From picoseconds to galaxies

Building electronics for Relativistic Heavy Ion Collider and for Dark Matter Search

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Outline

- Introduction.
- Electronics for PHOBOS at RHIC.
  - Time Equalizer electronics.
  - Universal Trigger Module for on-line trigger.
- Research and student projects at UofR.
- Electronics for Dark Matter Search.
- Tiled Diffraction Gratings at LLE.
- Summary and acknowledgements.

Electronics and software help achieve scientific goals

- My electronics and software developments are driven by science.

  Tools to help achieve scientific goals rather than goals in themselves.
- The tools are meant to be used in mission-critical applications.
- Therefore, no compromises are allowed concerning their quality.
- Electronics development required all of the following:
  - Schematic design, board layout and board assembly.
  - Hardware testing and debugging.
  - Software for embedded microcontroller.
  - Firmware for on-board FPGA.
  - GUI design and programming.
- The “one-man show” brings coherence to my designs.

Electronics for PHOBOS

PHOBOS experiment at RHIC

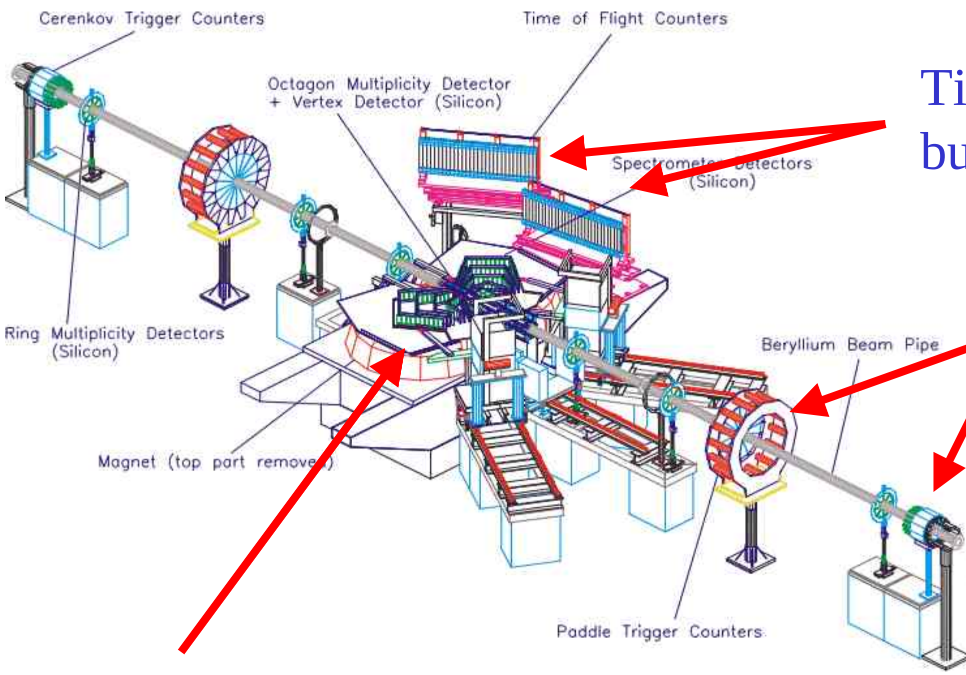
Relativistic Heavy Ion Collider, Brookhaven National Laboratory

<u>Scientific goals</u>:

Investigate hot, dense nuclear matter, that could have existed about 1μsec after the Big Bang .

Discover and characterize quark-gluon plasma.

PHOBOS @ RHIC



Time-of-flight counters (240 units) built at UofR Physics.

Fast trigger detectors made of scintillating plastic + phototubes.

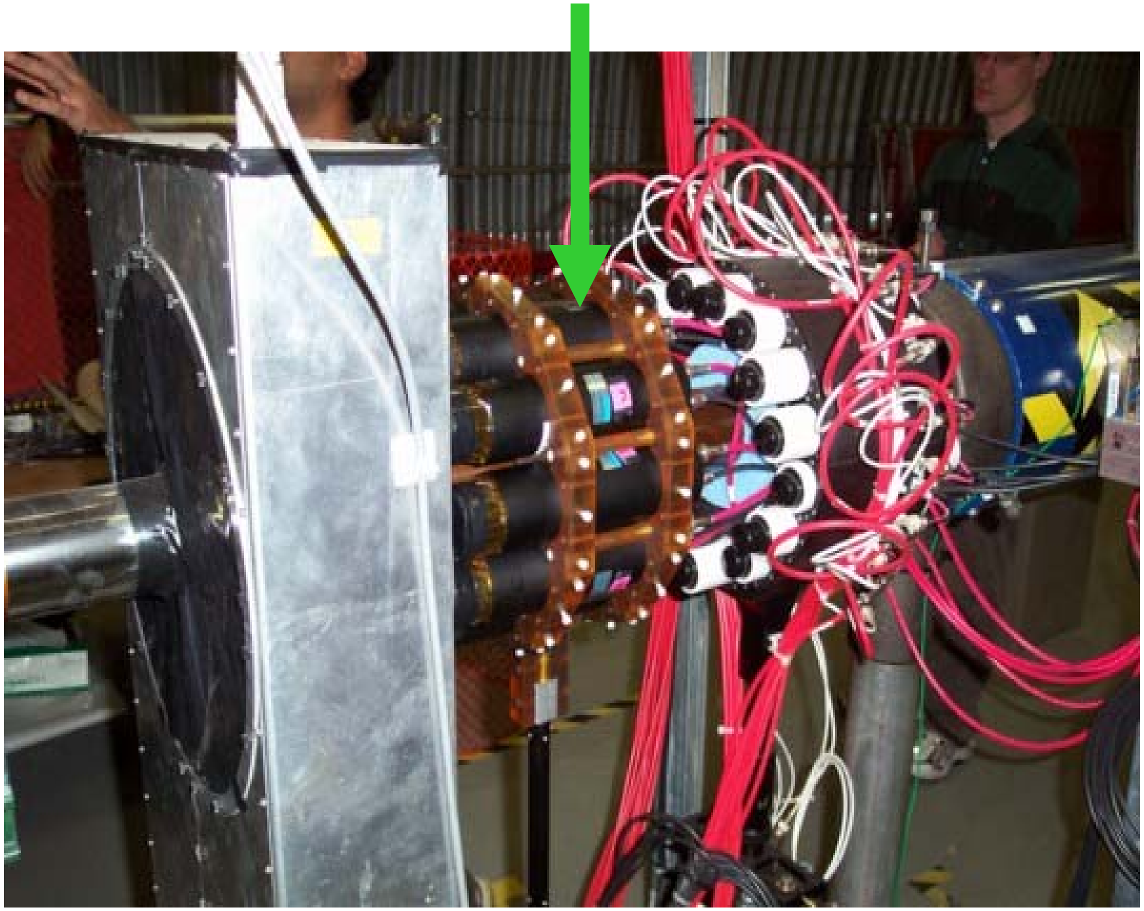
Silicon tracking detectors (150,000 channels)

Time Equalizer

for PHOBOS

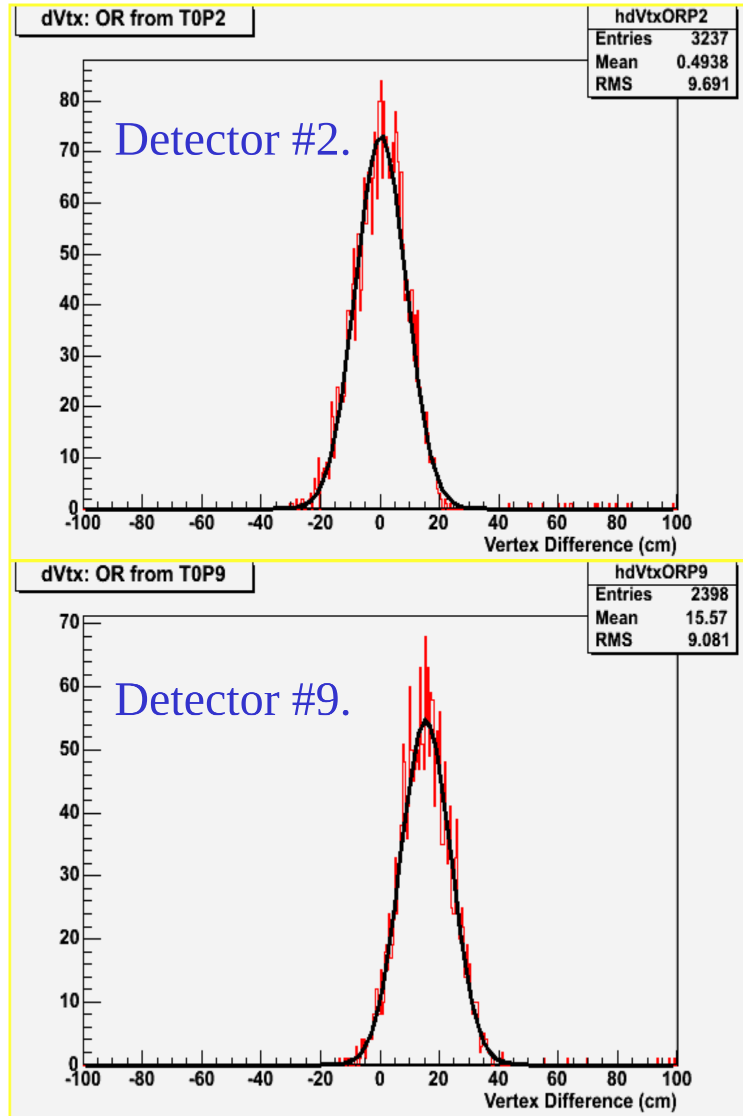
Cerenkov T-zero detector arrays

- Developed by the UofR Time-of-Flight group: Frank Wolfs (PI), Wojtek Skulski, Erik Johnson, Nazim Khan, Ray Teng.
- Two circular arrays of 16 Cerenkov counters, ~60ps resolution each counter.



Situation before Time Equalizer

- Individual Cerenkov T-zero detectors have a very good resolution of ~60ps.
- However, the time-of-arrival of signals from individual detectors was not aligned in the Counting House after propagation over long cables.
- The attainable spatial resolution would be adversely affected.
- What is plotted: time-of-arrival of a signal, translated to spatial domain (after taking the detector geometry into account).



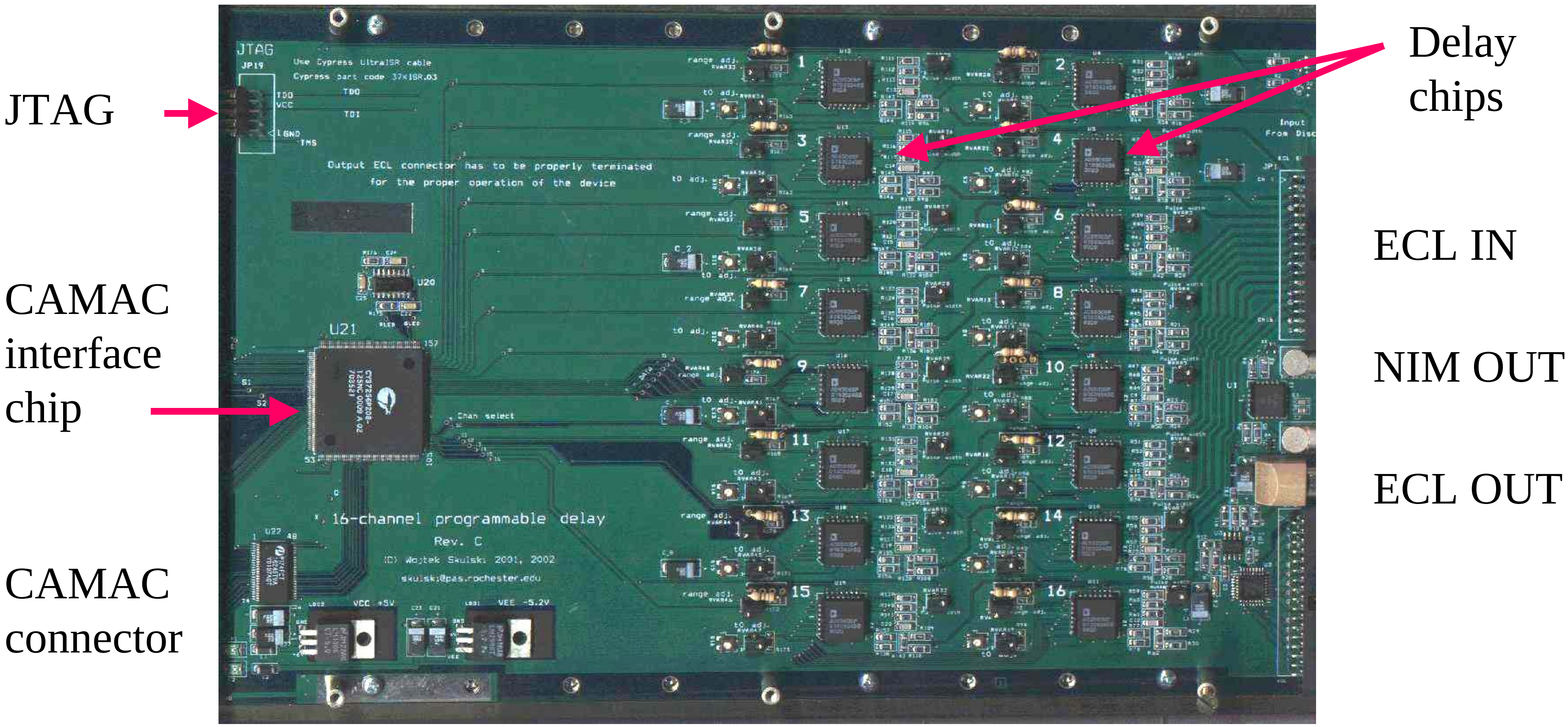
Interaction vertex definition (cm)

The purpose of the Time Equalizer

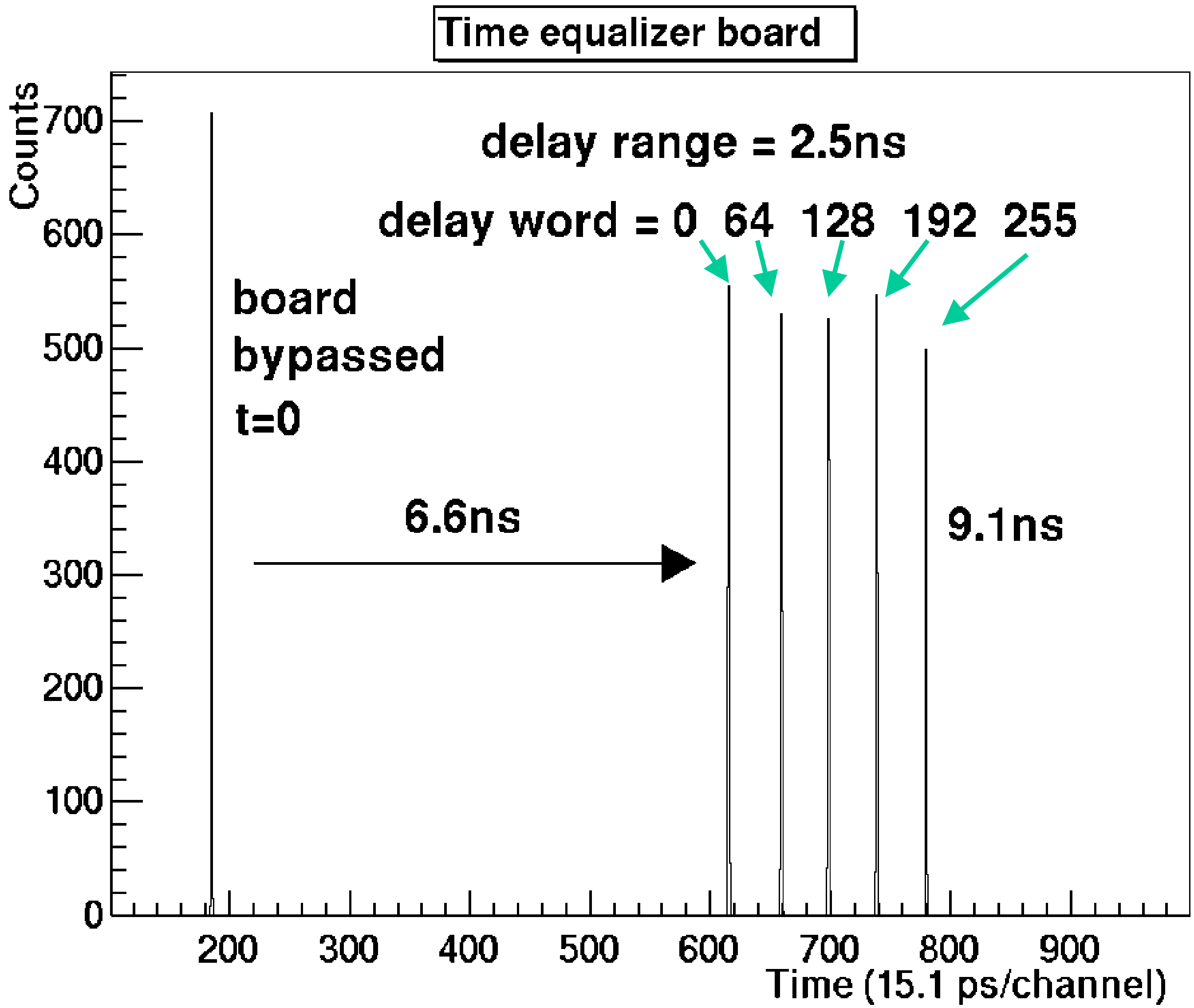
- I proposed, designed, and built the Time Equalizer in order to:
- Align timing signals from individual T-zero detectors.
- Preserve good timing resolution of individual detectors.
- Enable remote operation without entering the experimental area.
- Details:
  - **Number of channels** — **16**
  - **Signal in and out** — **ECL**
  - **Delay step** — **10 ps**
  - **Number of steps** — **256**
  - **Shortest delay range** — **2.5 ns (in 256 steps)**
  - **Delay range can be adjusted by swapping resistors**
  - **Formfactor** — **CAMAC**

Final version of the Time Equalizer

Four such boards are installed at PHOBOS



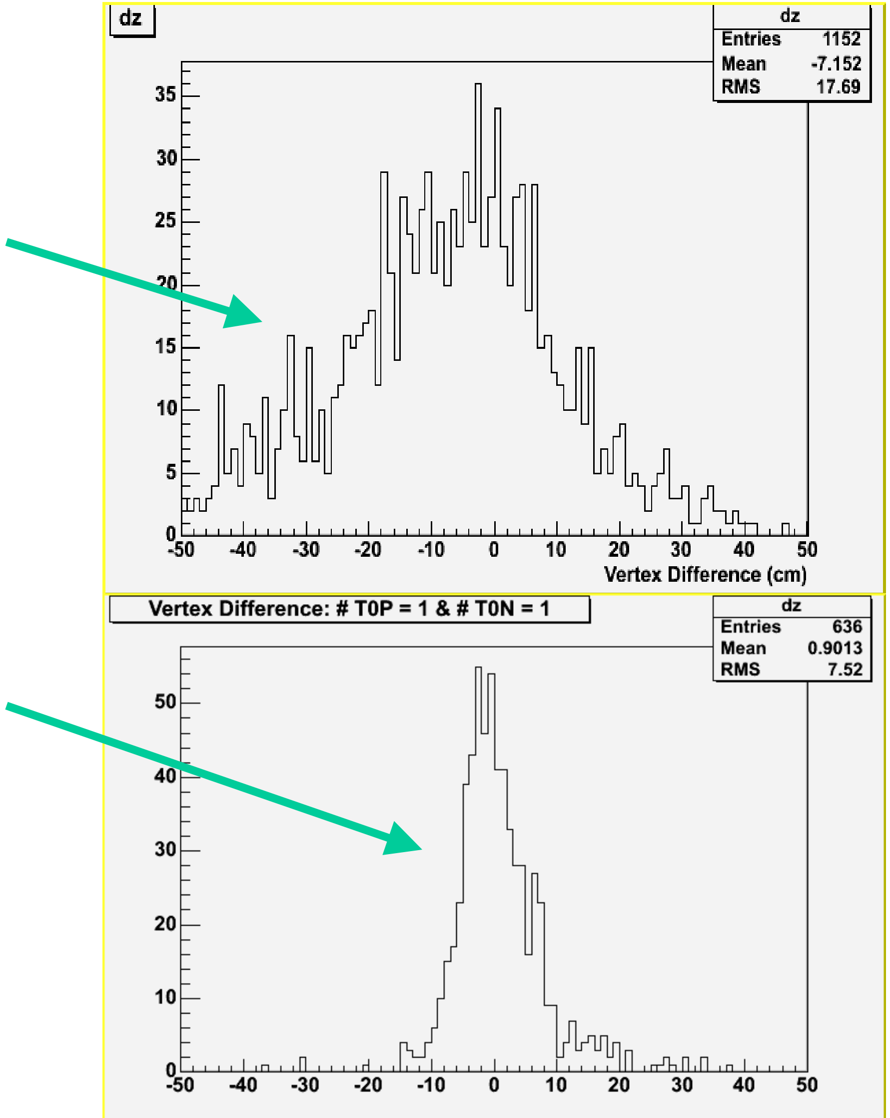
Response of an individual channel to a pulser



Result: improvement of vertex definition

- Detector delay not adjusted.

- Detector delay individually adjusted using Time Equalizer.



Interaction vertex definition (cm)

Universal Trigger Module

for PHOBOS

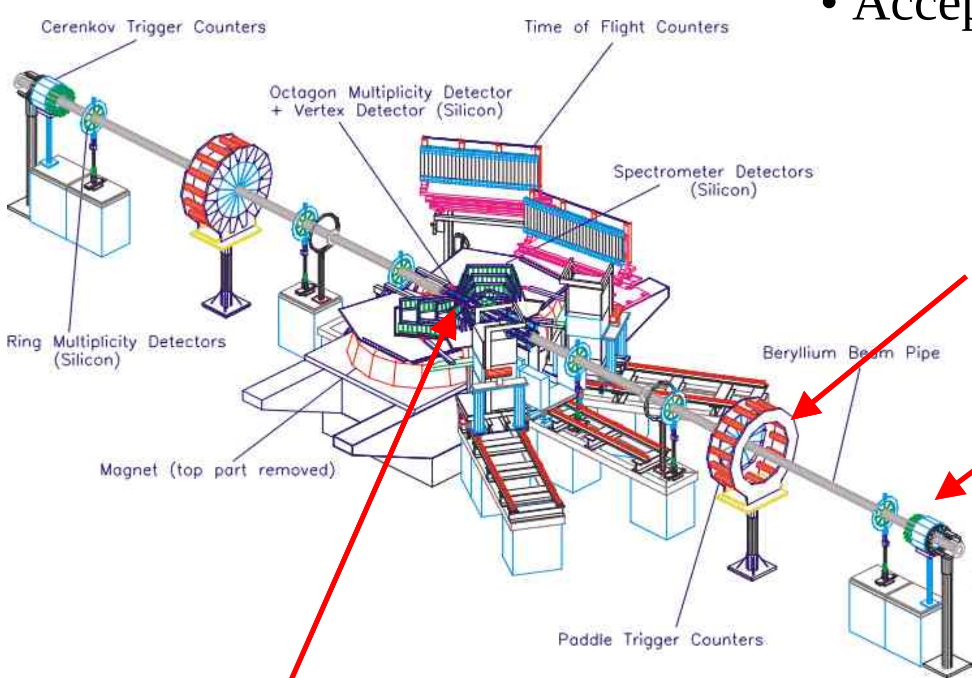
W.Skulski   Laboratory for Laser Energetics, Rochester, 22 September 2004

Universal Trigger Module for PHOBOS

Goal: vertex and centrality definition in real time

PHOBOS @ RHIC

- Analog signals: Paddles, T0, ZDC.
- Logic signals from conventional NIM.
- Signal processing: on-board FPGA.
- Accept/reject event within about 1 μsec.



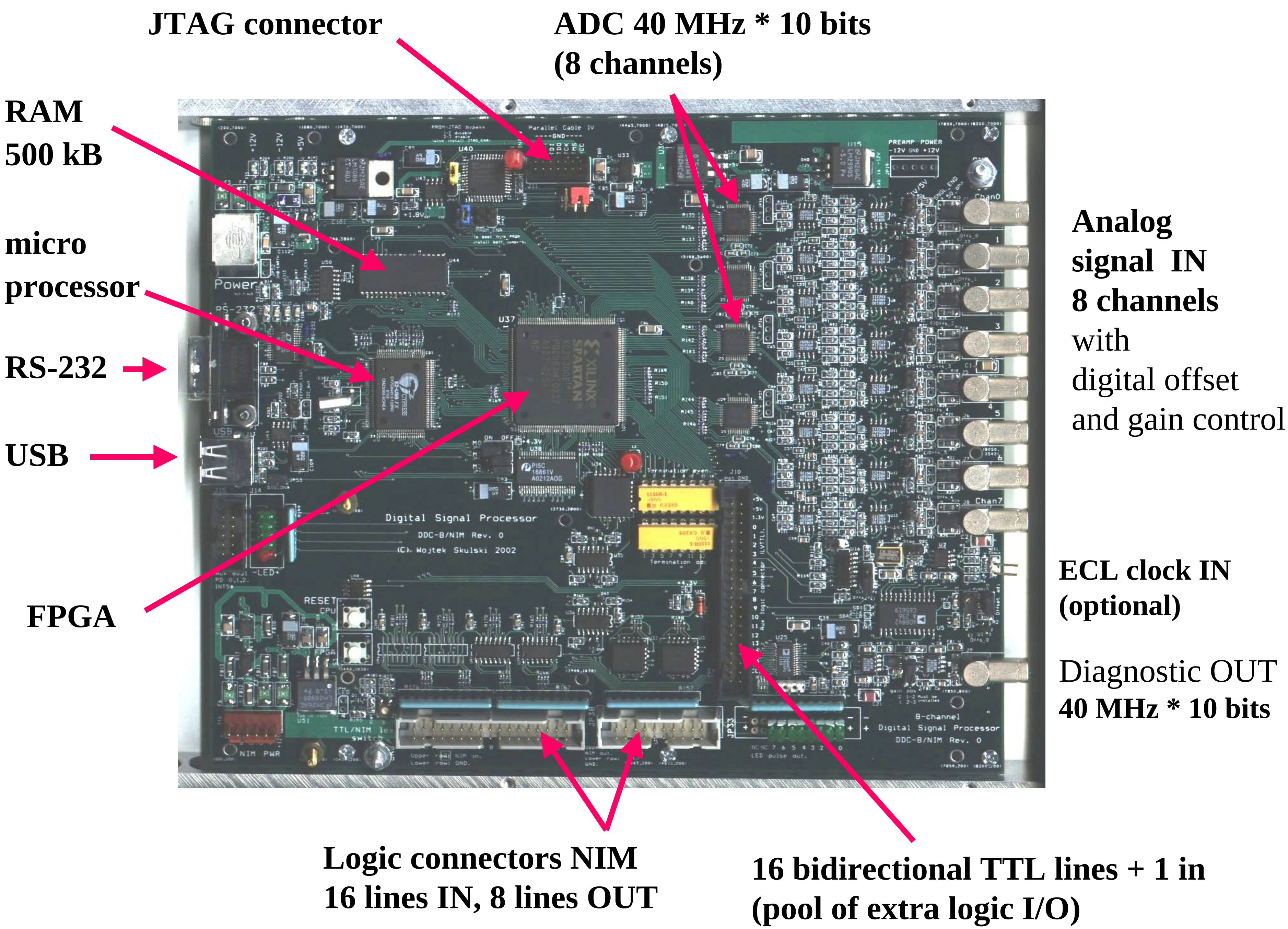
Centrality from paddle and ZDC.

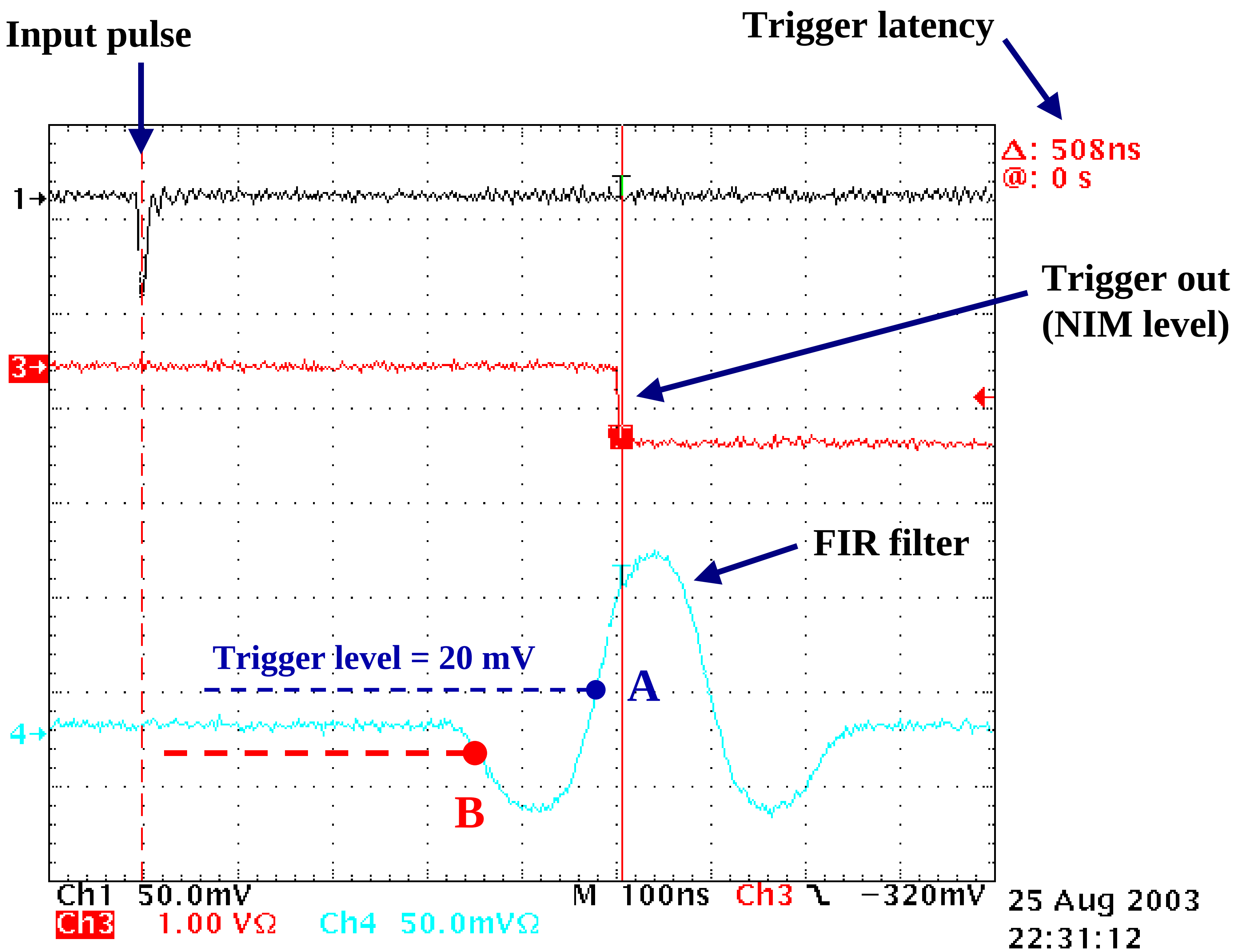
Vertex definition from TACs.
T0 OR Δt,
Paddle Δt,
ZDC Δt.

Interaction vertex is located inside silicon detector

The purpose of the Universal Trigger Module

- I proposed, designed, and built the UTM in order to:
- Provide PHOBOS with a programmable trigger logic module.
- Base the level-1 trigger decision on both analog and logic signals.
- Meet stringent timing constraints for level-1 trigger.
- Reduce the complexity of present "random trigger logic".
- Details:
  - **Number of analog inputs** **8**
  - **Number of logic I/O** **41**
  - **Architecture** **continuous waveform digitizing**
  - **Time step** **25 ns**
  - **Digitizer precision** **1024 ADC counts (i.e., 10 bits)**
  - **Digital "processing power"** **300,000 logic gates**


JTAG connector
ADC 40 MHz * 10 bits
(8 channels)
RAM
500 kB
micro
processor
RS-232
USB
FPGA
Analog
signal IN
8 channels
with
digital offset
and gain control
ECL clock IN
(optional)
Diagnostic OUT
40 MHz * 10 bits
Logic connectors NIM
16 lines IN, 8 lines OUT
16 bidirectional TTL lines + 1 in
(pool of extra logic I/O)



Input pulse
Trigger latency
Δ: 508ns
@: 0 s
1
3
Trigger out
(NIM level)
4
FIR filter
Trigger level = 20 mV
A
B
Ch1 50.0mV
M 100ns Ch3 ⤵ −320mV
Ch3 1.00 VΩ
Ch4 50.0mVΩ
25 Aug 2003
22:31:12

Status of the Universal Trigger Module for PHOBOS

- Technical requirements were met.
- Hardware, firmware, and software working and tested.
- One board loaned to University of Illinois at Chicago (UIC).
- Firmware will be customized at UIC for PHOBOS trigger.
- Master Thesis for Ian Harnarine, UIC.

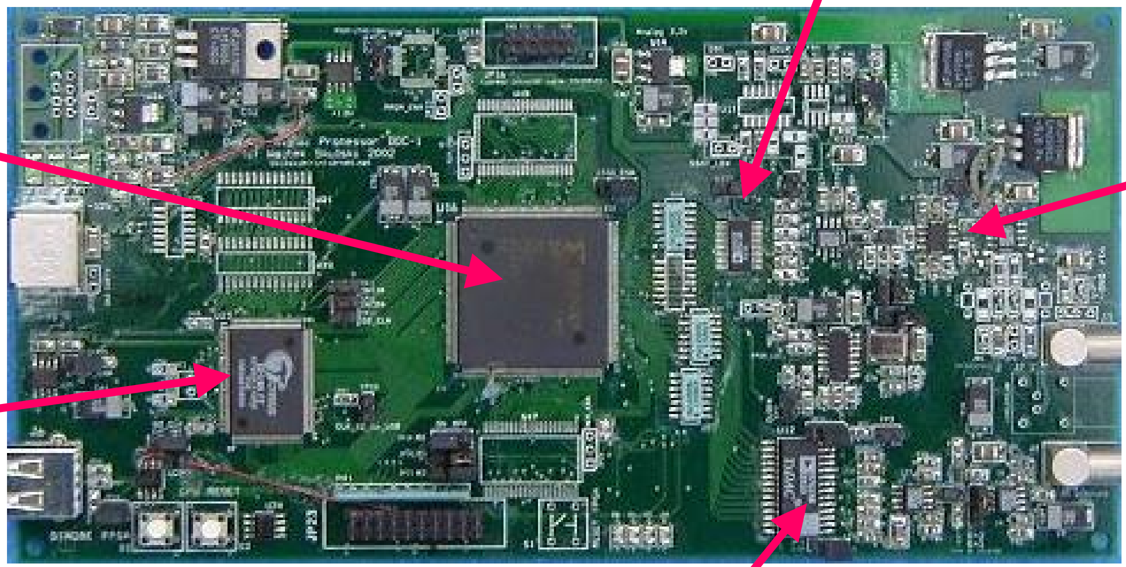
R&D and student projects at Physics and Astronomy

Single-channel, 12-bit DDC-1

Designed and built by WS.

Used in several student projects during last 2 years.

A predecessor of the Universal Trigger Module.



Education and R&D projects at Physics and Astronomy

- S.Zuberi, *Digital Signal Processing of Scintillator Pulses in Nuclear Physics Techniques*, Senior Thesis, Department of Physics and Astronomy, University of Rochester. Presented at Spring APS meeting, April 2003, Philadelphia, PA.
  - Awarded the Stoddard prize for the best Senior Thesis in the Department.

- D.Miner, W.Skulski, F.Wolfs, *Detection and Analysis of Stopping Muons Using a Compact Digital Pulse Processor*, Summer Research Experience for Undergraduates, Department of Physics and Astronomy, University of Rochester 2003 (unpublished).

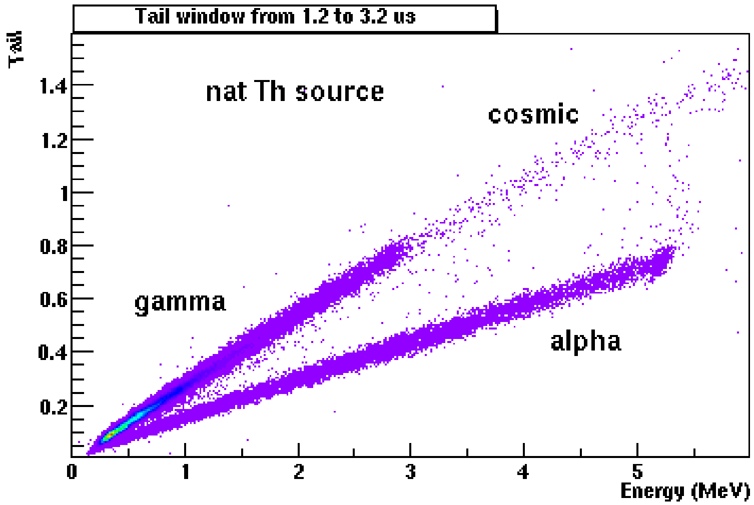
- P.Bharadwaj, *Digital and analog signal processing techniques for low-background measurements*, summer project 2004.

- F.Wolfs, W.Skulski, (UofR), Ian Harnarine, E.Garcia, D.Hofman (UIC), *Developing an efficient triggering system for PHOBOS at RHIC*, ongoing.

Particle ID from CsI(Tl)

Senior Thesis by Saba Zuberi

Best Senior Thesis 2003
Dept. of Physics and Astronomy
University of Rochester



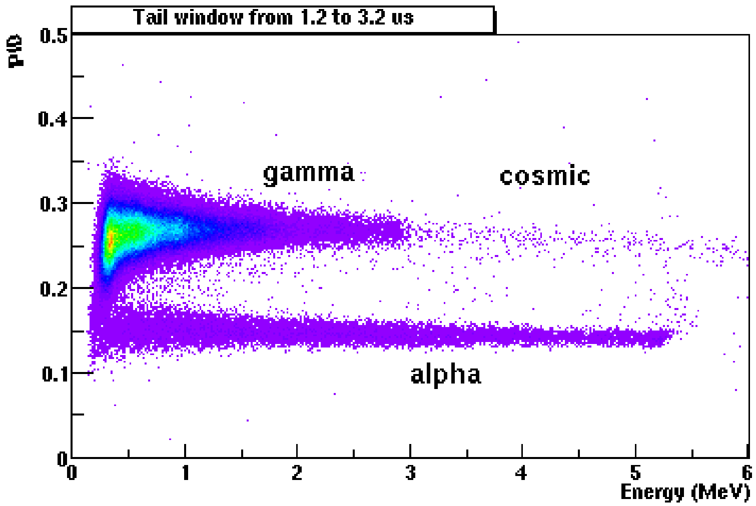
Traditional slow-tail representation

1 cm^3 CsI(Tl) + phototube

Single-channel digitizer DDC-1

at 48 Msamples/s * 12 bits

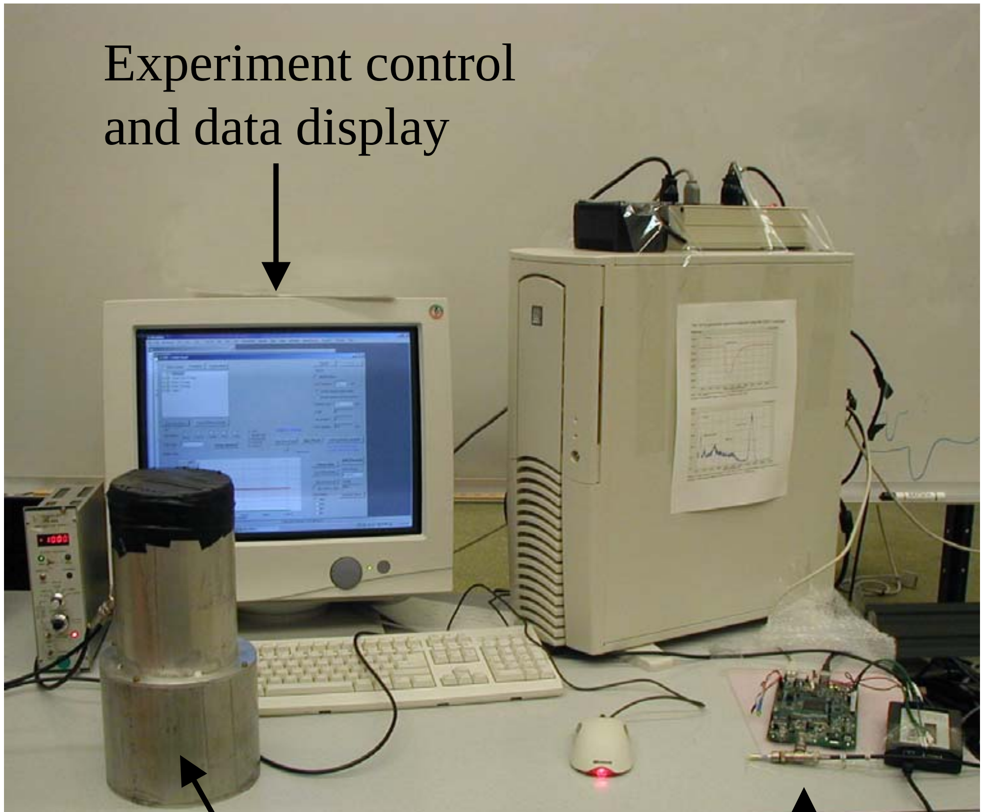
^{nat}Th radioactive source



PID = TAIL / TOTAL

Note energy-independent PID

Detection and analysis of stopping μ-mesons[#]



[#]Daniel Miner
University of Rochester
Summer 2003 REU

- Example of pulse processing & analysis
- Table-top experiment
- Several observables from one signal

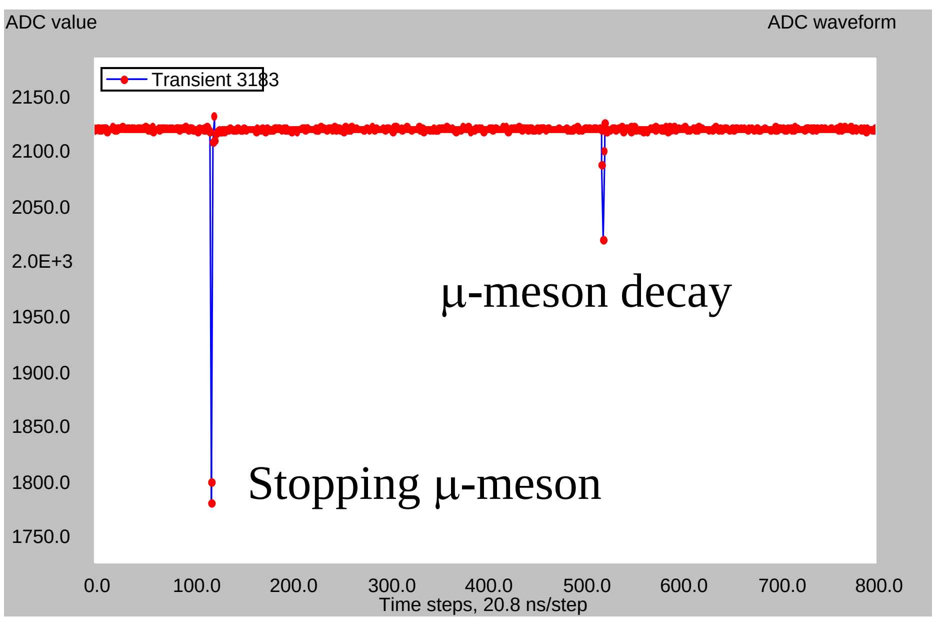
Detection and analysis of stopping μ-mesons

Daniel Miner, 2003 Summer Research Experience for Undergraduates

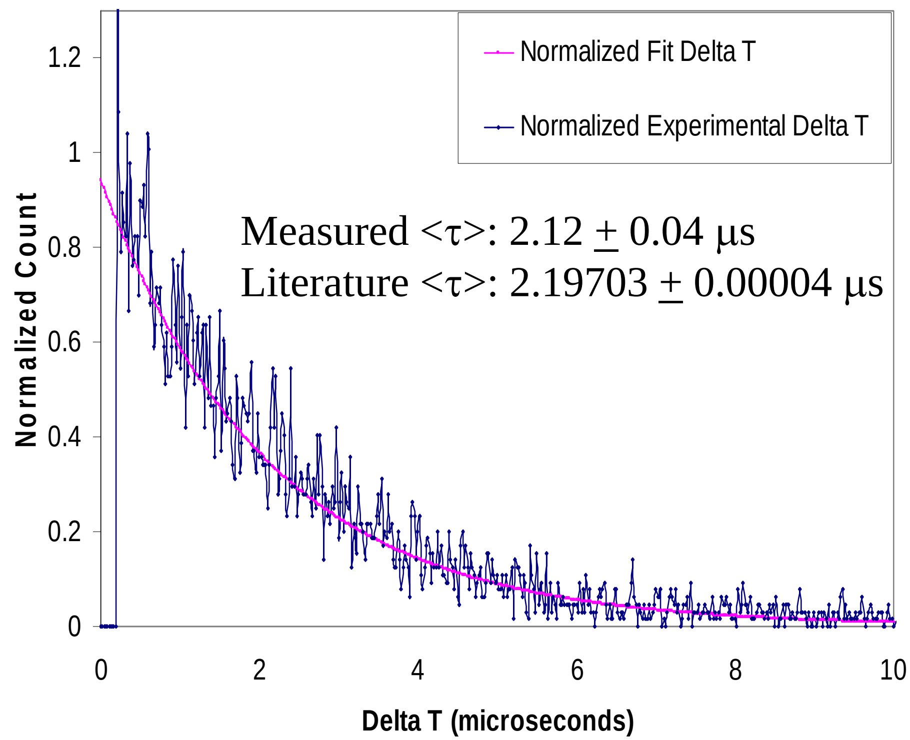
Waveform from a BC-400 5”x6” scintillator shows m-meson capture and subsequent decay.

After 4% capture correction the measured and accepted lifetimes agree to within 0.35%.

Waveform from plastic scintillator



Time between leading and trailing pulses

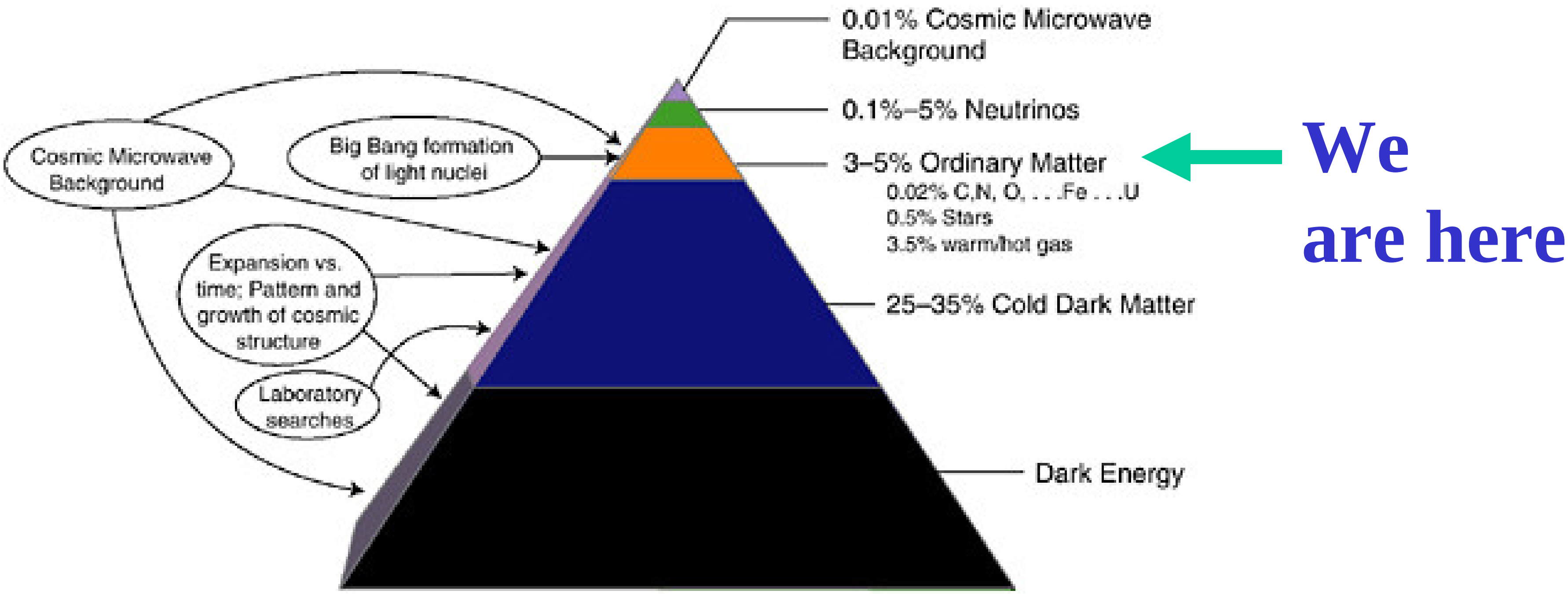


Electronics for

Dark Matter Search

The biggest mystery: where is almost Everything?

- Most of the Universe is missing from the books…
- … should we blame Enron?



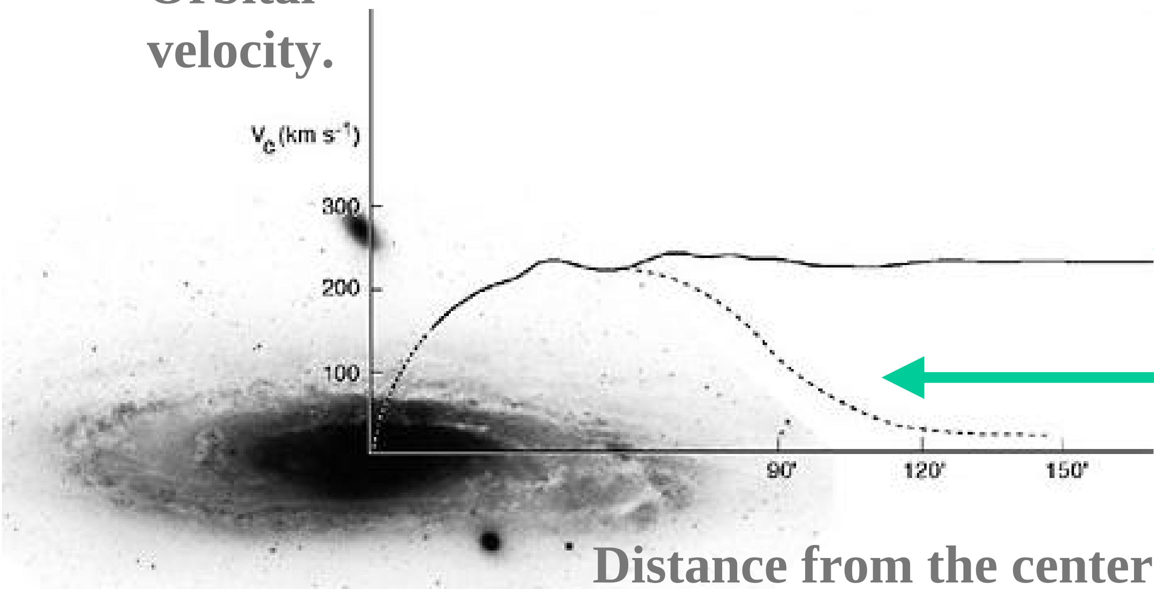
Source: *Connecting Quarks with the Cosmos*, The National Academies Press, p.86.

The 1st smoking gun: galactic rotation is too fast.

- Gravitational pull reveals more matter than we can see.

Rotation curve of the Andromeda galaxy.

Orbital velocity.



Observation.

Prediction based on visible matter.

Distance from the center.

Source: *Connecting Quarks with the Cosmos*, The National Academies Press, p.87.

The 2nd smoking gun: large-scale gravitational lensing.

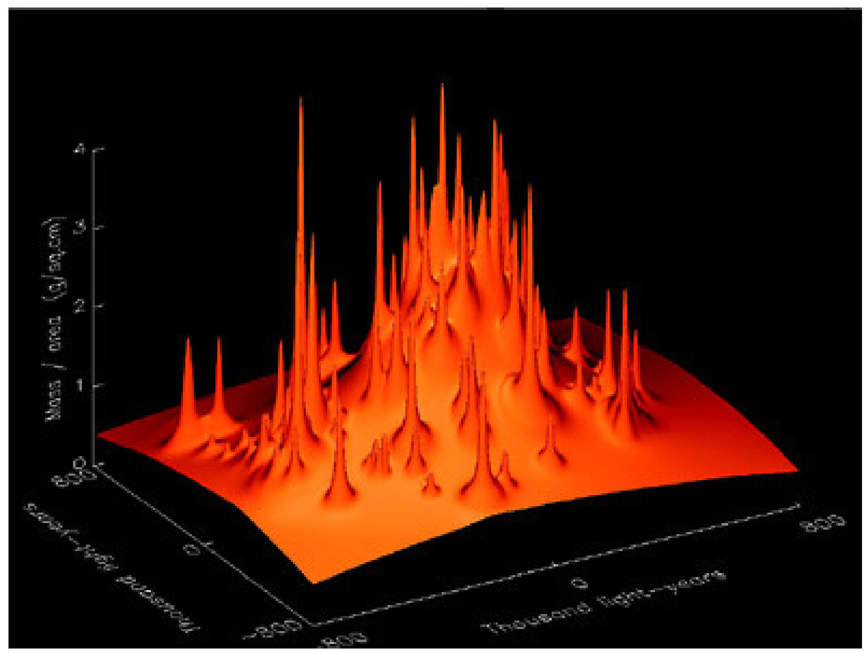
- Light from distant sources is deflected by clusters of galaxies.
- Visible mass cannot account for the observed lensing pattern.
- Reconstructed mass distribution shows mass between galaxies.

Observed lensing.

(a)

Reconstructed mass distribution.

(b)

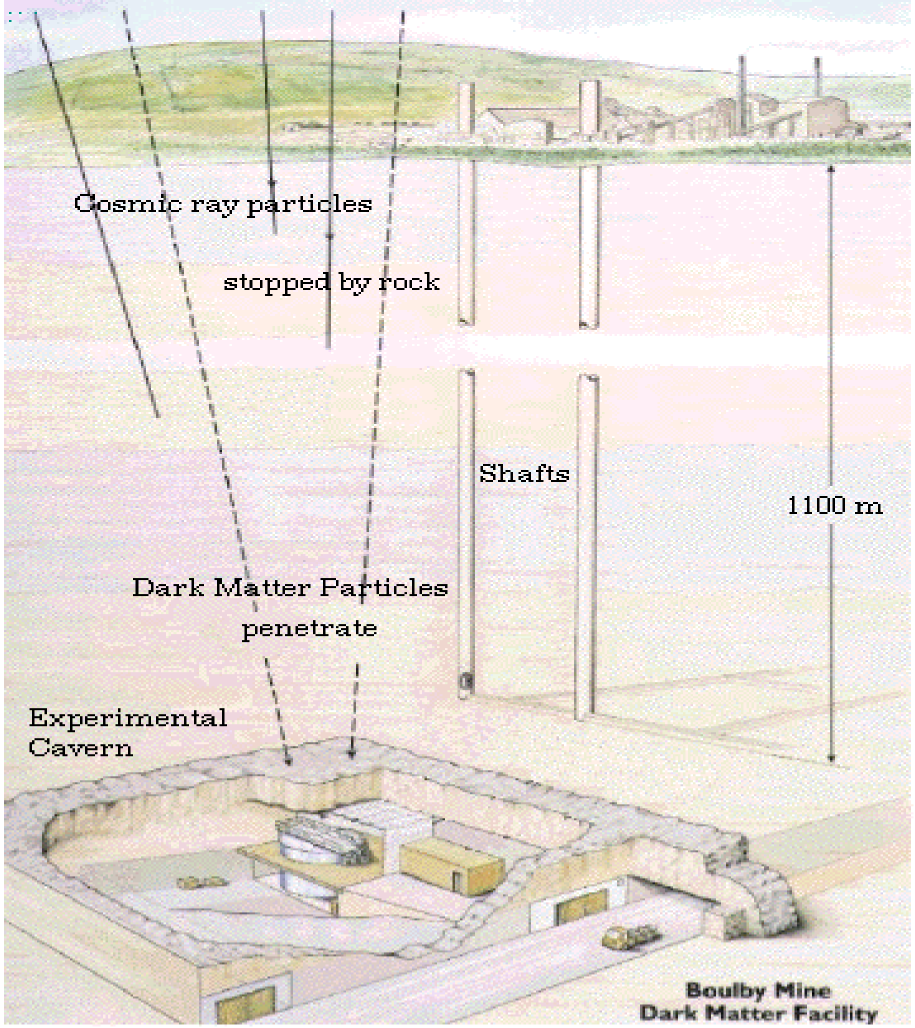


Source: *Connecting Quarks with the Cosmos*, The National Academies Press, p.89.

Who are the suspects? How to find them?

- Nobody knows, but there are candidates predicted by the theory …
- Axions: light particles that may explain CP violation.
- Neutralinos: heavy particles predicted by SUSY.
- We focus on the latter.
- The neutralino is neutral, weakly interacting, and as massive as an atom of gold.
- Occasionally it will bounce off an ordinary nucleus and produce some ionization.
- We will wait for the occasion at Boulby mine in the UK.
- We will use a two-phase liquid xenon detector named Zeplin.

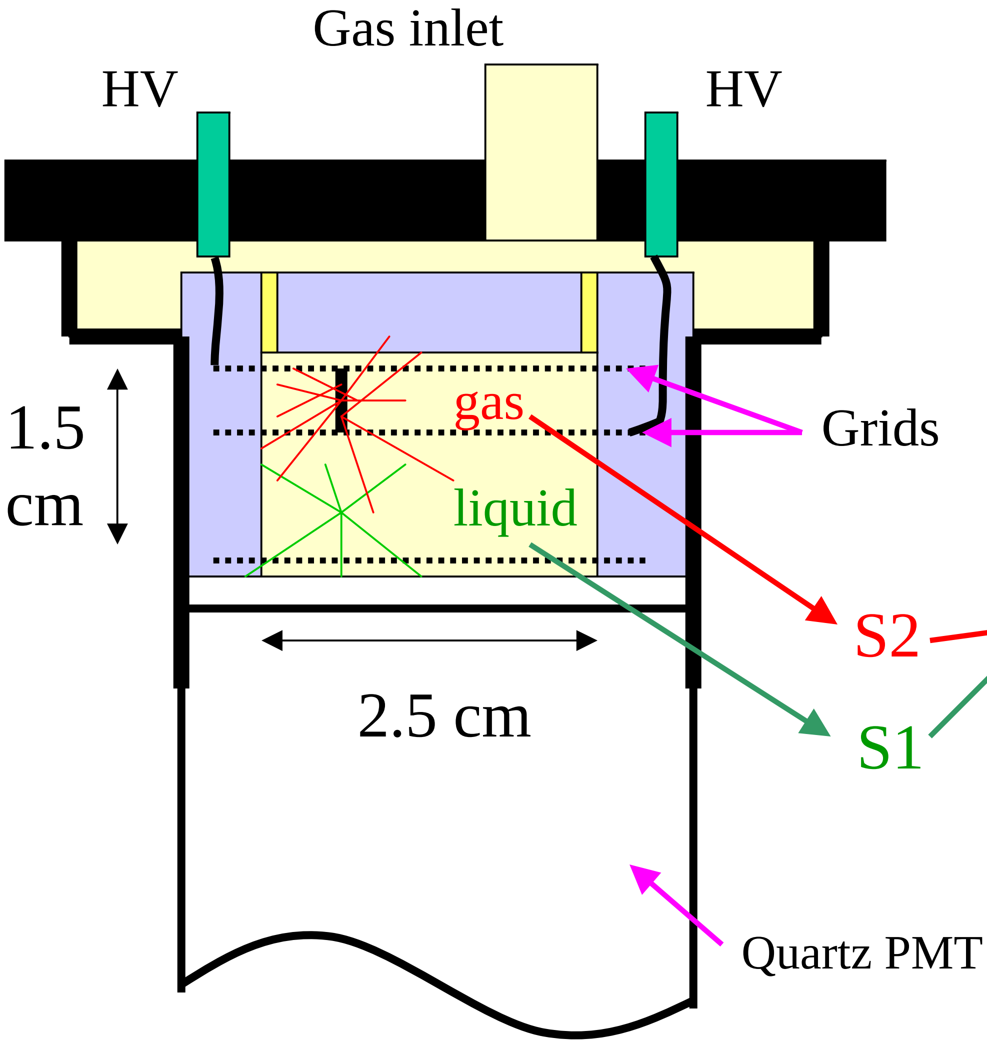
Underground low-background laboratory

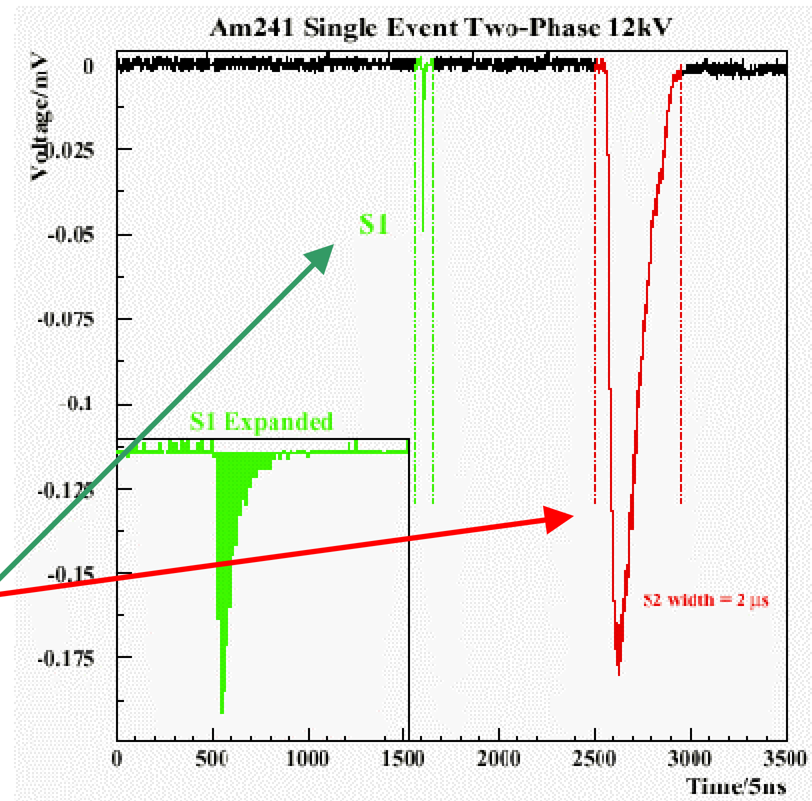


Cosmic particles stopped by 1 km of rock.

Dark Matter particles penetrate freely.

The principle of 2-phase xenon detector





S1: scintillation in liquid Xe.

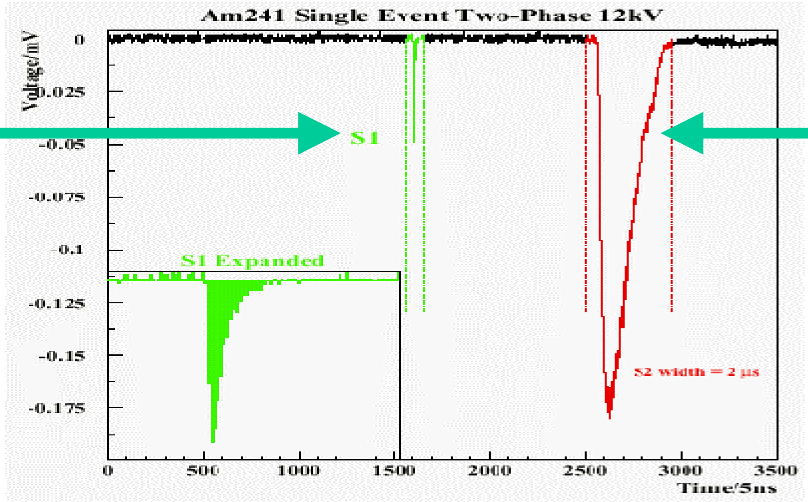
S2: electroluminescence in gas Xe.

Figure from: J.T.White, Dark Matter 2002.
http://www.physics.ucla.edu/hep/DarkMatter/dmtalks.htm

Figure from: T.J.Sumner *et. al.*,
http://astro.ic.ac.uk/Research/
Gal_DM_Search/report.html

Recorded signal from a 2-phase xenon detector

Primary scintillation in liquid phase.



Secondary scintillation in gas phase (electroluminescence).

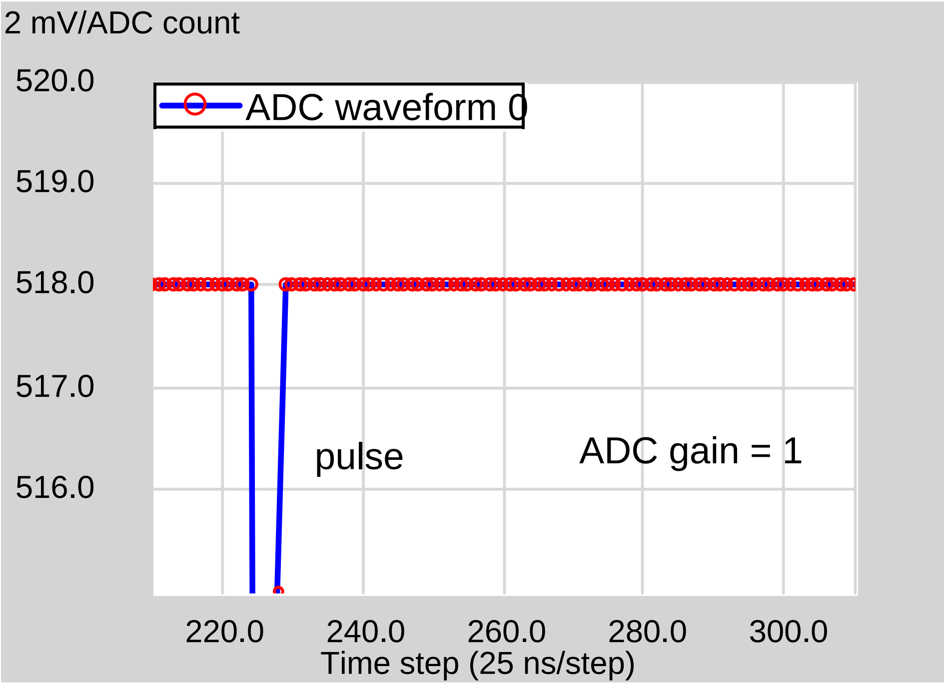
- Signal/background discrimination is derived from ratio S1/S2 and from S1 shape.
- Objectives: measure the areas of S1 and S2 pulses and analyze the shapes.
- The "intelligent waveform digitizer" is an ideal tool to meet the objectives.

- Low noise (see next slide).
- Large dynamic range.
- On-board user-defined data processing.

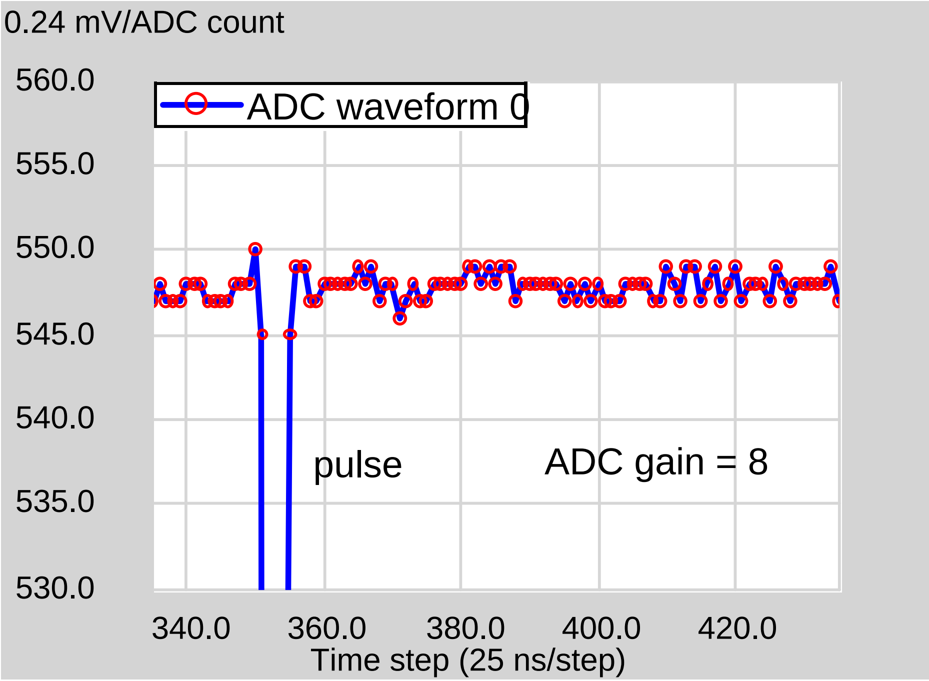
Figure from: T.J.Sumner *et. al.*, http://astro.ic.ac.uk/Research/Gal_DM_Search/report.html

UTM has intrinsic noise below 1 mV

Gain=1, noise below 1 LSB

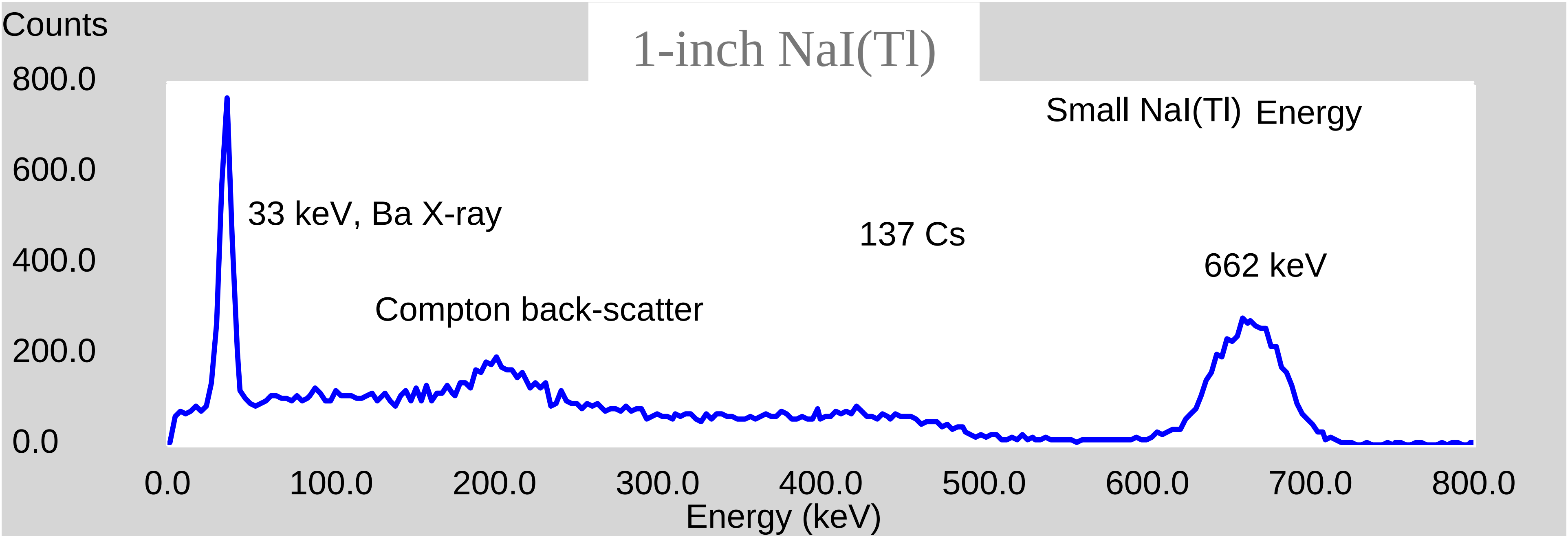


Gain=8, noise ~3 LSB (peak-peak)



Waveforms recorded with UTM

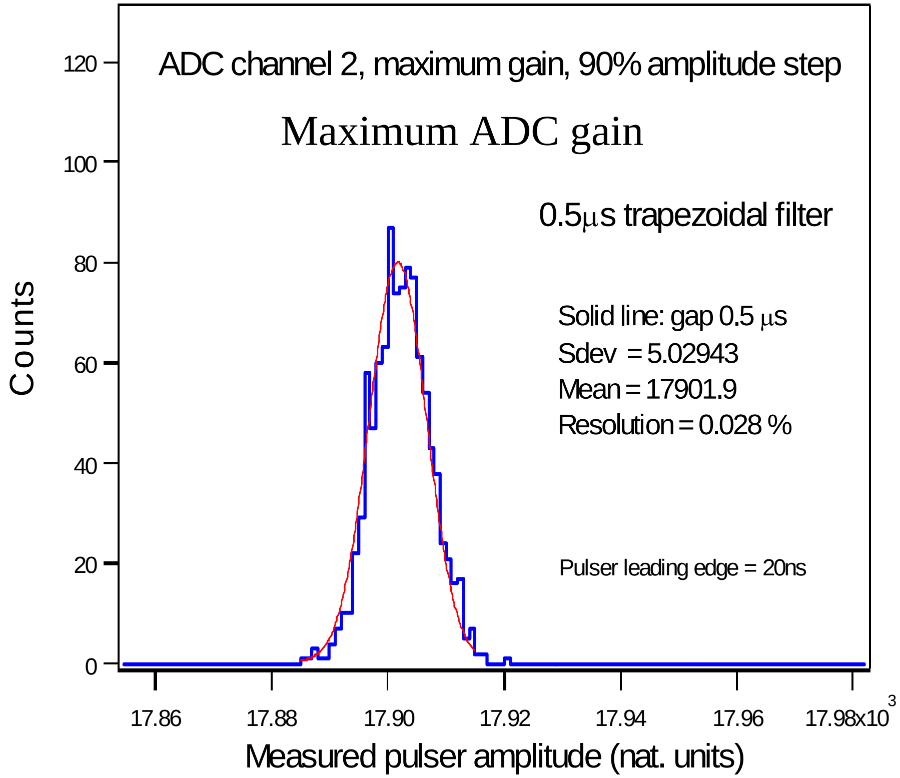
Low noise translates to low threshold = 5keV



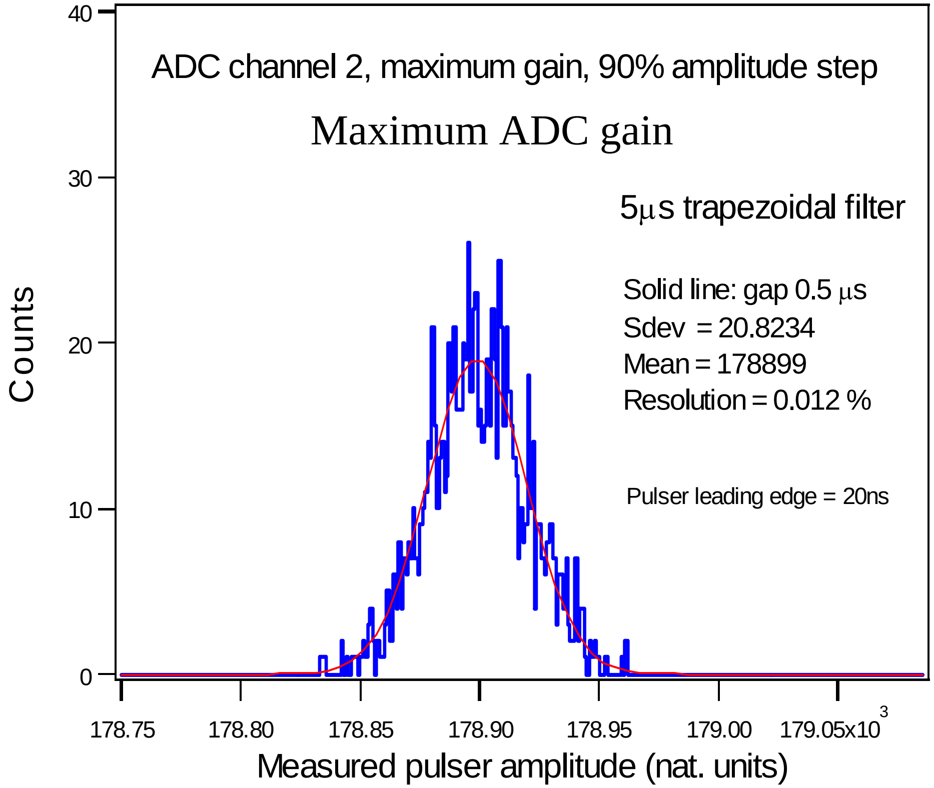
Pulse-height histogram measured with UTM

Dynamic range = 18 bits, resolution < 0.2 keV

Short filter, pulser resolution 0.37 keV



Long filter, pulser resolution 0.16 keV



Pulser peak = 179,000 ==> 18 bits

Plans for Dark Matter electronics

- Motivated by excellent performance of the UTM,
  I proposed to develop a digitizer board for Dark Matter Search.
  - 16 channels, 12/14 bits, 65 megasamples per second.
  - On-board Digital Signal Processor (800 mega-operations per second).
  - Remote control and diagnostics.
  - Low cost per channel.
  - Integration with existing infrastructure (VME).
- Status: schematic 75% finished.
  - Prototype can be ready this Winter.
- Applications other than Dark Matter.
  - Gamma-ray spectroscopy, neutron/gamma discrimination.
  - Arbitrary waveform processing.

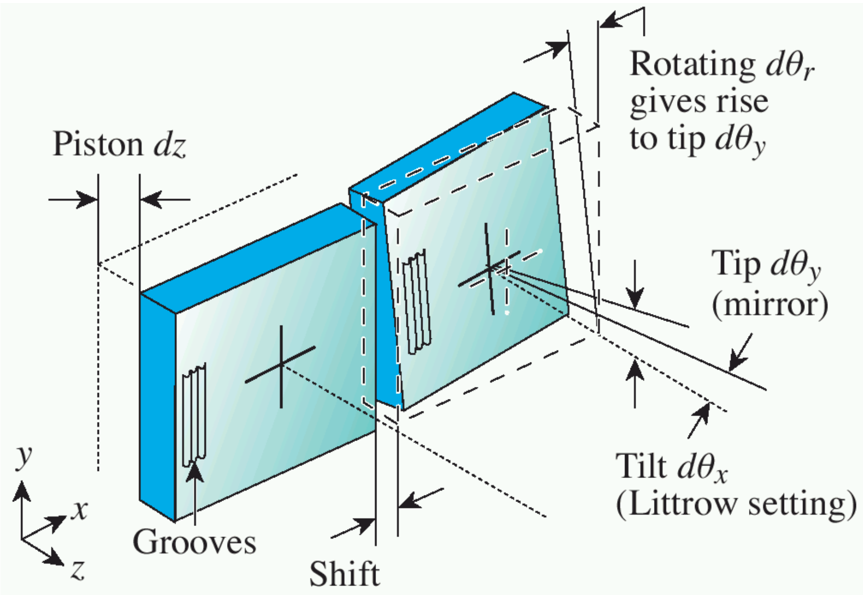
Tiled Grating Assembly

at LLE

Adaptive Optics Control Software for Tiled Diffraction Gratings

Laboratory for Laser Energetics, University of Rochester

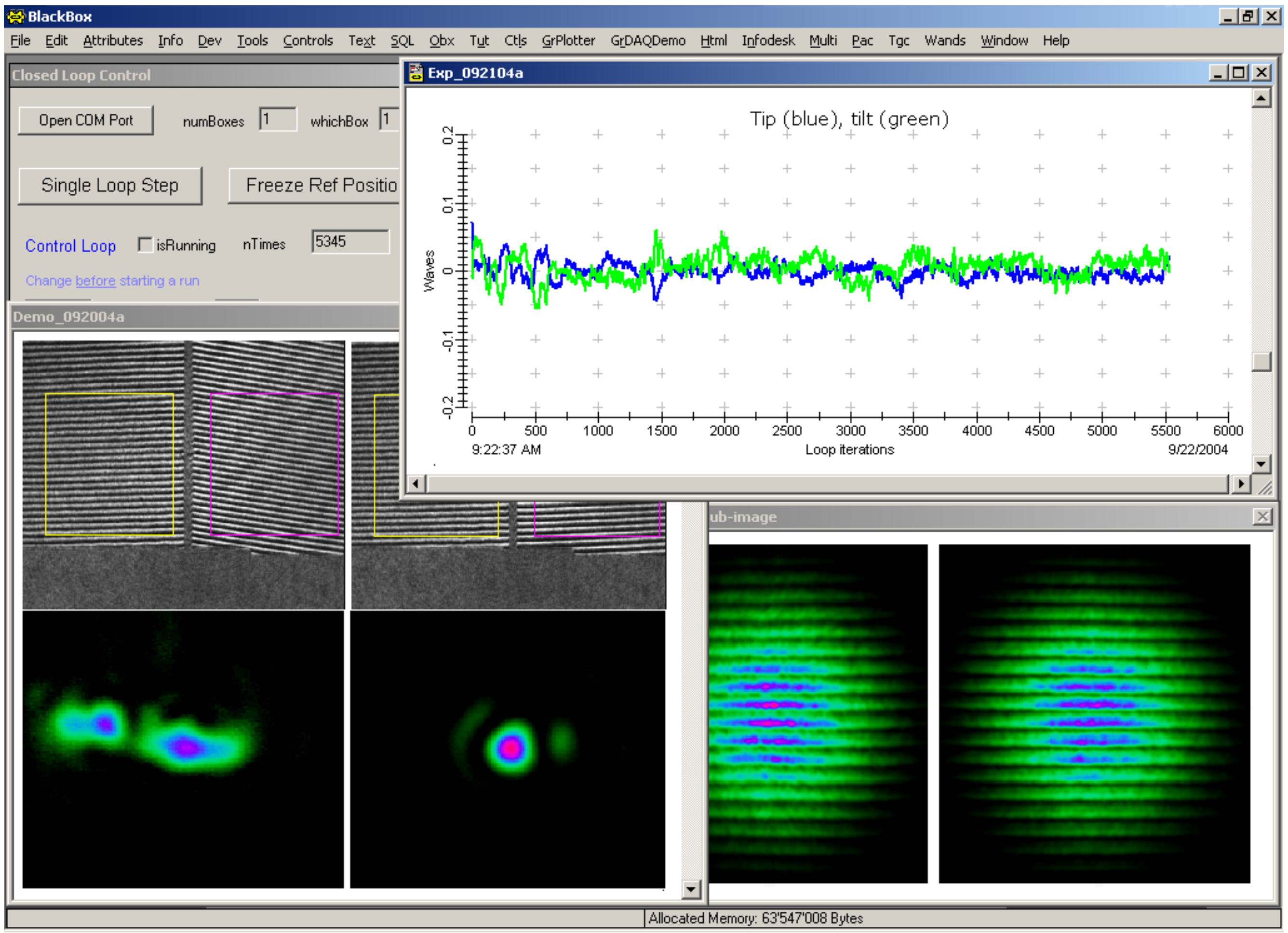
- Goal: align positions of tiled diffraction gratings in a closed loop.



- Interferogram acquired from the CCD camera.
- Calculation of tip, tilt, and piston.
- Calculation of actuator steps.
- Recording of history of tip, tilt, and piston.
- Acquisition and recording of Far Field.
- Open-ended and modular design:
  New features added as needed.
- Internal variables and matrices available
  for inspection.
- Intuitive GUI and graphics.
- Robust: run-time crash does not happen.

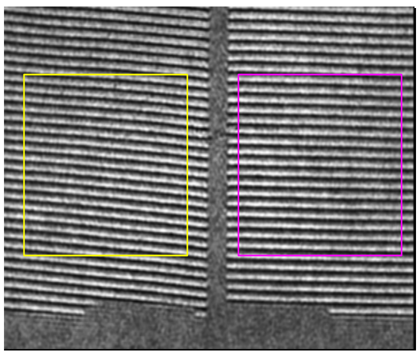
Adaptive Optics Control Software for Tiled Diffraction Gratings

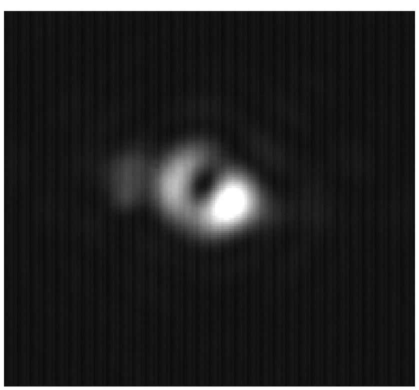
- Intuitive GUI and graphics.
- Internal variables and matrices available for diagnostic.

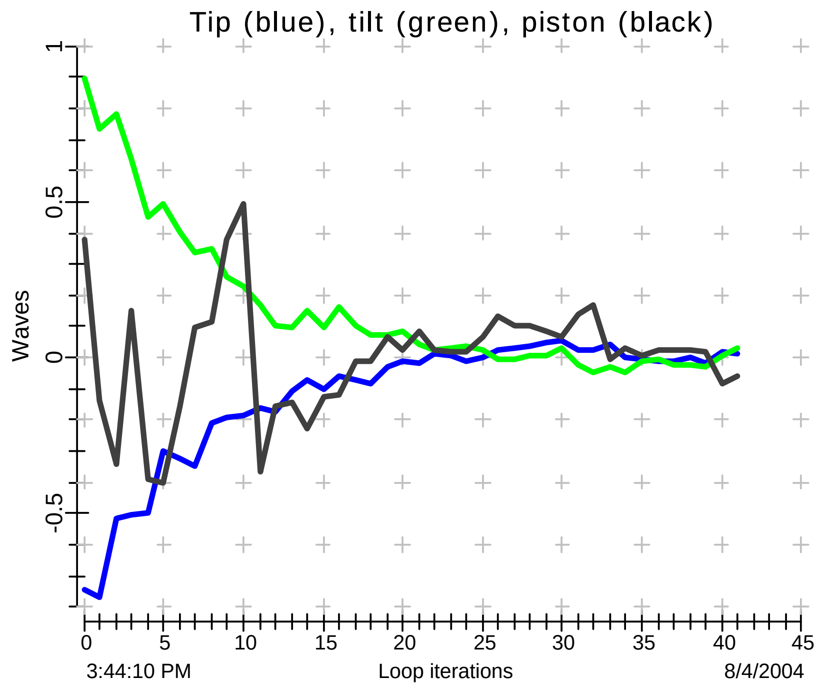


Adaptive Optics Control System for Tiled Diffraction Gratings

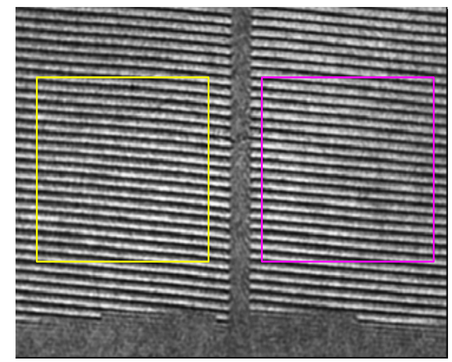
Before...

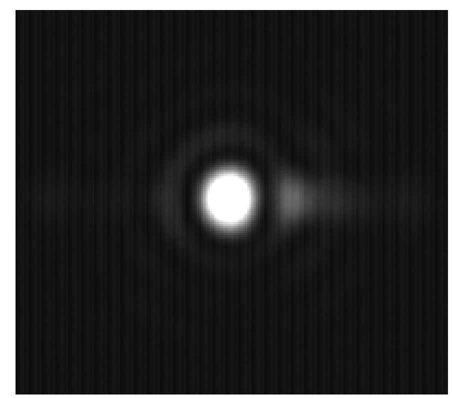






…after





Record of a control run with motors engaged.
Two out of three motors (motors A and B) were driven by (+50,-50) steps, then software was allowed to take control.

Summary

- Development of TGA software at LLE has been a success.
  Software is intuitive, open-ended, and robust.
- Electronics development required all of the following:
  - Schematic design, board layout and board assembly.
  - Hardware testing and debugging.
  - Software for embedded microcontroller.
  - Firmware for on-board FPGA.
  - GUI design and programming.
- Time Equalizers are being used in a mission-critical application.
- Waveform digitizers are under development for PHOBOS, Dark Matter Search, in-beam spectroscopy, and other demanding applications.
- Several student projects and table-top experiments were completed.

Possible applications at LLE

- Software: control and data processing systems that are robust, open-ended, and graphically rich.
- Time Equalizer: accurate alignment of fast timing pulses.
- Waveform digitizers and digital signal processors. Their function is defined by embedded firmware and software (FPGA and DSP).
    - Pulse-height spectroscopy.
    - Pulse shape analysis.
    - Particle discrimination (e.g., gamma/neutron).
    - Real-time processing of arbitrary waveforms.
    - User-defined data acquisition and processing.

Acknowledgements

- SkuTek Instrumentation.
  - Joanna Klima, WS (Principal Investigator for electronics).
- University of Rochester.
  - Frank Wolfs, Ray Teng, Tom Ferbel (Physics), Jan Toke (Chemistry).
  - Joachim Bunkenburg, Larry Iwan, Terry Kessler, Charles Kellogg, Conor Kelly, Matthew Swain (LLE).
- Robert Campbell (BAE Systems).
- Wolfgang Weck and Cuno Pfister (Oberon Microsystems).
- PHOBOS Collaboration.
- Students.
  - Erik Johnson, Nazim Khan, Suzanne Levine, Daniel Miner, Len Zheleznyak, Saba Zuberi, Palash Bharadwaj.
- My work was supported by grants from NSF and DOE.