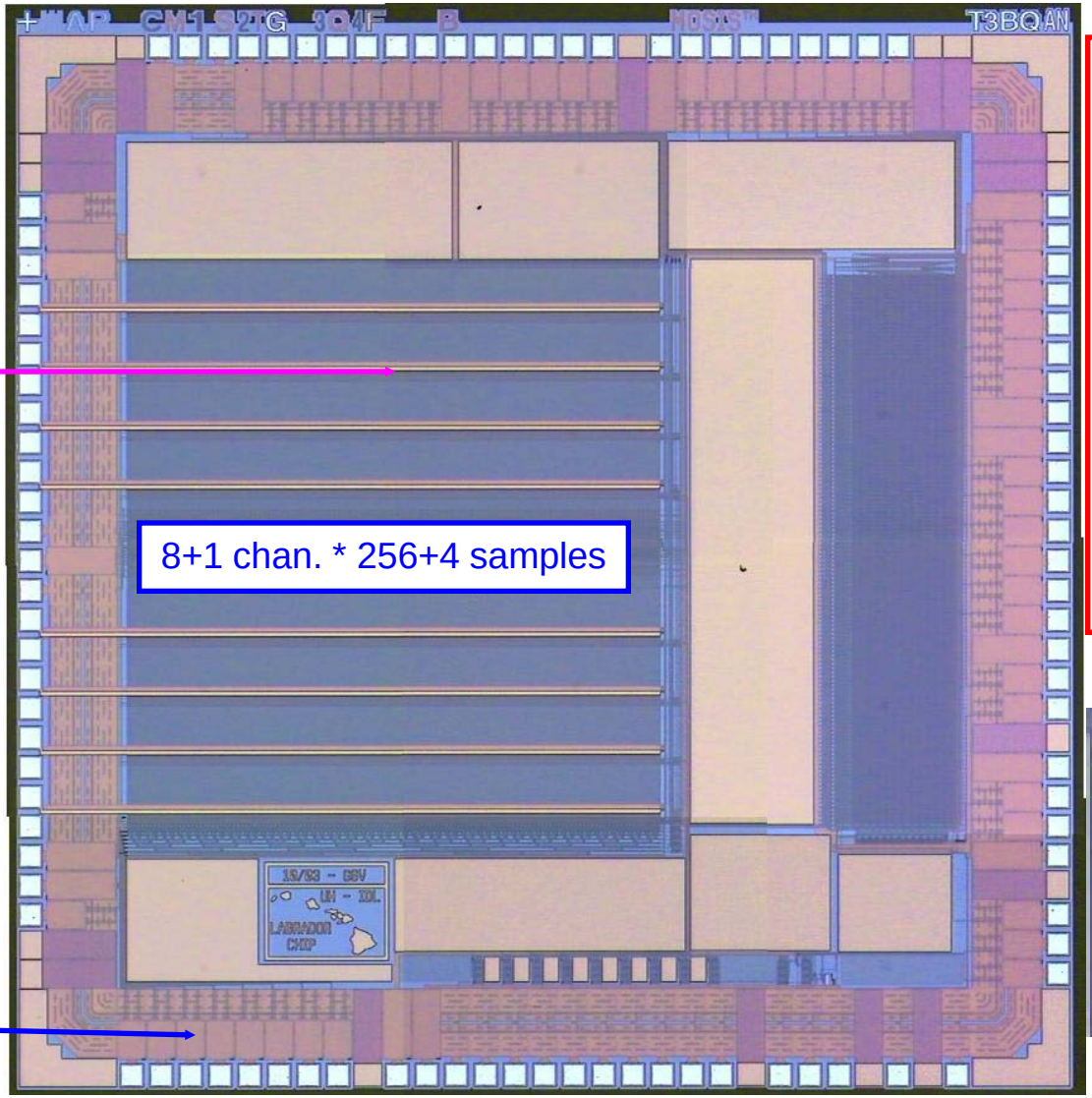
Effective "telescope" aperture:

- ~250 km^3 sr @ 10^{18} eV
- ~10^4 @ km^3 sr 10^{19} eV

(compare to ~1 km^3 at lower E)

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

Straight Shot RF inputs

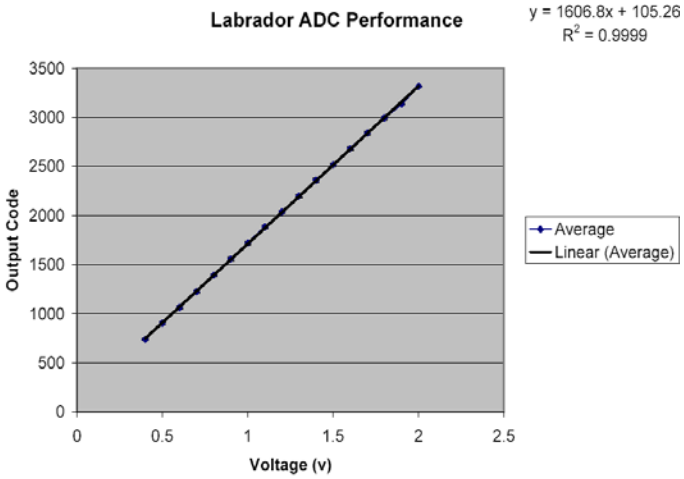


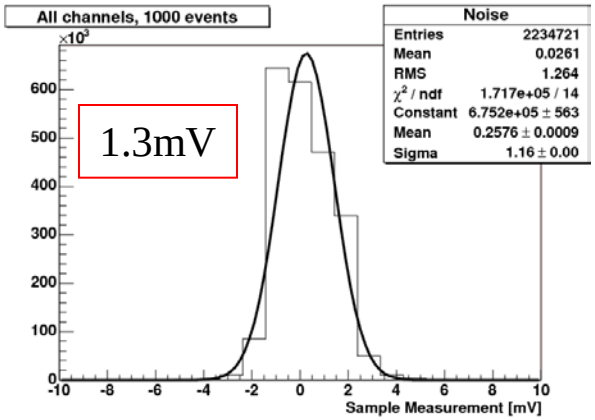
- Switched Capacitor Array (SCA)
- Massively parallel Wilkinson ADC array

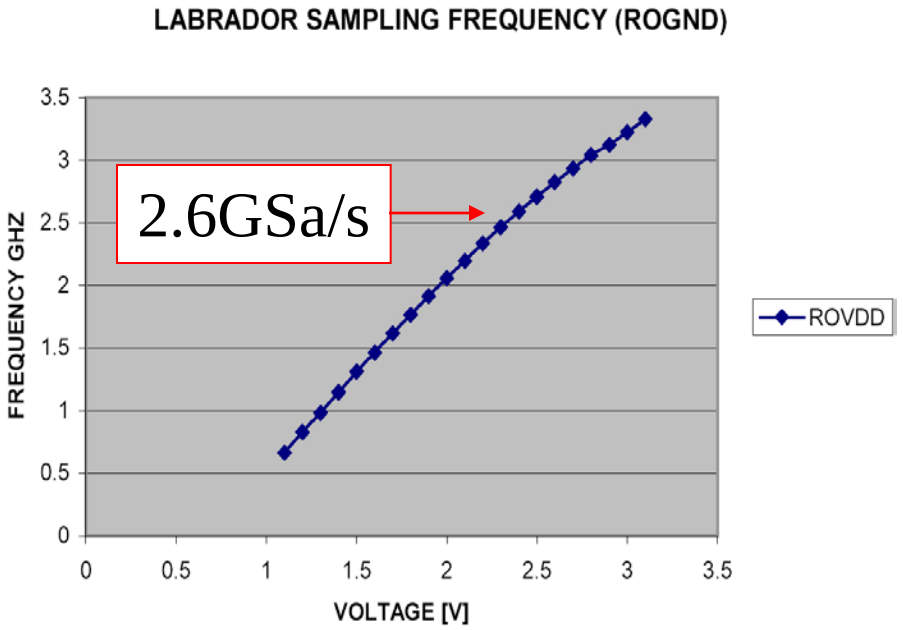
- Common STOP acquisition
- 3.2 x 2.9 mm
- Conversion in 120μs (all 2340 samples)
- Data transfer takes 80μs
- Ready for next event in 200μs

LABRADOR performance

12-bit ADC





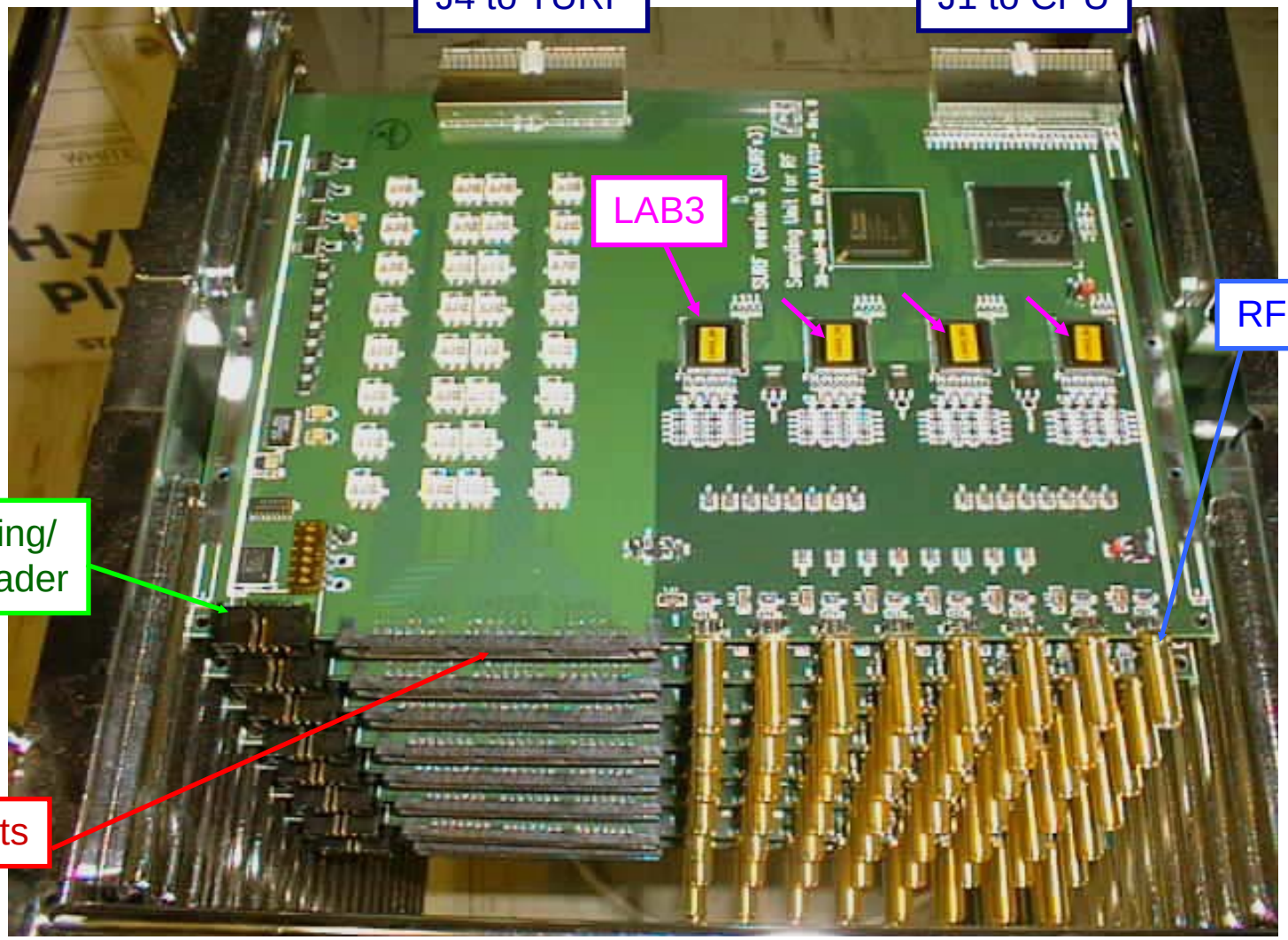


- 10 real bits (1.3V/1.3mV noise)

- Excellent linearity, noise
- Sampling rates up to 4 GSa/s with voltage overdrive

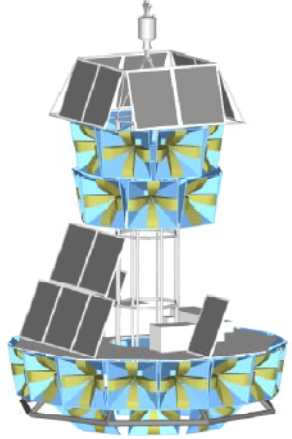
(SURF = Sampling Unit for RF)
(TURF = Trigger Unit for RF)

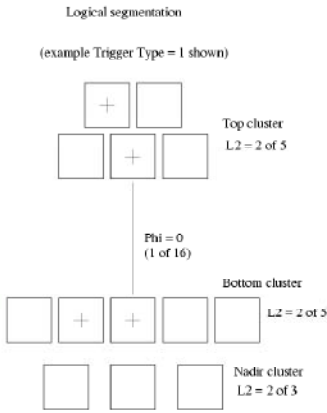
SURFv3 Board



PCI bus: 64bits, 66MHz ~ 0.5 GigaByte/s (upgrading for 3rd flight)

A “high rate” Experiment





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

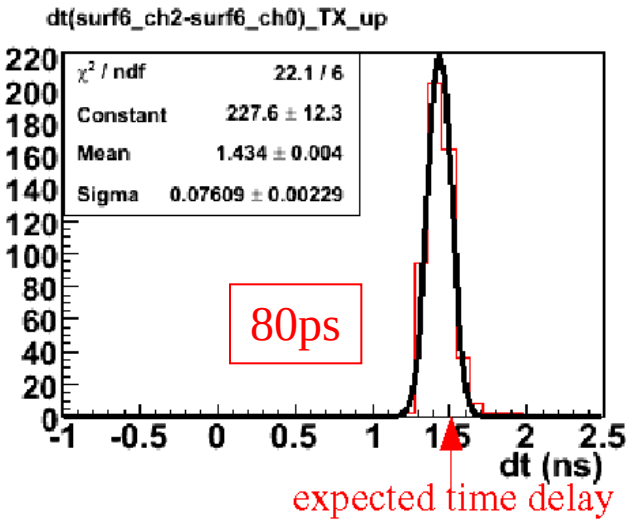
Permits thermal noise level operation

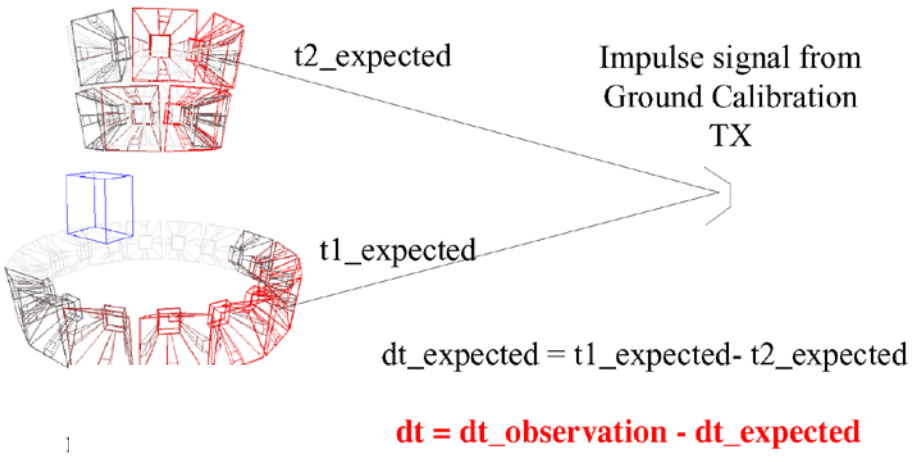
Timing vs Angle (with Impulse Calibration Radio Signal)

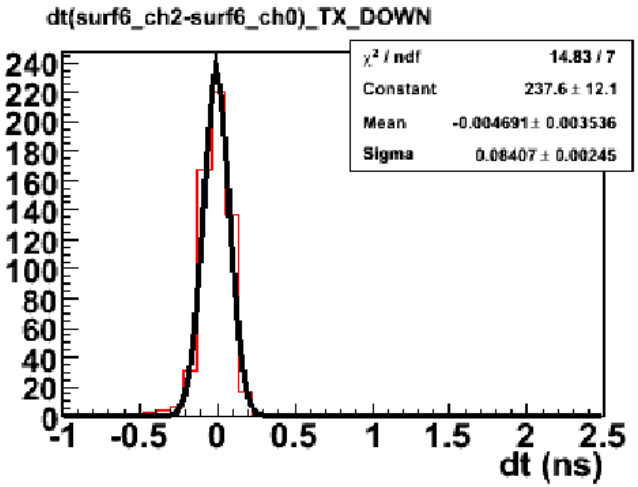
TX Up
by 1.56 m

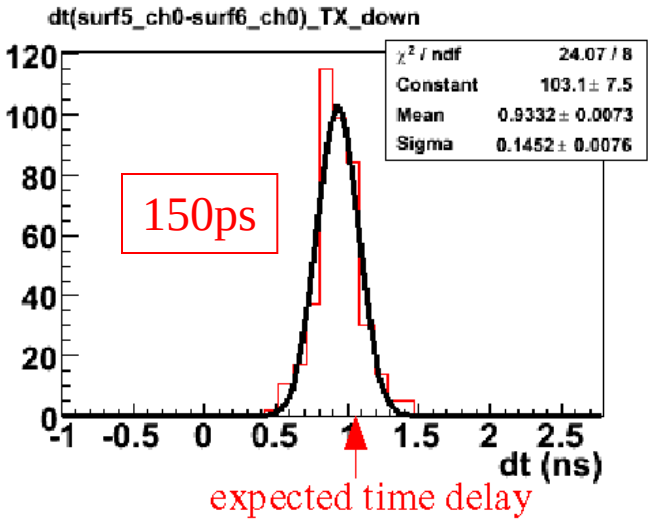
Vertical Angle
Dependency

TX Down









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

Jiwoo Nam
UC Irvine

Pulse Phase interferometry

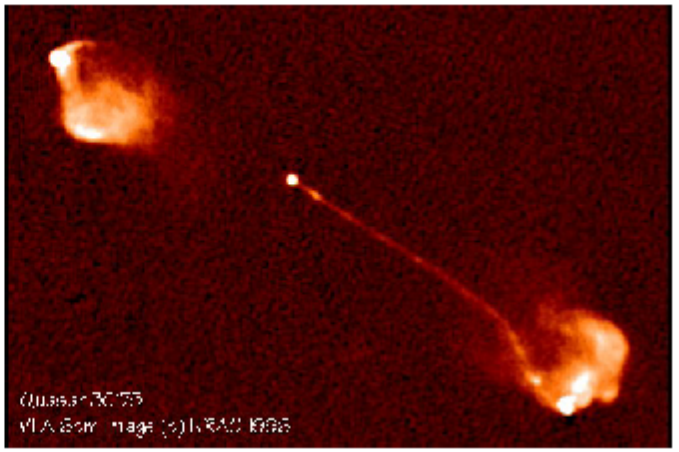
A. Romero-Wolf (Hawaii)

Ultrawide-band Interferometry

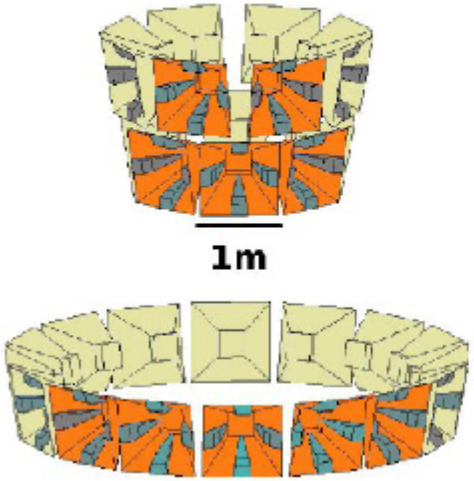
-Interferometric technique applied by radio astronomers.

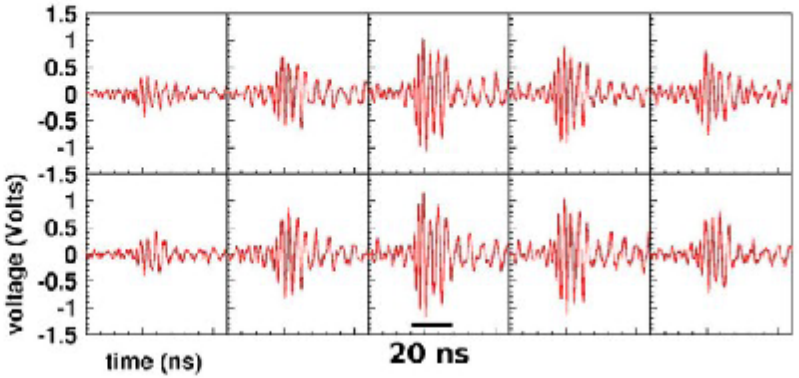
-They use single narrow band frequency.

-More interested in source imaging rather than point source direction reconstruction.



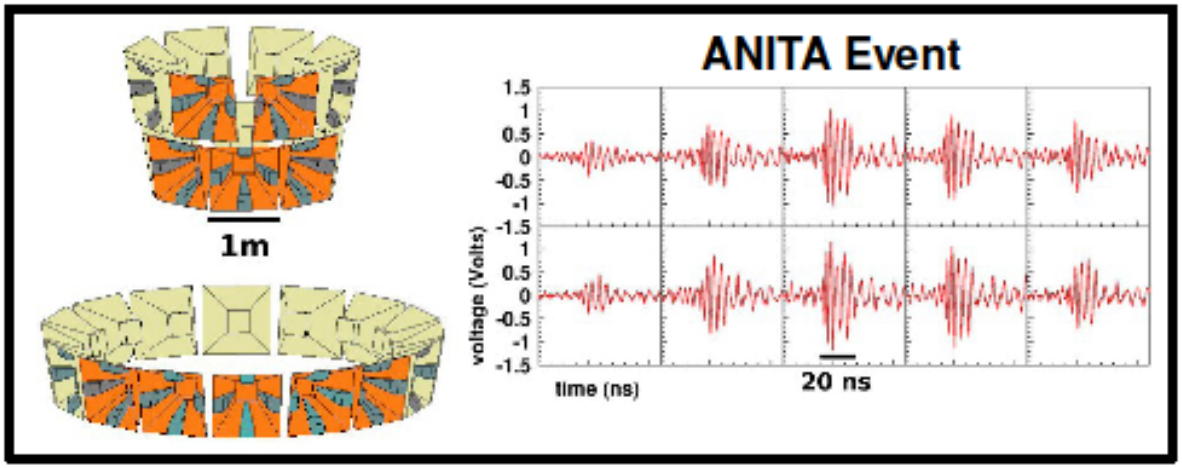
Produce Ultrawide-band Interferometric Images with ANITA



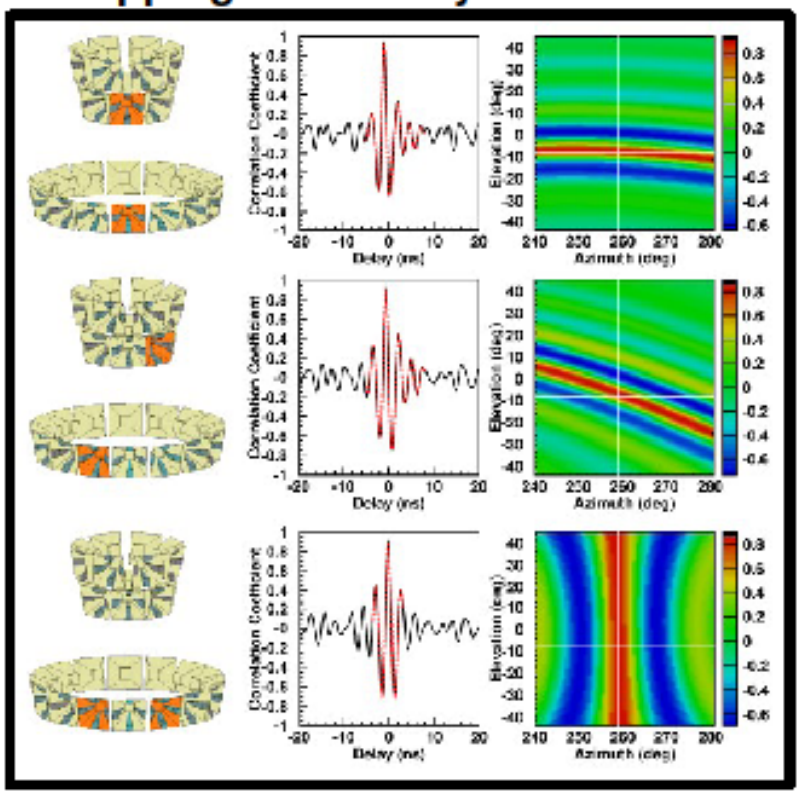


~30ps (16ps) resolution between channels

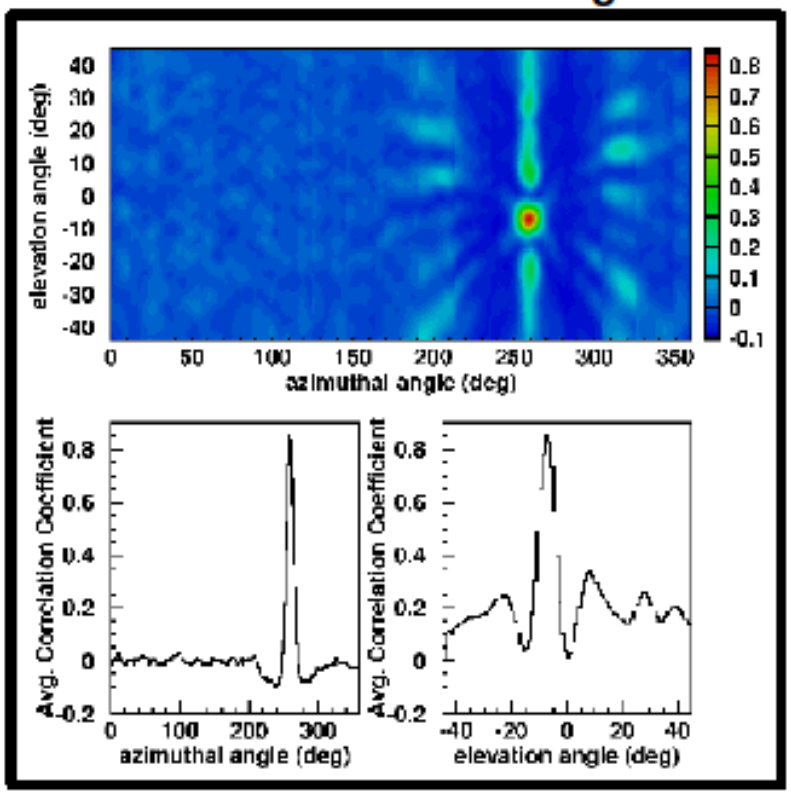
Mapping Waveforms to Interferometric Images



Mapping Time Delay Correlations

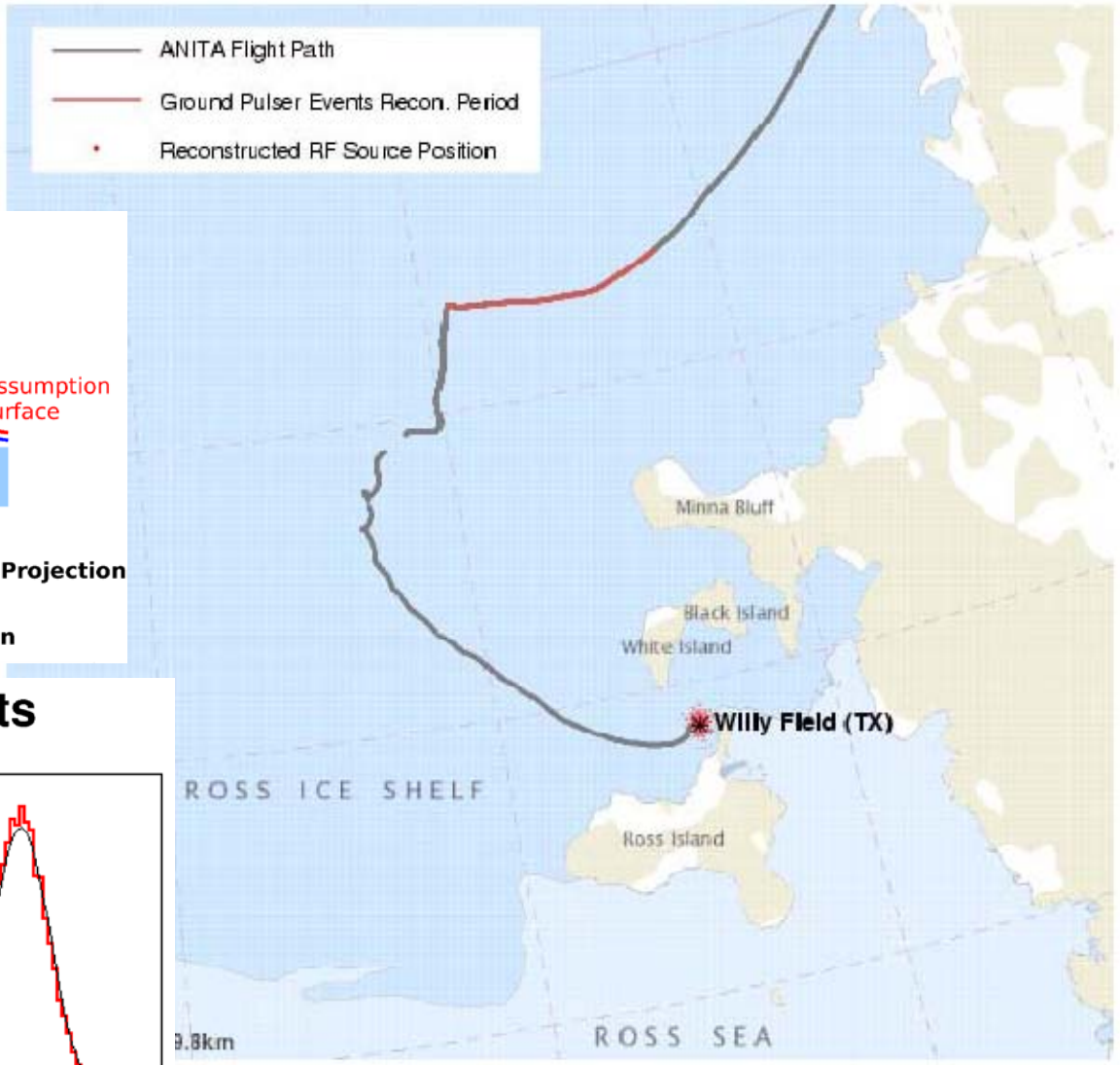


Interferometric Image

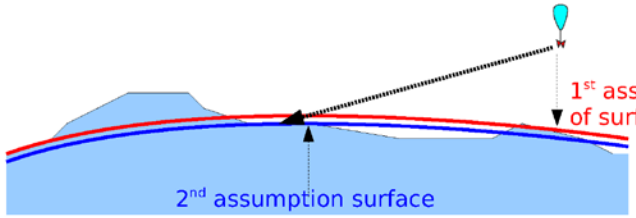


After full calibration – 100's km

<30ps timing



RF Projection onto the surface



Fast Algorithm: Line Sphere intersection

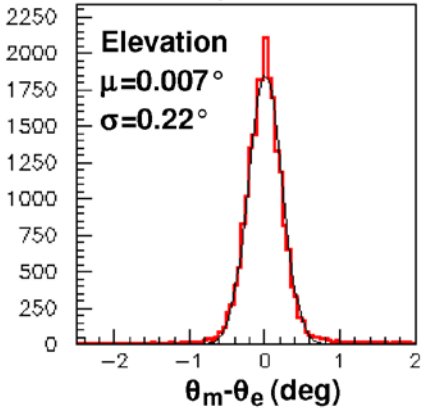
1st R_{earth} =Geoid + Surface @ Ballon position -> Rough Projection

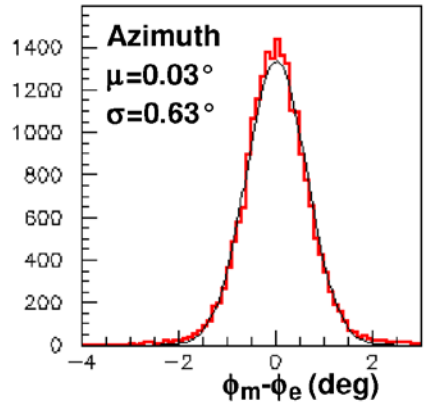
2nd R_{earth} = Geoid + Surface @ (position from 1st)

3rd: one more iteration -> converged after 2nd iteration

V-pol results

Borehole Data (used for calibrations)





The “no free lunch” Theorem

- Excellent results obtained

  1. Made the ANITA project possible & highly successful

  2. Similar architectures being studied for new and upgraded experiments

  3. Minimize costs for large systems

- Not a magic solution
  - Significant constraints
  - Technology in its infancy – will continue to improve

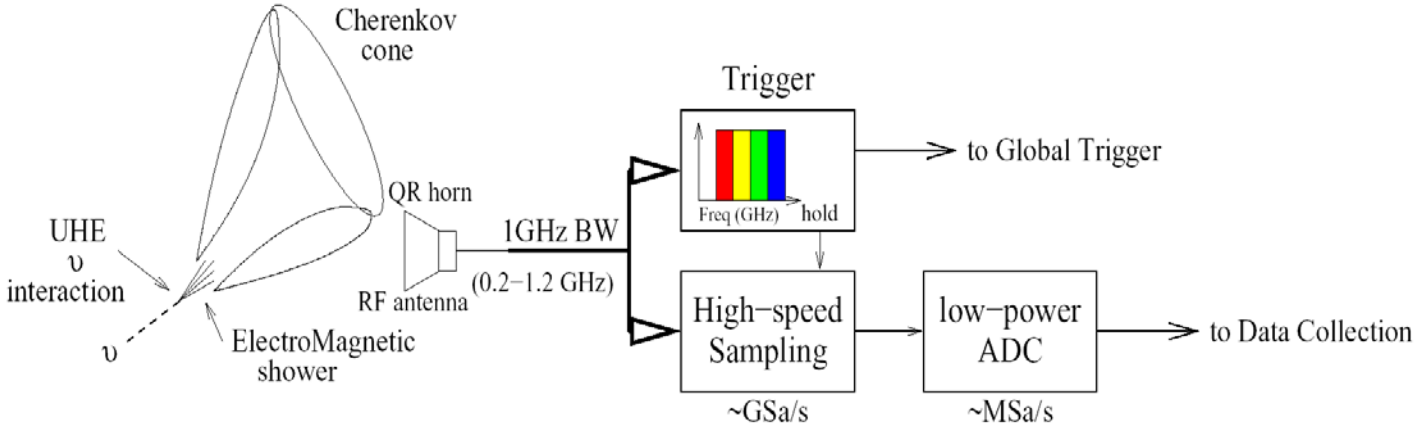
- Limits and future directions

The technology, in a bit more detail

Constraint 0: An Intrinsic Limitation

No power (performance savings) for continuous digitization

Won't displace Flash ADCs

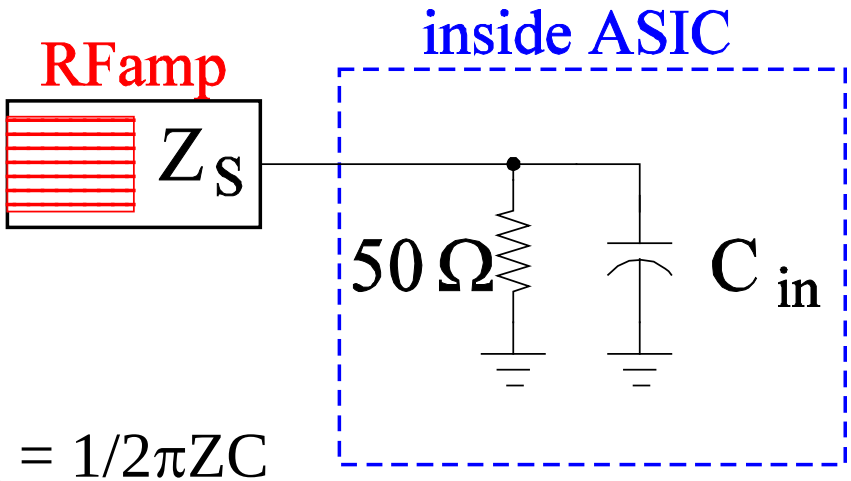


"down conversion"

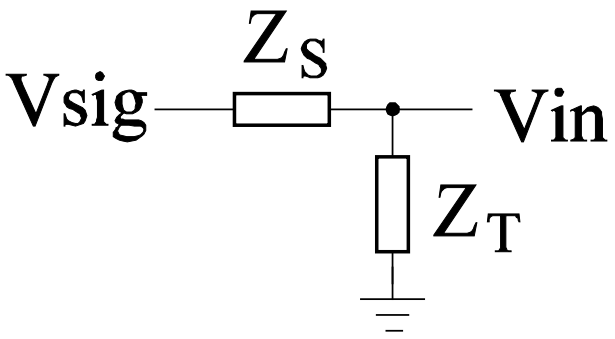
→ For most "triggered" 'event' applications, *not a serious drawback*

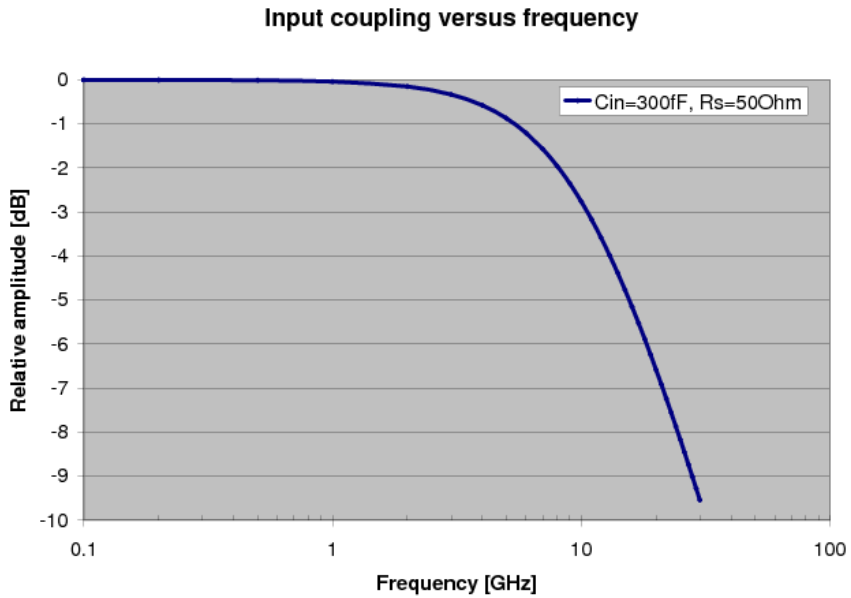
Constraint 1: Analog Bandwidth

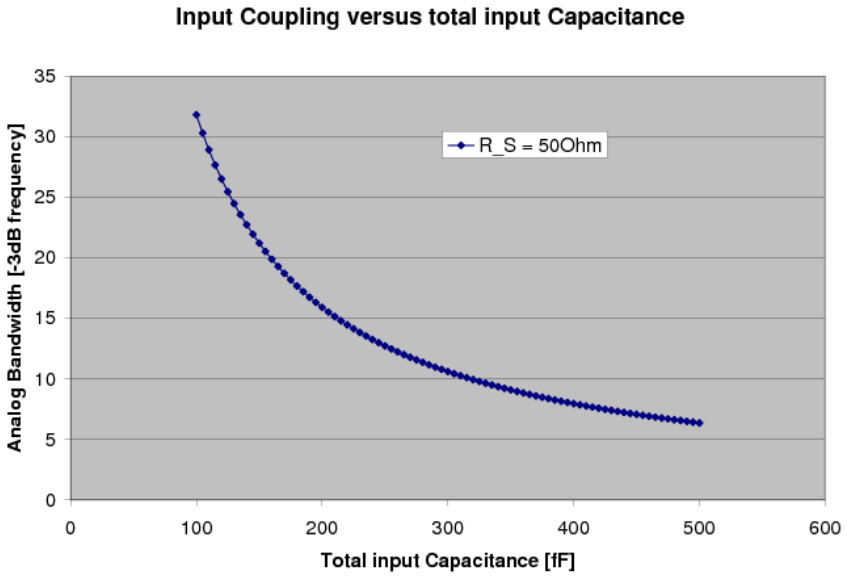
Difficult to couple in Large BW (C is deadly)



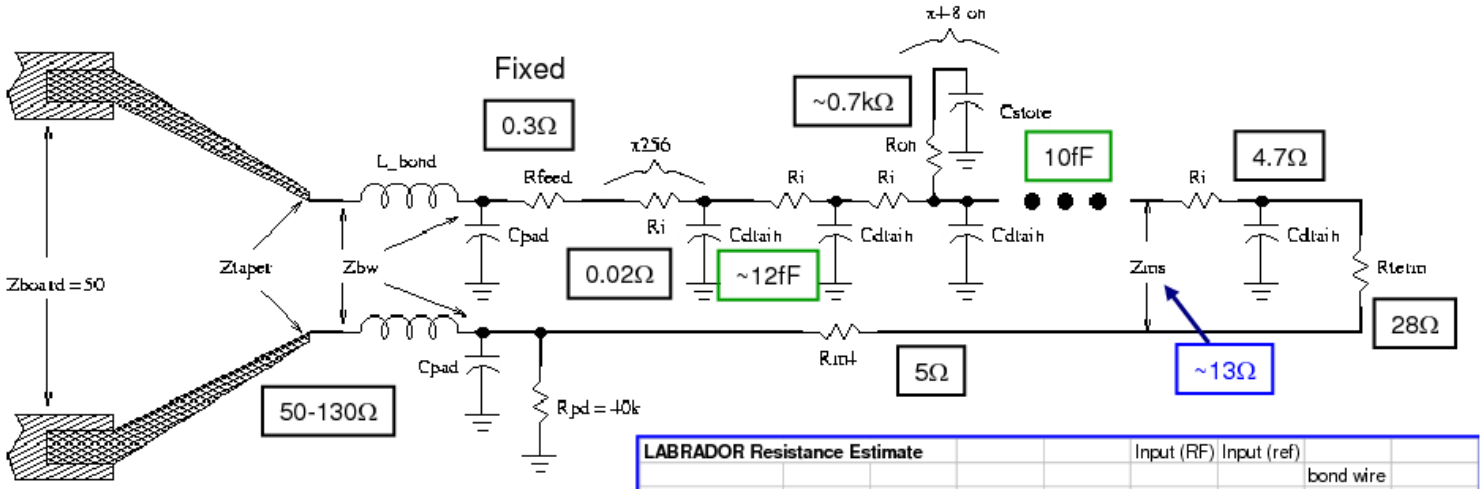
$f_{3dB} = 1/2\pi ZC$

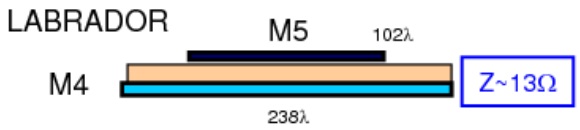






Bandwidth Limitations (LAB1 example)





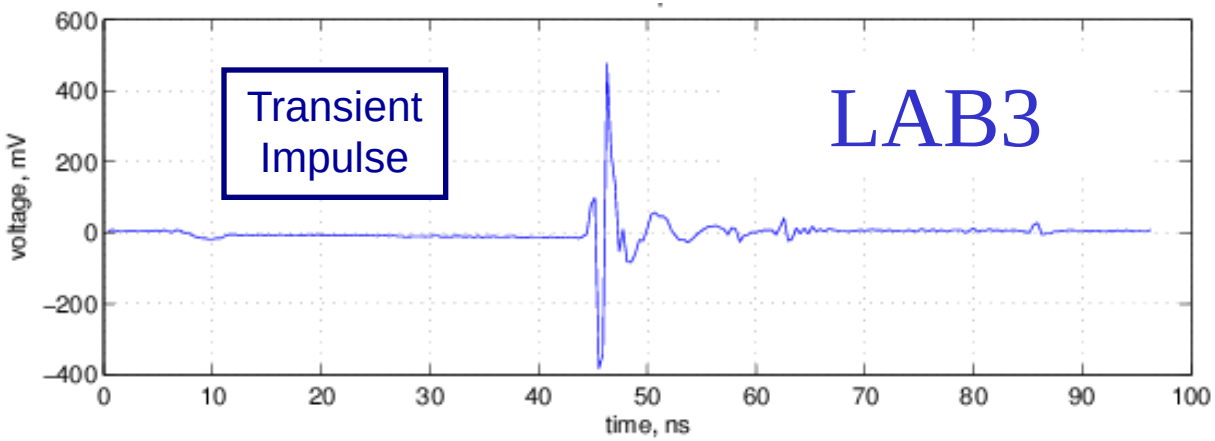
LABRADOR Resistance Estimate					Input (RF)	Input (ref)	
							bond wire
Length	17000	λ			0.0	0.1	pad
			70			0.2	M5-M4
Metal 4(sheet) =	0.07	Ohm/sq		71.42857		5.0	typ length (sq.)
Metal 5(sheet) =	0.03	Ohm/sq	166.6667		5.0		typ length (sq.)
Poly contact =	5.1	Ohm	6	6	0.9	0.9	
via 1=	2.7	Ohm	6	3	0.5	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

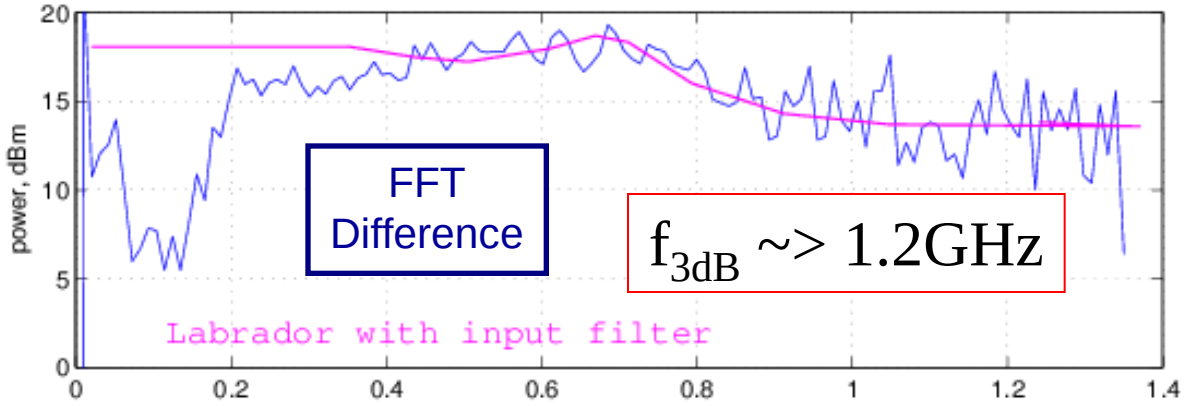
$$f_{3dB} = 1/2\pi ZC$$

Would like smallest possible Cstore

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

An Example Bandwidth Evaluation



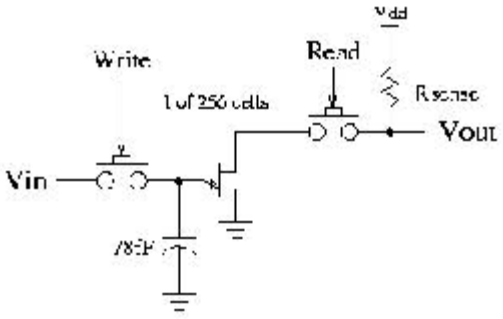


9 channels of
256 samples

To do
better,
reduce
input and
storage C

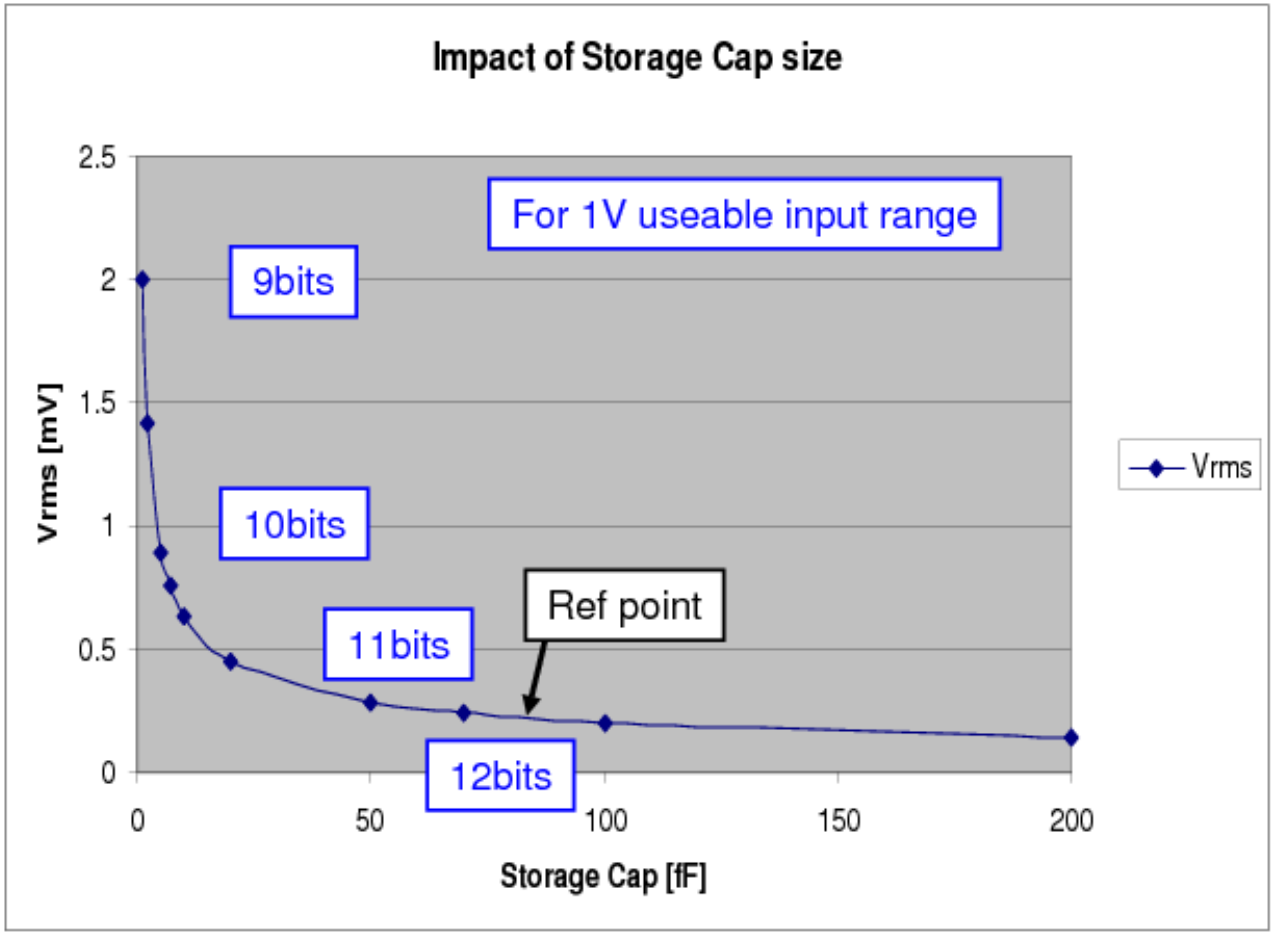
Constraint 2: kTC Noise

Want small storage C, but…



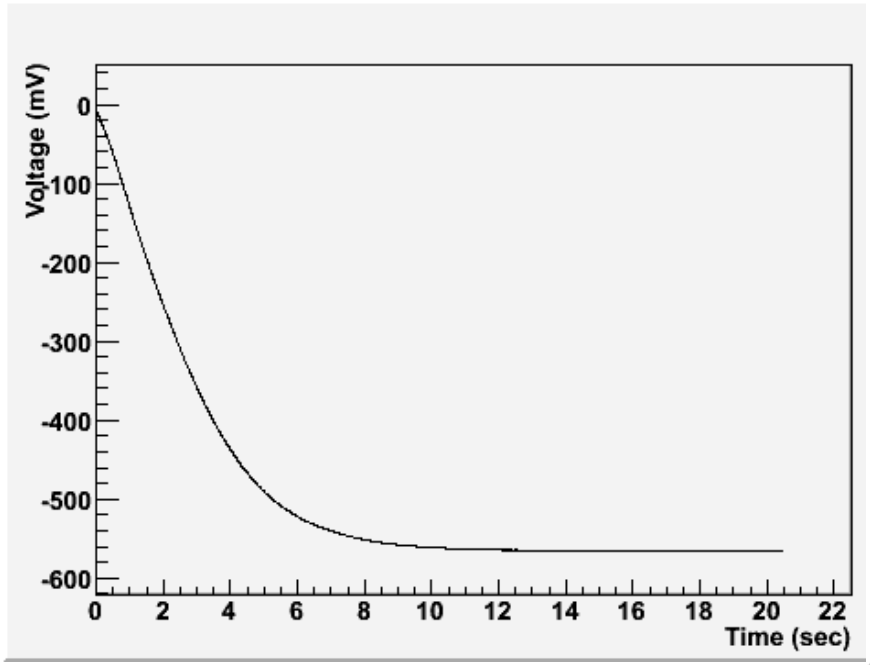
$$v_{rms} = \sqrt{\frac{kT}{C_{store}}} = 0.23mV$$

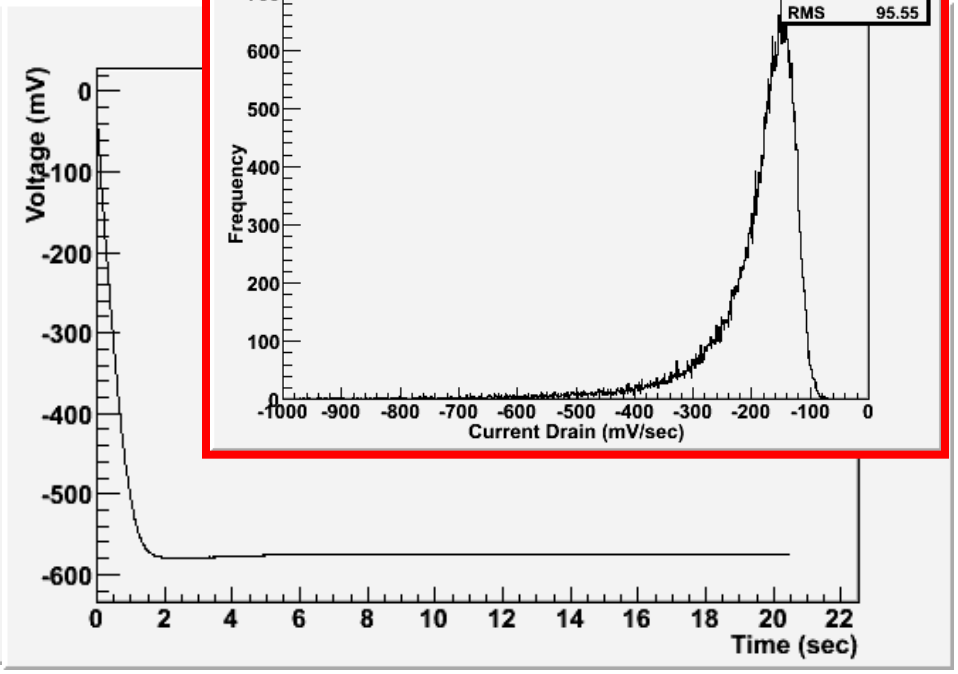
C_{store} = 78fF



Similar Constraint 2b: Leakage Current

Increase C or reduce conversion time << 1mV



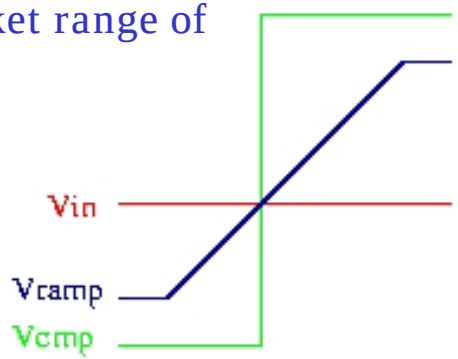


Sample channel-channel variation

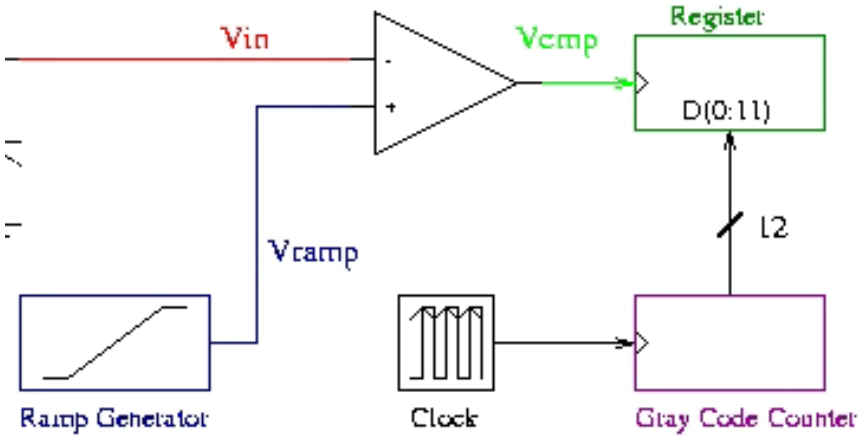
~ fA leakage typically

Constraint 3: Digitization

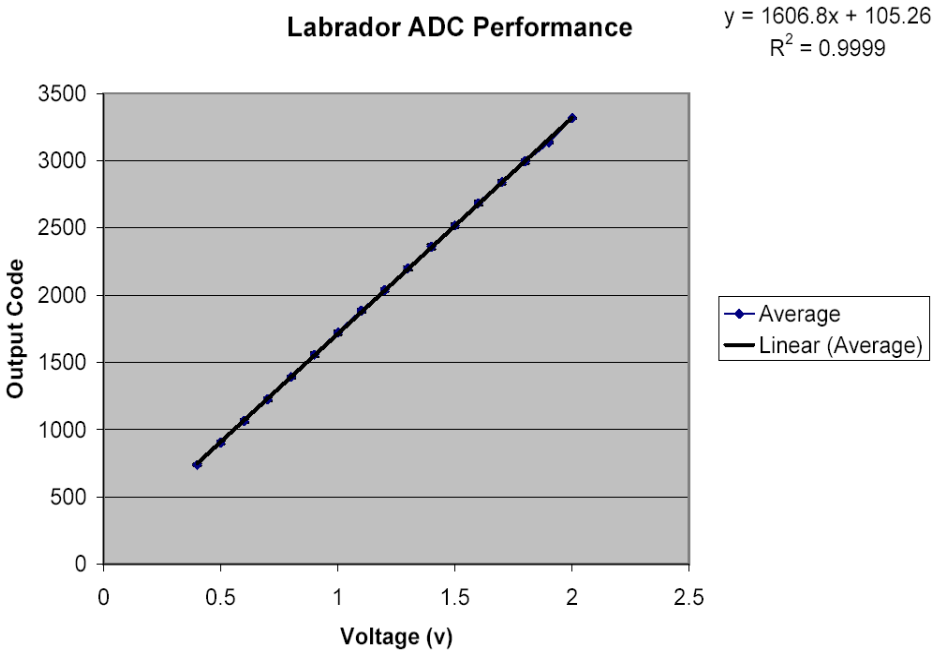
- No missing codes
- Linearity as good as can make ramp
- Can bracket range of interest



Run count during ramp



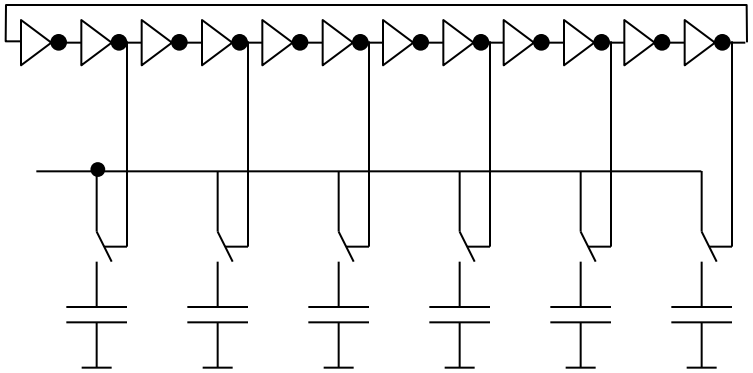
12-bit ADC

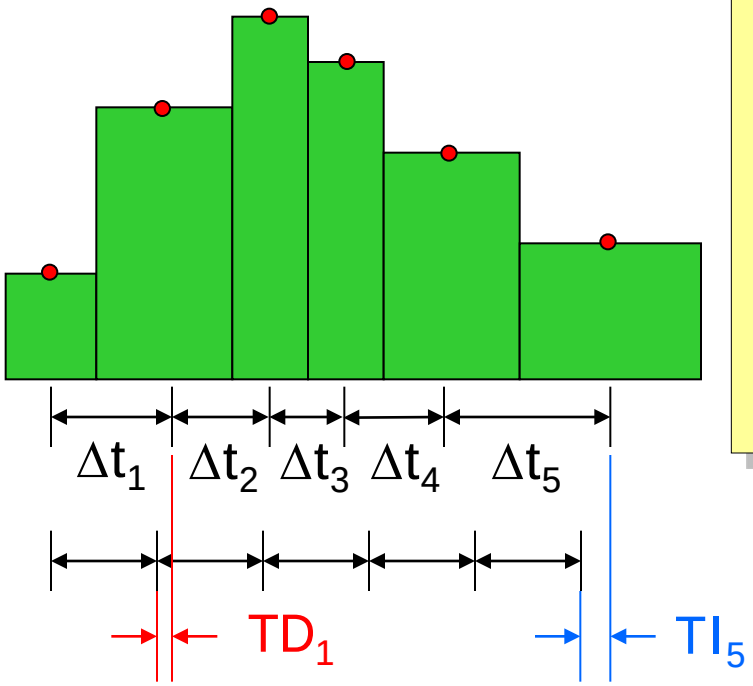


Wilkinson ADC

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

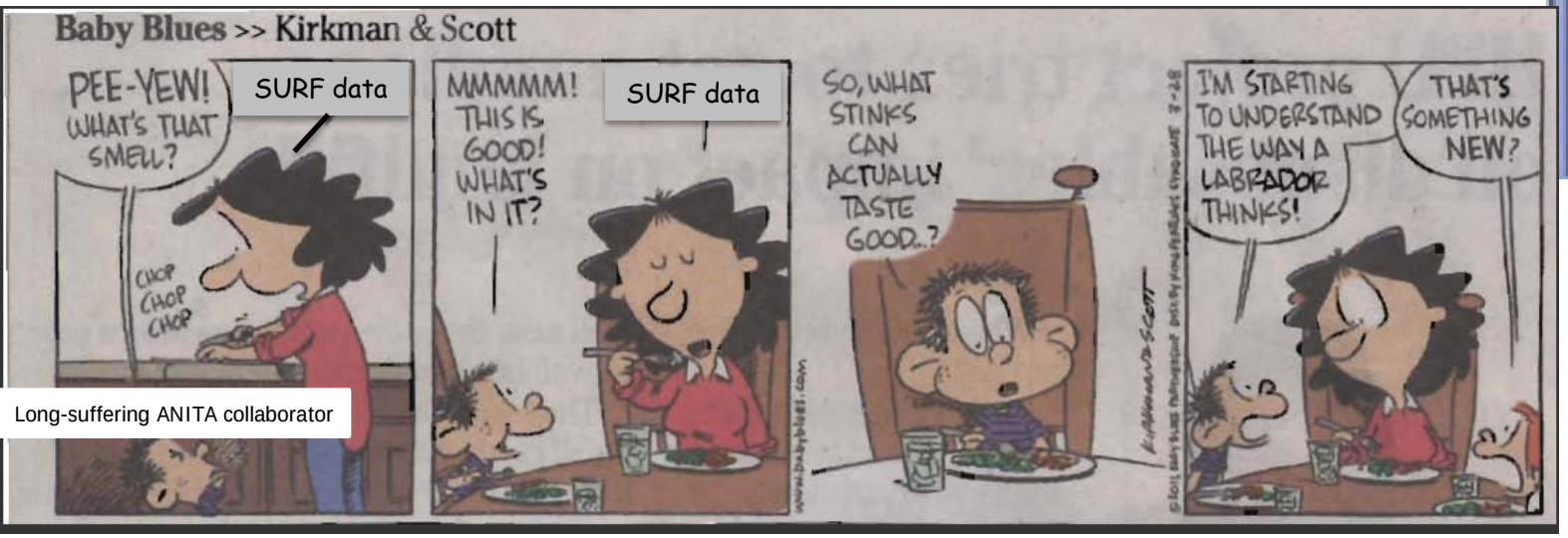
Constraint 4: Sample Aperture Variance





- Inverter chain has transistor variations
  → Δt_i between samples differ
  → "Fixed pattern aperture jitter"
- "Differential temporal nonlinearity"
  $TD_i = \Delta t_i - \Delta t_{nominal}$
- "Integral temporal nonlinearity"
  $TI_i = \Sigma \Delta t_i - i \cdot \Delta t_{nominal}$
- "Random aperture jitter" = variation of Δt_i between measurements

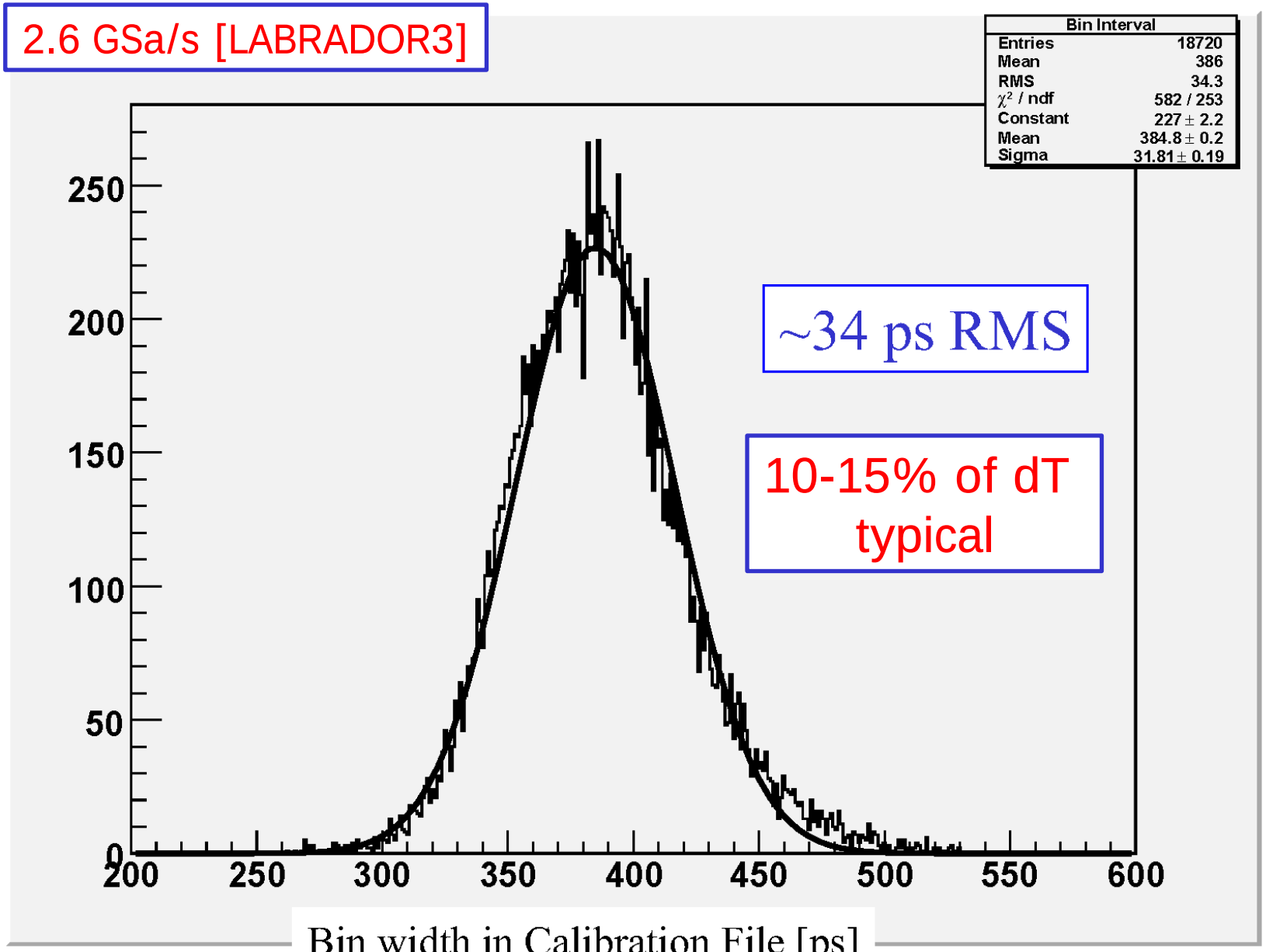
Non-uniform sampling timebase



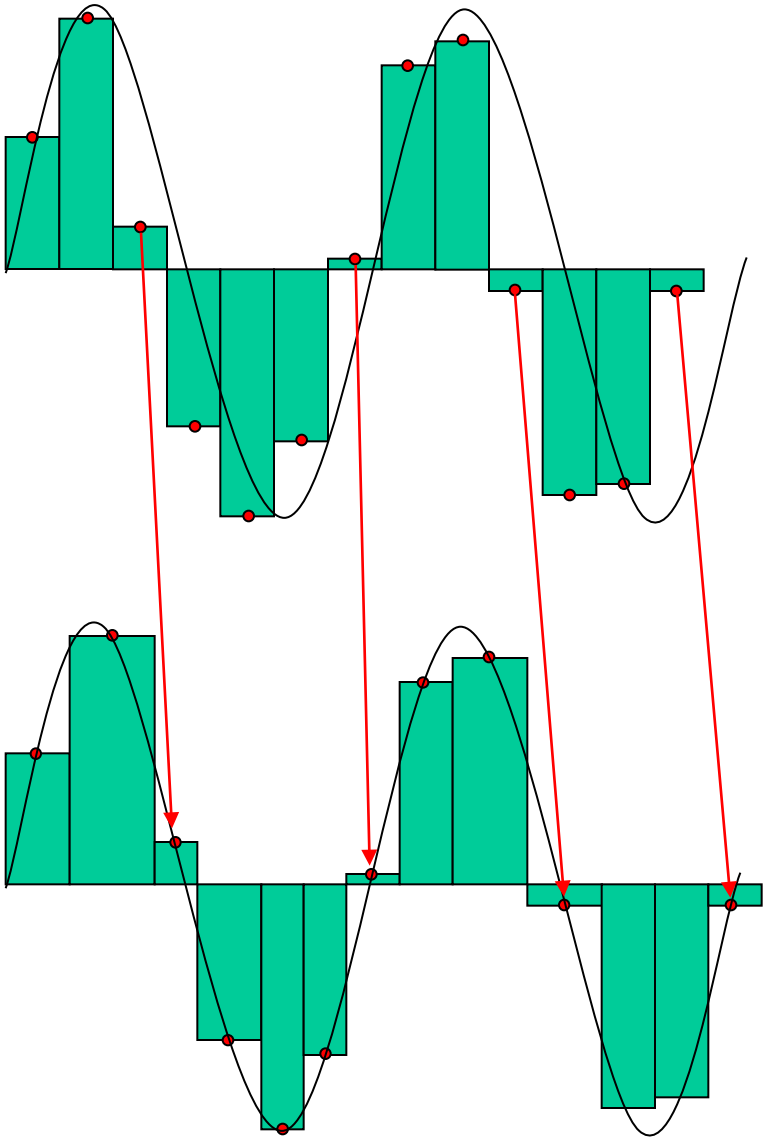
Long-suffering ANITA collaborator

dT Spread

2.6 GSa/s [LABRADOR3]

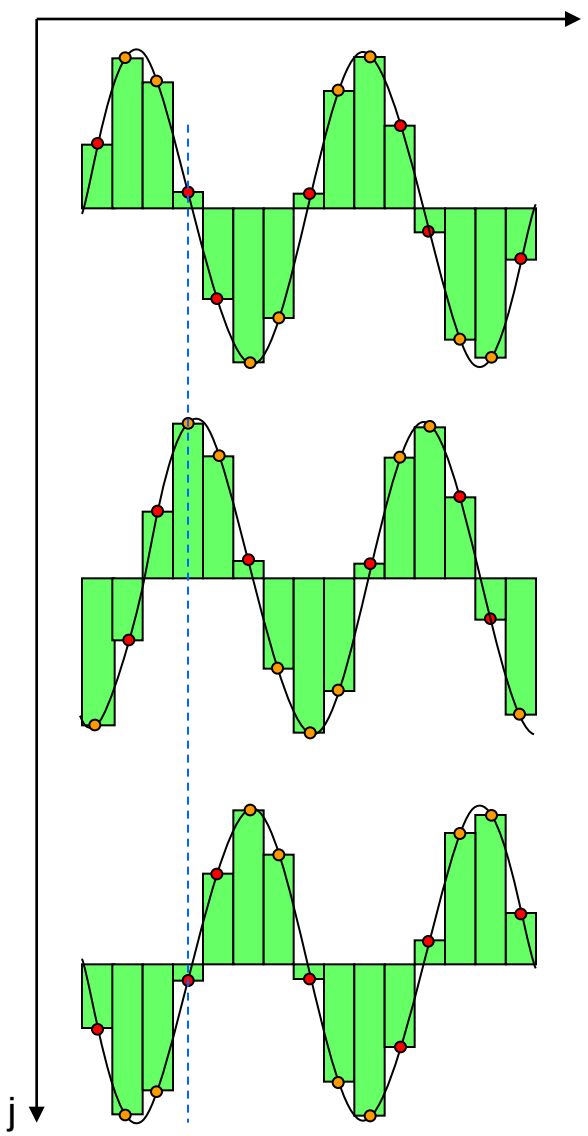


Average aperture calibration



- Fixed aperature offsets are constant over time, can be measured and corrected
- Several methods are commonly used (sine fit [left], zero-crossing)
- Most use sine wave with random phase and correct for TD_i on a statistical basis

Sine Curve Fit Method



$$\chi^2 = \sum_{j=0}^{500} \sum_{i=0}^{1024} (y_{ji} - (a_j \sin(i \frac{2\pi}{f_j} + \alpha_j + \beta_i) + o_j))^2 \rightarrow \min$$

y_{ji} : i-th sample of measurement j

a_j f_j α_j o_j : sine wave parameters

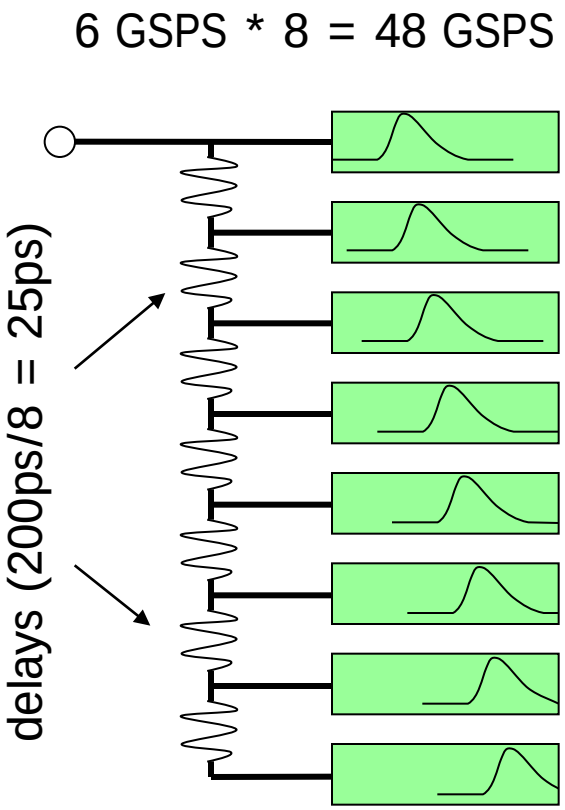
β_i : phase error $\rightarrow$ fixed jitter

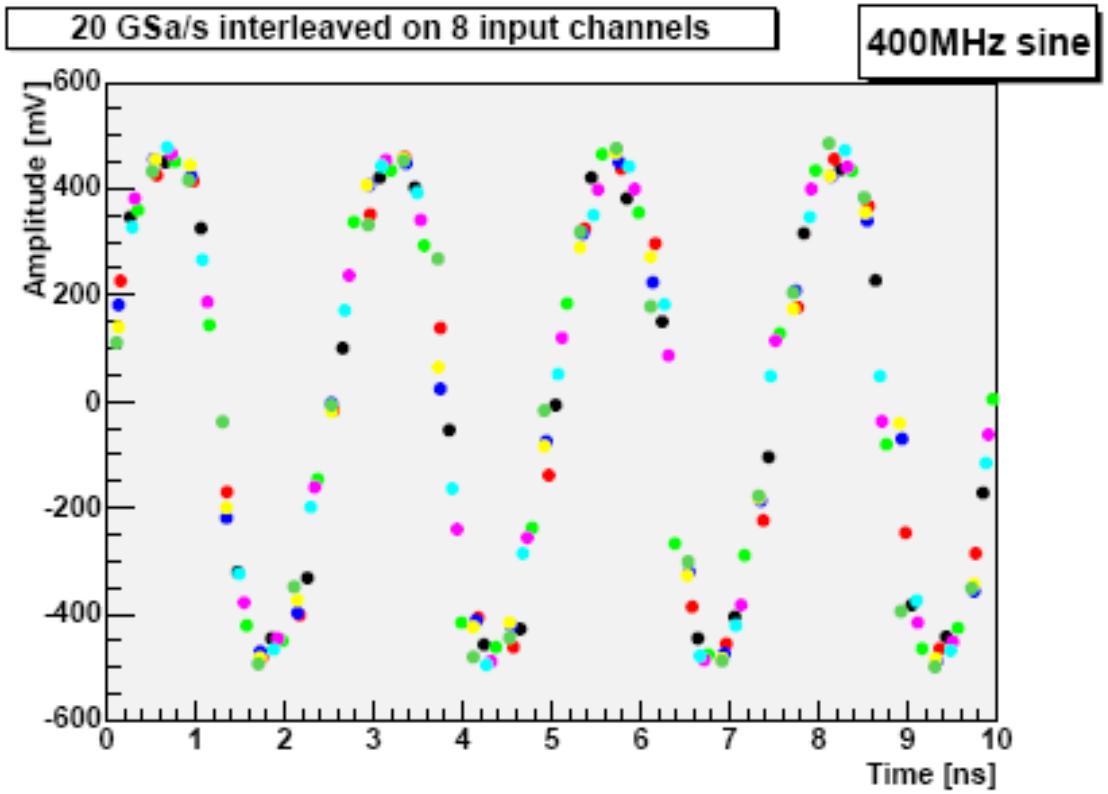
"Iterative global fit":

- Determine rough sine wave parameters for each measurement by fit
- Determine β_j using all measurements where sample "i" is near zero crossing
- Make several iterations

S. Lehner, B. Keil, PSI

Option 1: Even Faster Sampling

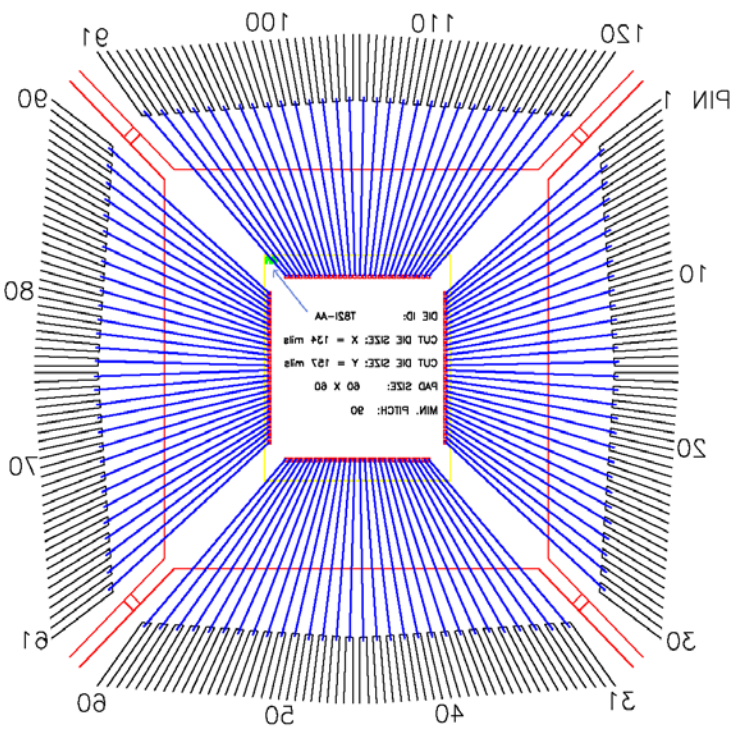


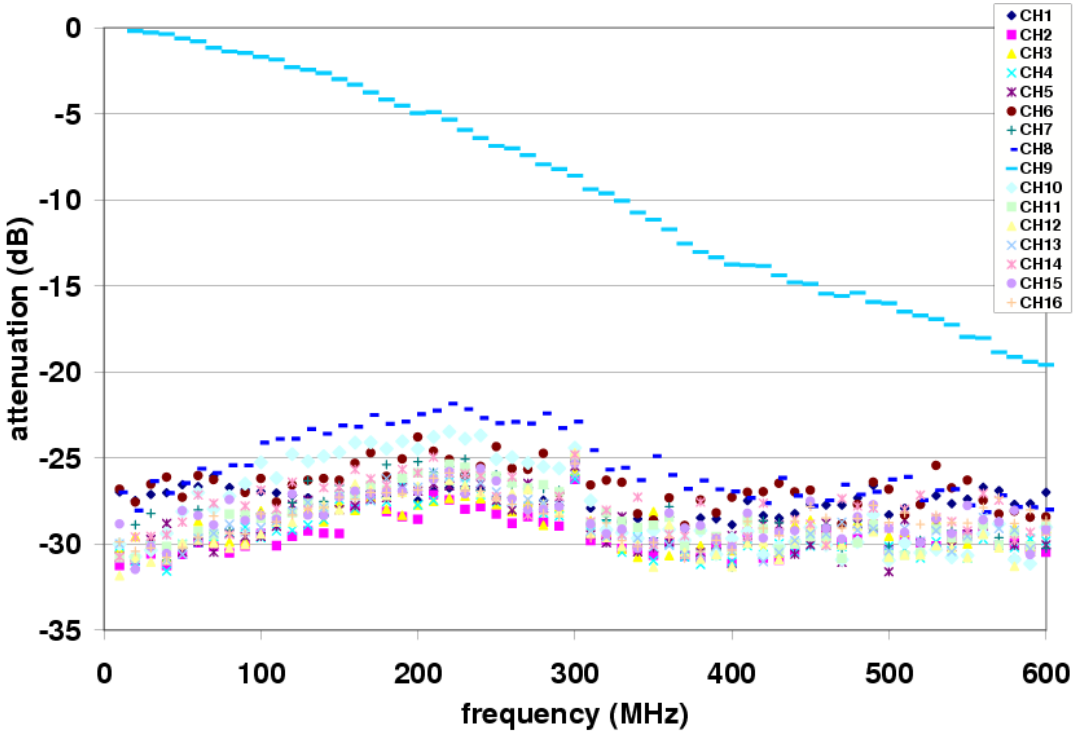


Possible with delay is implemented on PCB

Constraint 5: Cross-talk

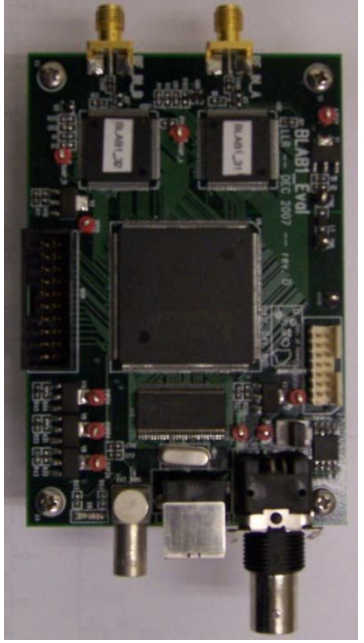
Coupling between wire-bonds, Vref

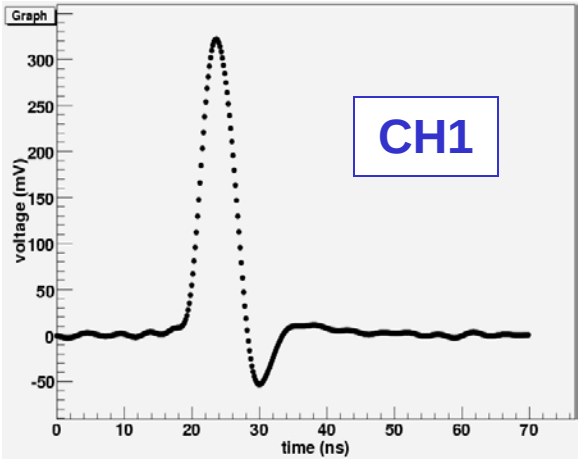


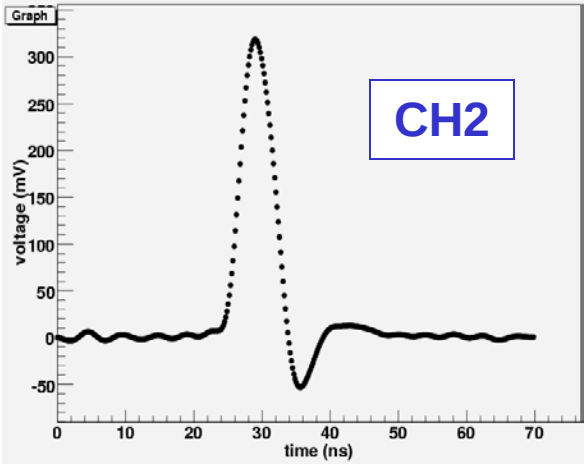


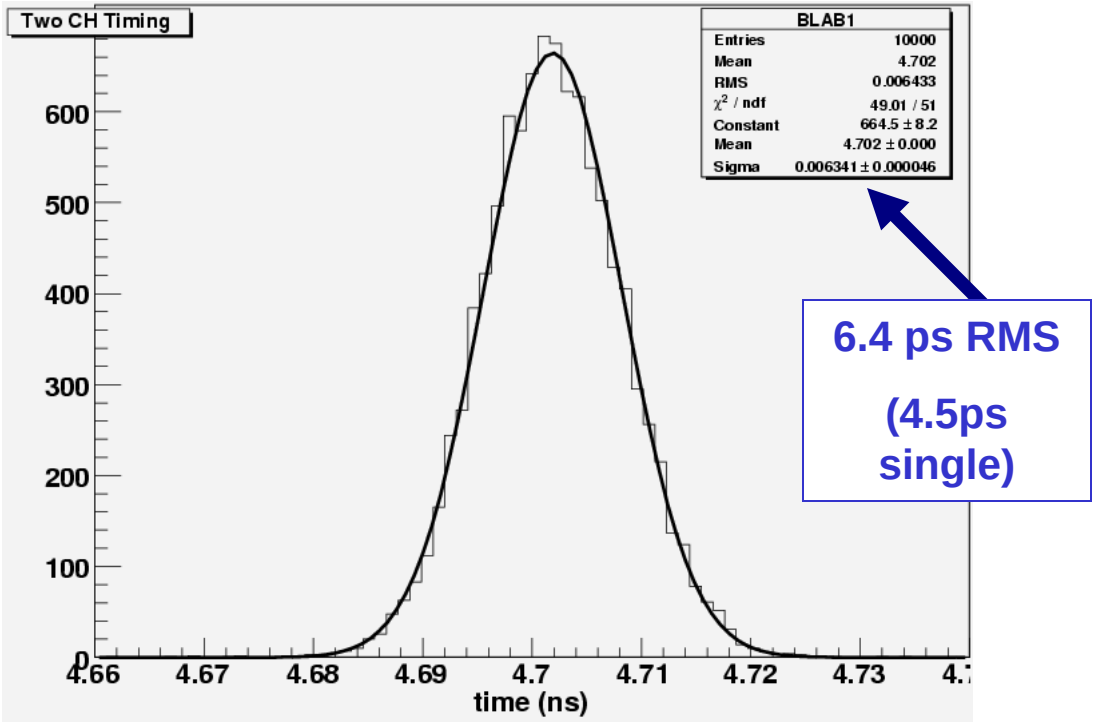
Advantage 1: Compact, low-power

- Comparable performance to best CFD + HPTDC
- Time difference measurement of recorded pulses
- Using full samples significantly reduces the impact of noise





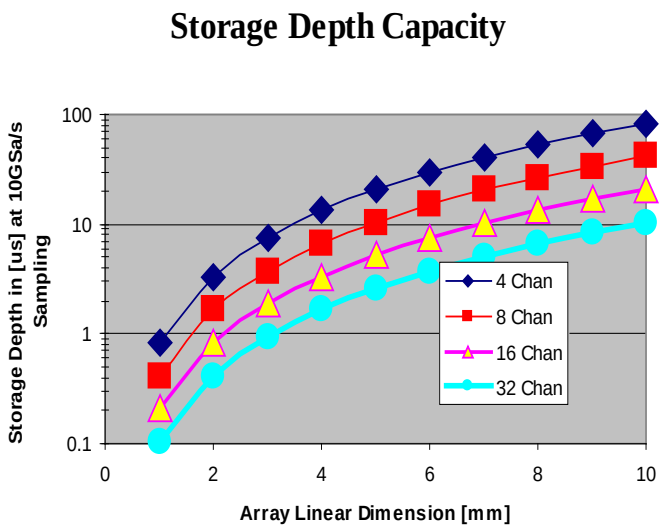


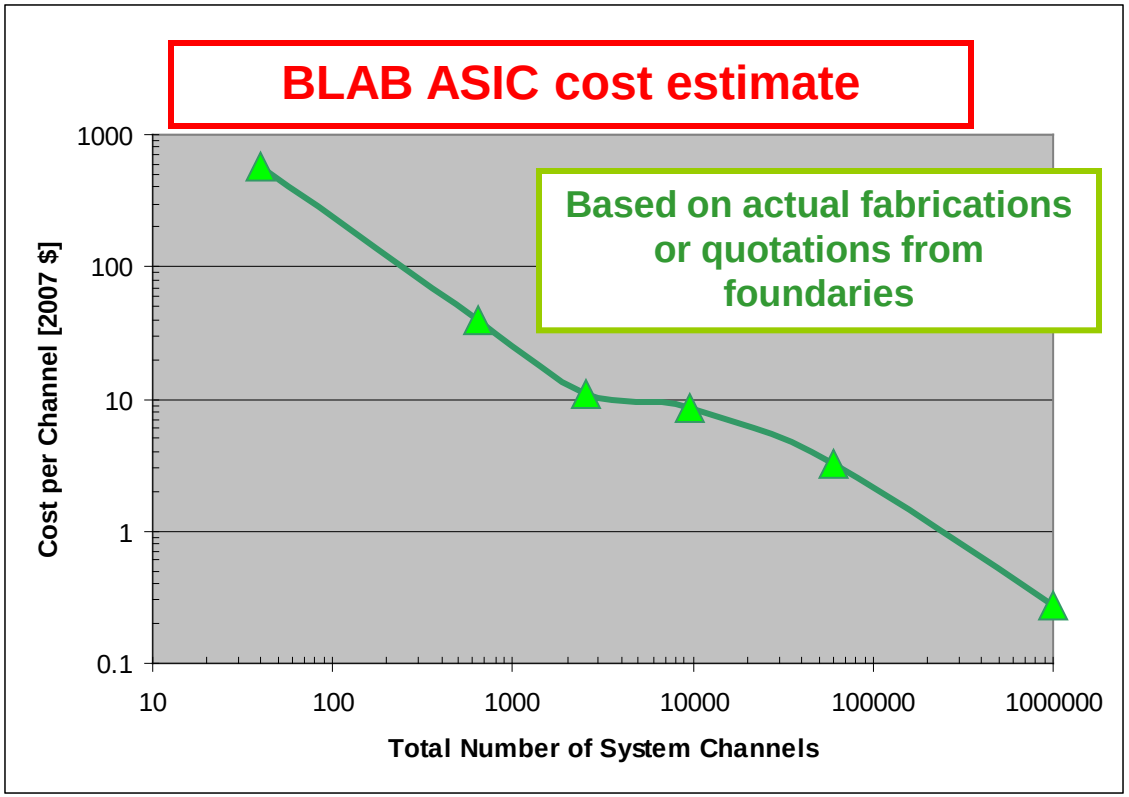


Advantage 2: Scaling to Large Systems

- ASIC costing well understood, very competitive!

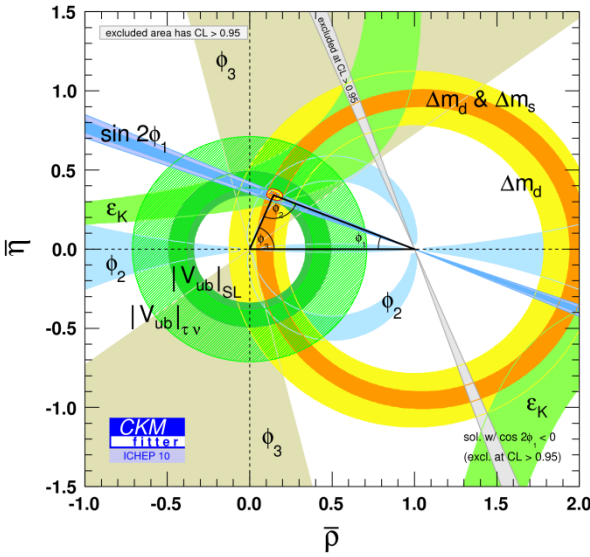
NIM A591 (2008) 534-345.

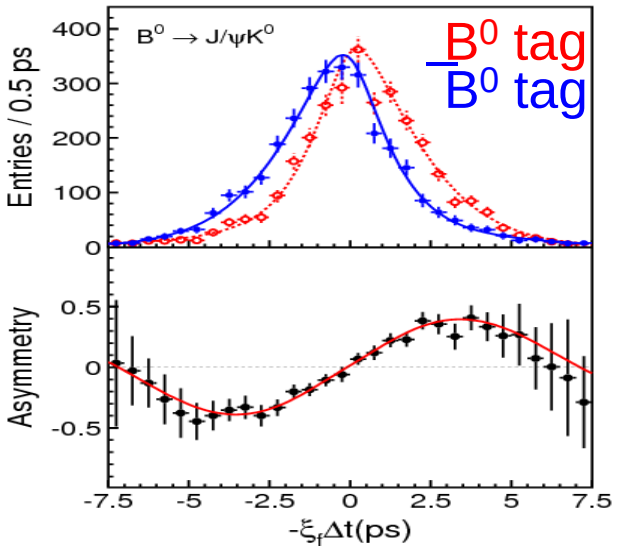




B-factory Detectors – a huge success!

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decays (e.g., B→τν, Dτν)
- b→s transitions: probe for new sources of CPV and constraints from the b→sγ branching fraction
- Forward-backward asymmetry (A_{FB}) in b→sll has become a powerfull tool to search for physics beyond SM.
- Observation of D mixing
- Searches for rare τ decays
- Observation of new hadrons





Are we done yet ?

Из эффекта С. Окубо
при большой температуре
для Вселенной сгинула надобность
по ее кривой фигуре

НАРУШЕНИЕ CP-ИНВАРИАНТНОСТИ, C-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

BAU: CKM mechanism still short by 10 orders of magnitude.

“Super” B Factory strategy

B factories → is SM with CKM right?

Super B factories → How is the SM wrong?

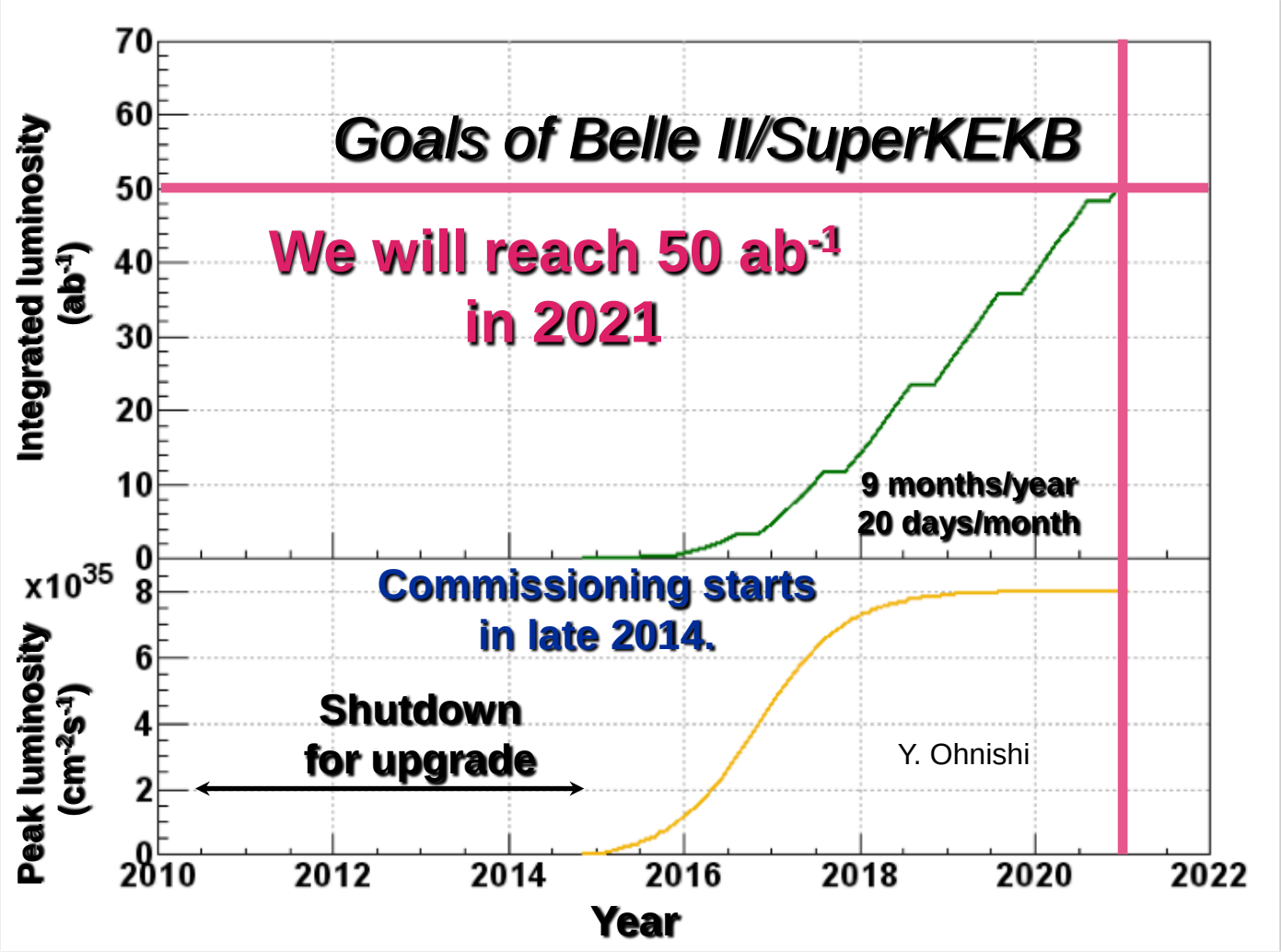
→ Need much more data (two orders!) because the SM worked so well until now → Super B factory

However: it will be a different world in four years, there will be serious competition from LHCb and BESIII → PANDA

Still, e^+e^- machines running at (or near) Y(4s) will have considerable advantages in several classes of measurements, and will be complementary in many more

Update of the physics reach with 50 ab^{-1} (75 ab^{-1}):
Physics at Super B Factory (Belle II authors + guests) hep-ex > arXiv:1002.5012
SuperB Progress Reports: Physics (SuperB authors + guests) hep-ex > arXiv:1008.1541

SuperKEKB luminosity profile



Requirements for the Belle II detector

Critical issues at L= 8 x 10^{35}/cm^2/sec

- **Higher background (×10-20)**

  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM Calorimeter

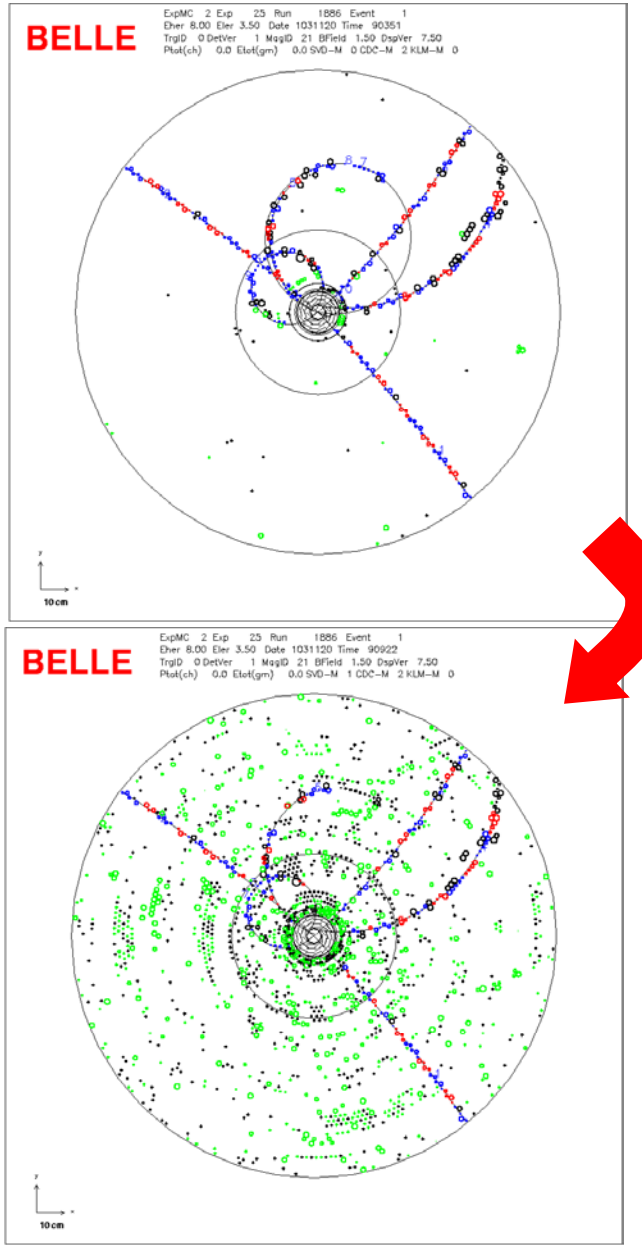
- **Higher event rate (×10)**

  - higher rate trigger, DAQ and computing

- **Special features required**

  - low p μ identification ← σμμ recon. eff.
  - hermeticity ← ν "reconstruction"

Result: significant upgrade

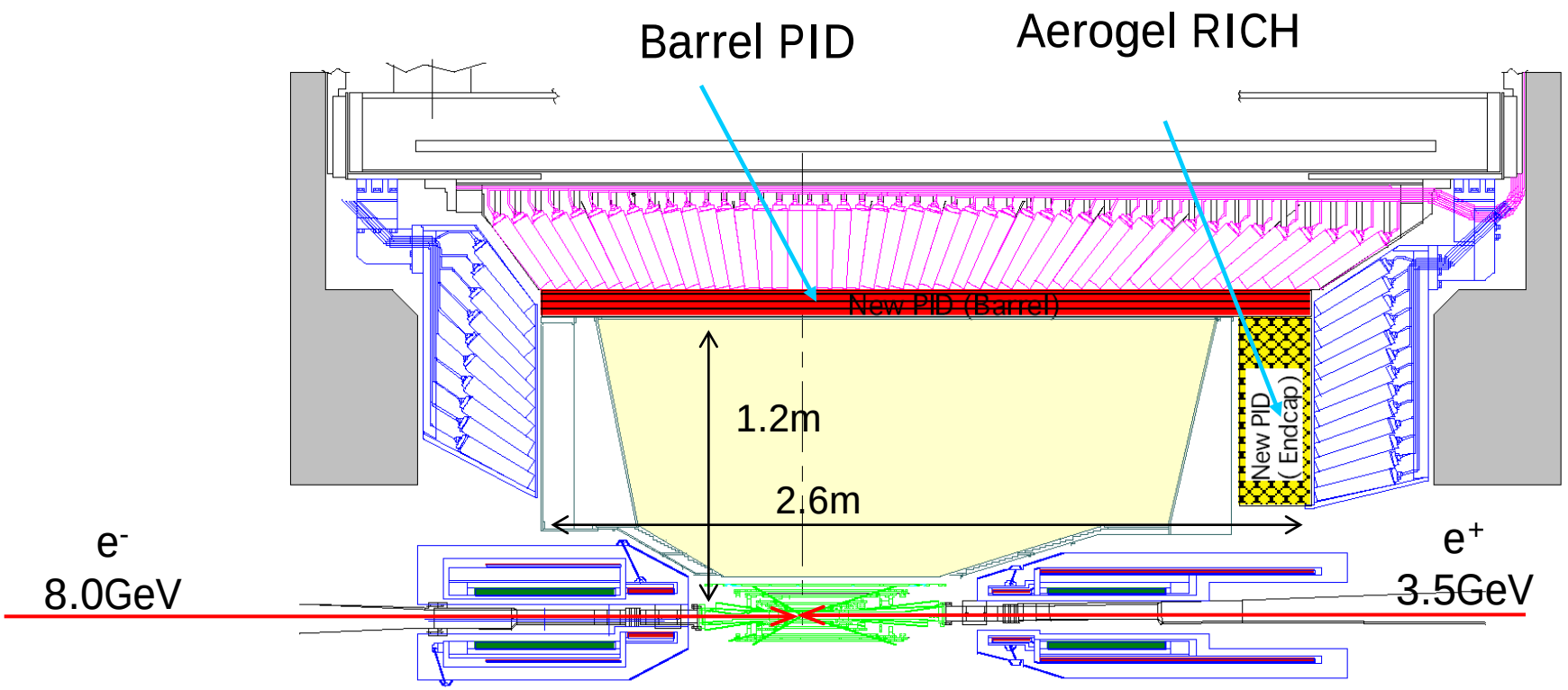


Upgraded Belle detector

- PID (π/K) detectors
- Inside current calorimeter
- Use less material and allow more tracking volume

→ Available geometry defines form factor

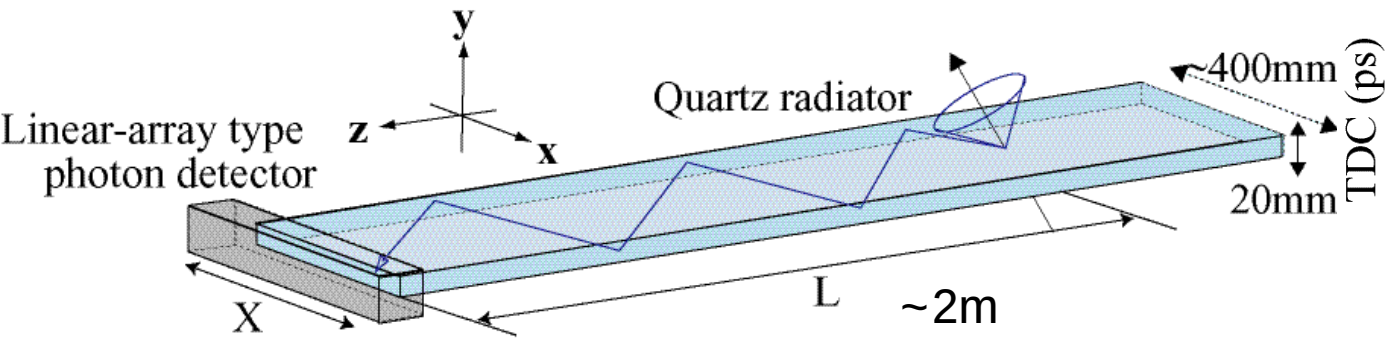
-

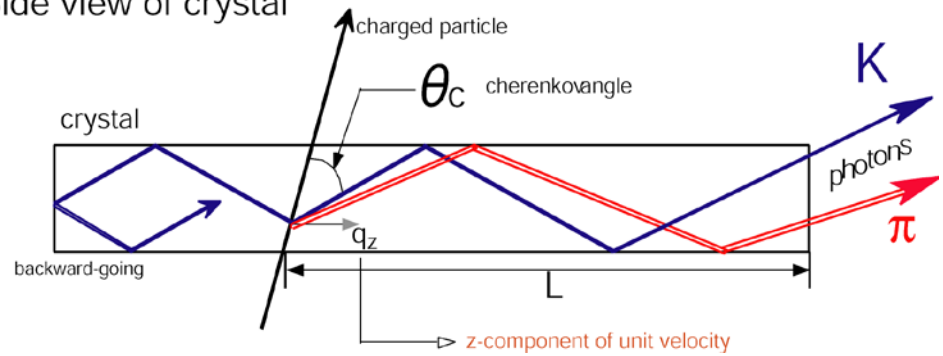


Original TOP counter concept

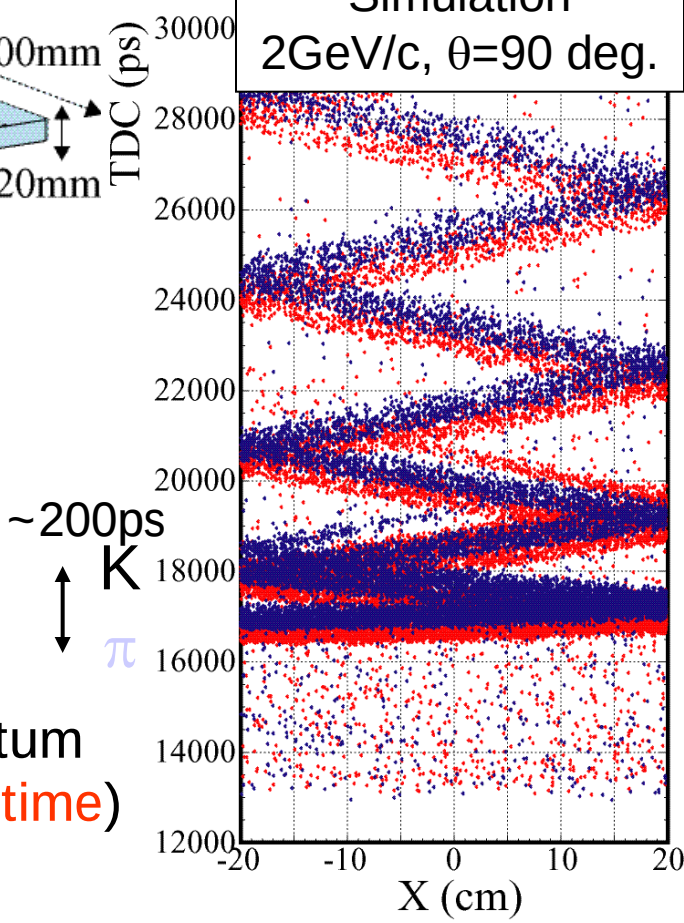
Linear array PMT (~5mm)
Time resolution σ~40ps

- Measure Position+Time





Simulation
2GeV/c, θ=90 deg.



~200ps
K
π

Different opening angle for the same momentum
→ Different propagation length(= propagation time)

+ TOF from IP works additively.

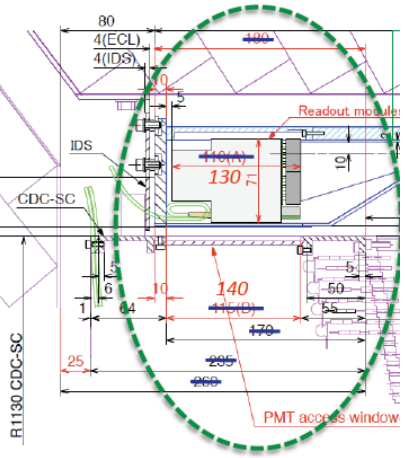
Slightly Enhanged “image plane”

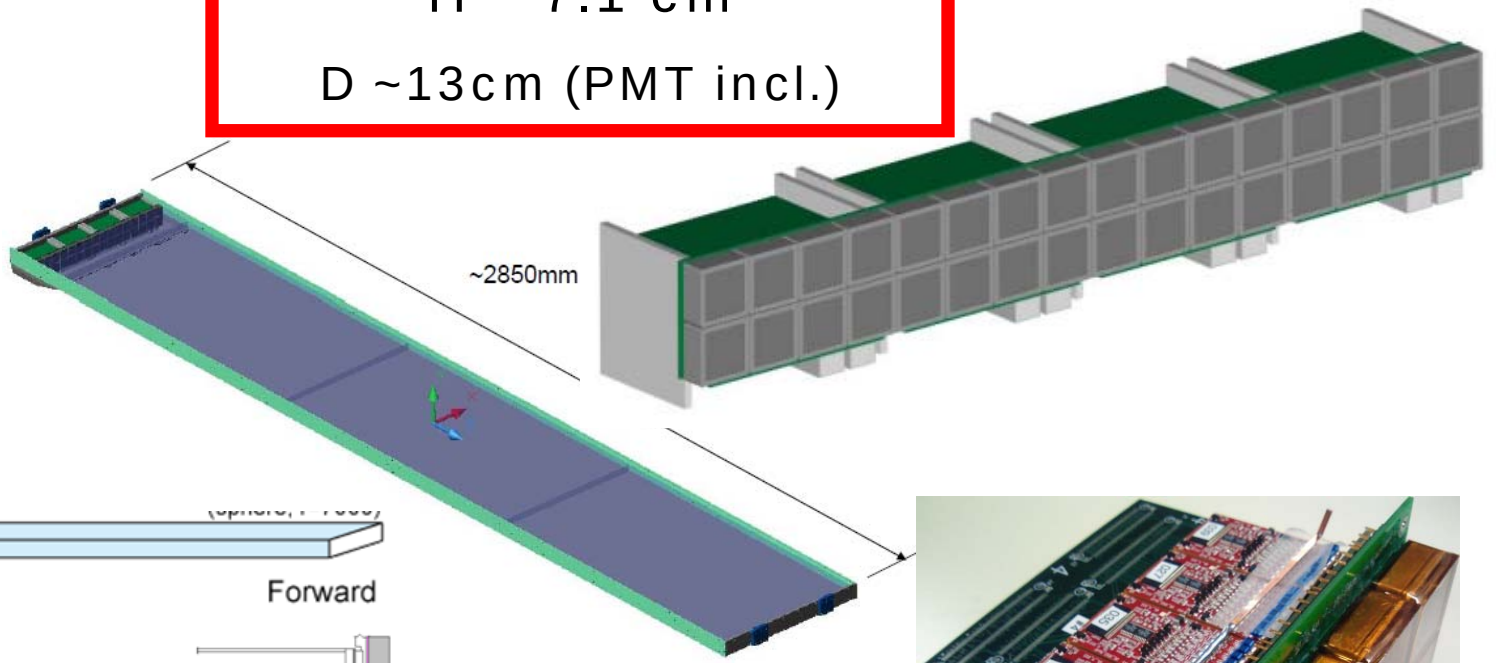
- Must fit in a very crowded envelope

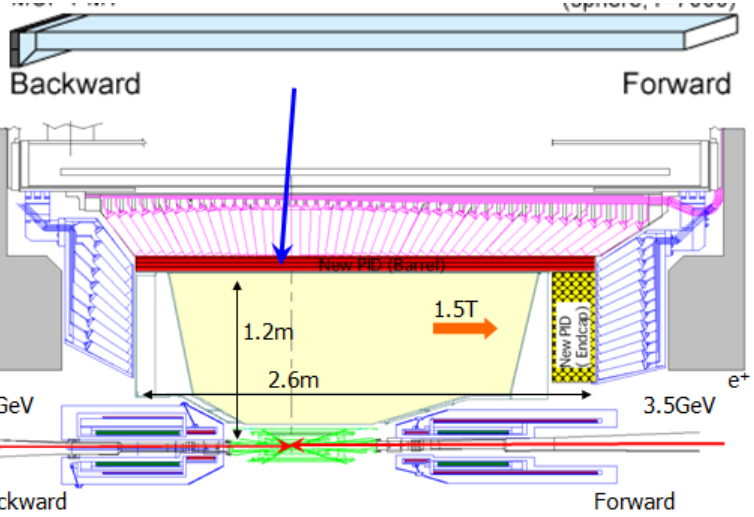
H ~ 7.1 cm

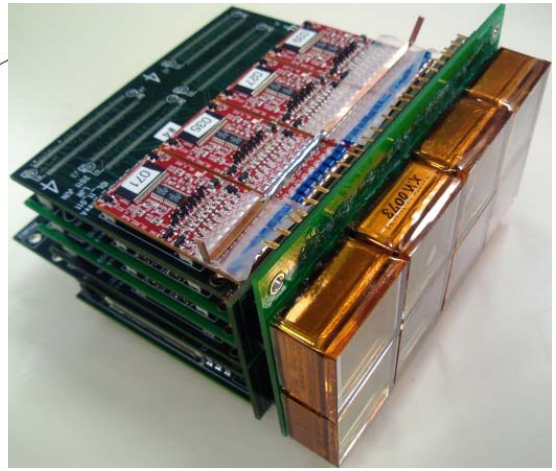
D ~13cm (PMT incl.)

512 channel readout



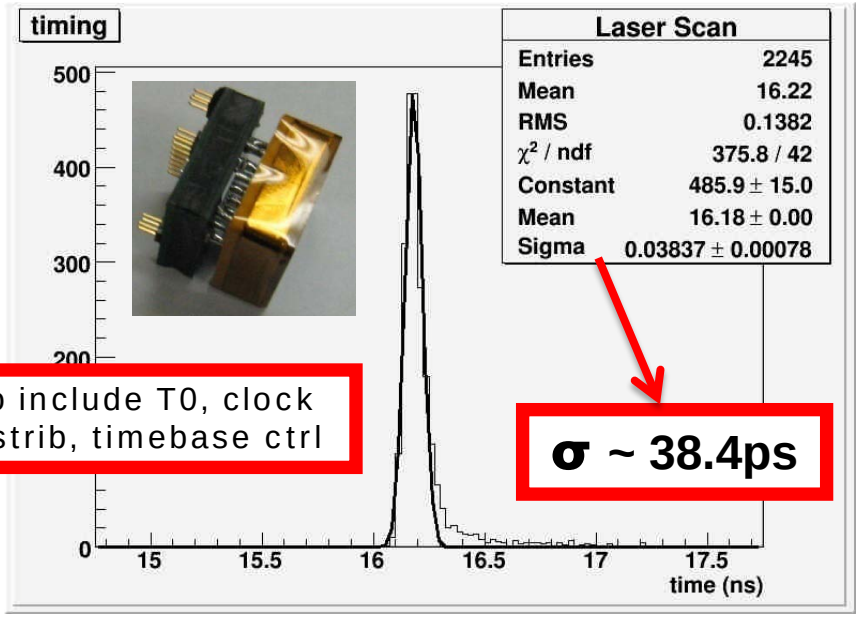


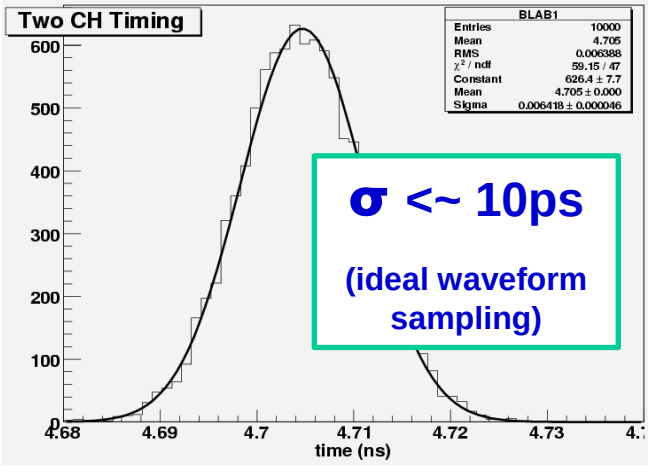




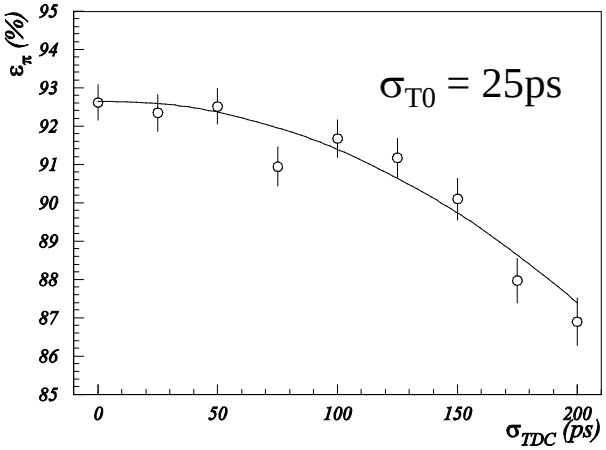
Performance Requirements (TOP)

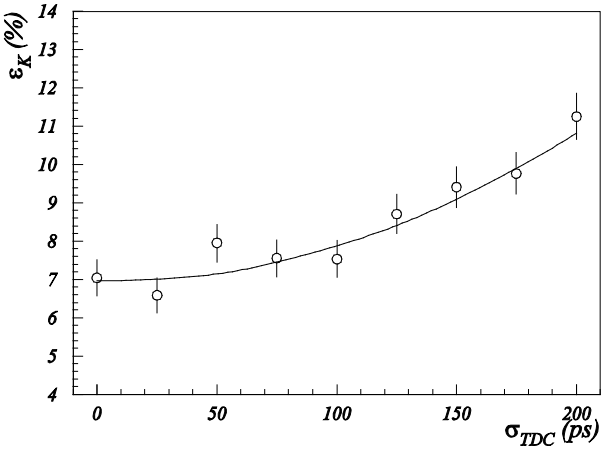
- Single photon timing for MCP-PMTs





NIM **A602** (2009) 438



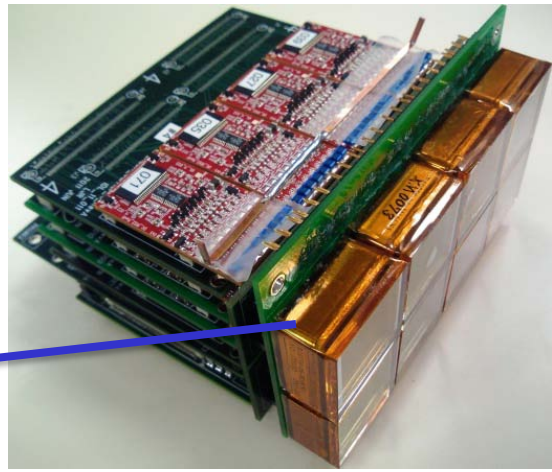


σ <~ 50ps target

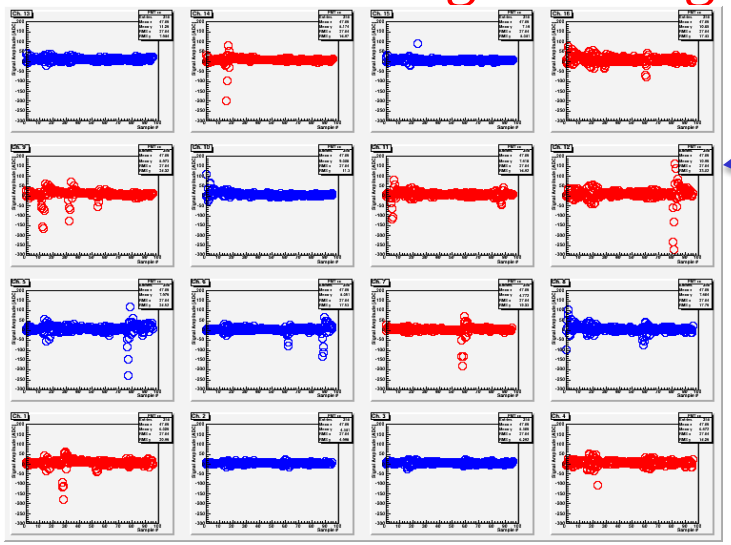
NOTE: this is single-photon timing, **not** event start-time "T_0"

Readout Option Chosen

- Why Waveform Sampling?



- Lower power, high density, cost effective
  - Handle charge-sharing/cross-talk



Single PMT (beam test data – 90ns windows)

Leverage experience from radio-neutrino work (<=30 ps on large, solar-powered payload)

- Why Not use existing ASIC?

- No suitable existing ASICs (reason why current ASICs developed)
  - BLAB/IRS are only GSa/s SCA ASICs with 5μs depth (L1 trig)
    - Triggerless operation? → higher power, 330x data rate

Readout ASIC Specifications

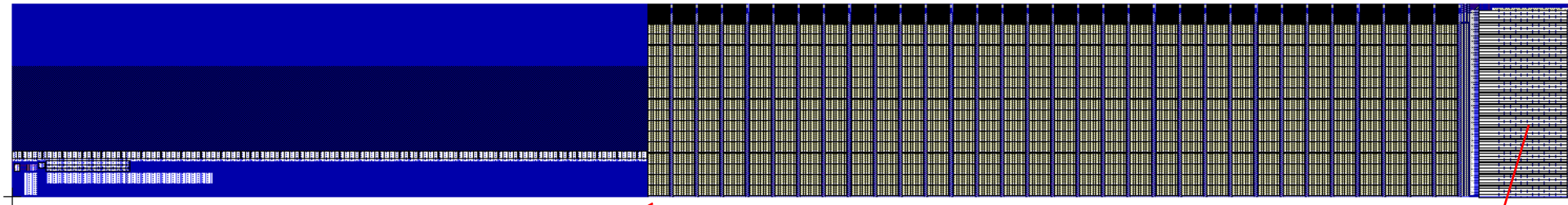
32768	samples/chan (>5.2μs trig latency)
8	channels/BLAB3 ASIC
8	Trigger channels
~9	bits resolution (12[10]-bits logging)
64	samples convert window (~16ns)
4	GSa/s
1	word (RAM) chan, sample readout
1+n*0.02	μs to read n samples (of same 64)
30	kHz sustained readout (multibuffer)

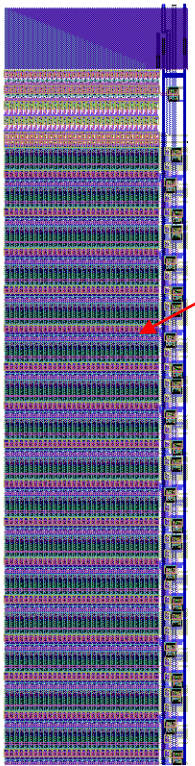
- Time alignment critical
  - Synchronize sampling to accelerator RF clock (Belle TOF)
  - >5μs buffer depth a must for trigger, since single photon rates high

ASIC Single Channel

- Sampling: 128 (2x 64) separate transfer lanes

Recording in one set 64, transferring other (“ping-pong”)



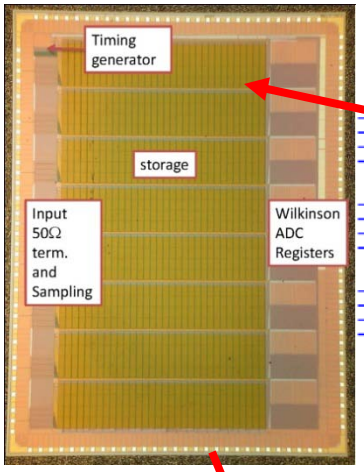


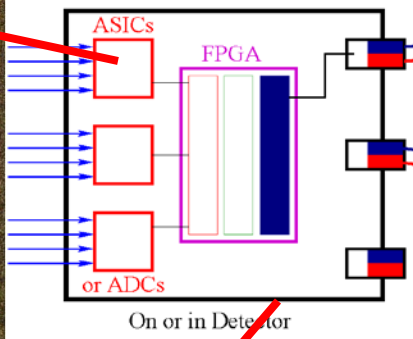
- Concurrent Writing/Reading
- Only 128 timing constants
- Storage: 64 x 512 (512 = 8 * 64)
- Wilkinson (64x1): was (32x2)
- 64 conv/channel

TOP Readout Architecture

16 COPPER

Waveform sampling ASIC

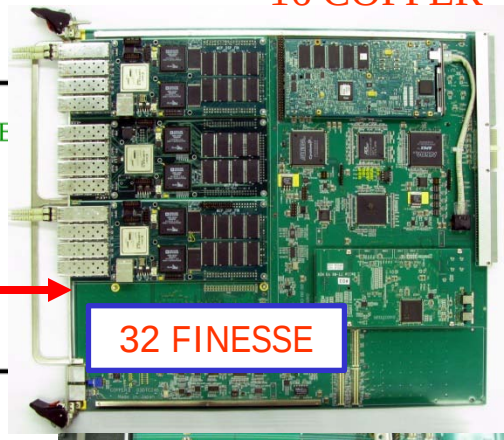




Giga-bit Fiber Transceiver Links

COPPER

FINESSE



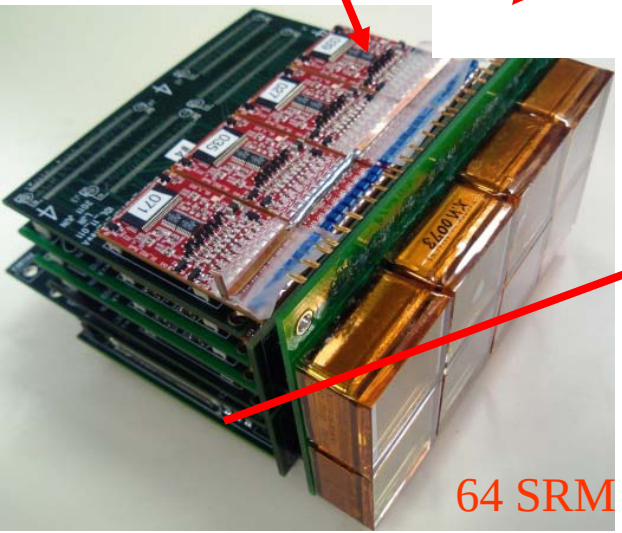
Global Decision Logic

Clock/Event Timing Distribution

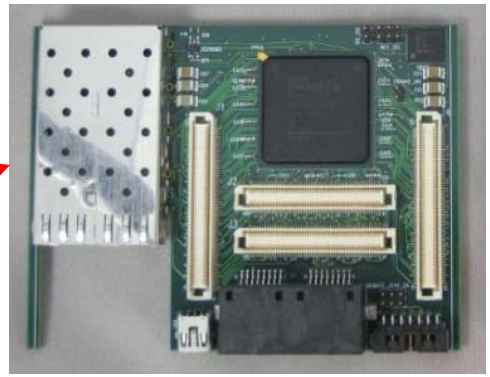
FPGA firmware consists of 3 parts:
1) ASIC/ADC driver (common)
2) Trigger feature extract (subdet. specific)
3) Unified DAQ transport protocol

8k channels
1k 8-ch. ASICs

Clock jitter cleaners



64 SRM



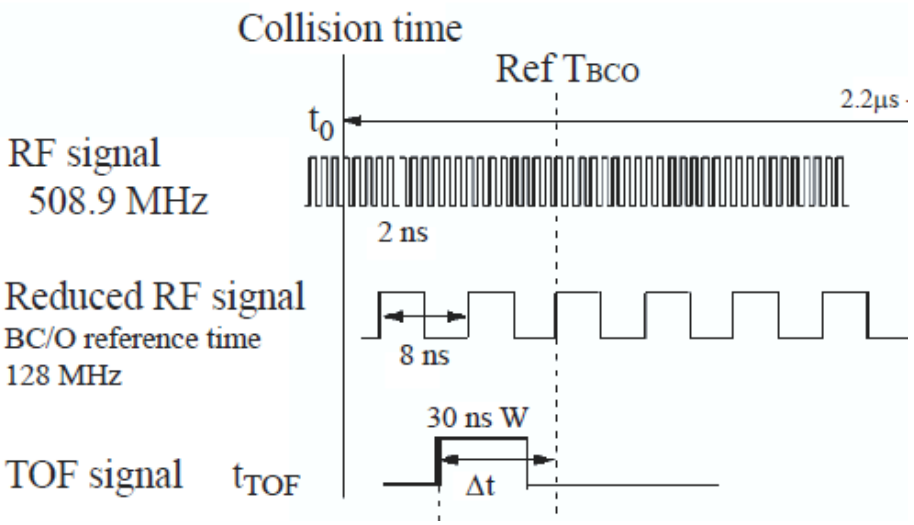
SRM Control "SCROD"

FTSW clock, trigger, programming

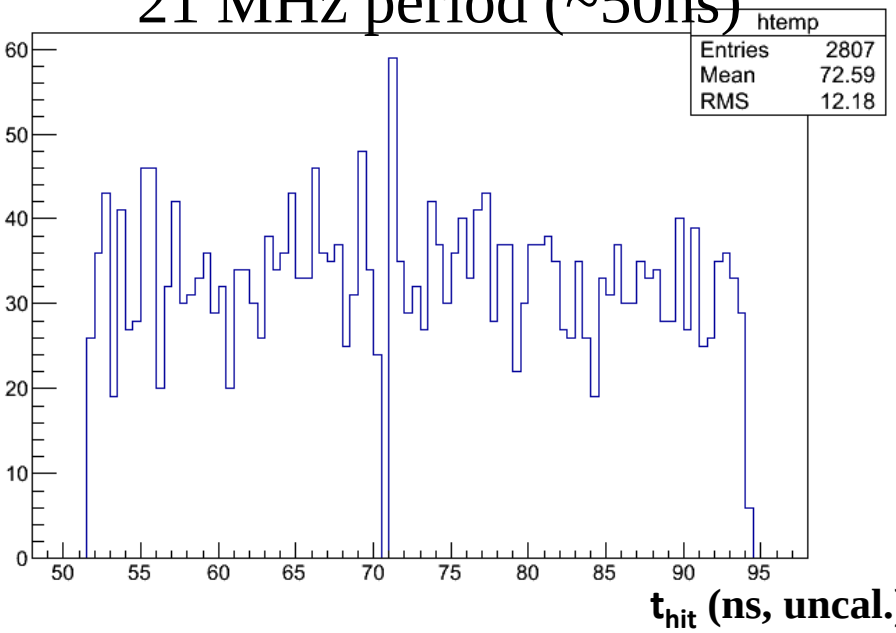
16 FTSW

Event Timing

- At Super-KEKB the timing of signals should be **fixed** relative to trigger (system clock)
  - But it is random with respect to 21 MHz derived (Super-KEKB RF clock).
  - t_{hit} from waveform must be combined with t_{FTSW} from CAMAC TDC to align events.
  - $t_{global} = t_{hit} + t_{ftsw}$



21 MHz period (~50ns)



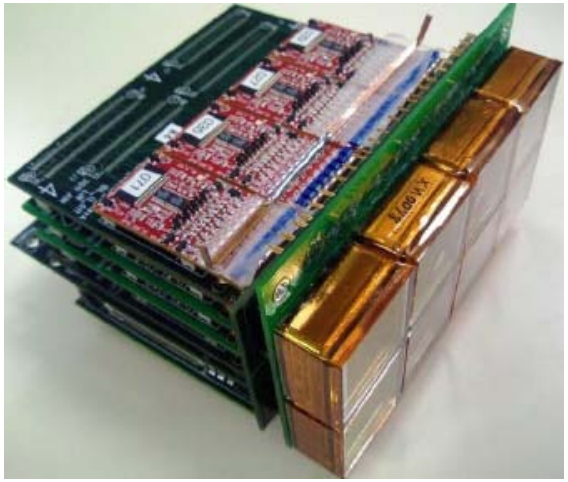
System Synchronization

Crucial to obtain required performance

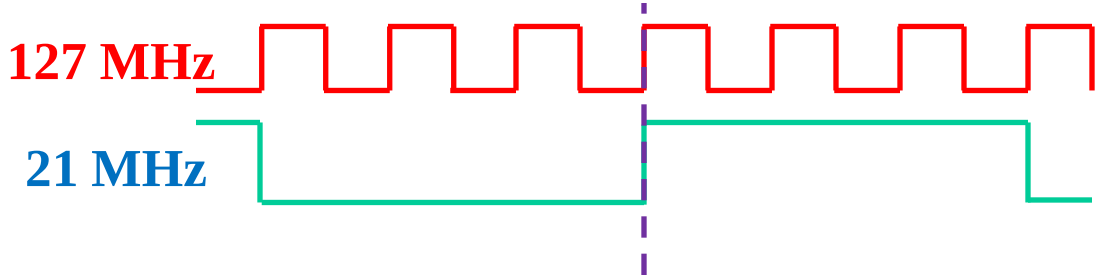
FTSW (Timing & Trigger Distribution board)

127 MHz clock

Serial data (trigger & synchronization)

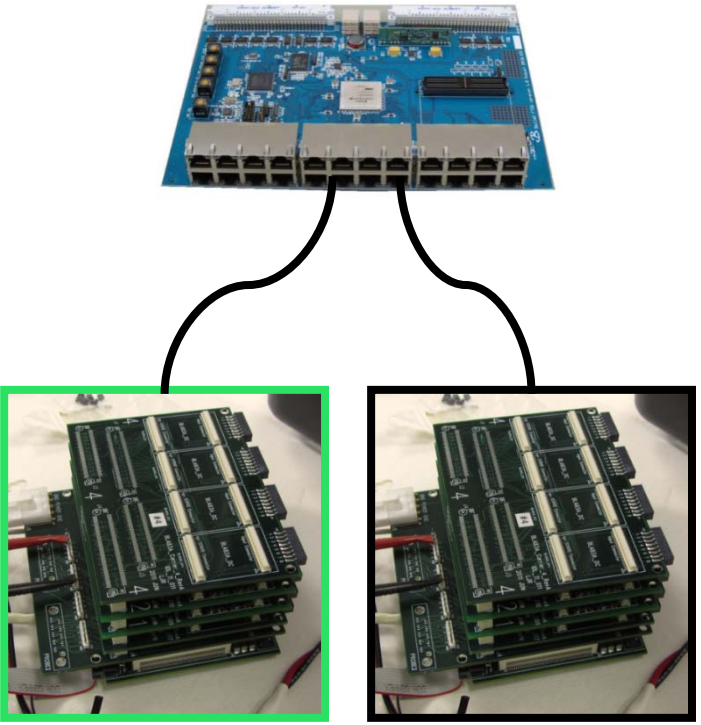


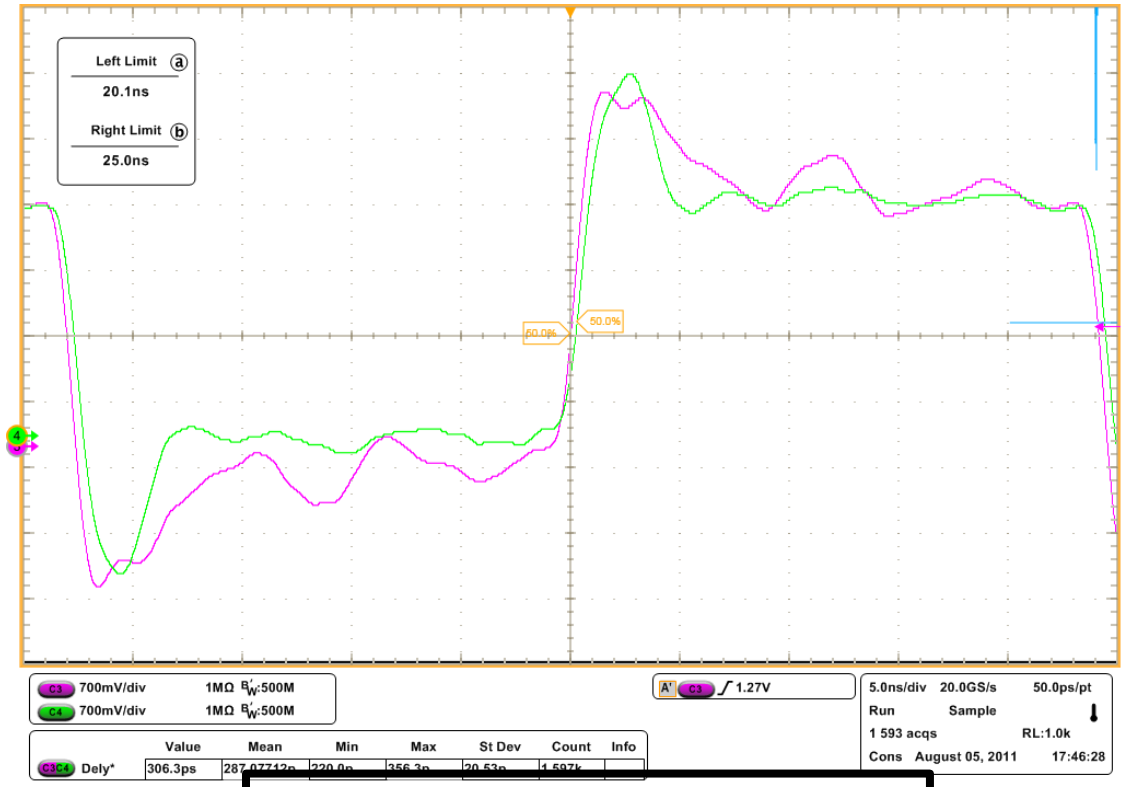
- **127 MHz clock is divided by 6 on front-end module to ~21 MHz**
  - **This corresponds to sampling rate of ~2.7 GSa/s**
  - **FPGA uses serial data stream to determine clock phase**



Clock Distribution Performance

- Test results performed as part of the cosmic ray test stand integration at Nagoya Univ in August 2011:

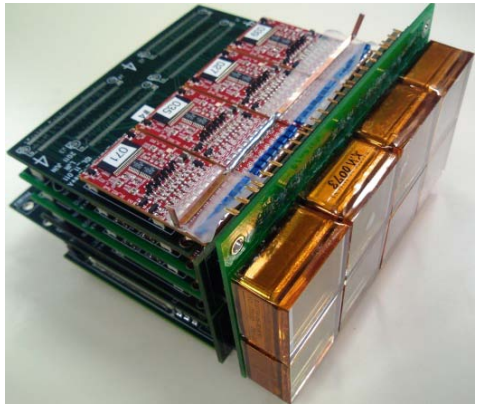




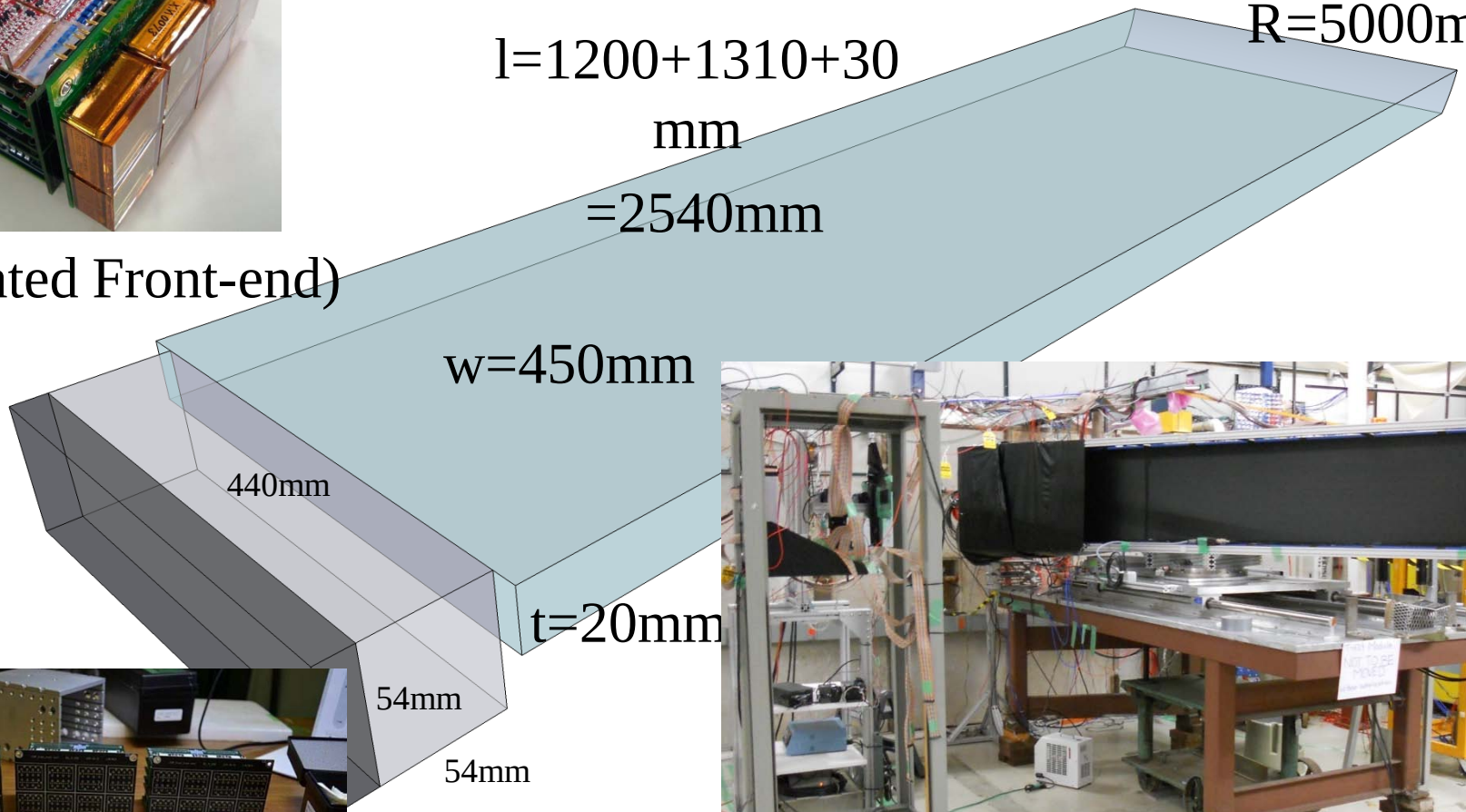
Measured phase and jitter of 21.2 MHz clock from two modules (on oscilloscope)

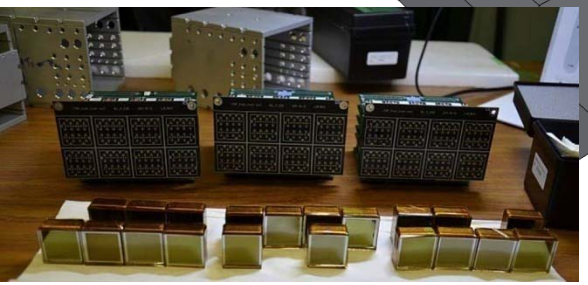
Clocks are <u>phase-aligned</u>.
➔ Measured jitter: 20 ps RMS.

2011-2012 Fermilab Beam Test

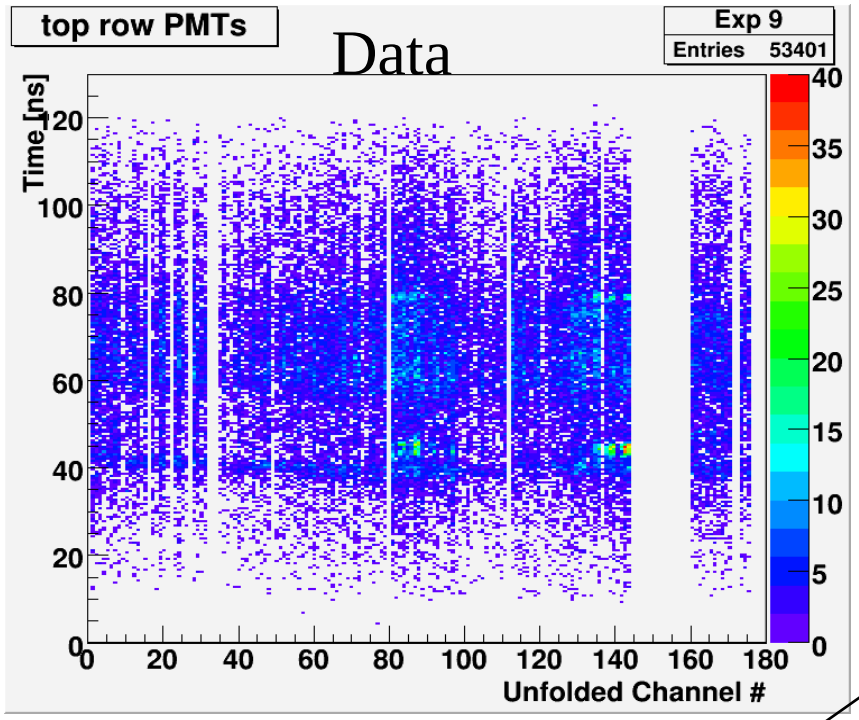


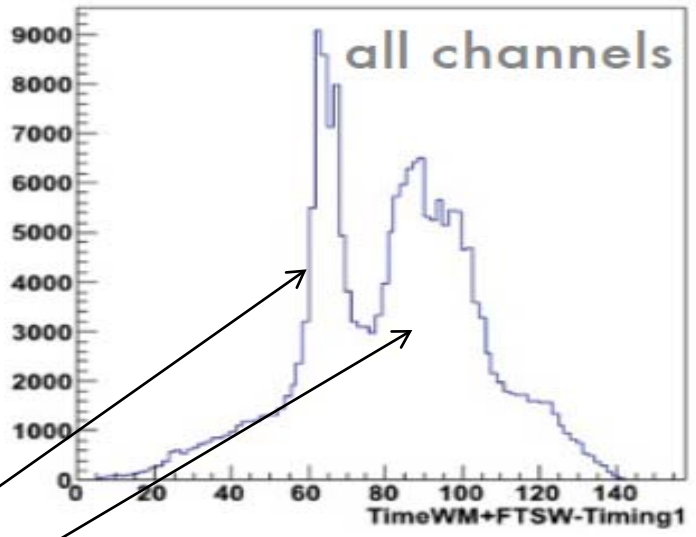
(Integrated Front-end)

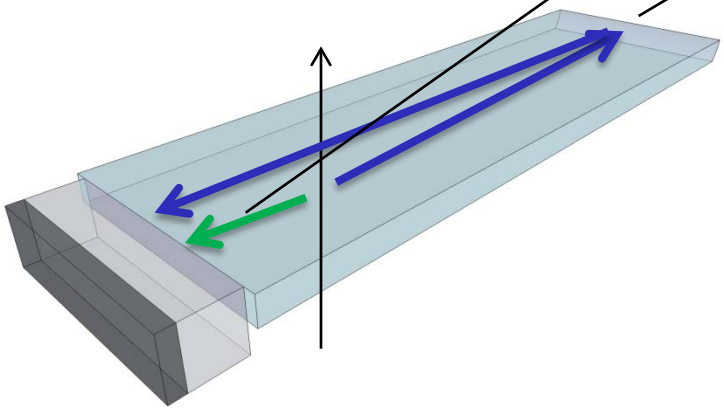




Hit distribution for normal incidence





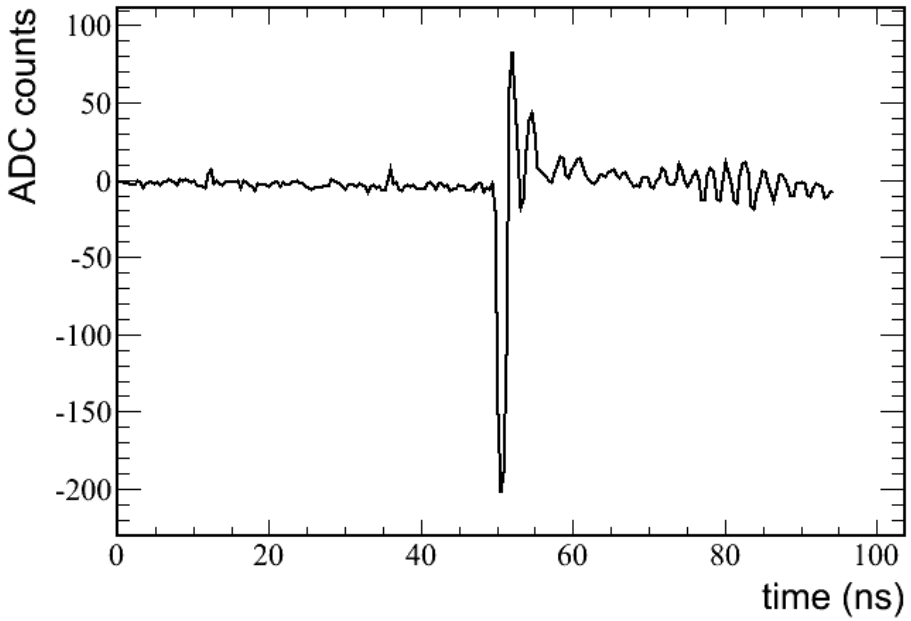


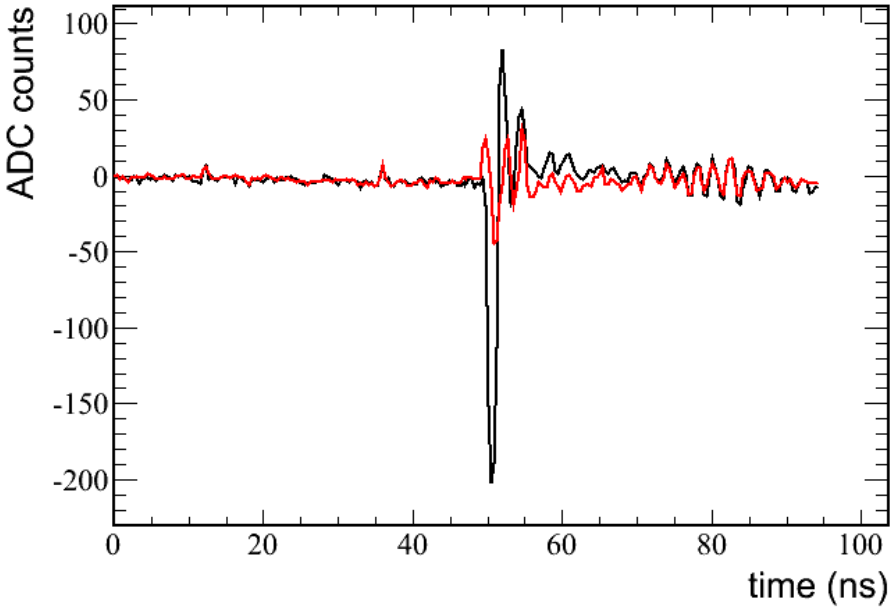
Could see direct photons and mirror-reflected photons.

However, there is large background

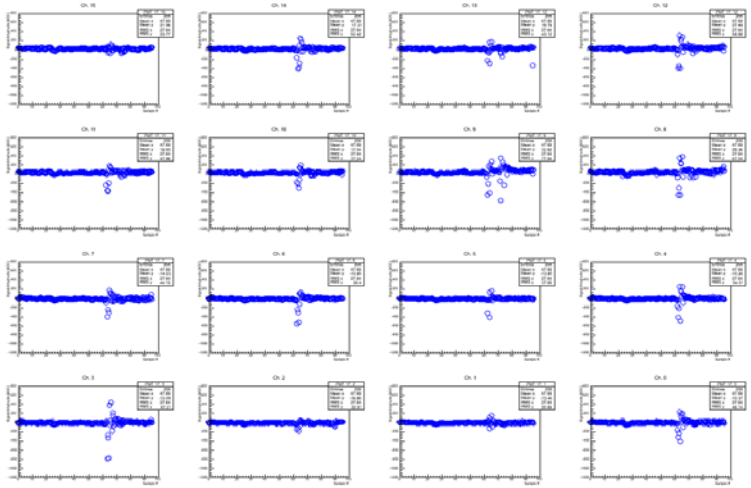
Veto shower and cross-talk cuts needed

Signal processing





Clean hit (center of Anode pad)

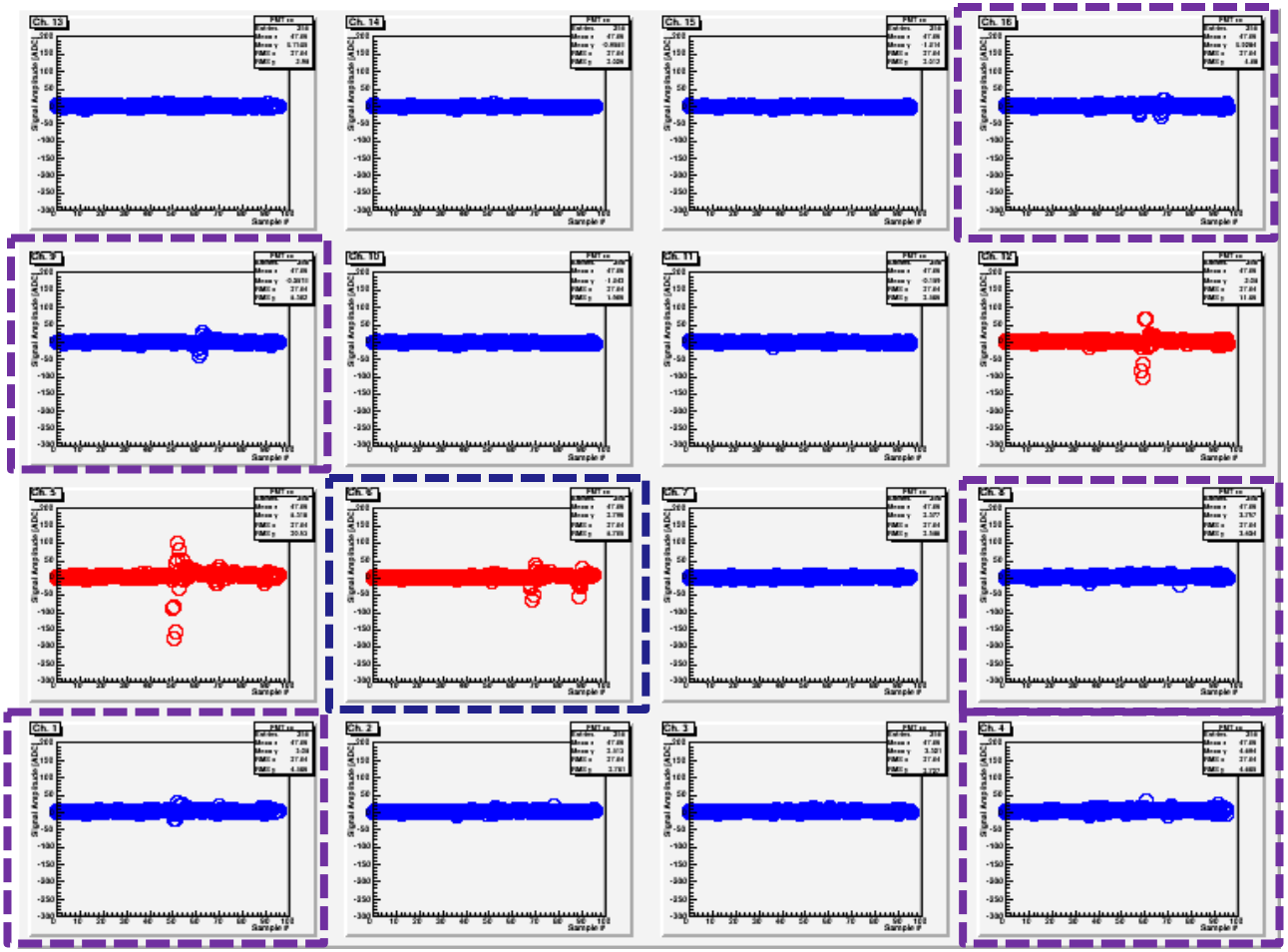


Depending upon amplitude, "cross talk" hit (red) == remove by filtering

Can (in principle) decouple PMT, wiring & readout x-talk

Photon Counting Studies

Example event, waveforms from all channels of one MCP-PMT



Red – waveform with a hit to be counted in total N_γ

Blue – waveform with no hit

Testbed for:

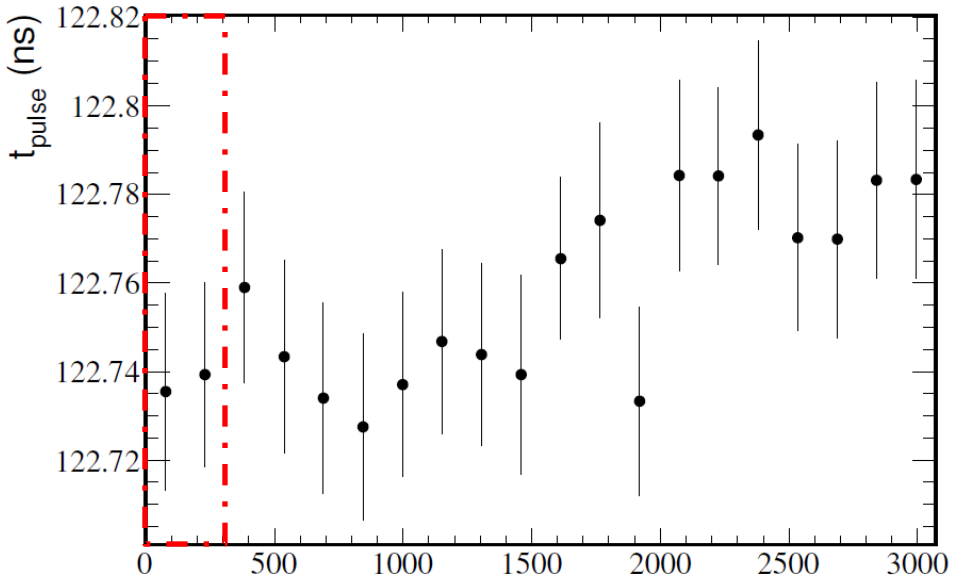
- **Ensuring cross-talk or charge sharing events are not double counted.**
- **Counting double hits.**
- **Avoiding any artificial digital glitches that might otherwise be counted.**

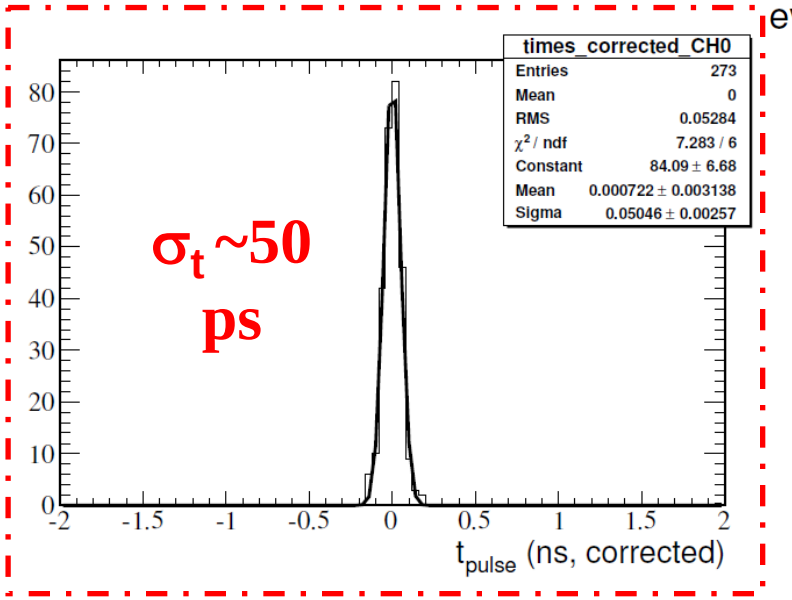
➔ **Single p.e. laser studies allow a more controlled environment to check cross-talk from various sources.**

Temperature Dependence

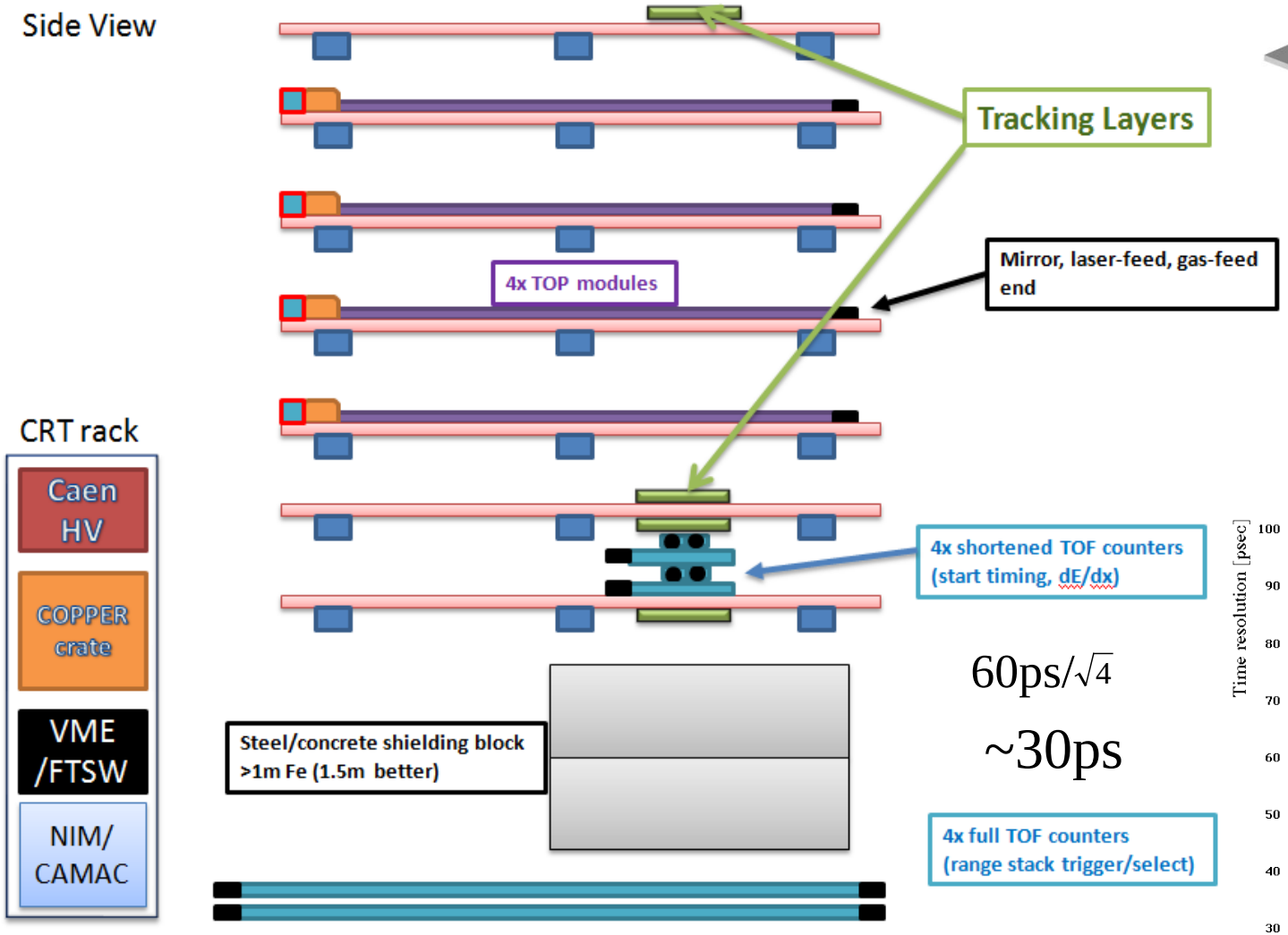
- Timing observed to drift over event number
  - Contributions:
    - Baseline shifts in waveforms
    - Change of time-base with temperature
  - Timing over limited event region demonstrates improvement in timing resolution by removing these effects

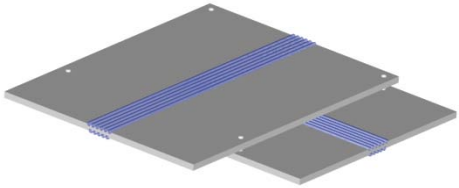
For pulsed channel, hit_time vs





Cosmic Ray Telescope (Fuji Hall, KEK)

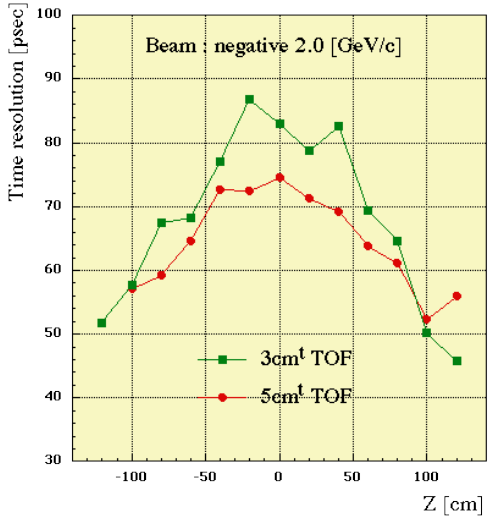




~1mm resolution Sci Fi tracker over ~2 meters < ~1mrad

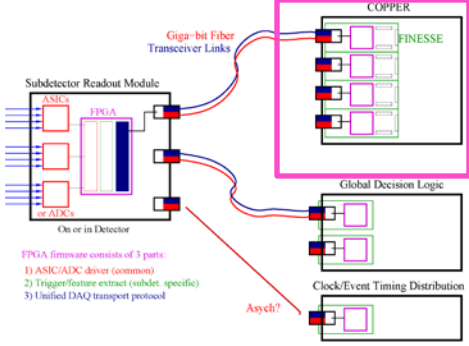
$60ps/\sqrt{4}$

~30ps

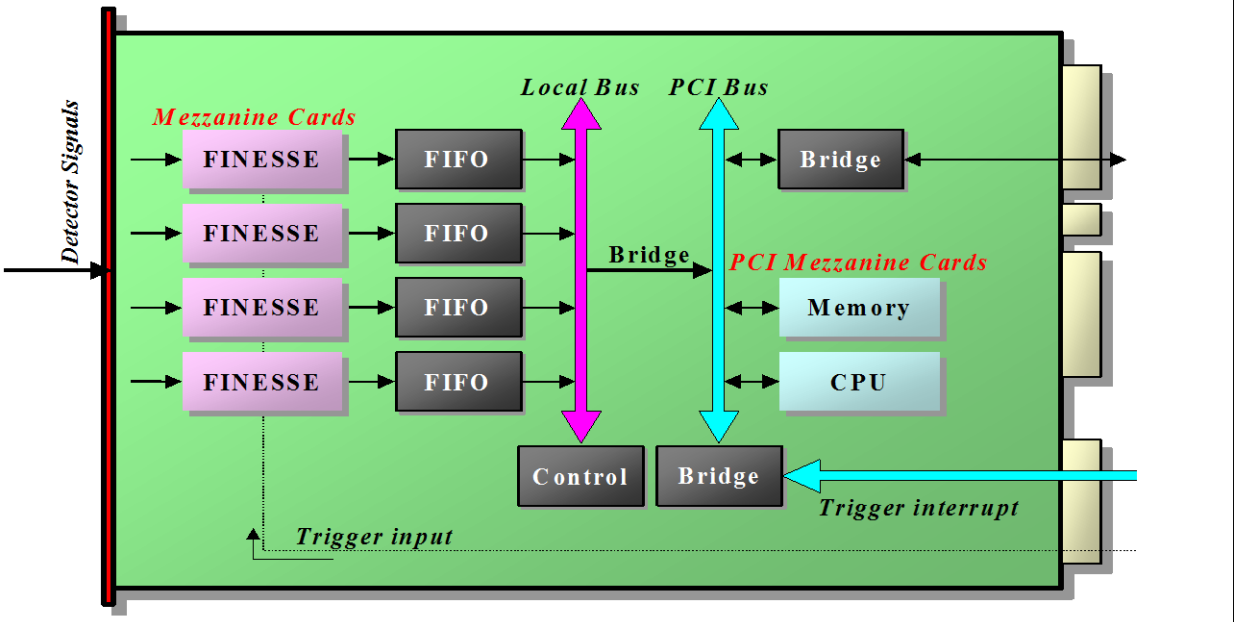


Under construction now: testbed for "final" ASIC, pre-production electronics

CRT Platform: Back-end processing



Schematic Drawing of the COPPER



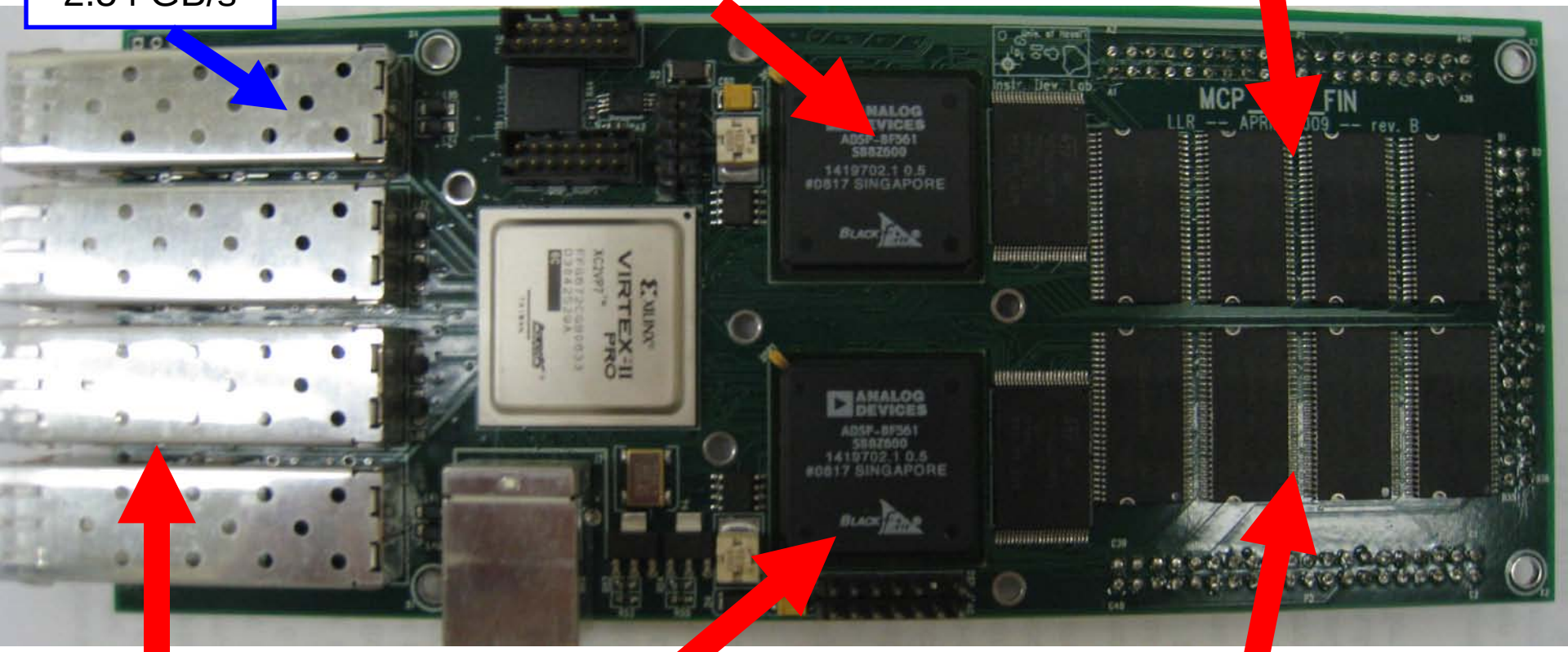
Upgraded for Belle II

- COPPER (COmmon Pipelined Platform for Electronics Readout)
- Used in Belle, J-PARC experiments
- FINESSE (Front-end Instrumentation Entity for Subdetector Specific Electronics)

Fast-feature extraction -- beam & CRT

- 500 MHz processor per core
- 32x waveform channels per core
- 60k Waveforms/s benchmarked

DSP_FIN

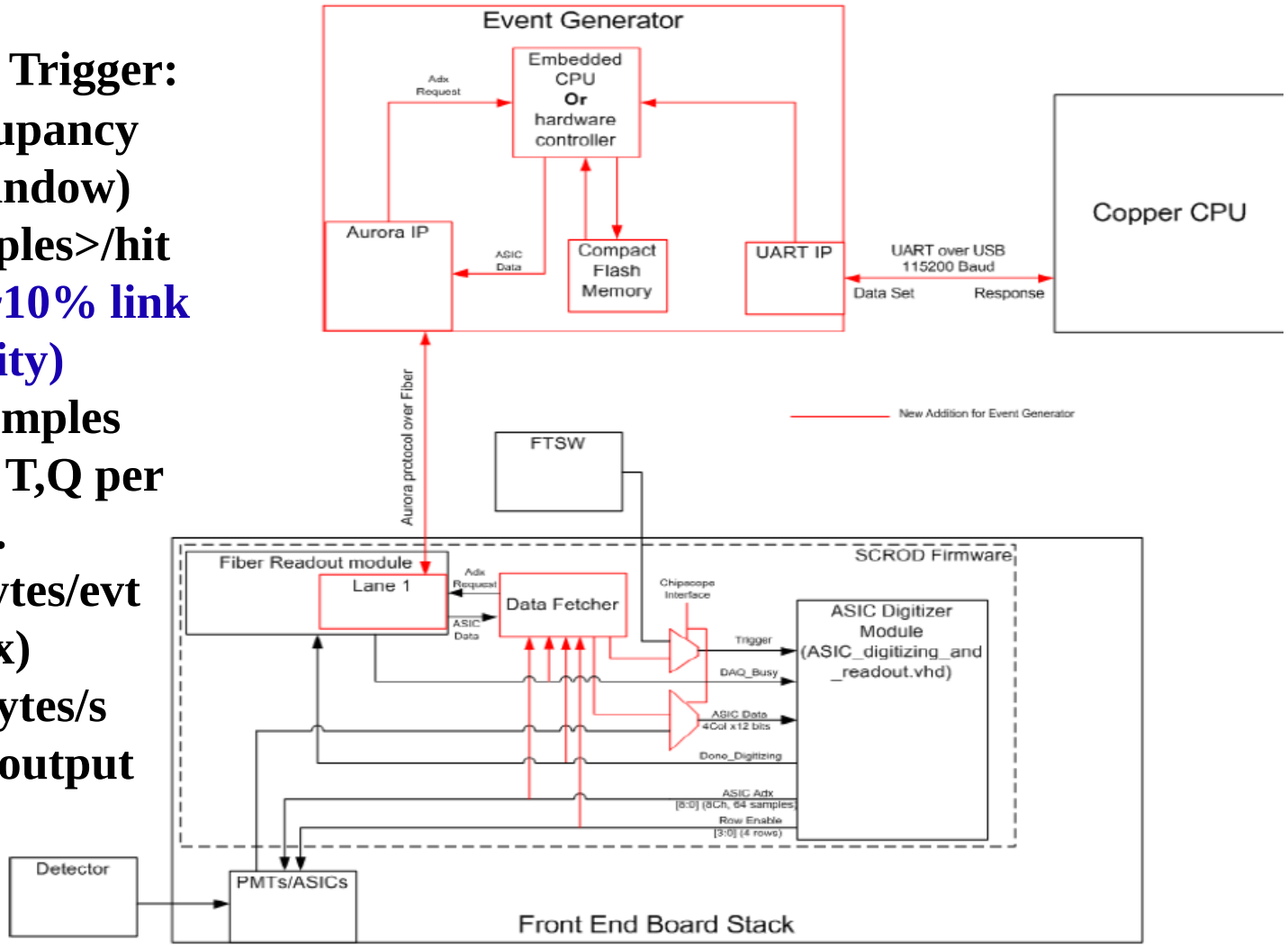


Data Reduction Exercises

Event Generator Design

"full speed" testing

- **30kHz L1 Trigger: 2.5% occupancy (100ns window)**
- **<100 samples>/hit**
- **0.3Gbps (~10% link capacity)**
- **~100 samples reduced to T,Q per p.e.**
- **Few kBytes/evt (max)**
- **13 Mbytes/s expected output**



Belle II TOP Readout Status

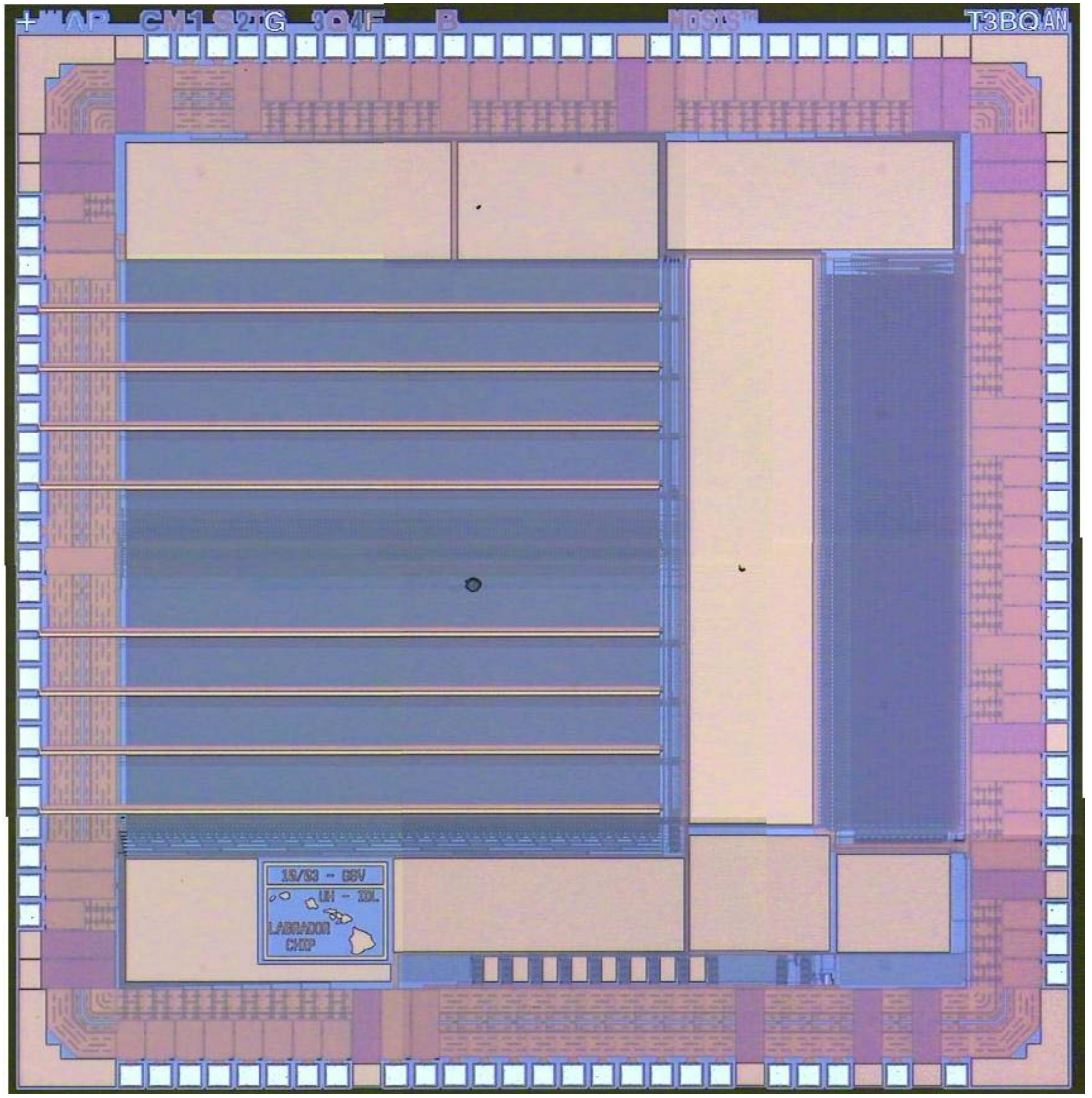
- **IRS3B fabricated** ("final ASIC, if no changes needed")
- Next generation control firmware in development v.2 fDIRC CRT; v.3 IRS3B, backend processing
- Redesign, fab of next generation board stack
  - Improved HV, cooling
  - Feedback control, in-situ calibration
  - Amplifier options being studied (N.B.: 5×10^5 gain)
- Experience with confirming prototypes by end of 2012, "pre-production" early 2013
- Production in late 2013-2014
- Installation, commissioning and operations: 2015-2016

Summary

The "Giga" Era of Instrumenation is here

- Enables whole new ways of instrumenting detectors
- Commodity components and processes open whole new opportunities

Back-up slides

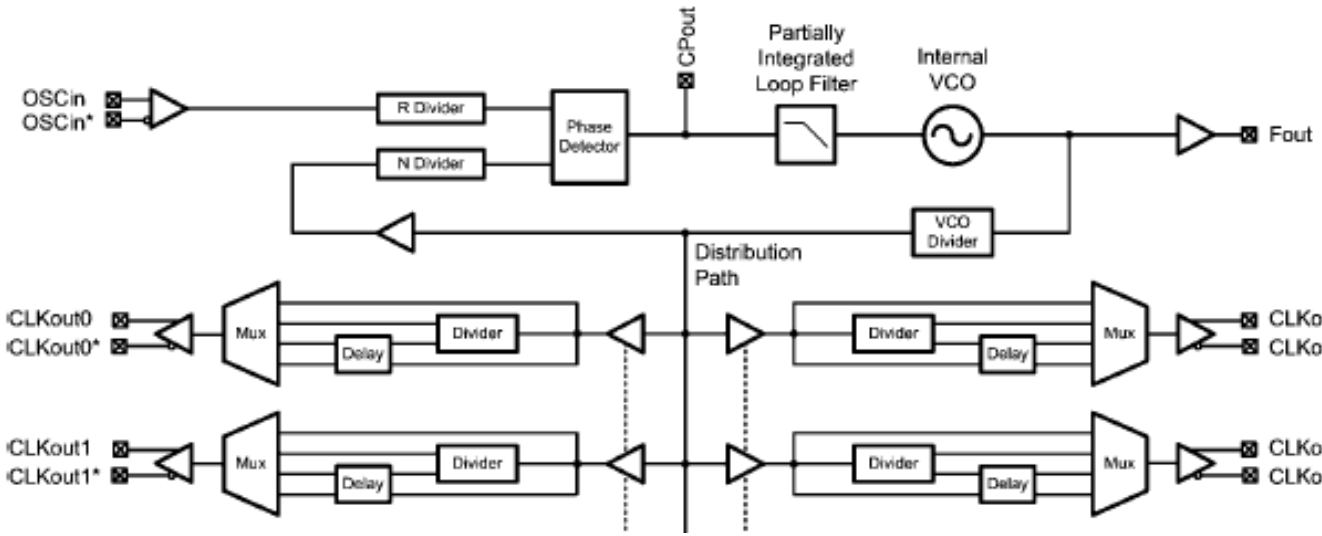


Timing Big Systems I

LMK03000 Clock Conditioner
(National Semiconductor)

Jitter: 400 fs

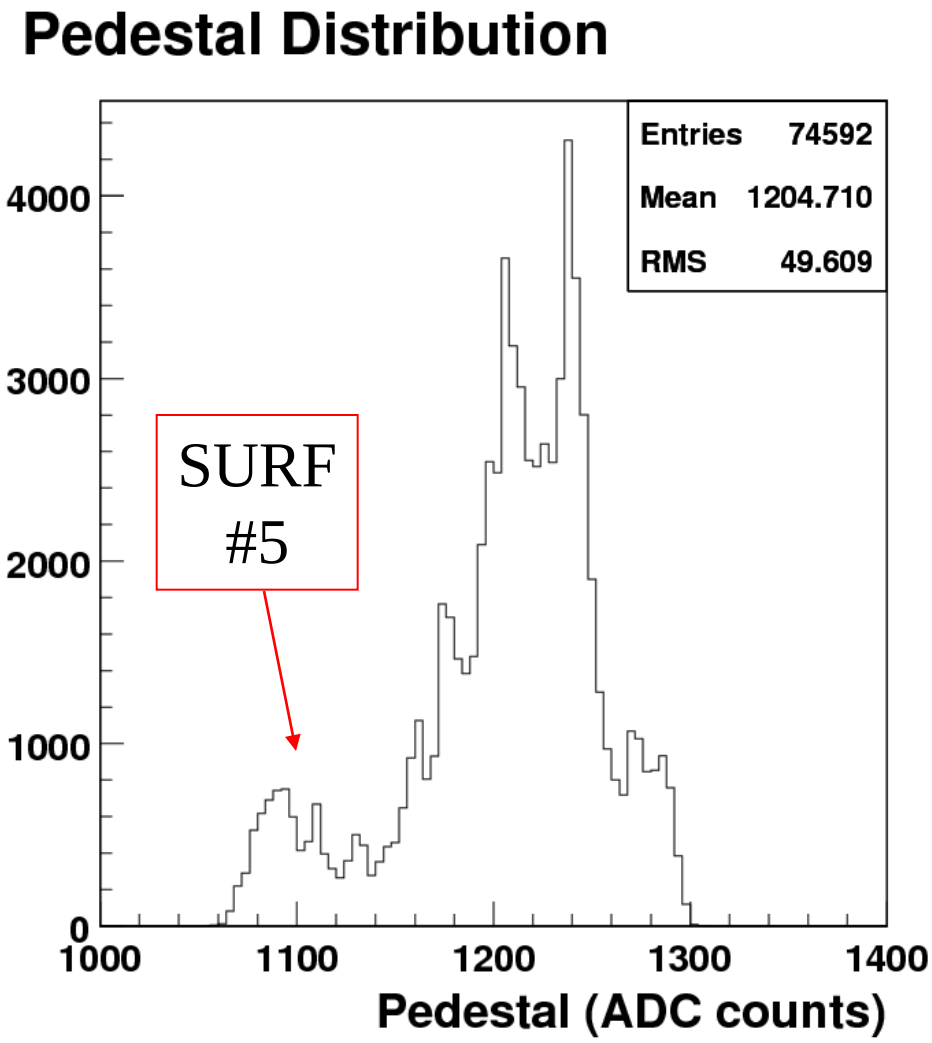
Global
Clock
~20 MHz

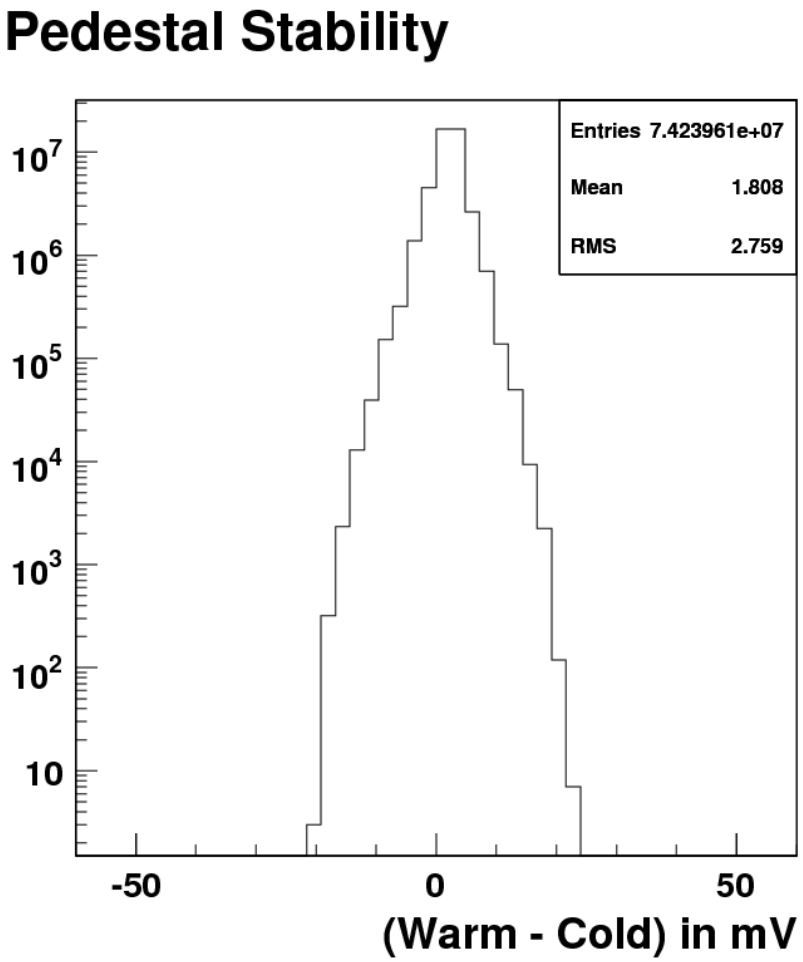


Reference
Clock for
DRS4 PLL
2.5 MHz

Reference
Clock for
timing
channel

Pedestal and Pedestal Stability

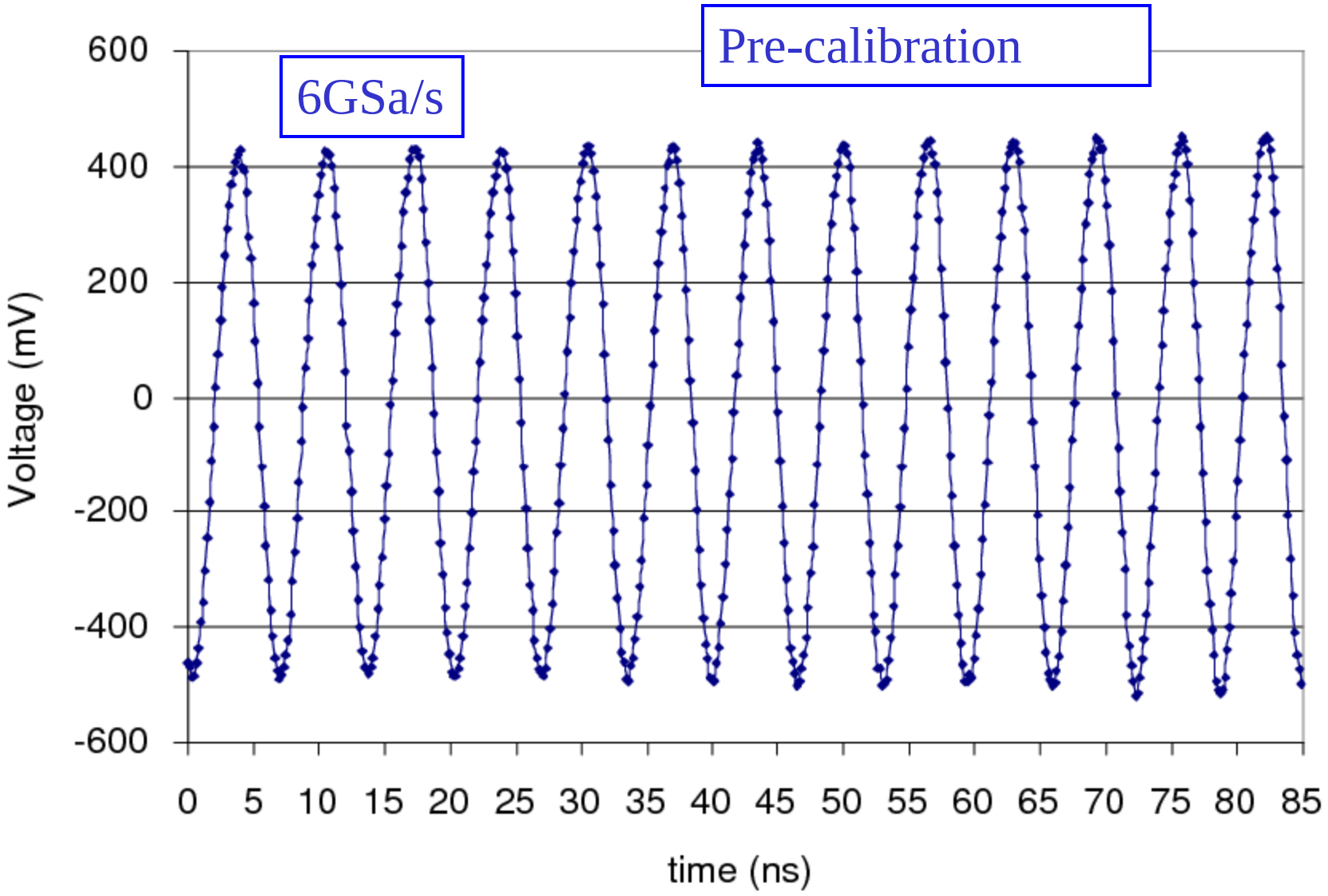




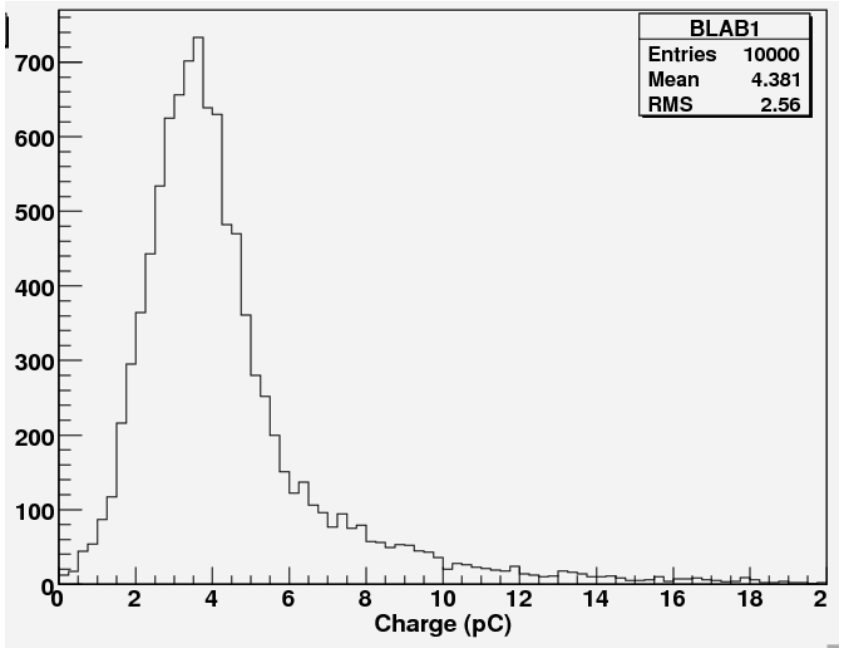
$\Delta T = 17C$ ($\delta t \sim 24$hours)
~0.052mV/C

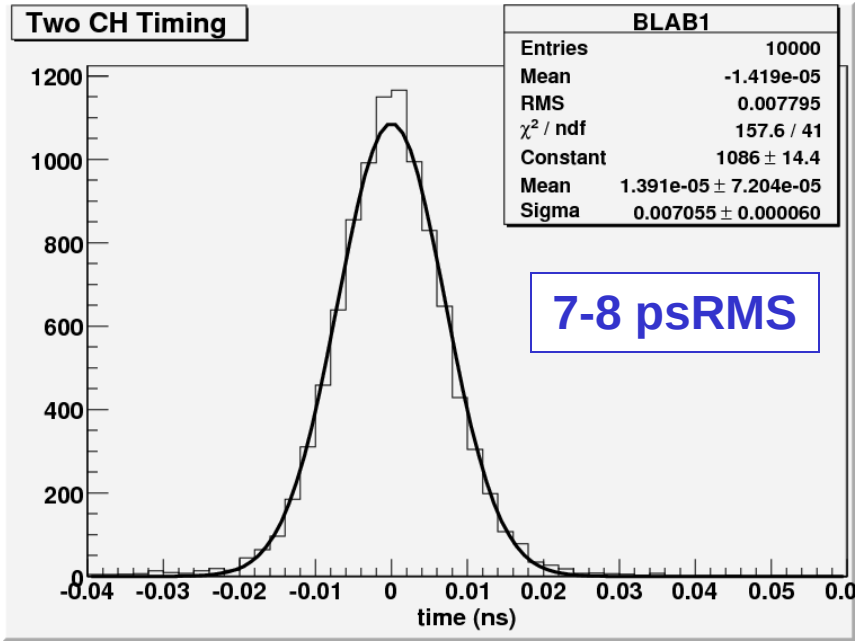
- AC coupled input

125MHz sine wave



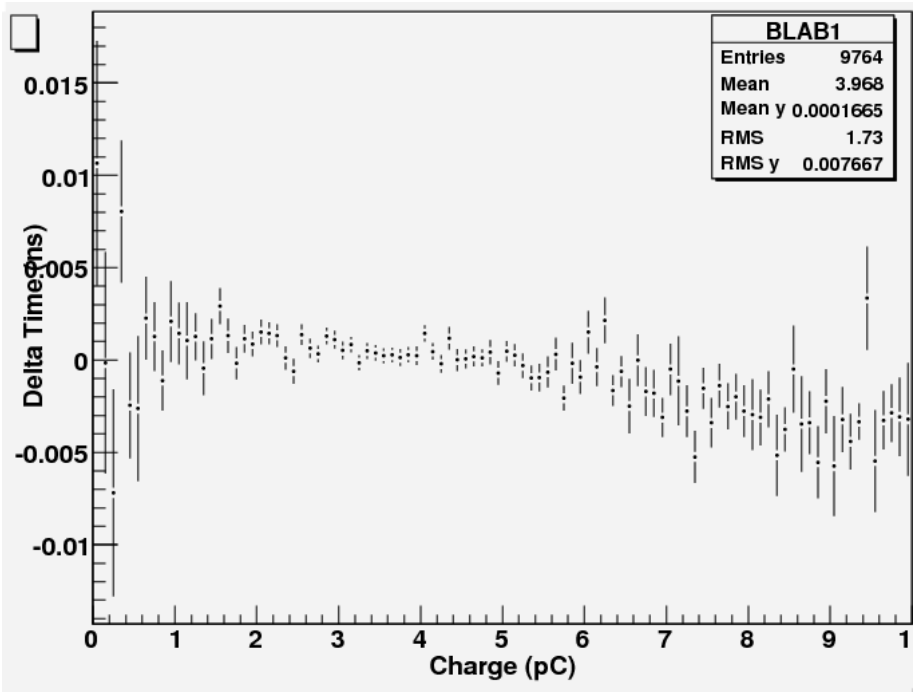
Real MCP-PMT Signals (with BLAB2)





7-8 psRMS

Residual Time Walk



Rather robust for amplitude invariant signals,
TOF still hard, but can shape extract

Simulated Performance vs. SNR

300MHz ABW, 5.9GSa/s