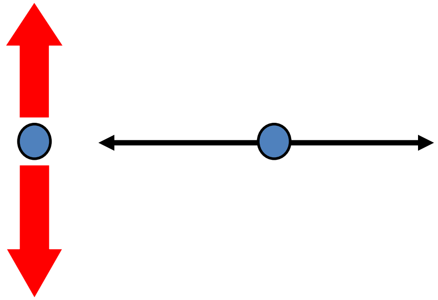
FP420/AFP Fast Timing

WHO? UT-Arlington (**Brandt**), Alberta (Pinfold),
Fermilab (Albrow), Louvain (Piotrzkowski)
+UC-London, Prague, Saclay, Stoneybrook, Giessen, BNL,
Kansas…

WHY? **Pileup Background Rejection for Diffractive Higgs ($pp\rightarrow pHp$)**

Ex: Two protons from one interaction and two b-jets from another



How? **Compare z-vertex position measured with silicon tracking (δz=50μm) with vertex measured from time difference of protons (δz=2.1mm for δt=10 psec)**

How Fast? **Stage I: LHC luminosity 2 x10^{33} δt < 20 ps (<2 year)**
Stage II: 10^{34} δt < 10 ps (<4 years)

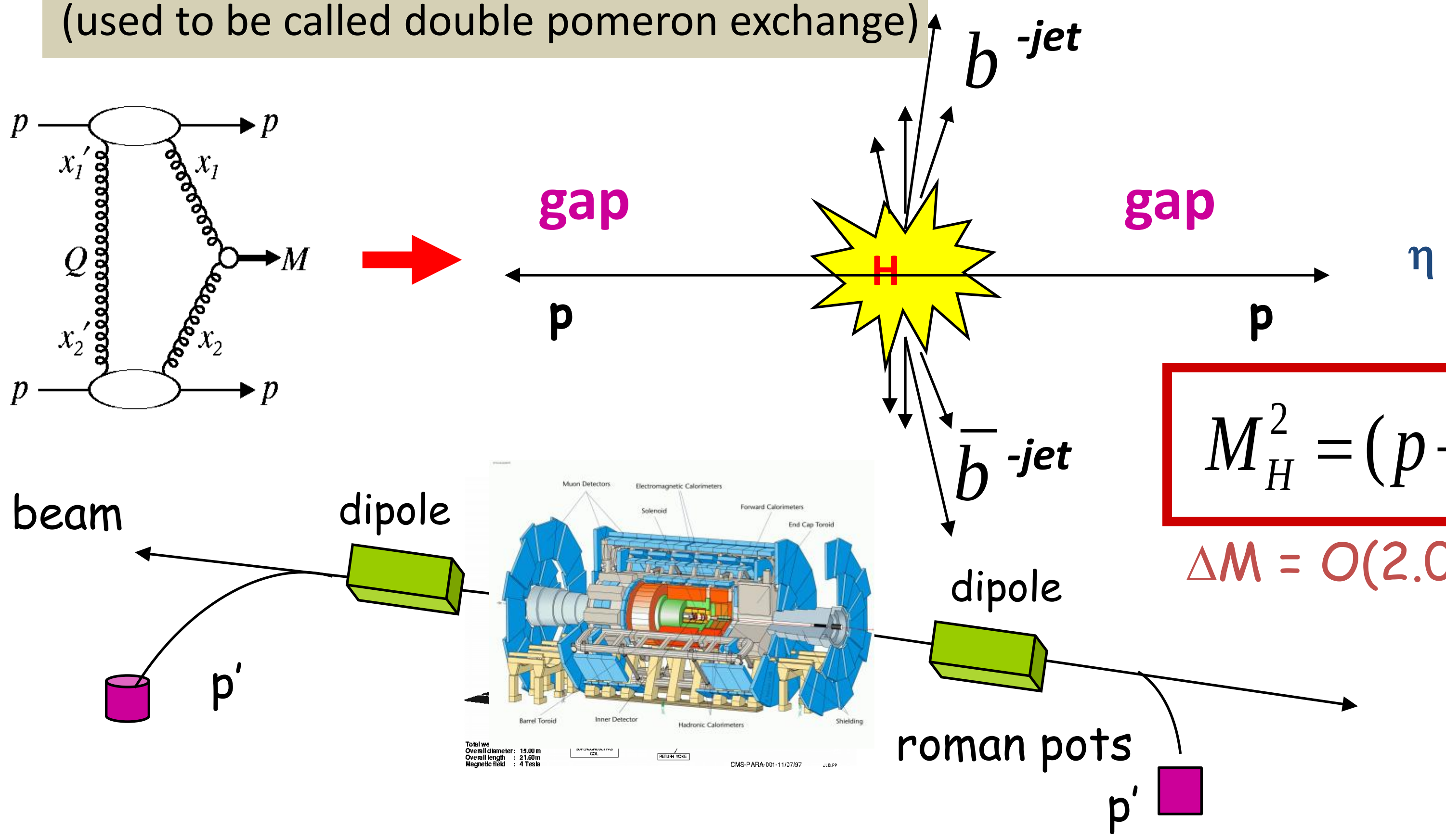
Outline

- Introduction to FP420/AFP
- AFP Cerenkov detectors and test beam results
- Rate and lifetime issues
- Laser tests

Forward Protons at LHC (FP420, AFP)

Central Exclusive Higgs production pp→ p H p : 3-10 fb

(used to be called double pomeron exchange)



$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

$\Delta M = O(2.0)$ GeV

``The FP420 R&D Project: Higgs and New Physics with Forward Protons at the LHC,'' FP420, arXiv:0806.0302 [hep-ex].

``Letter of Intent for ATLAS FP: A Project to Install Forward Proton Detectors at 220 m and 420 m Upstream and Downstream of the ATLAS Detector,'' A. Brandt, B. Cox, C. Royon *et al.*, AFP Collaboration.

NOTE AFP LOI under review by ATLAS management; seeking approval to proceed to TDR in July

Physics with Forward Protons

- FP420 turns the LHC into a energy tunable glue-glue (and $\gamma\gamma$) collider

- At "low" to "intermediate" luminosity (30-100 fb-1) we can :

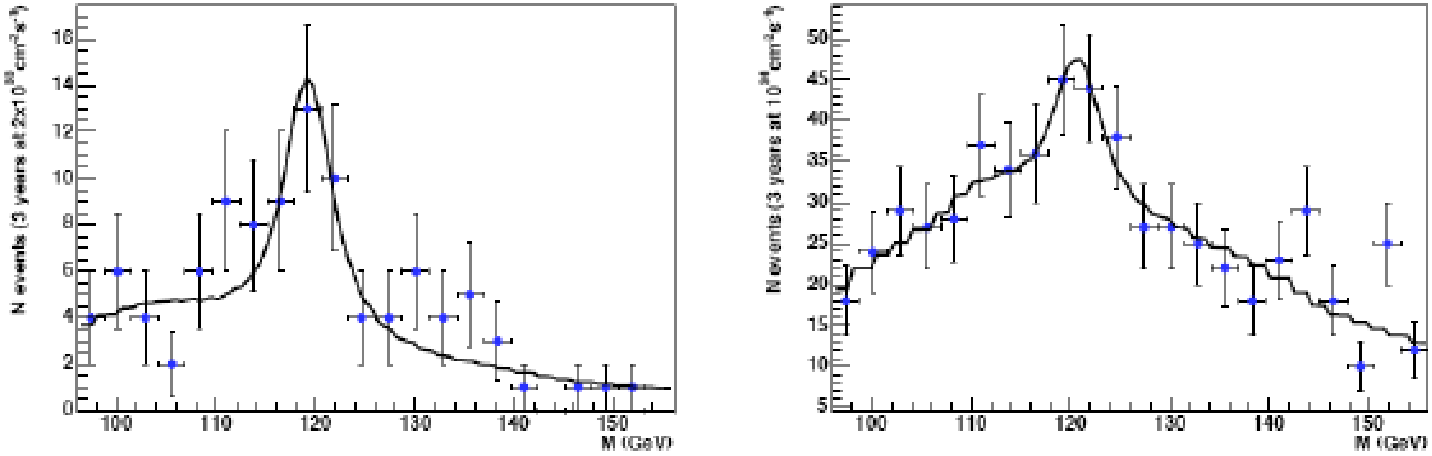
1) Establish the quantum numbers and measure the mass of a light SM Higgs **OR** be the discovery channel if there is an MSSM Higgs (or three) with favorable parameters
2) Perform a wide range of $\gamma\gamma$ physics including anomalous couplings
3) Perform interesting QCD measurements (0.002 < xIP < 0.01)

- In addition, at higher luminosity (> 100 fb-1) we can :

1) Search for exotic bound states such as gluinoballs
2) Make direct observation of CP violation in some SUSY Higgs scenarios
3) Disentangle wide range of SUSY scenarios, including ~degenerate Higgs

The University of Manchester

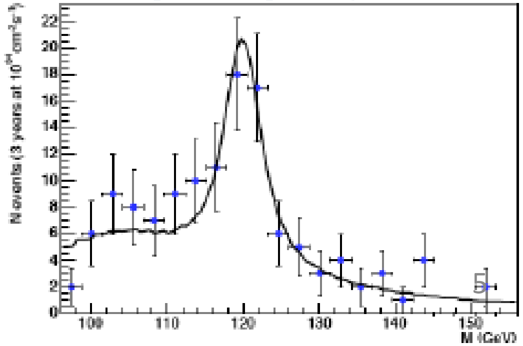
The Physics case : MSSM h/H



(a) (b)

Fig. 6: Figure (a) shows a typical mass fit for 3 years of data taking at 2×10^{33} cm^{-2} s^{-1} (60 fb^{-1}). The significance of the fit is 3.5σ and uses only events with both protons tagged at 420m. Figure (b) shows a mass fit for 3 years of data taking at 10^{34} cm^{-2} s^{-1}. The significance is 3σ The L1 trigger strategy and analysis cuts are described in the text.

Better pileup rejection

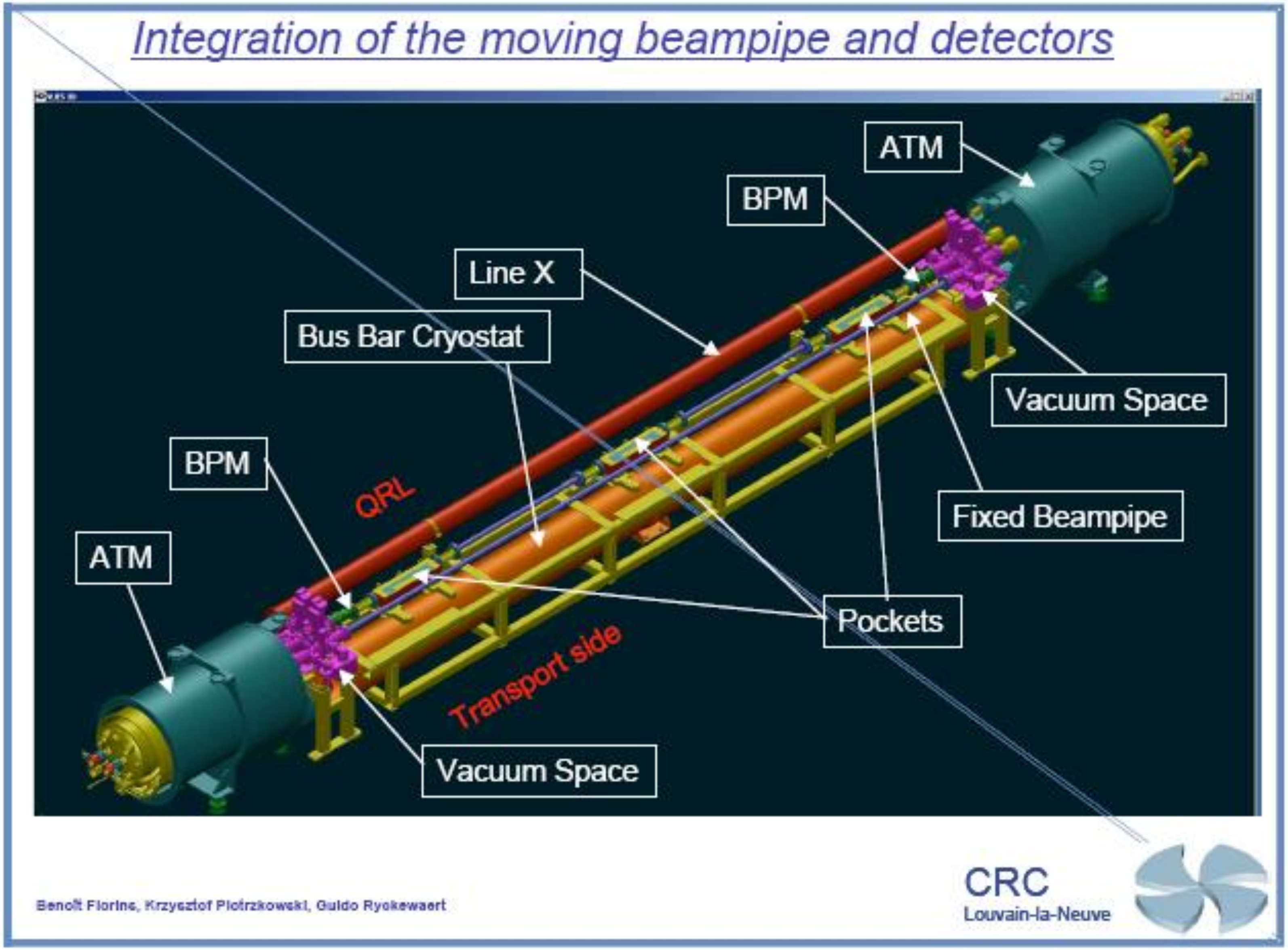


B. E. Cox, F. K. Loebinger and A. D. Pilkington, JHEP **0710** (2007) 090 [arXiv:0709.3035 [hep-ph]].

Key Components of AFP

- Space in tunnel: New Connection Cryostat (for 420m only)
- “Hamburg Beam Pipe” to house detectors
- 3D silicon detectors for measuring proton postion
- Trigger and Readout
- **Fast Timing Detector**

UTA Focus



Integration of the moving beampipe and detectors

Benoît Florins, Krzysztof Piotrzkowski, Guido Ryckewaert

CRC
Louvain-la-Neuve

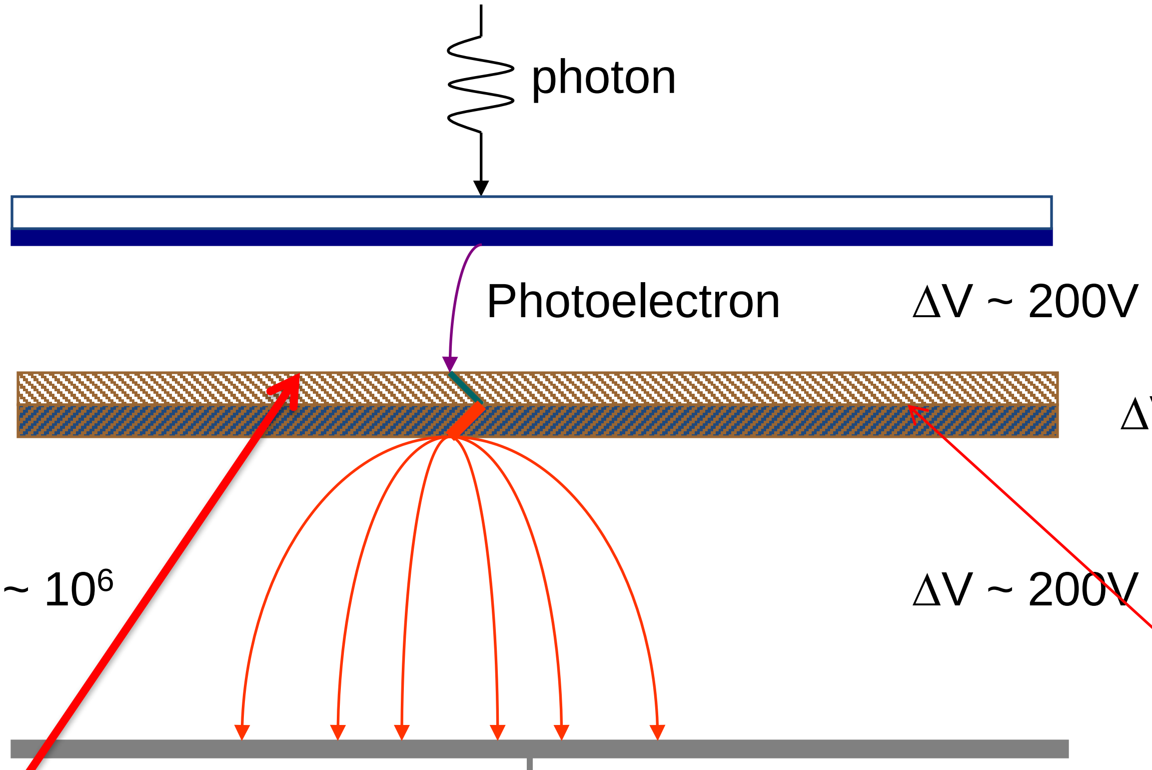
Fast Timing Is Hard!

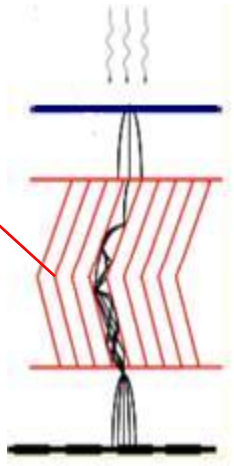
ISSUES

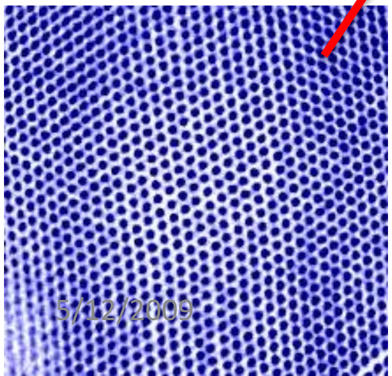
Time resolution for the full detector system:
1. Intrinsec detector time resolution
2. Jitter in MCP-PMT's or other photosensor
3. Electronics (AMP/CFD/TDC)
4. Reference Timing

- 3 mm =10 ps
- Rate and lifetime issues
- Background in detector and MCP
- Multiple proton timing
- Rad Hardness of detector, phototube and electronics, where to put electronics in tunnel

Micro-channel Plate Photomultiplier Tube (MCP-PMT)

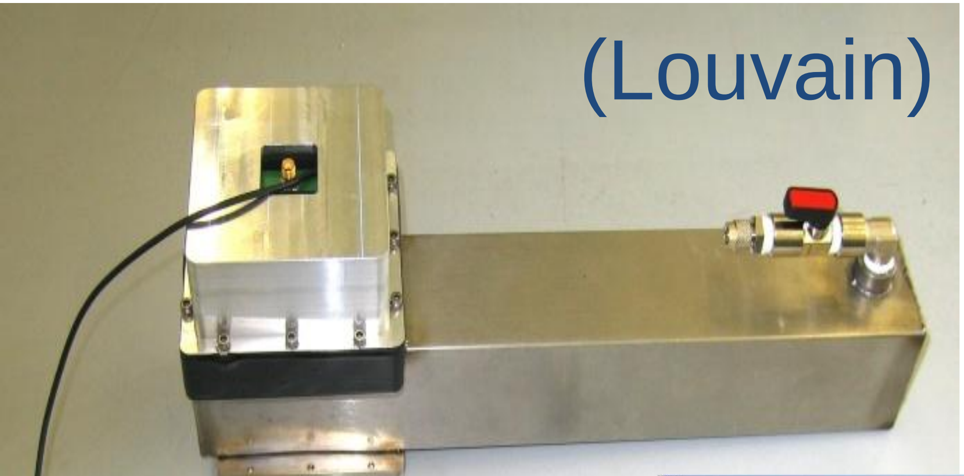


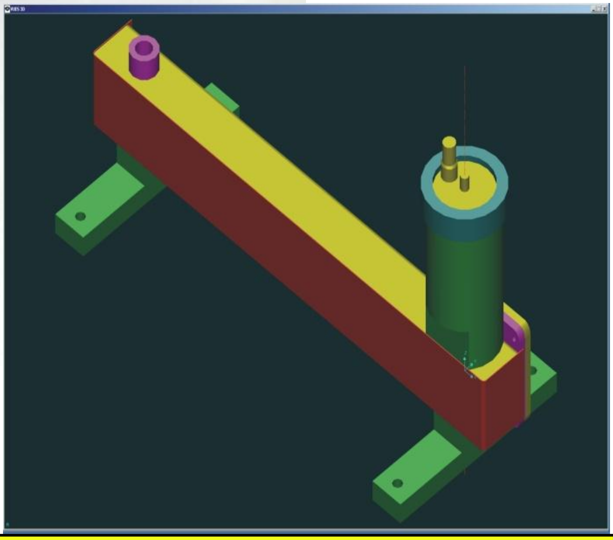




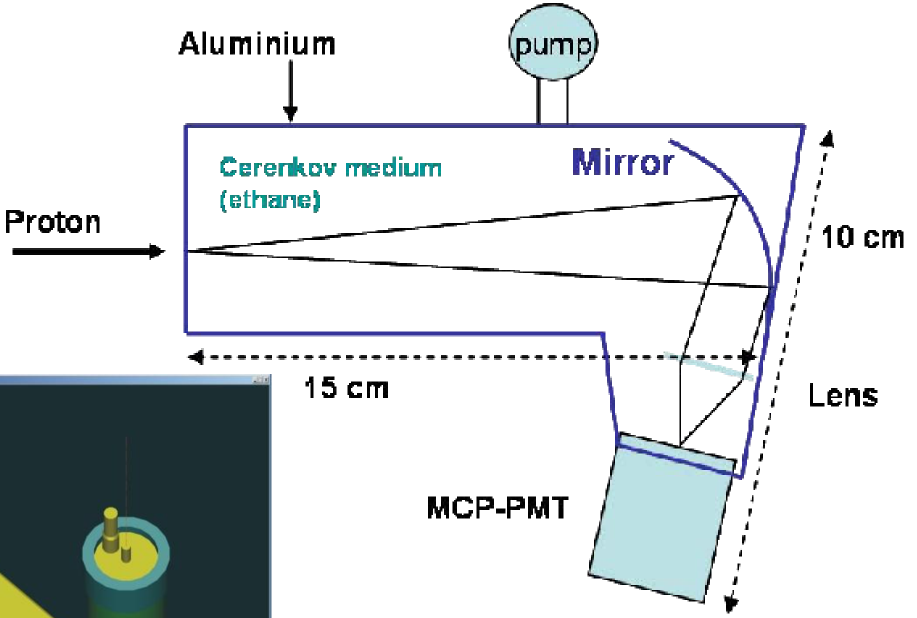
A photograph of an MCP showing an array of 12µm pores (holes)

Fast Timing Detector: GASTOF


(Louvain)



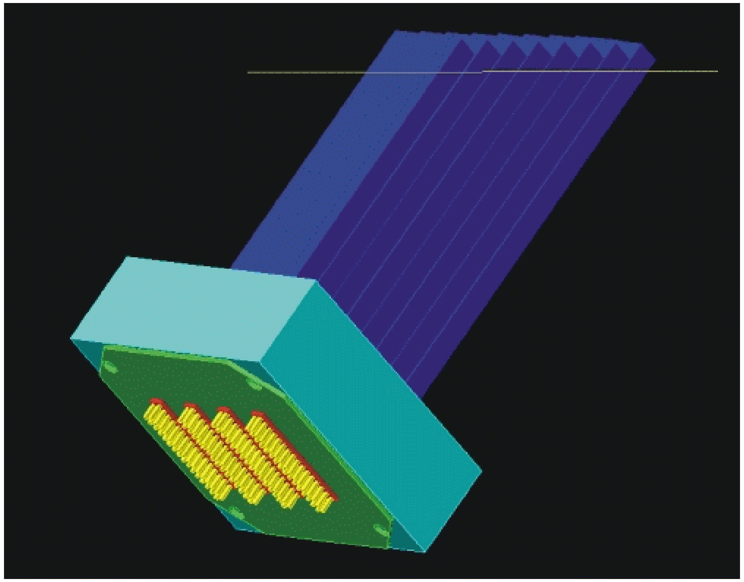
gastof™



Hamamatsu R3809U-50
6 µm pore tube with
Mini-circuits ZX-60 amplifier

Gas Cerenkov detector has low index of refraction, which limits total light, but full Cerenkov cone is captured. Simulations show yield of about 10 pe's accepted within few ps! Have obtained 13 ps in TB (from fits to data).

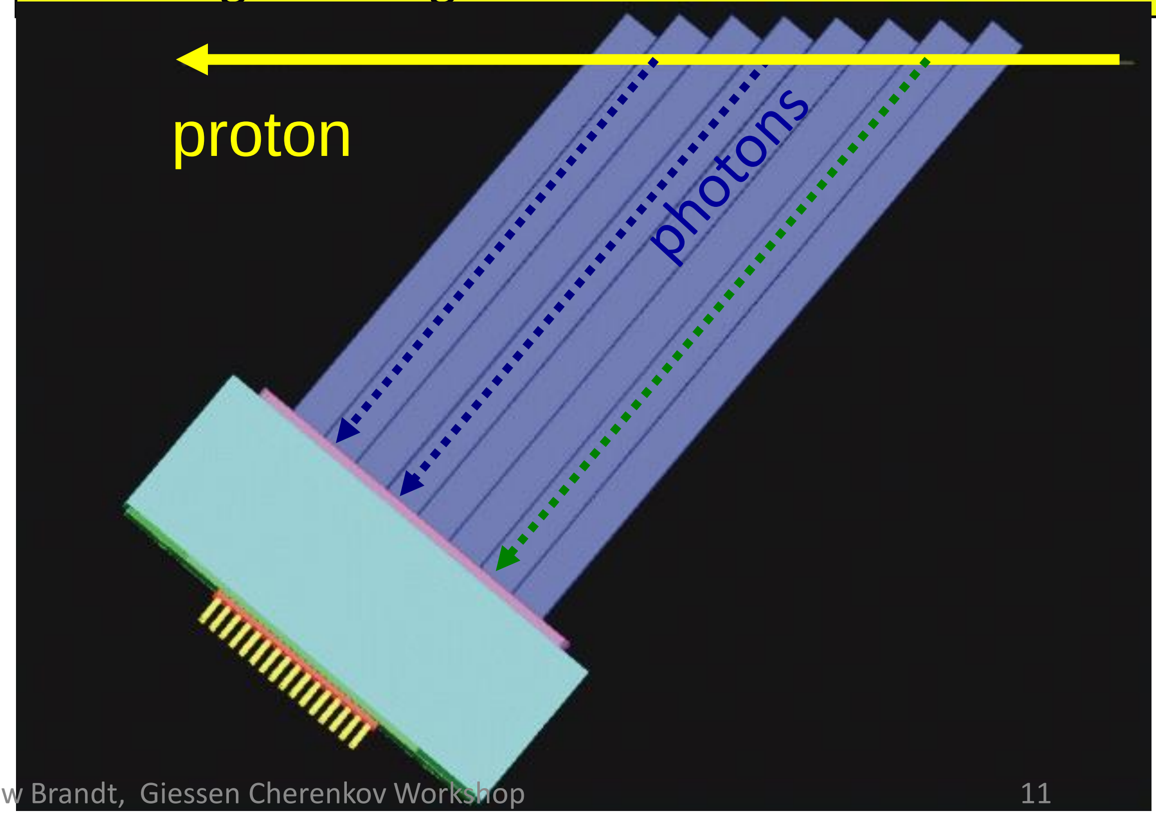
Fast Timing Detector : QUARTIC

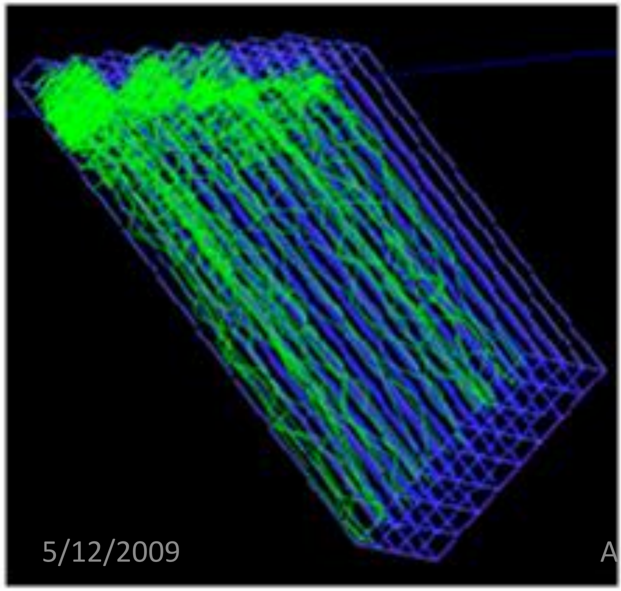


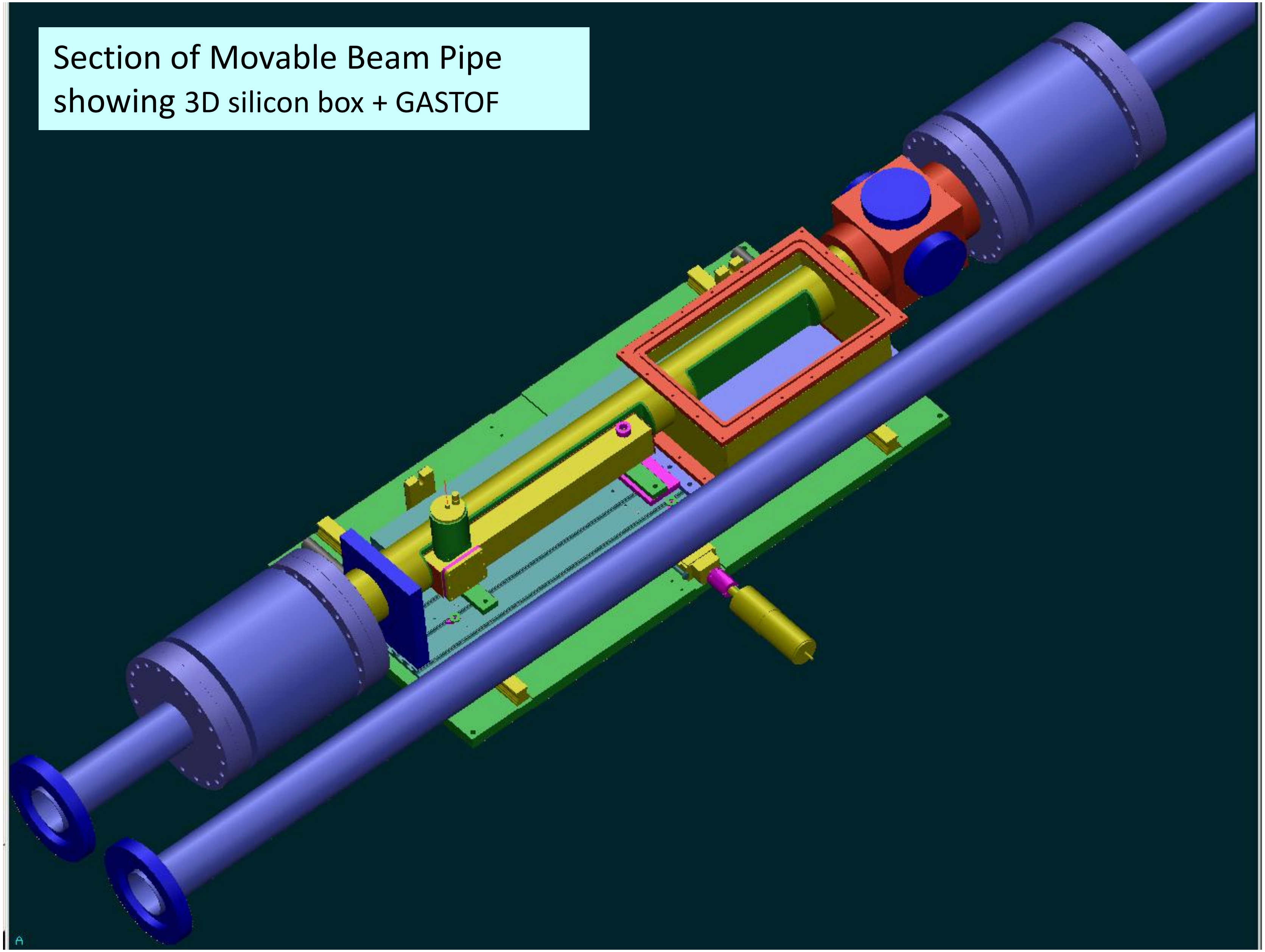
4x8 array of 6 mm^2 fused silica bars

UTA, Alberta, FNAL

Only need 40 ps measurement if you can do it 16 times (2 detectors with 8 bars each)! Has advantage of x-segmentation

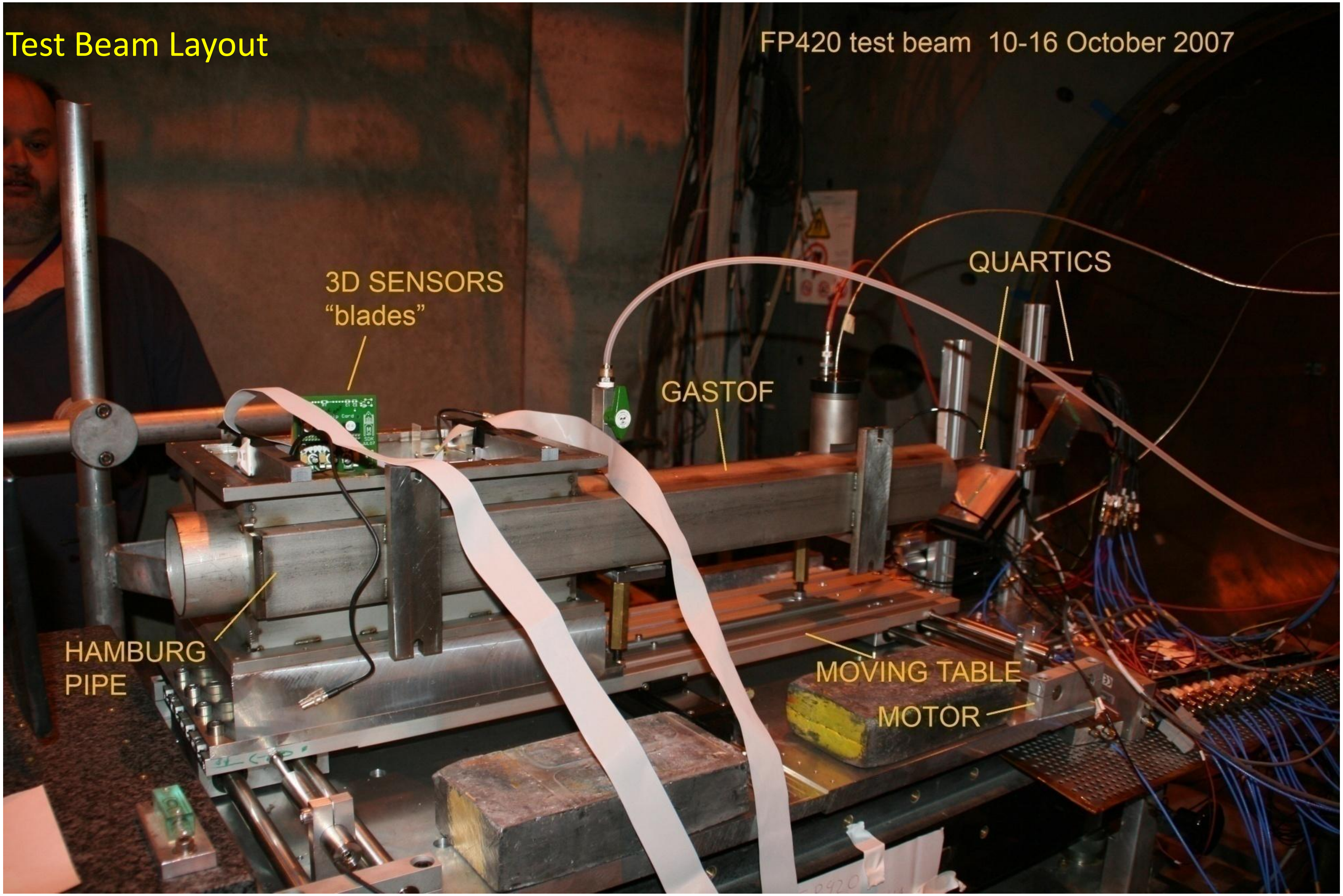




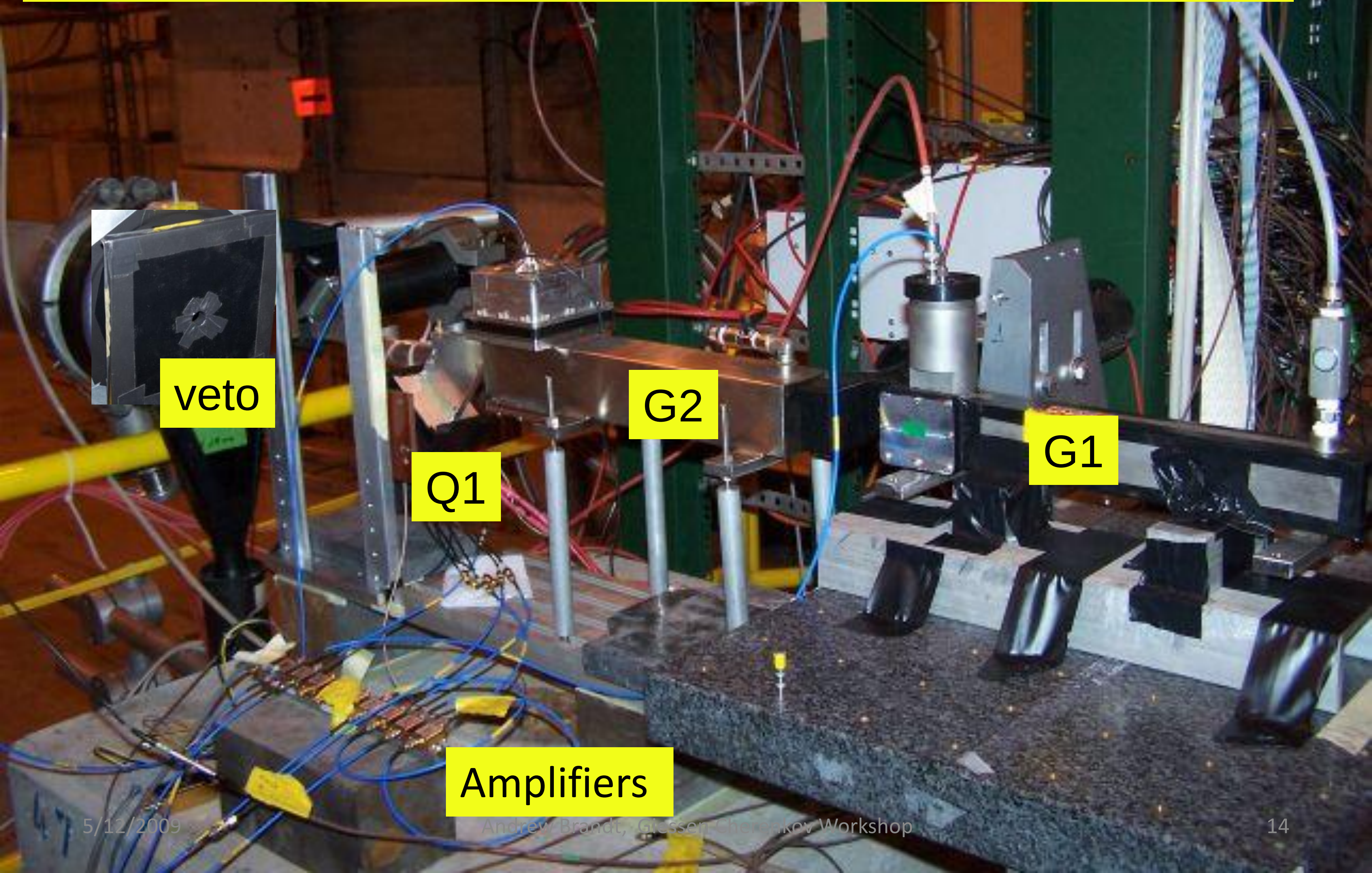


Section of Movable Beam Pipe showing 3D silicon box + GASTOF

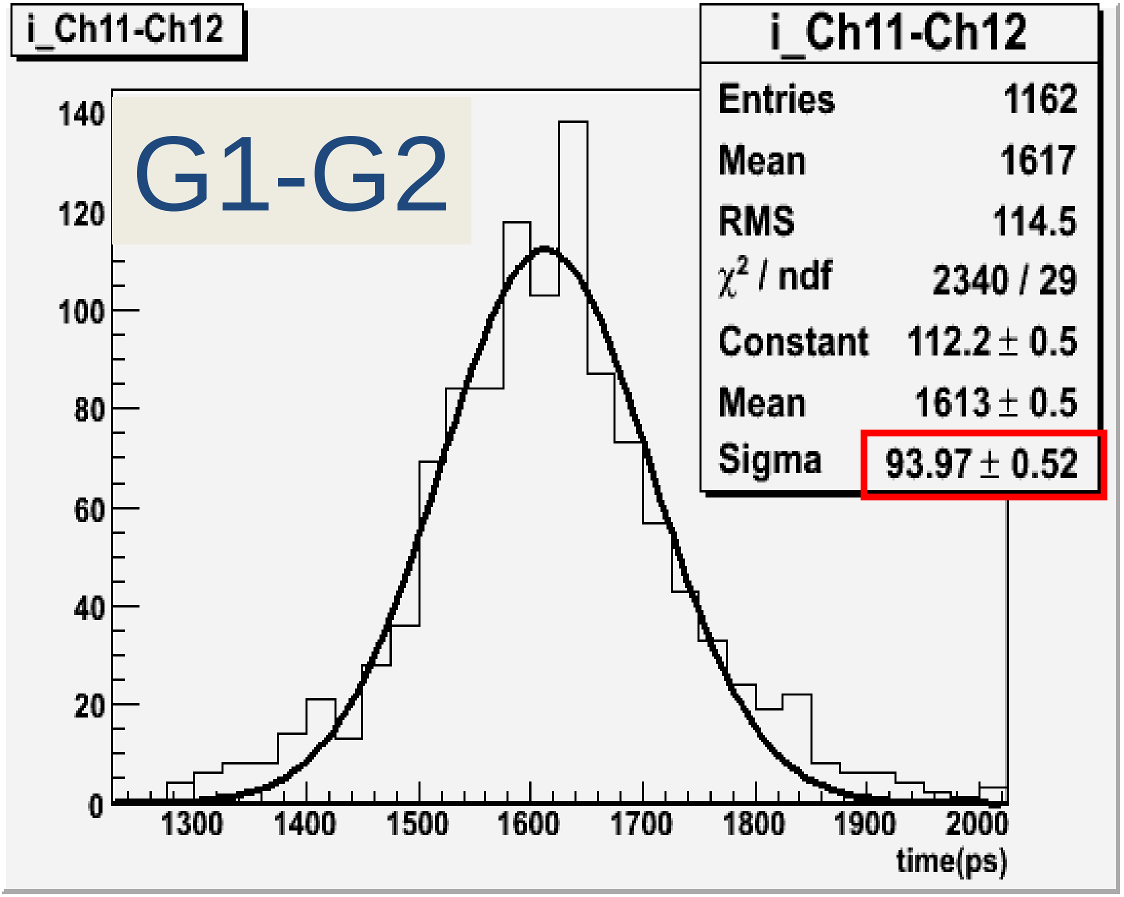
Test Beam Layout



FP420 Timing Setup June 2008 CERN TB



First TB Results (Fall 2006)

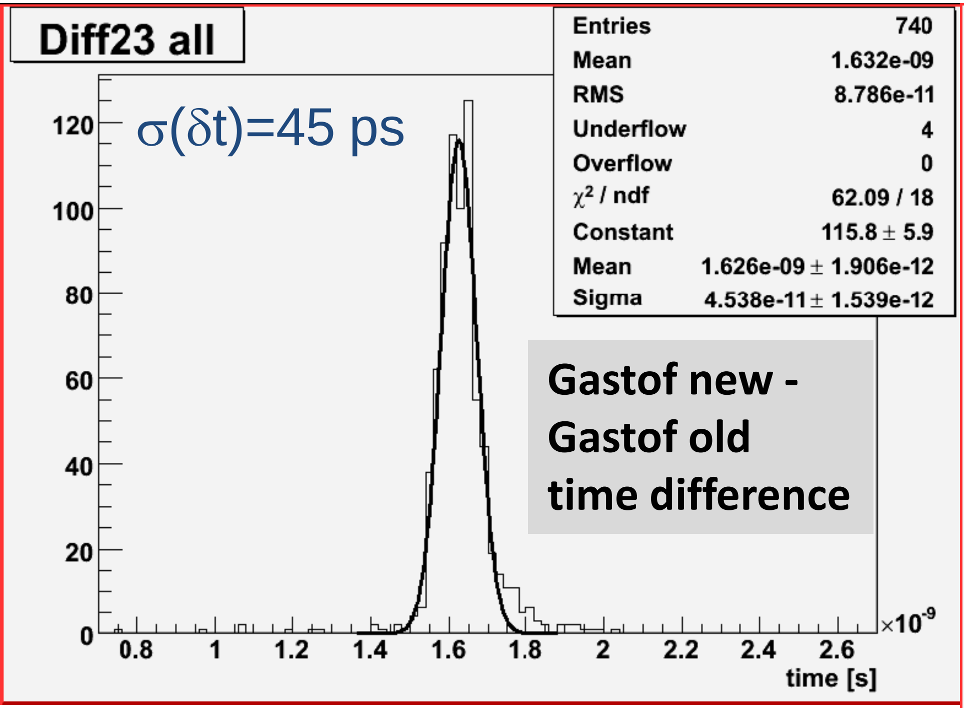


For QUARTIC bar
110 psec
Efficiency 50-60%

For events with a few bars on see anticipated √N dependence

<70 psec/Old style Gastof (Burle 25 um 8x8 tube, Σ4 pixels)
>90% efficiency, dominated by CFD resolution (used Ortec 934)

March 2007 Test Beam

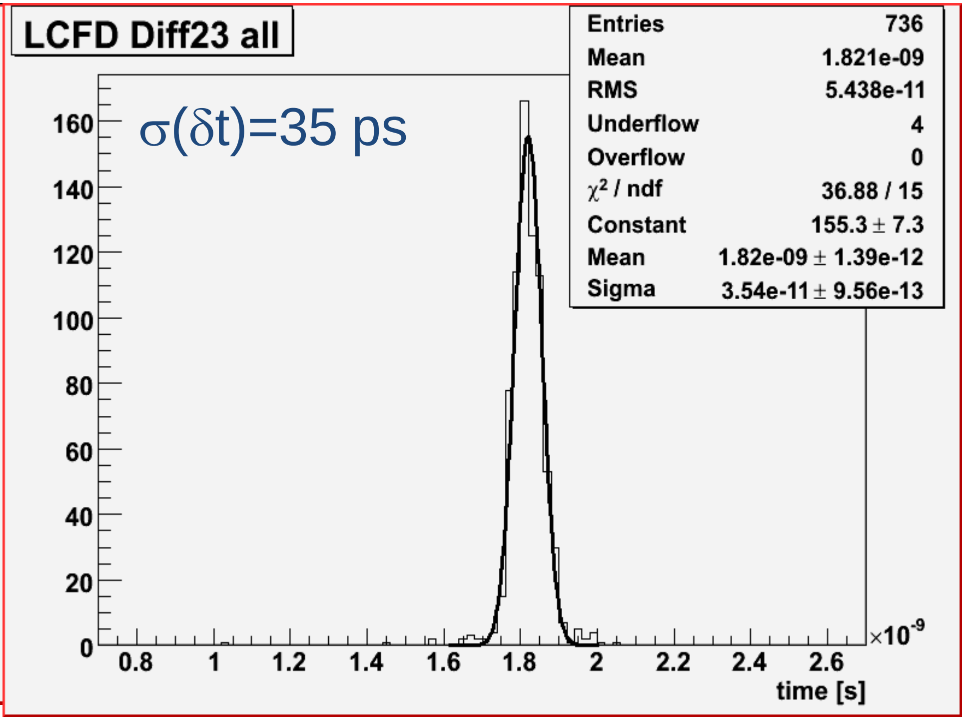


Entries	740
Mean	1.632e-09
RMS	8.786e-11
Underflow	4
Overflow	0
χ^2 / ndf	62.09 / 18
Constant	115.8 ± 5.9
Mean	1.626e-09 ± 1.906e-12
Sigma	4.538e-11 ± 1.539e-12

σ(δt)=45 ps

Gastof new - Gastof old time difference

Threshhold discrimination



Entries	736
Mean	1.821e-09
RMS	5.438e-11
Underflow	4
Overflow	0
χ^2 / ndf	36.88 / 15
Constant	155.3 ± 7.3
Mean	1.82e-09 ± 1.39e-12
Sigma	3.54e-11 ± 9.56e-13

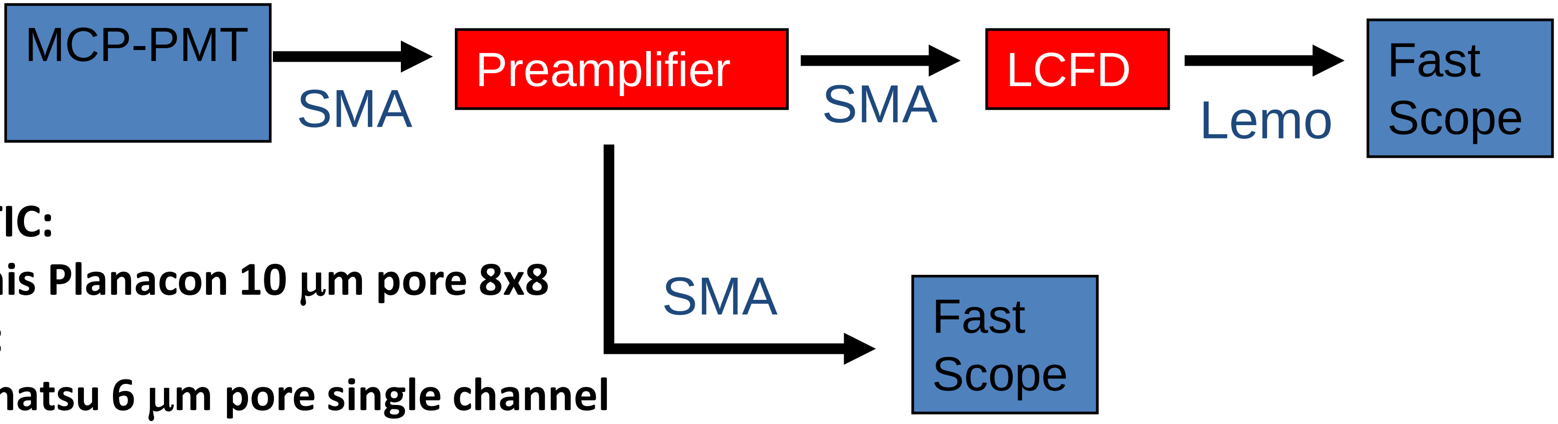
σ(δt)=35 ps

CFD algo simulated

If G1=G2 then δt=25 ps each, but G1 (Gastof new) has faster tube (Hamamatsu 6 μm pore vs 25 μm Burle) and better mirror then G2 (Gastof old); extract resolution G1=13 ps G2=32 ps, initial estimate 80% efficient

QUARTIC
80 ps/bar
(15 mm bar)
80% efficient

Test Beam Electronics



MCP-PMT

SMA

Preamplifier

SMA

LCFD

Lemo

Fast Scope

SMA

Fast Scope

QUARTIC:

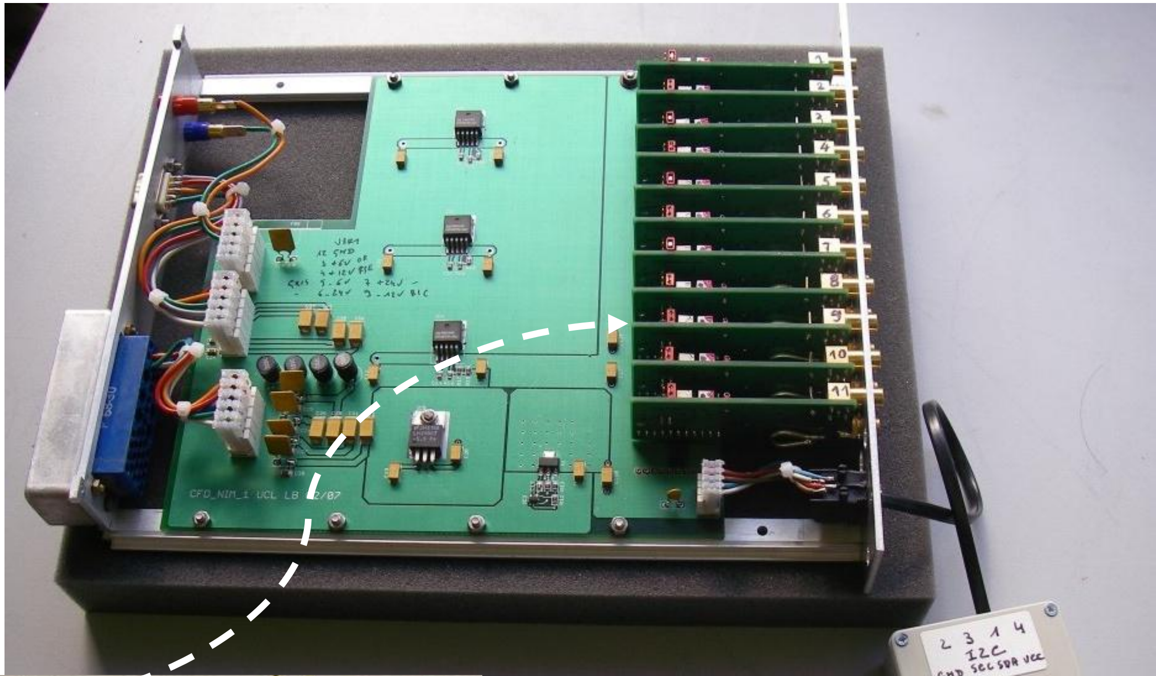
Photonis Planacon 10 μm pore 8x8

Gastof:

Hamamatsu 6 μm pore single channel

LCFD

Louvain (Luc Bonnet engineer) developed LCFD (Louvain Constant Fraction Discriminator) mini-module approach tuned LCFD mini-module to Burle and Hamamatsu rise times; 12 channel NIM unit

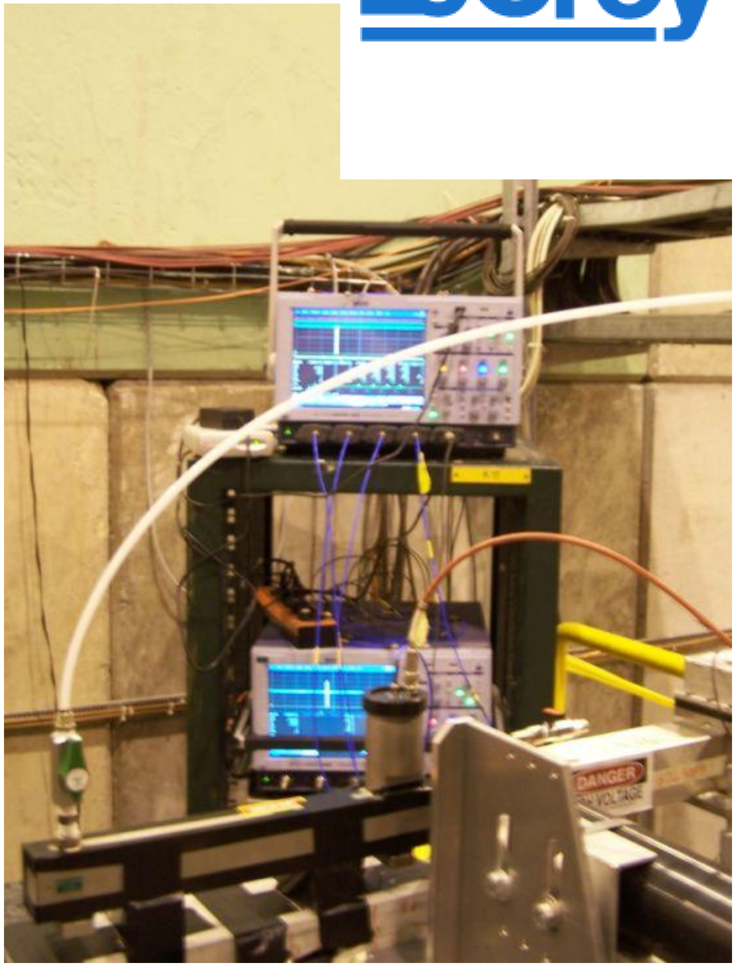


Remote control for threshold

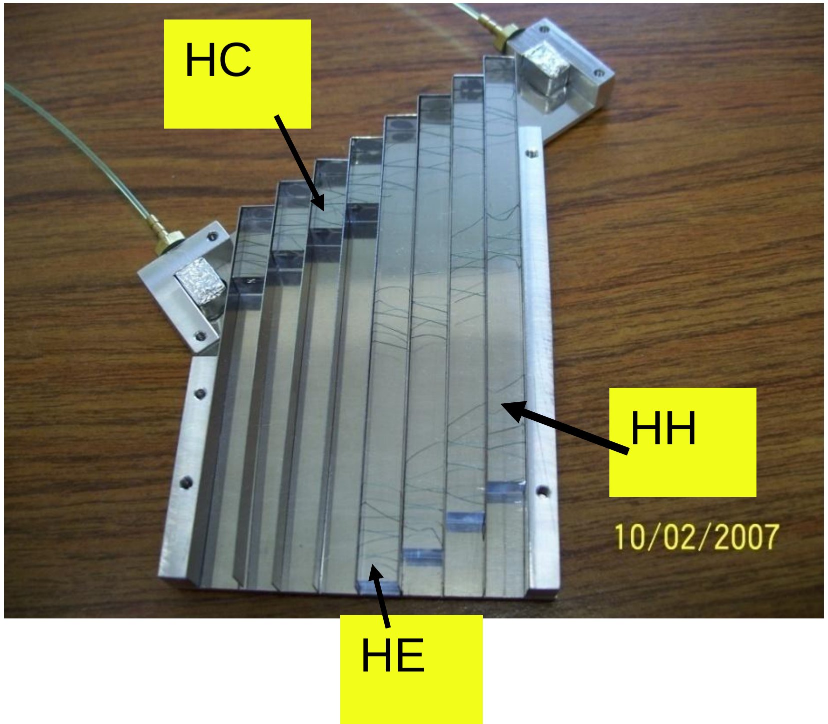
Data Acquisition

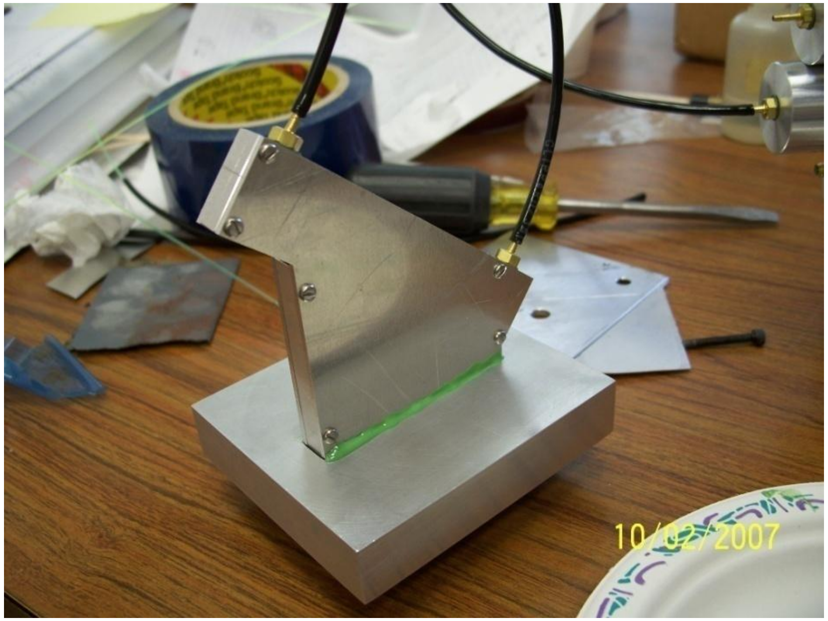
- Lecroy 8620A 6 GHz 20 Gs (UTA)
- Lecroy 7300A 3 GHz 10-20 GS (Louvain)
- Remotely operated from control room using TightVNC
- Transfer data periodically

  with external USB drive



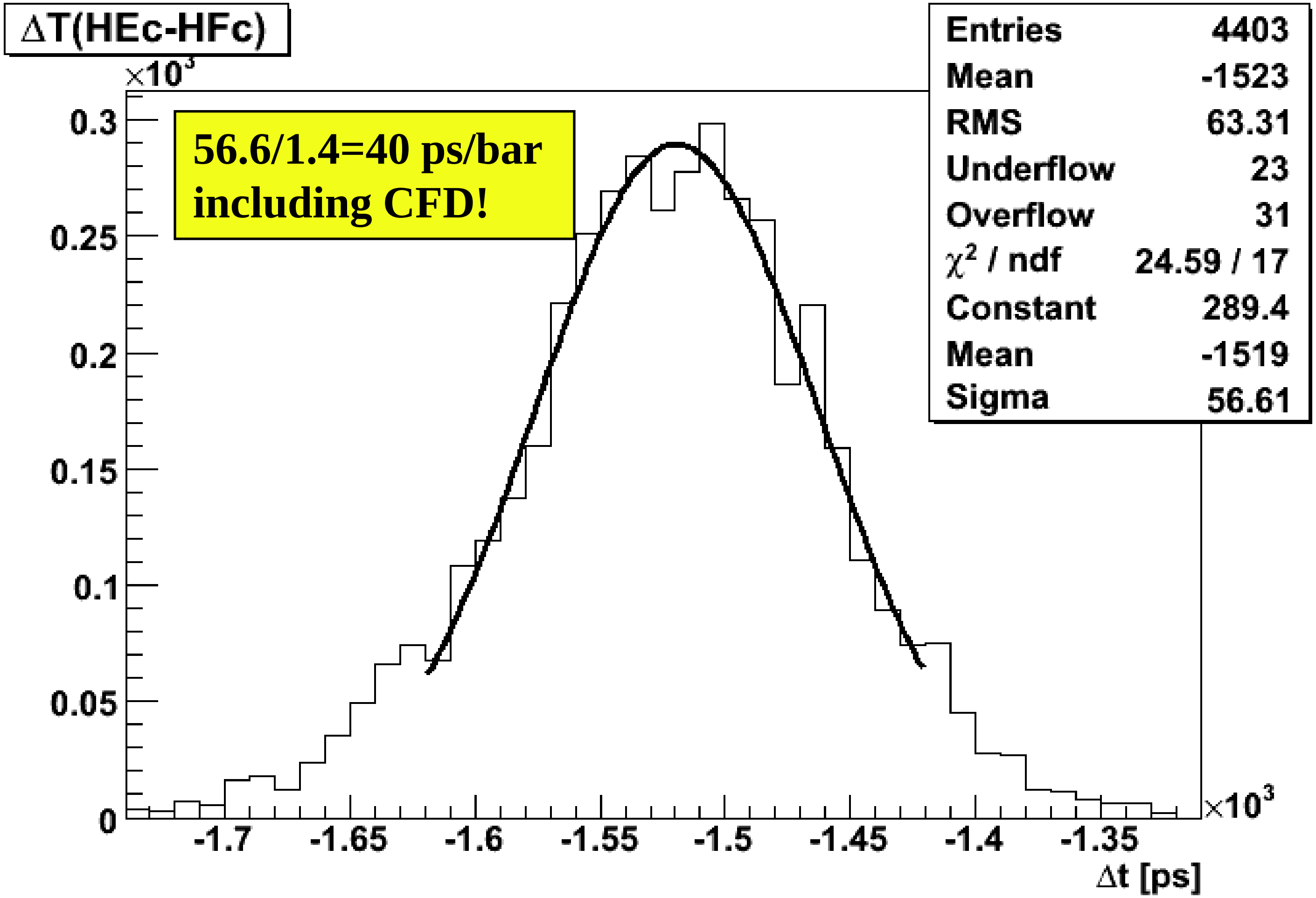
Latest QUARTIC Prototype





Testing long bars 90 mm (HE to HH) and mini bars 15 mm (HA to HD). Simulations show that long bars have more light from total internal reflection vs. losses from reflection in air light guide, but more time dispersion due to $n(\lambda)$

QUARTIC Timing 2008 CERN TB



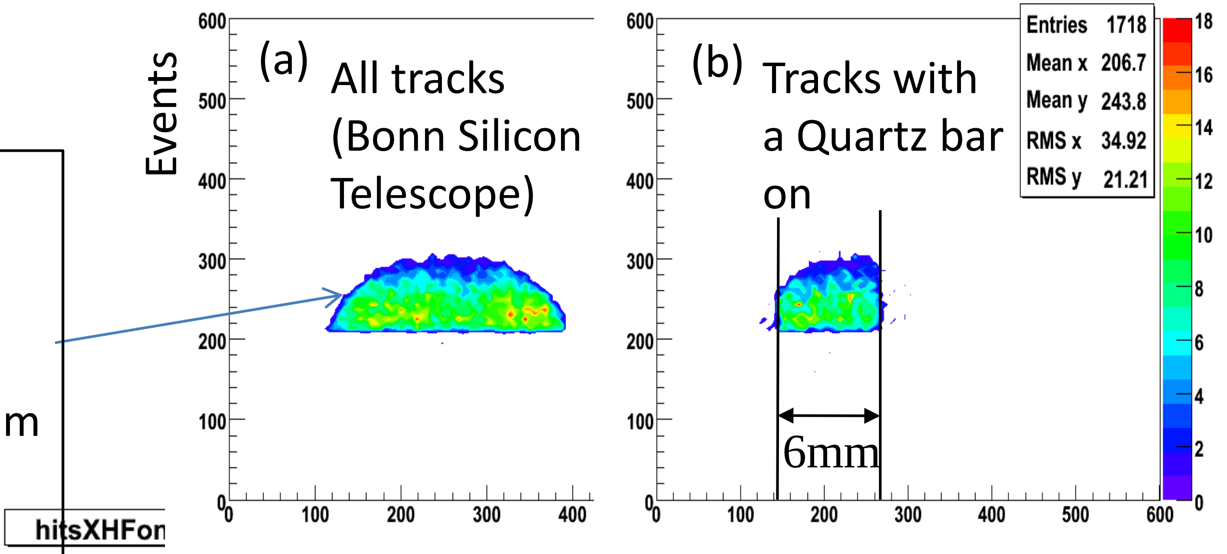
56.6/1.4=40 ps/bar including CFD!

CERN TB
June 2008

Time difference between two 9 cm quartz bars after Louvain constant fraction discrimination is 56 ps, implies a single bar resolution of 40 ps

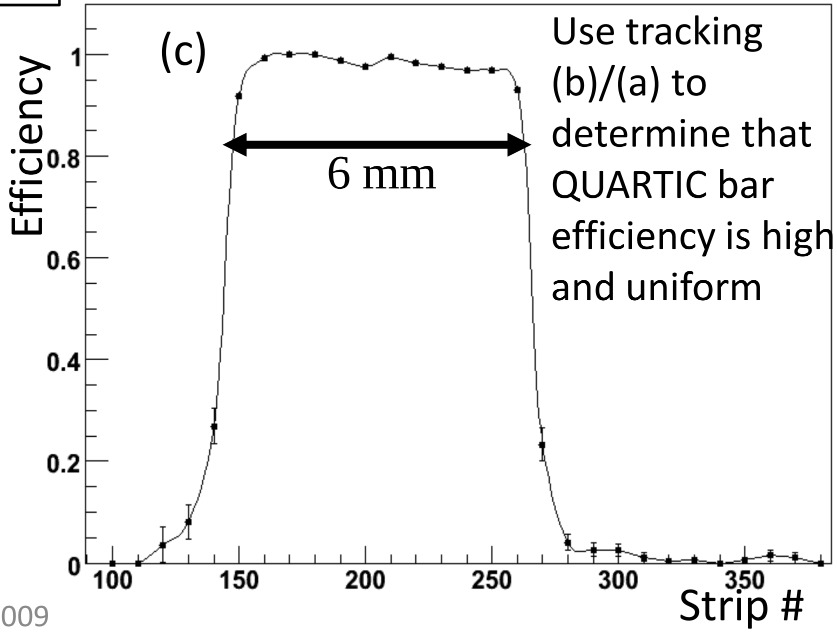
QUARTIC Efficiency Using Tracking

Shape due to veto counter with 15mm diameter hole



(a) All tracks (Bonn Silicon Telescope)

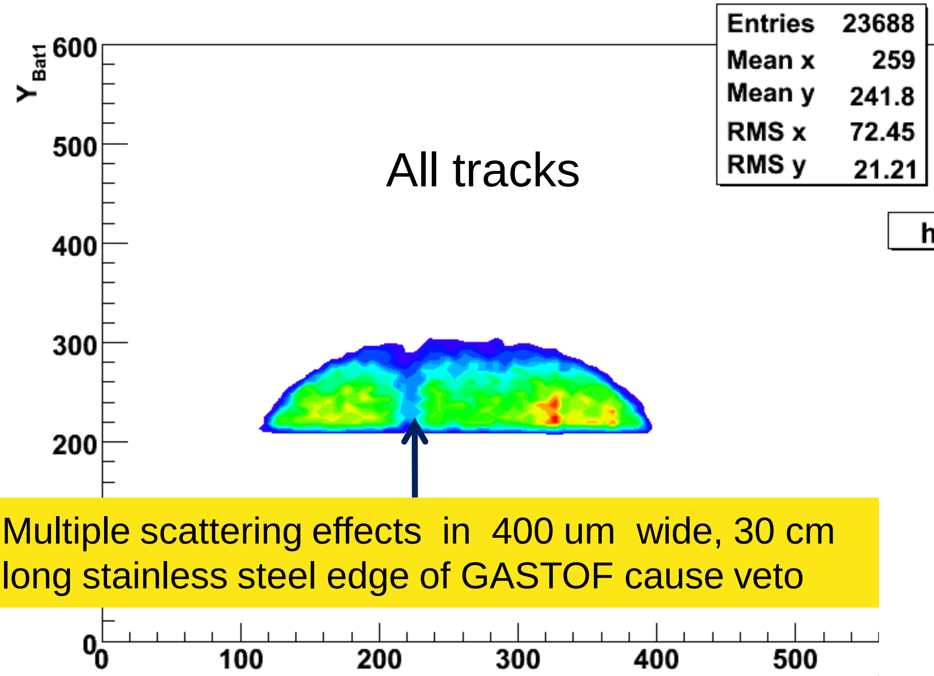
(b) Tracks with a Quartz bar on



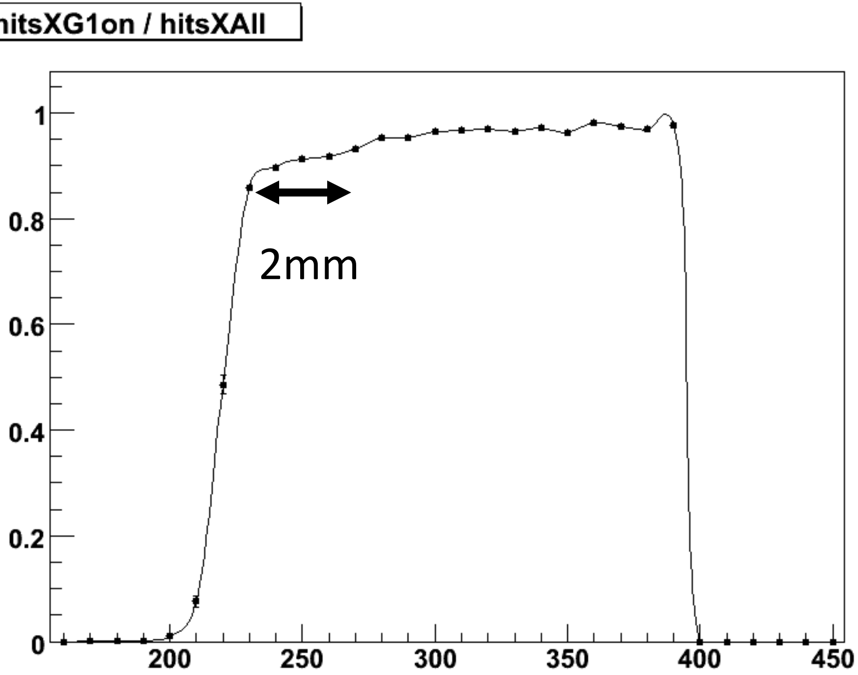
Use tracking (b)/(a) to determine that QUARTIC bar efficiency is high and uniform

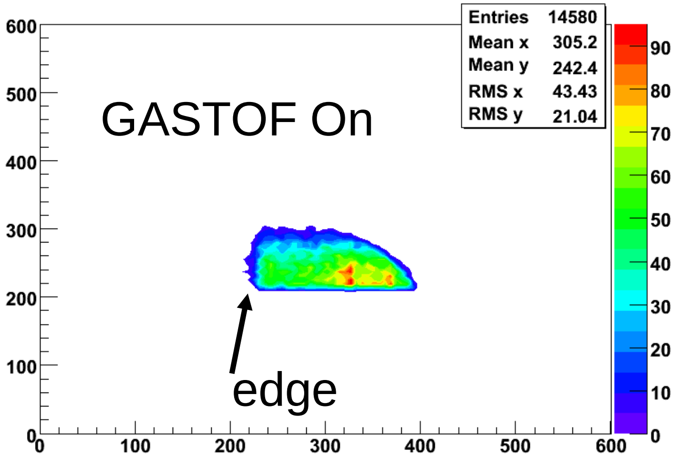
Used scintillator trigger to synchronize silicon tracking data sample and oscilloscope data sample

GASTOF Efficiency (Displaced 19 mm)



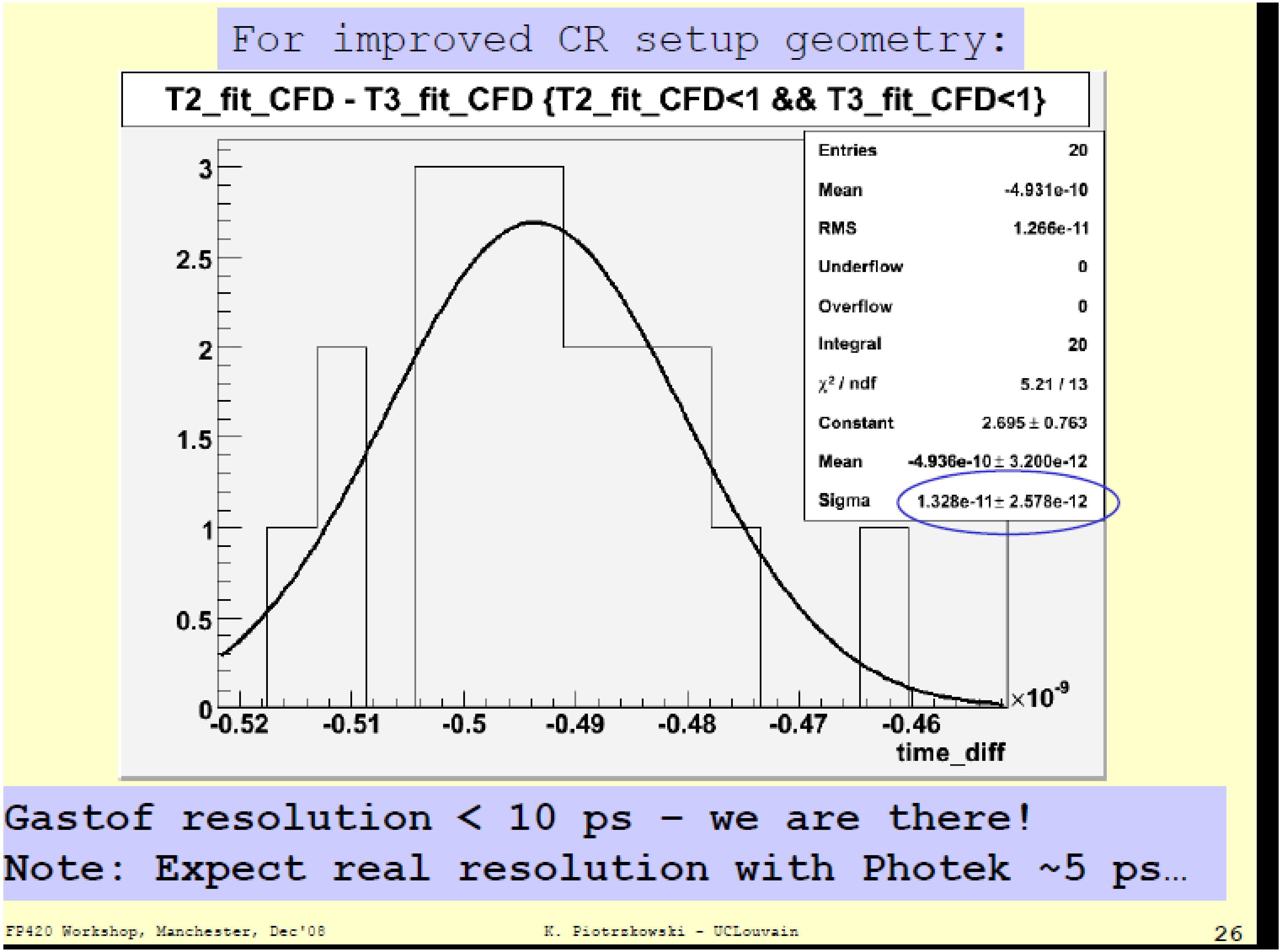
Multiple scattering effects in 400 um wide, 30 cm long stainless steel edge of GASTOF cause veto





Fraction of events with good track and G1 on as a function of track position 90 to 99%, loss at edge understood from simulation, can be improved with mirroring of inside of GASTOF

Gastof Cosmic Ray Results



For improved CR setup geometry:

T2_fit_CFD - T3_fit_CFD {T2_fit_CFD<1 && T3_fit_CFD<1}

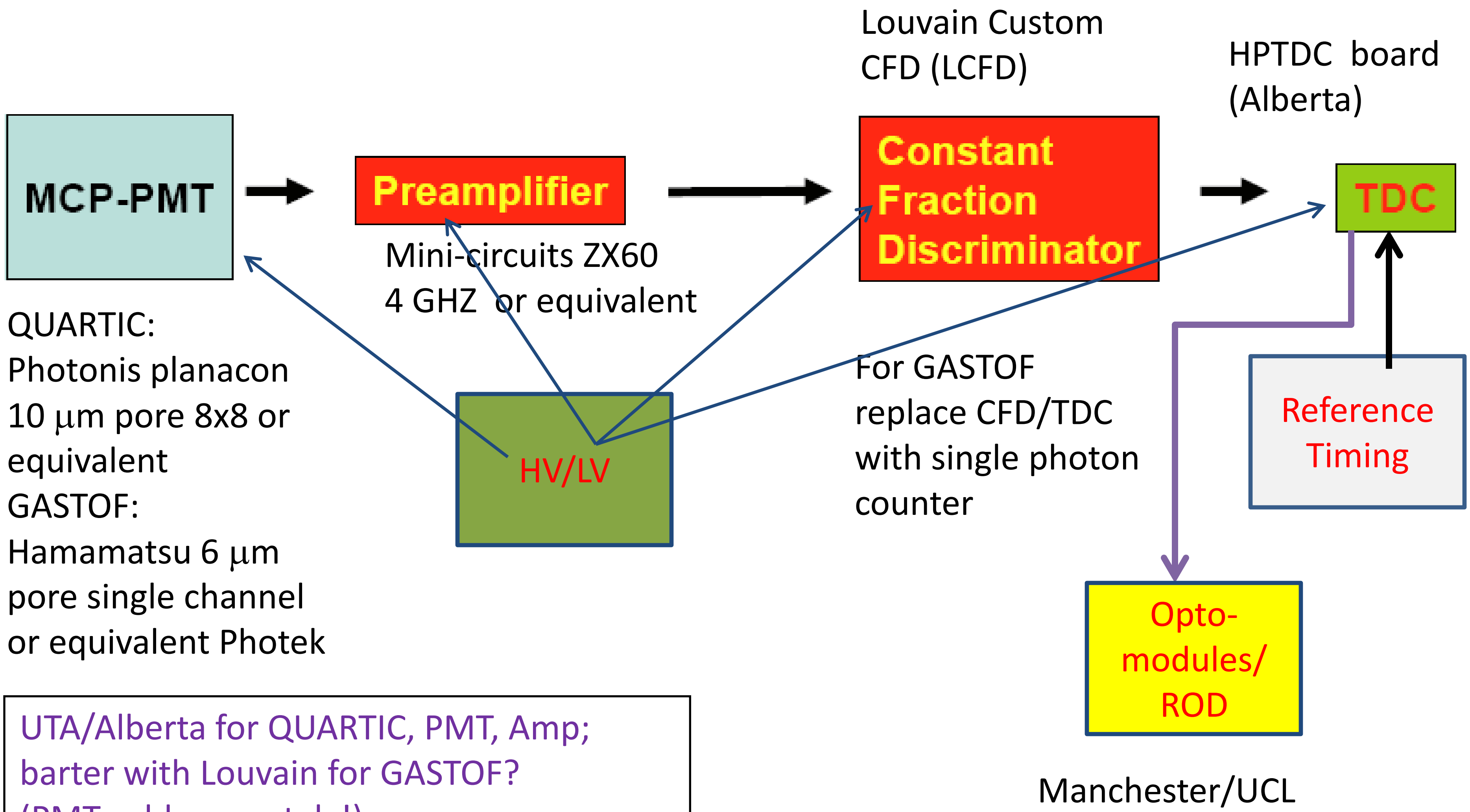
Entries	20
Mean	-4.931e-10
RMS	1.266e-11
Underflow	0
Overflow	0
Integral	20
χ^2 / ndf	5.21 / 13
Constant	2.695 ± 0.763
Mean	-4.936e-10 ± 3.200e-12
Sigma	1.328e-11 ± 2.578e-12

Gastof resolution < 10 ps – we are there!
Note: Expect real resolution with Photek ~5 ps…

FP420 Workshop, Manchester, Dec'08 K. Piotrzkowski - UCLouvain 26

Photek PMT210
3 μm pore
<100 ps rise time!

Components of Fast Timing System



MCP-PMT

Preamplifier

Mini-circuits ZX60
4 GHZ or equivalent

Louvain Custom
CFD (LCFD)

Constant Fraction Discriminator

HPTDC board
(Alberta)

TDC

QUARTIC:
Photonis planacon
10 μm pore 8x8 or
equivalent
GASTOF:
Hamamatsu 6 μm
pore single channel
or equivalent Photek

HV/LV

For GASTOF
replace CFD/TDC
with single photon
counter

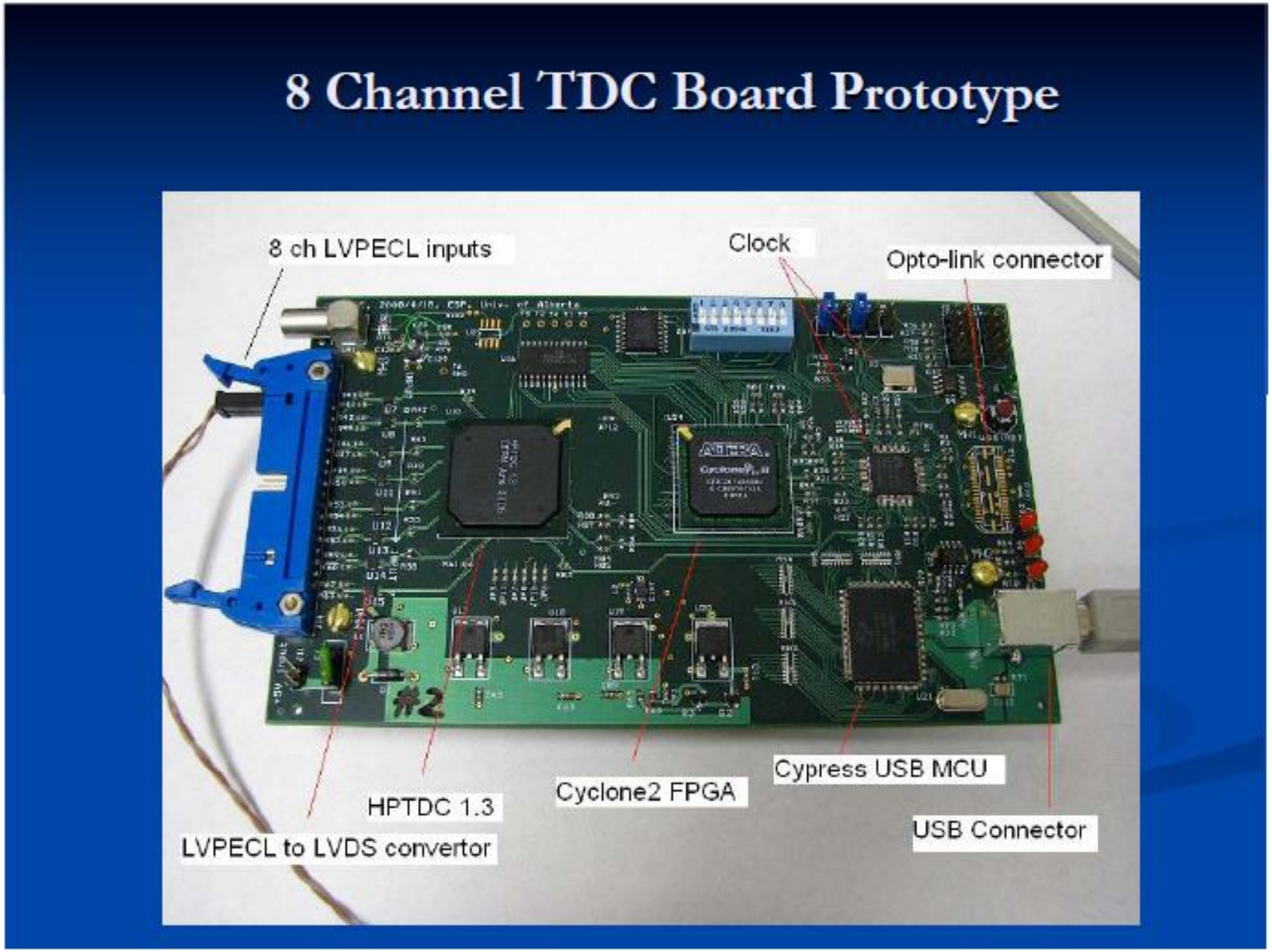
Reference Timing

Opto-modules/ ROD

Manchester/UCL

UTA/Alberta for QUARTIC, PMT, Amp;
barter with Louvain for GASTOF?
(PMT sold separately!)

Alberta HPTDC board



8 Channel TDC Board Prototype

12ps resolution with pulser; Successfully tested last week with laser/10 μm tube/ZX60 amp/LCFD/ scope

Rate and Current Limits

The LHC is a high rate accelerator and we need to establish if the MCP-PMT's are capable of coping with the large expected rates: from 1 MHz in a 6mm x 6mm pixel at 2×10^{33} luminosity to up to 15 MHz at 10^{34}

The limiting quantity is not actually the rate, but the current in the tube:

Cathode Current = proton frequency x number of photo-electrons generated by each proton x electron charge

Anode Current = Cathode Current x gain

In order to keep the Anode current at tolerable levels, lower gain is preferable as well as less photoelectrons (but precise timing needs as many pe's as possible). In addition smaller pores improve timing and give more pores/area reducing the current in any one pore.

When the current demanded of the tube is too high the tube does not give as big an output signal, we call this saturation.

Using 1 MHz/15 MHz and a gain of 10^5 (!) and 10 pe's expected for our detector, we require 1.6 to 24 pA (Cathode) or 0.16 μA/2.4 μA (Anode) in a .36 cm^2 pixel

Lifetime Issues

Lifetime issues believed to be due to photocathode damage from +ions:

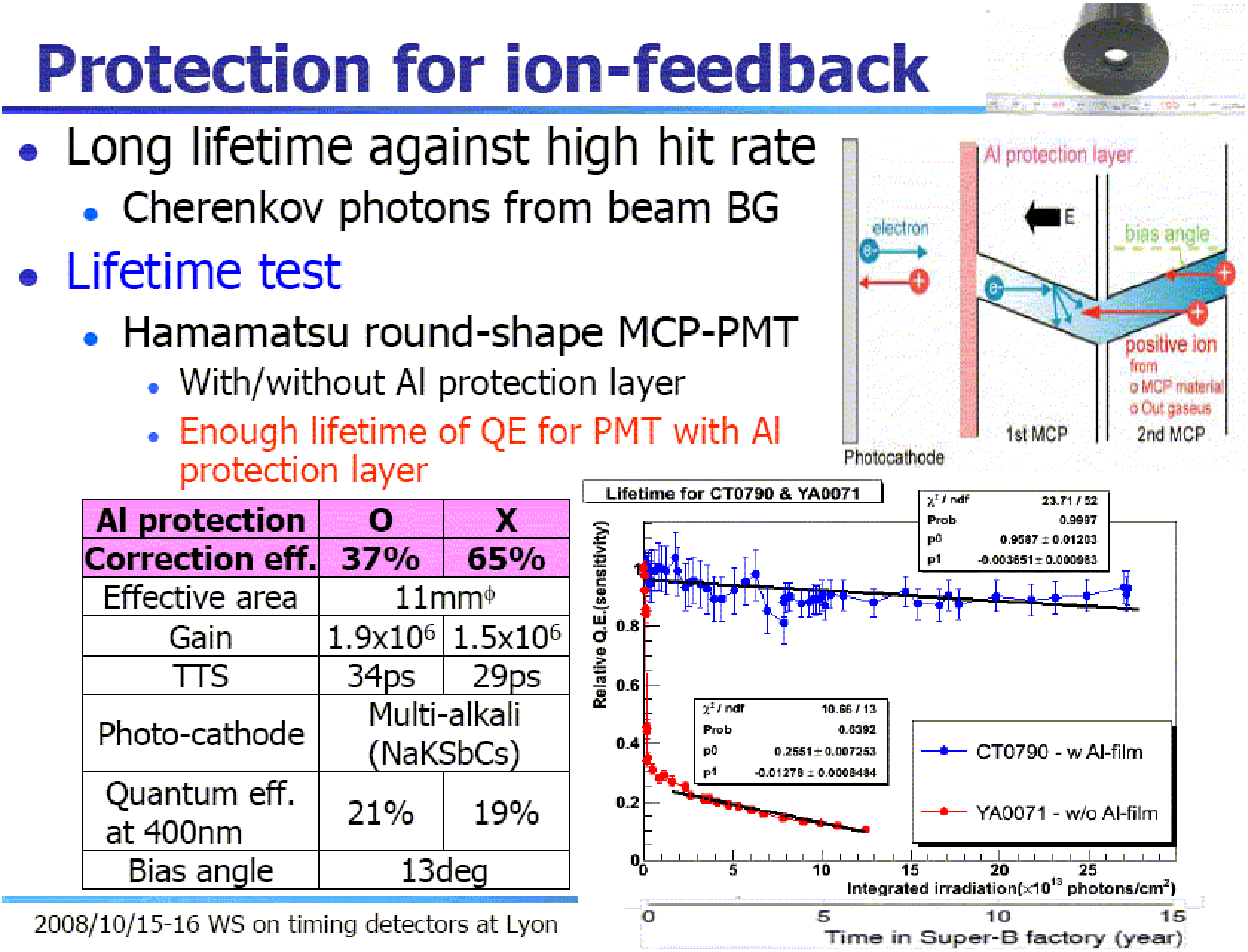
Q/year = I*10^7 sec/year

Assuming Gain=10^5 :

Q in Phase I =1.6 to 4.8 C/year (in a 0.36 cm^2 pixel!)

Q in Phase II 5x worse (up to 24 C/year or 72 C/ cm^2/yr)

From Lyon picosecond workshop:



Protection for ion-feedback

- Long lifetime against high hit rate
  - Cherenkov photons from beam BG
- Lifetime test
  - Hamamatsu round-shape MCP-PMT
    - With/without Al protection layer
    - Enough lifetime of QE for PMT with Al protection layer

Al protection	O	X
Correction eff.	**37%**	**65%**
Effective area	11mm$^\phi$	
Gain	1.9x10^6	1.5x10^6
TTS	34ps	29ps
Photo-cathode	Multi-alkali (NaKSbCs)	
Quantum eff. at 400nm	21%	19%
Bias angle	13deg	

χ^2 / ndf	23.71 / 52
Prob	0.9997
p0	0.9587 ± 0.01203
p1	-0.003651 ± 0.000983

χ^2 / ndf	10.66 / 13
Prob	0.6392
p0	0.2551 ± 0.007253
p1	-0.01278 ± 0.0008484

Resolving Rate and Lifetime Issues

I.) Measure using new UTA laser test stand

II.) Work with PMT companies to develop solutions

III.) Look into alternative technology if necessary

Initial Laser Test Goals

- Develop useful flexible laser test facility
- Study rate properties (gain, timing) of MCP-PMT's
- Some questions we are trying to answer:

1) How does timing depend on gain as f(#pe's)
2) What is maximum rate? How does this depend on gain, number of pe's, area, pore size, number of pixels hit?
3) Establish minimum gain to achieve timing goals of our detector given expected number of pe's (~10). Evaluate different amp/cfd/tdc choices at the working point of our detector
4) Eventually lifetime tests

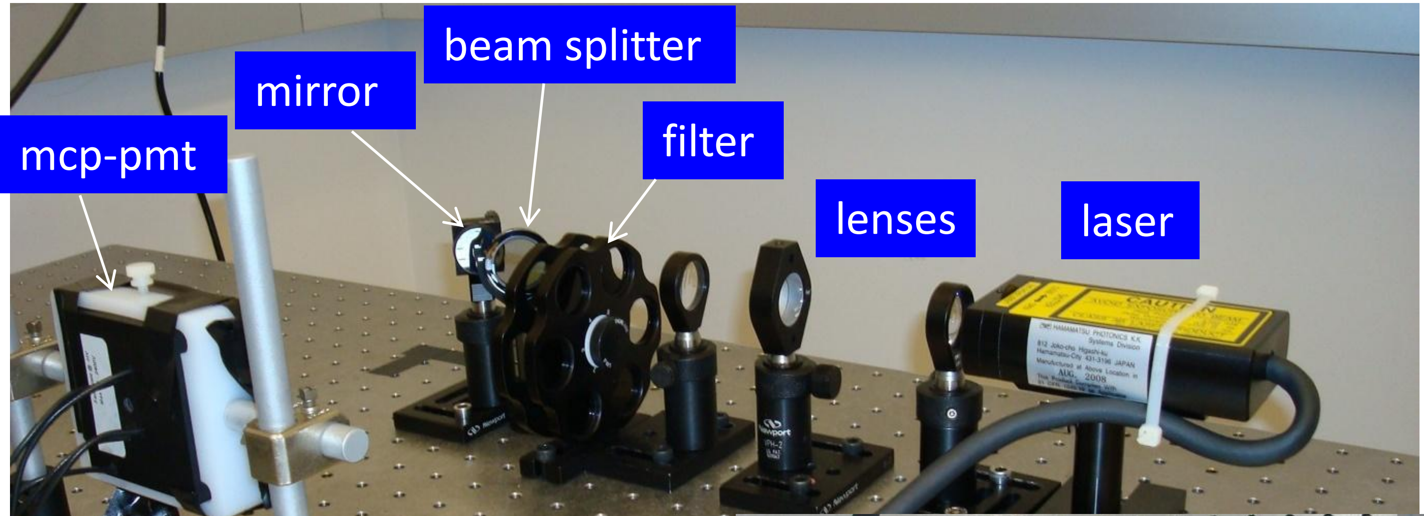
NOTE: All results are preliminary

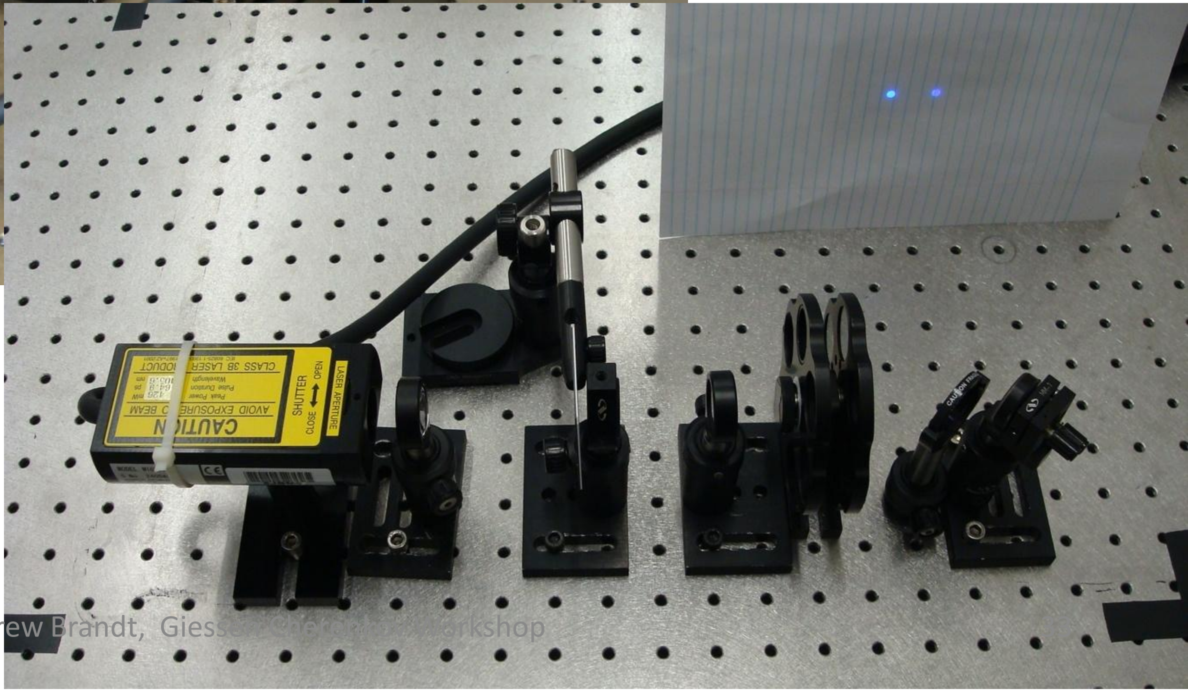
Laser Gang

¾ of laser gang: Ryan Hall, Larry Lim, Mason MacPhail (Ian Howley not shown)

UTA Laser Tests

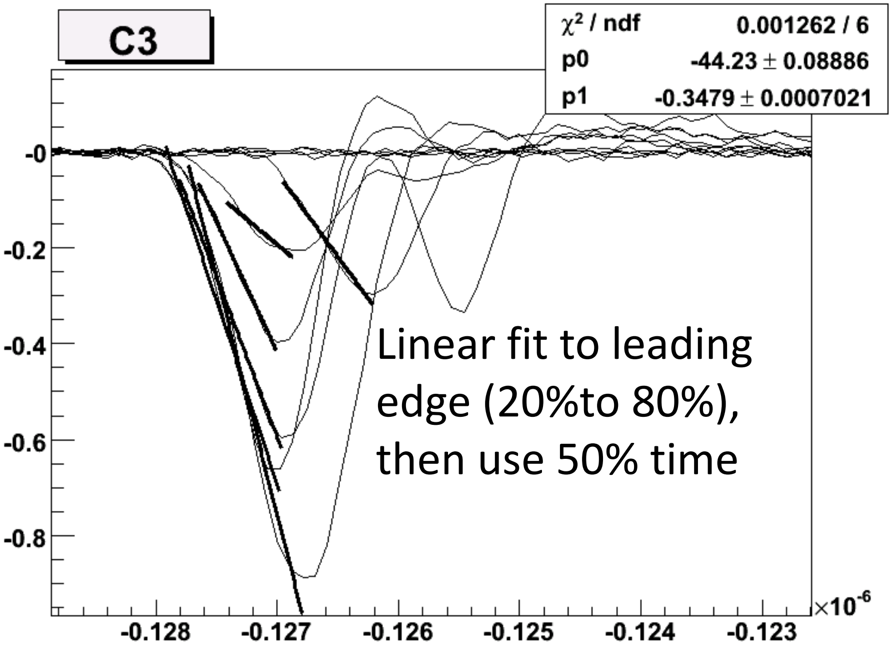
Support: Texas ARP,
DOE ADR,
Burle/Photonis



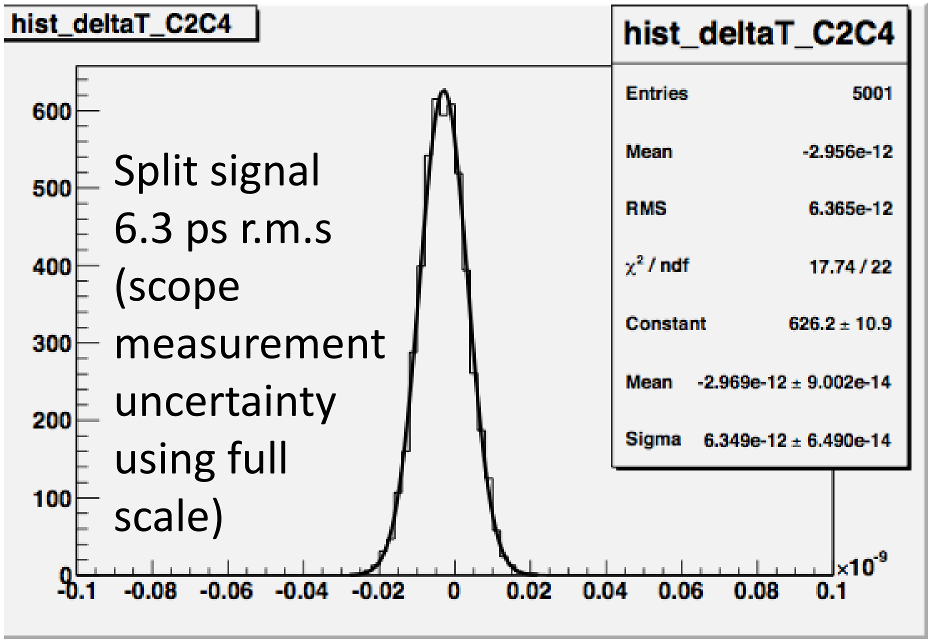


Hamamatsu PLP-10 405 nm laser
Burle 85001 4 ch 25 μm
(initial studies with 25 μm tube)
beam is about 5 mm diameter
unless indicated otherwise

Measuring Time



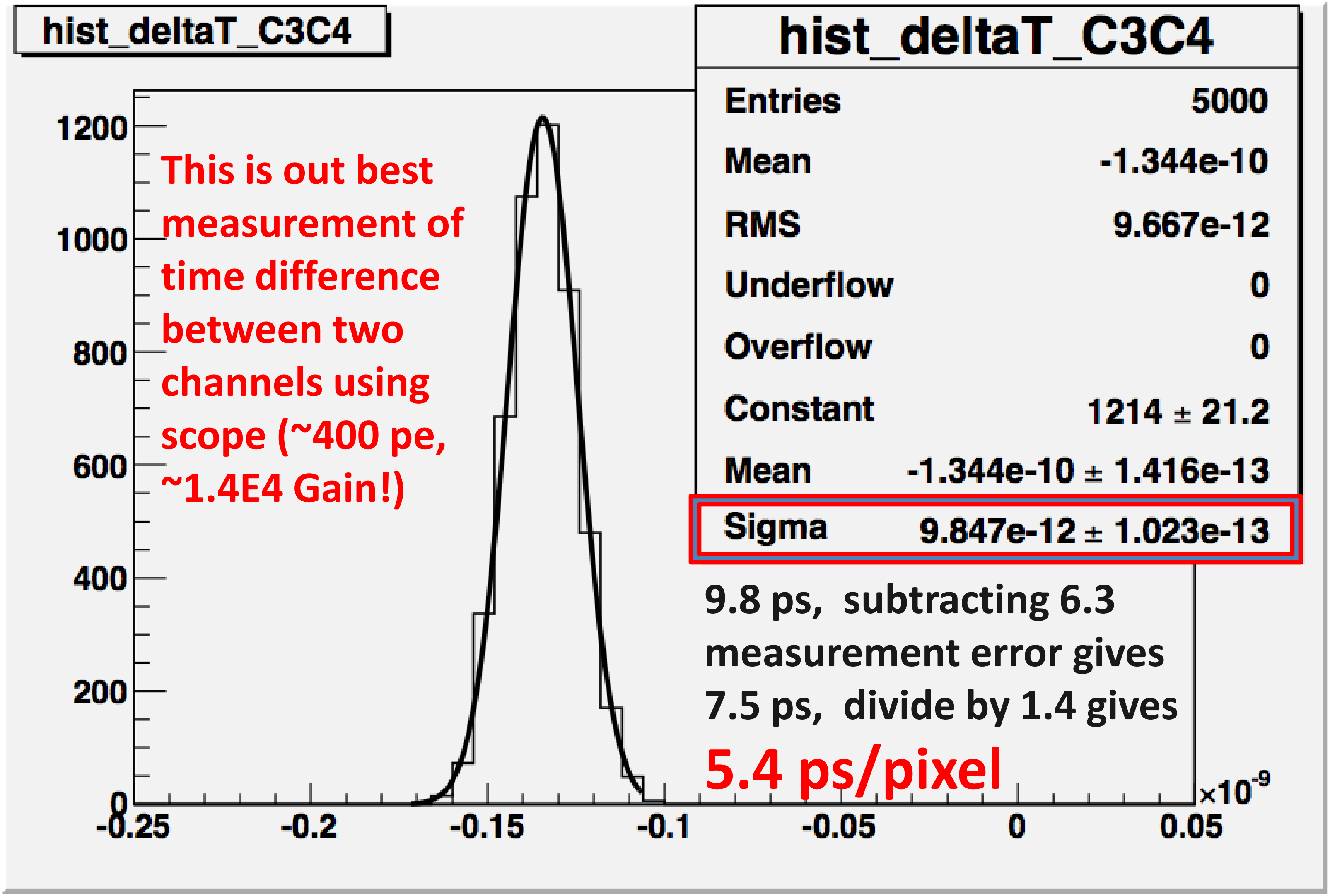
Linear fit to leading edge (20%to 80%), then use 50% time



Split signal 6.3 ps r.m.s (scope measurement uncertainty using full scale)

More accurate measurements using LCFD (<4ps scope error)

Best Time Measurement of (25μm) Microchannel Photomultiplier Tube



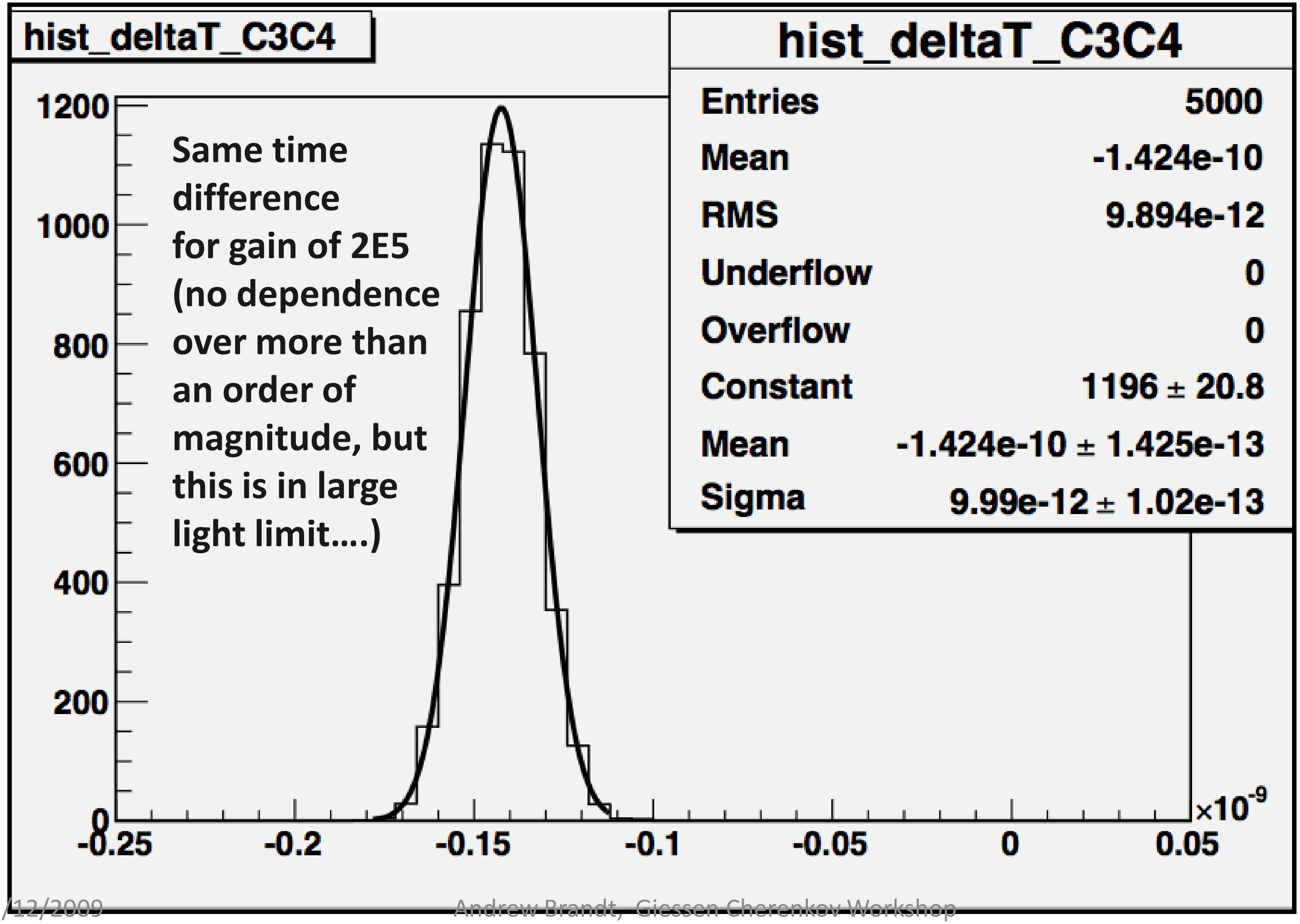
This is out best measurement of time difference between two channels using scope (~400 pe, ~1.4E4 Gain!)

9.8 ps, subtracting 6.3 measurement error gives 7.5 ps, divide by 1.4 gives

5.4 ps/pixel

Shows test stand performing at reasonable level

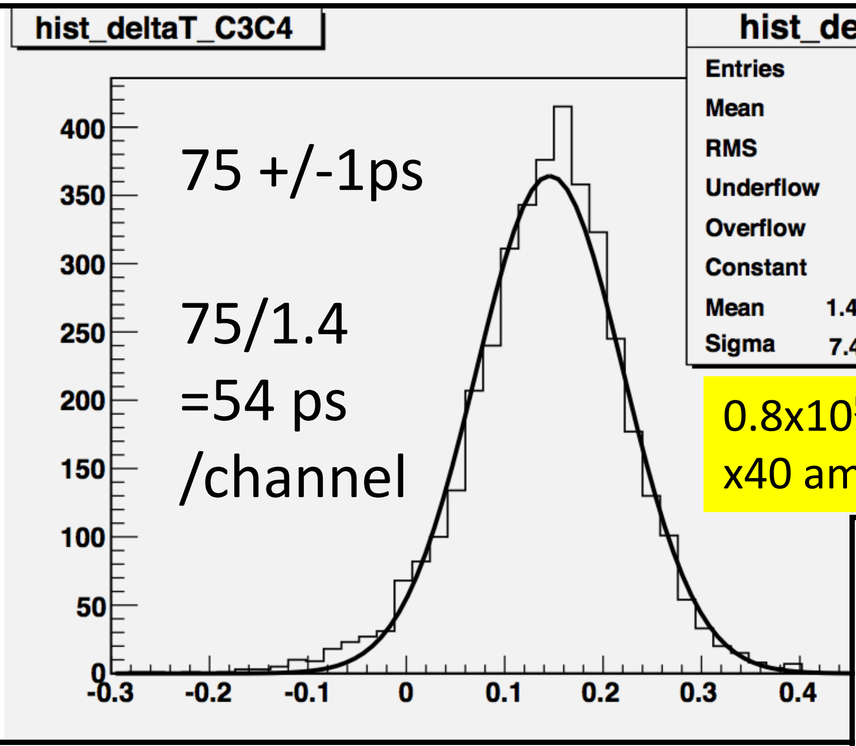
No Gain Dependence of Timing



hist_deltaT_C3C4	
Entries	5000
Mean	-1.424e-10
RMS	9.894e-12
Underflow	0
Overflow	0
Constant	1196 ± 20.8
Mean	-1.424e-10 ± 1.425e-13
Sigma	9.99e-12 ± 1.02e-13

Same time difference for gain of 2E5 (no dependence over more than an order of magnitude, but this is in large light limit….)

Timing Resolution vs. Gain (10 pe’s)



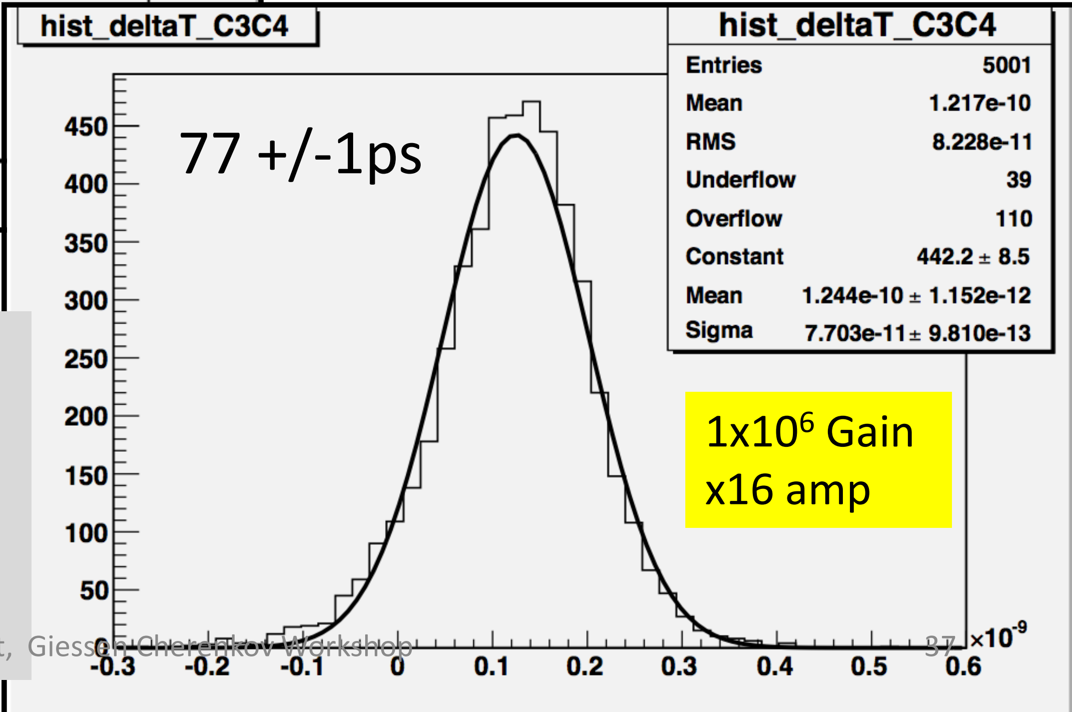
hist_deltaT_C3C4	
Entries	4000
Mean	1.429e-10
RMS	8.027e-11
Underflow	53
Overflow	61
Constant	364.3 ± 7.9
Mean	1.458e-10 ± 1.246e-12
Sigma	7.482e-11 ± 1.065e-12

75 +/-1ps

75/1.4
=54 ps
/channel

0.8×10^5 Gains
x40 amp

No gain dependence on time measurement for 10 pe’s over large range in gain for 25 μm tube!



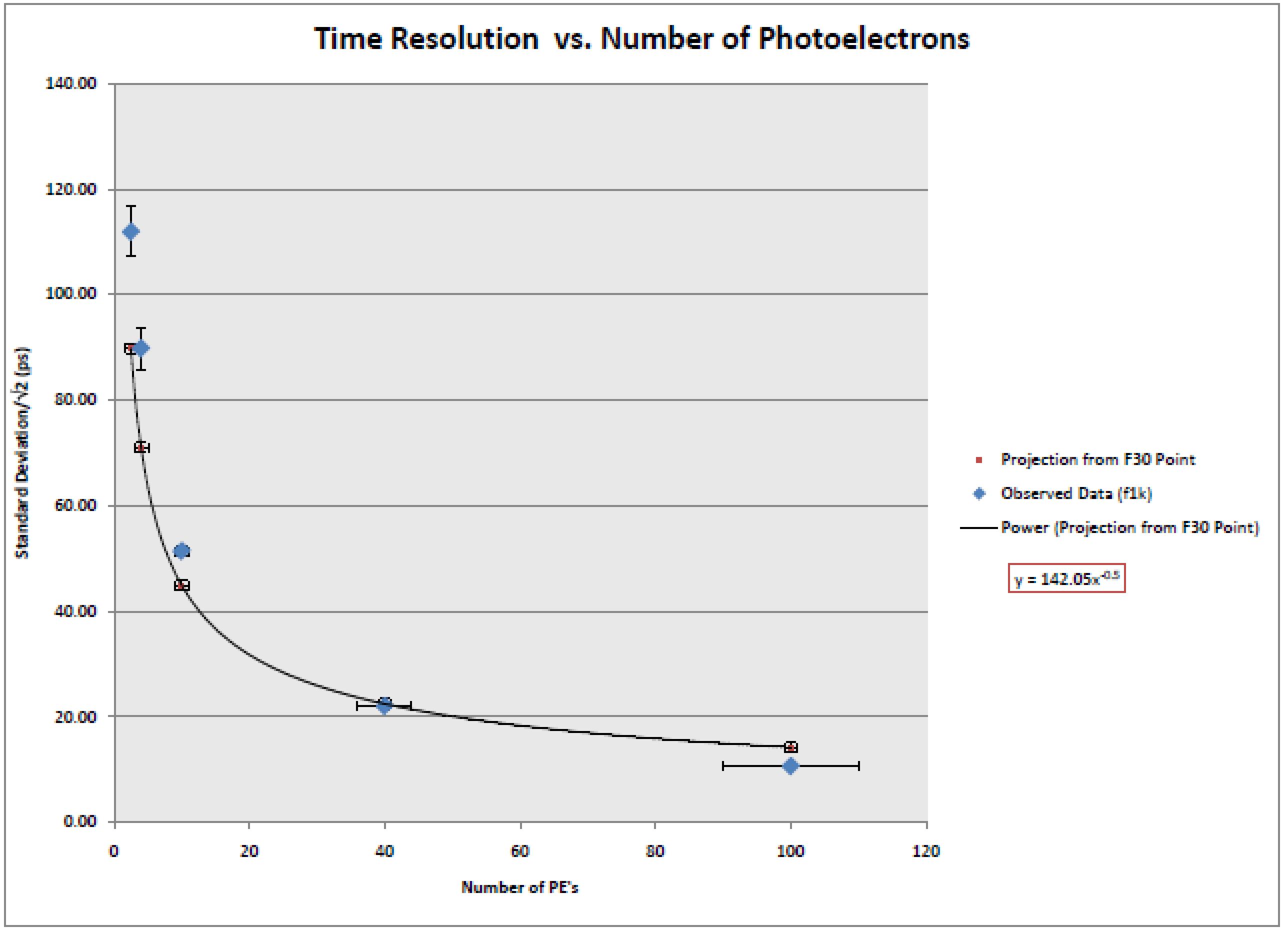
hist_deltaT_C3C4	
Entries	5001
Mean	1.217e-10
RMS	8.228e-11
Underflow	39
Overflow	110
Constant	442.2 ± 8.5
Mean	1.244e-10 ± 1.152e-12
Sigma	7.703e-11 ± 9.810e-13

77 +/-1ps

1×10^6 Gain
x16 amp

Conventional wisdom is that high gain is important for timing—I believe this is largely based on single pe work; clearly there is a large gain plateau where timing does not depend on gain (more in 10 μm tube section)

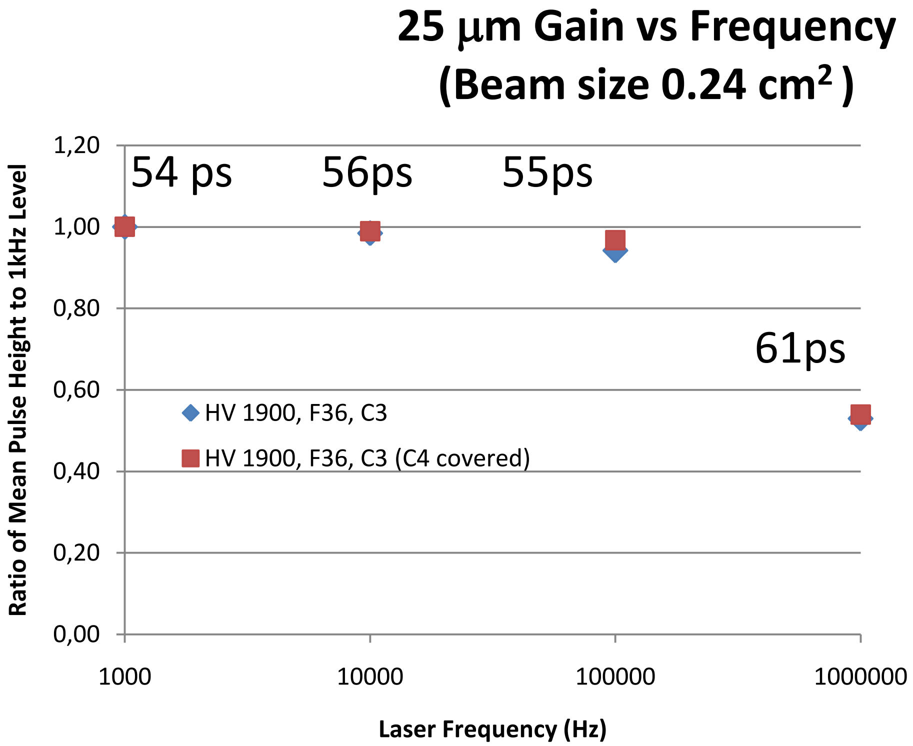
Timing vs. Number of PE's



Measurement roughly shows expected √Npe behavior for 25 μm pore tube

Rate Dependence of Amplitude/Timing

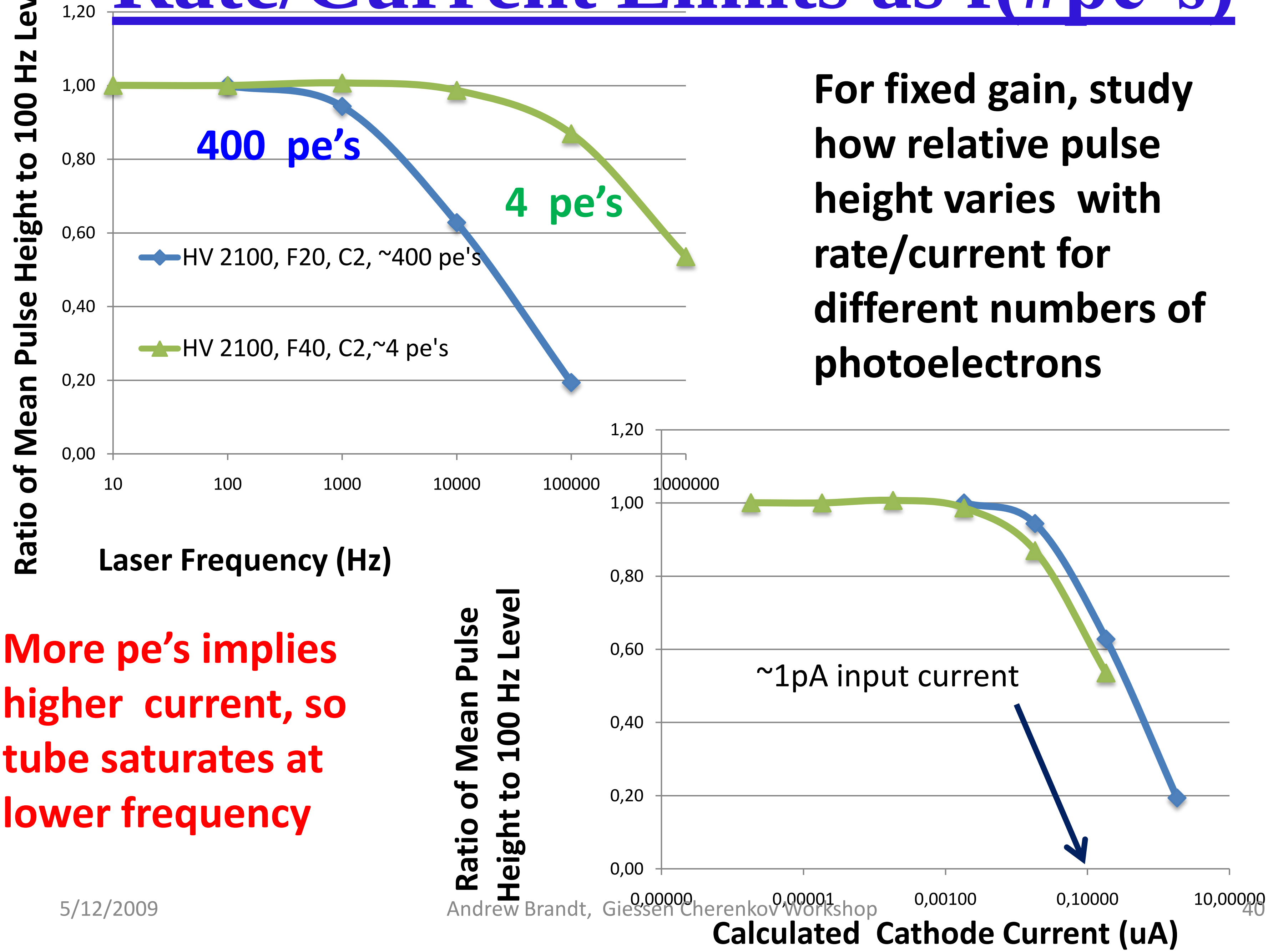
(~10 pe, gain ~0.8E5)



Pulse height decreases to 60% of initial value, timing 10% worse for 1MHz (~ equivalent to proton rate in max rate pixel @2x10^{33} at 420m)

Blue squares: repeated amplitude vs rate for one channel only--no change in rate behavior--implies that limitation is local current (experts at ANL Workshop agreed—this implies that there is no penalty for hitting 8 pixels in same tube)

Rate/Current Limits as f(#pe's)



400 pe's

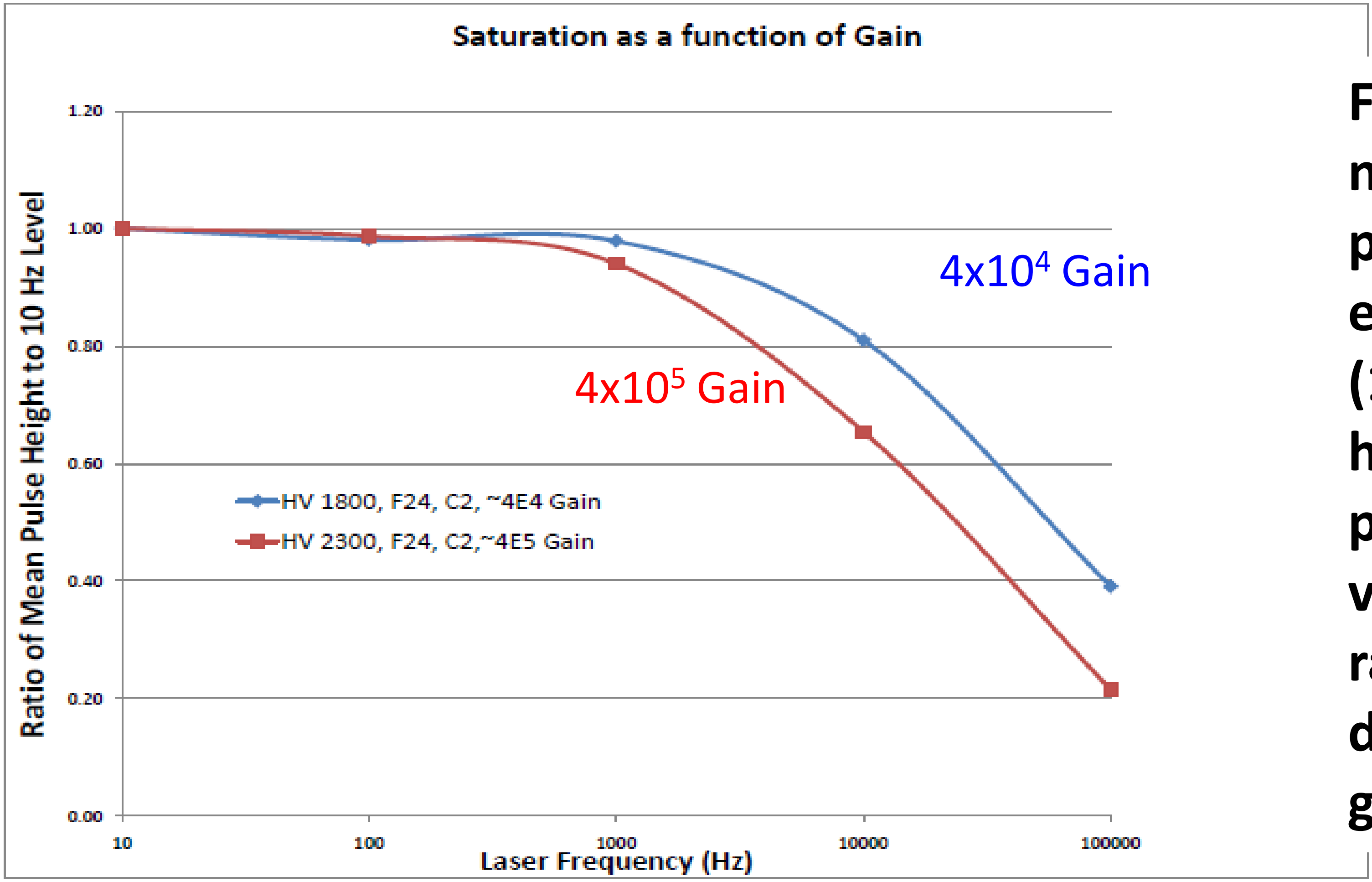
4 pe's

~1pA input current

For fixed gain, study how relative pulse height varies with rate/current for different numbers of photoelectrons

More pe's implies higher current, so tube saturates at lower frequency

Rate Limits as f(gain)

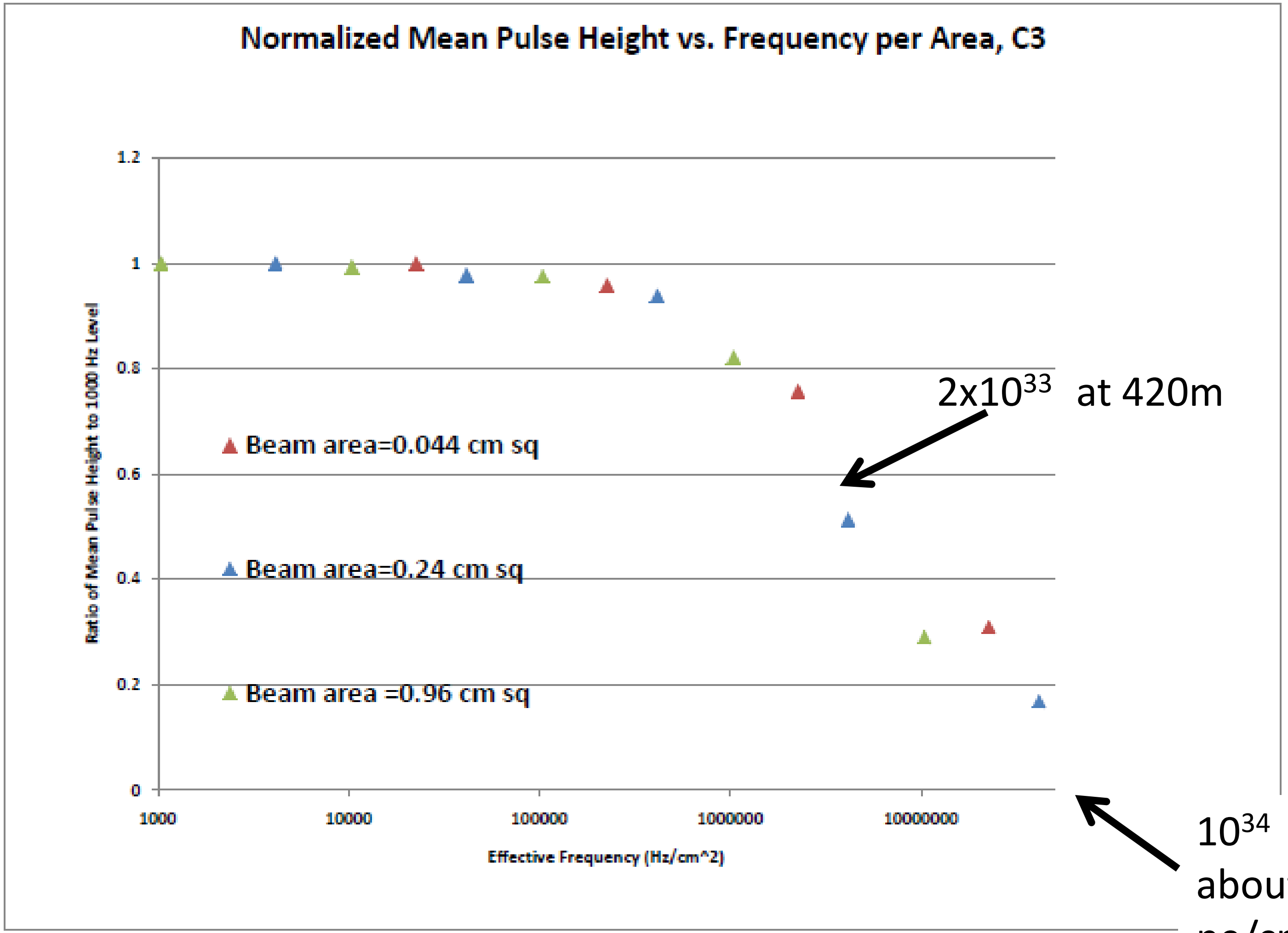


For fixed number of photo-electrons (160) study how relative pulse height varies with rate for two different gain values

Saturation decreases with decreased gain, but not linear

Rate Limits as f(beam area)

(~10 pe, gain ~0.8E5)



$2\text{x}10^{33}$ at 420m

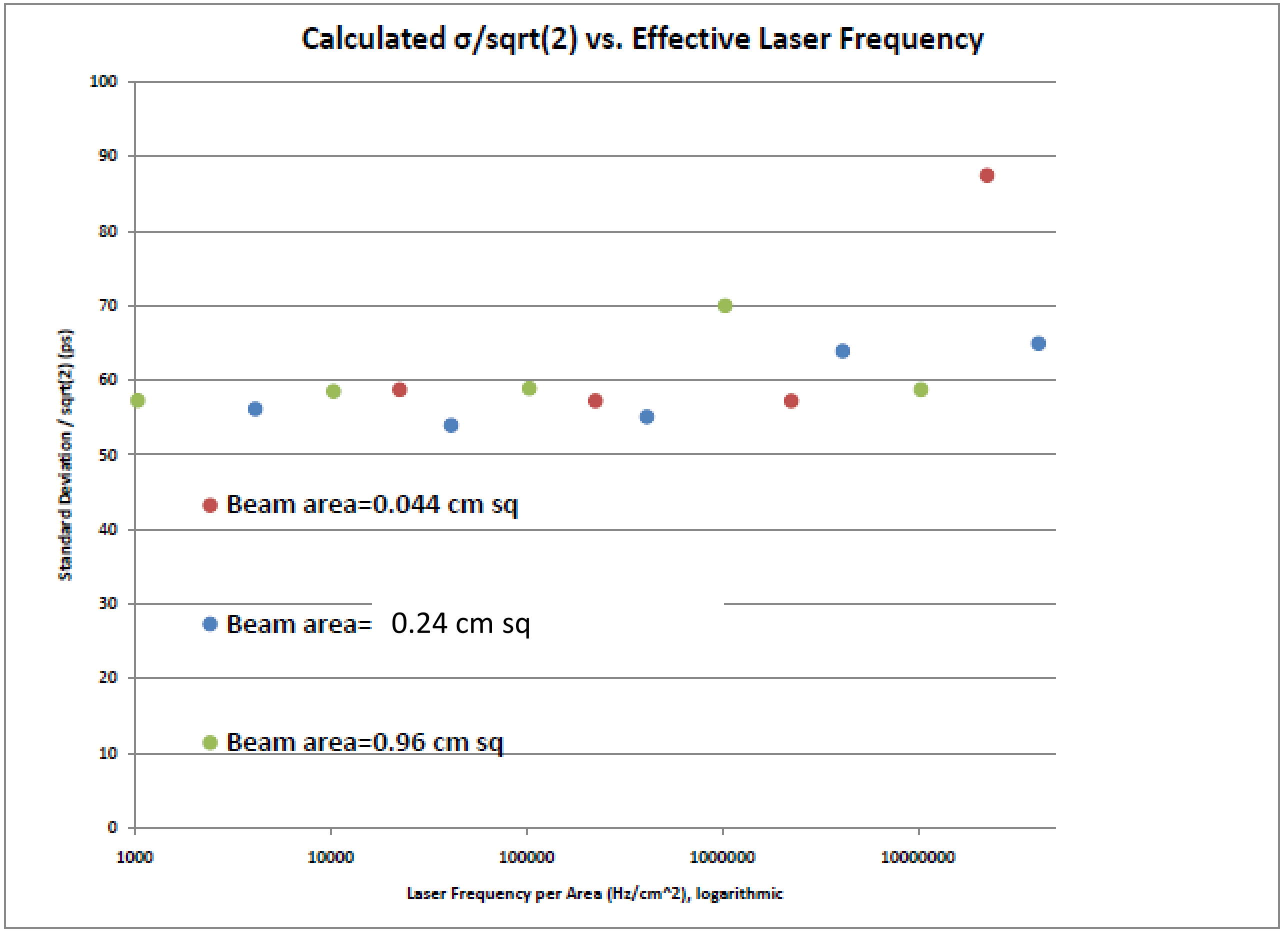
10^{34} at 220m
about 450 MHz
pe/cm^2

Note the last point is ~400 MHz/cm^2 pe rate!
10 pe's at 10 MHz with 0.24 cm^2 area
at gain of $0.8\text{x}10^5$

Scaling of saturation with beam area as expected

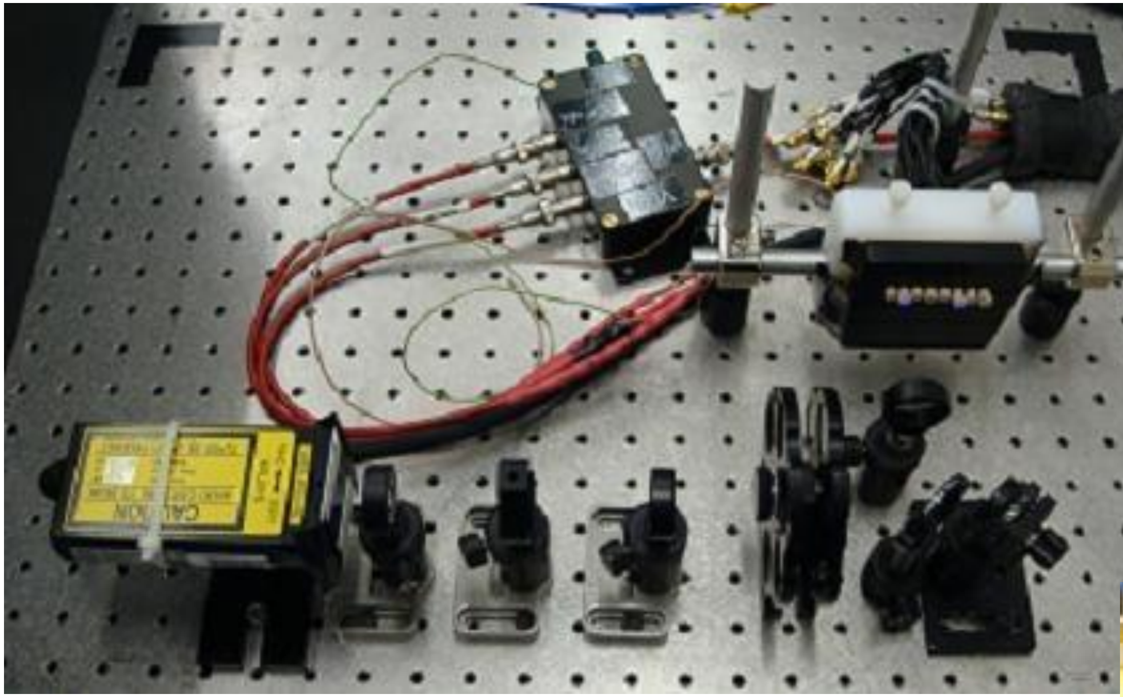
Timing vs Track Rate/cm^2

(~10 pe, gain ~0.8E5)



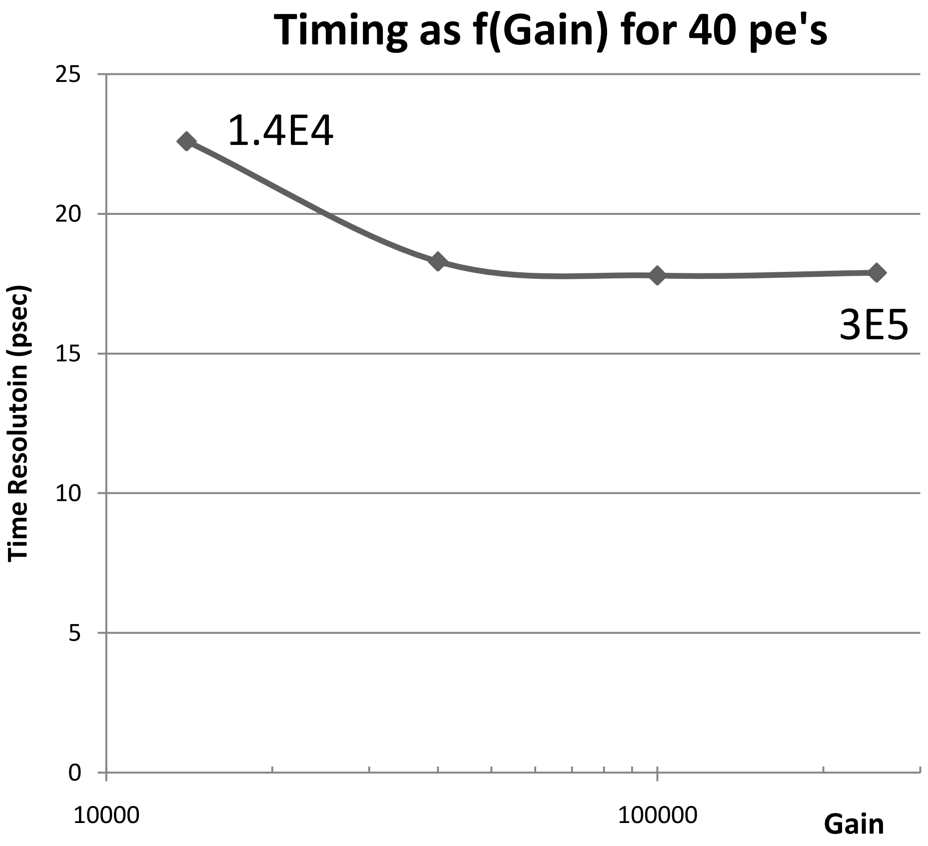
Timing degrades only slowly with rate, but up to 50% efficiency loss at high rate

10 μm Laser Setup (2/20/09)

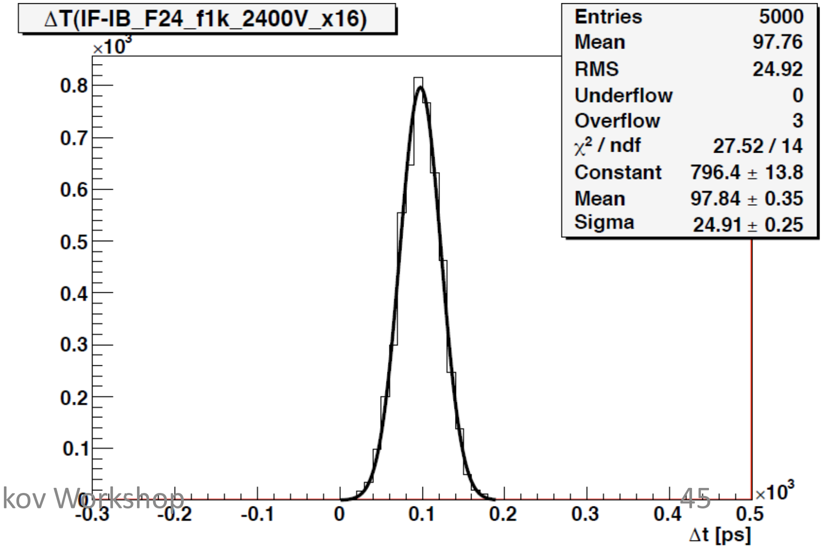


Allows us to study all channels ~easily (manually)

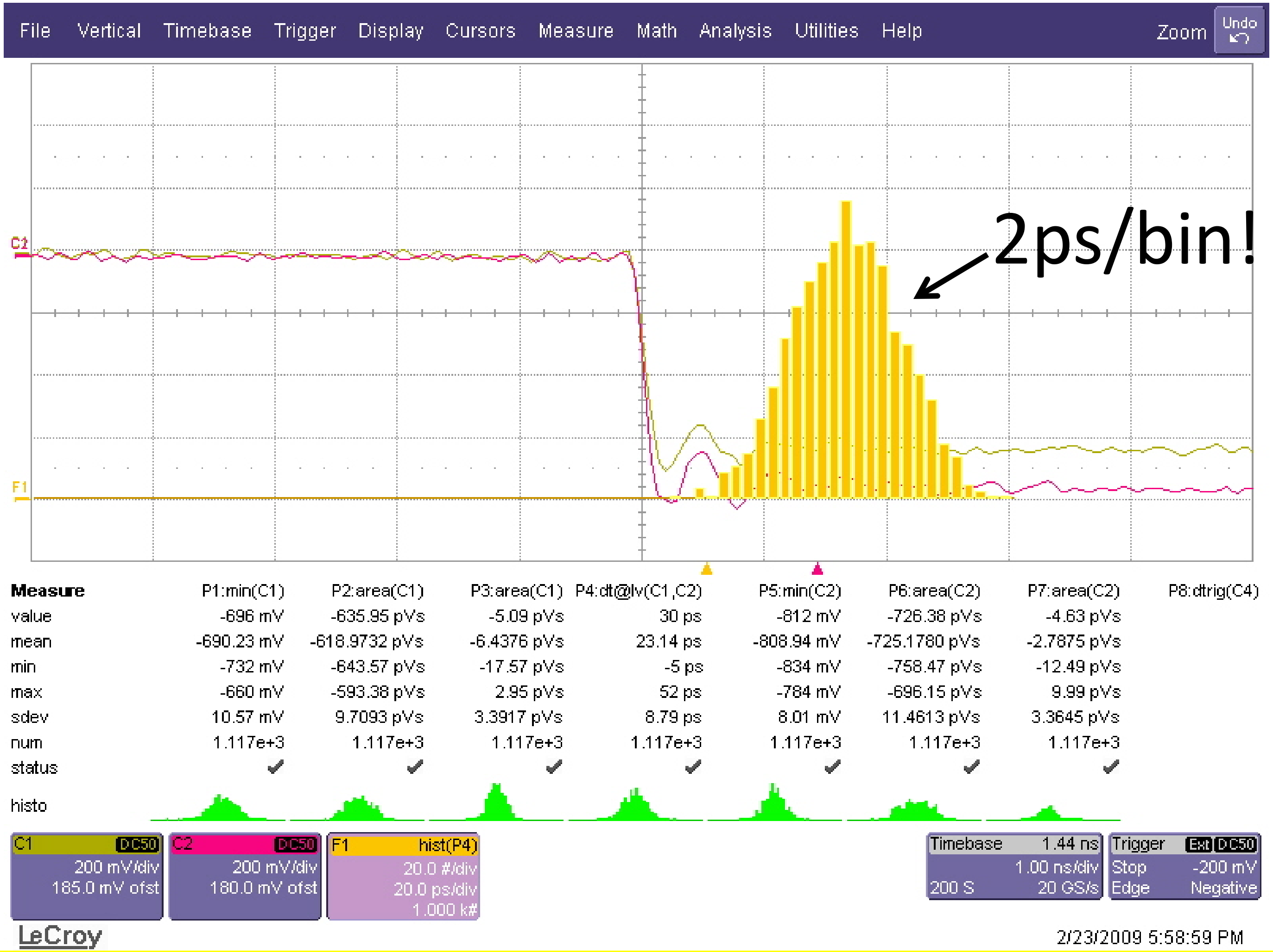
Timing vs Gain for 10 μm Tube



So at very low gain (<4E4) start to see timing dependence on gain! For many applications should be able to use tube with 20x reduction in gain compared to canonical 1E6 (need good amplifier)



10 μm Timing



2ps/bin!

Measure	P1:min(C1)	P2:area(C1)	P3:area(C1)	P4:dt@lv(C1,C2)	P5:min(C2)	P6:area(C2)	P7:area(C2)	P8:dtrig(C4)
value	-696 mV	-635.95 pVs	-5.09 pVs	30 ps	-812 mV	-726.38 pVs	-4.63 pVs	
mean	-690.23 mV	-618.9732 pVs	-6.4376 pVs	23.14 ps	-808.94 mV	-725.1780 pVs	-2.7875 pVs	
min	-732 mV	-643.57 pVs	-17.57 pVs	-5 ps	-834 mV	-758.47 pVs	-12.49 pVs	
max	-660 mV	-593.38 pVs	2.95 pVs	52 ps	-784 mV	-696.15 pVs	9.99 pVs	
sdev	10.57 mV	9.7093 pVs	3.3917 pVs	8.79 ps	8.01 mV	11.4613 pVs	3.3645 pVs	
num	1.117e+3	1.117e+3	1.117e+3	1.117e+3	1.117e+3	1.117e+3	1.117e+3	
status	✓	✓	✓	✓	✓	✓	✓	
histo								

C1 DC50 200 mV/div 185.0 mV ofst

C2 DC50 200 mV/div 180.0 mV ofst

F1 hist(P4) 20.0 #/div 20.0 ps/div 1.000 k#

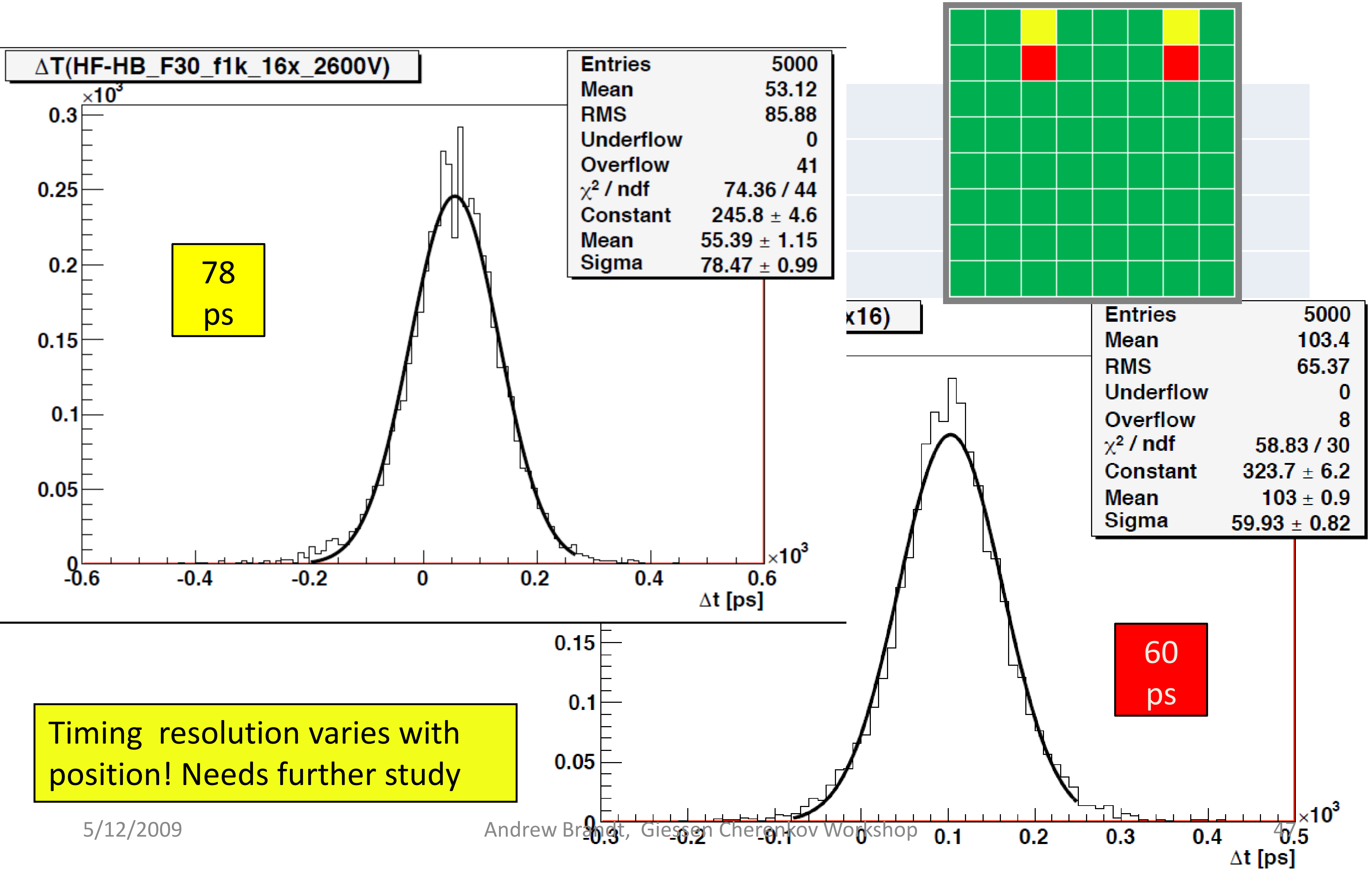
Timebase 1.44 ns 1.00 ns/div 200 S 20 GS/s

Trigger Ext DC50 Stop -200 mV Edge Negative

2/23/2009 5:58:59 PM

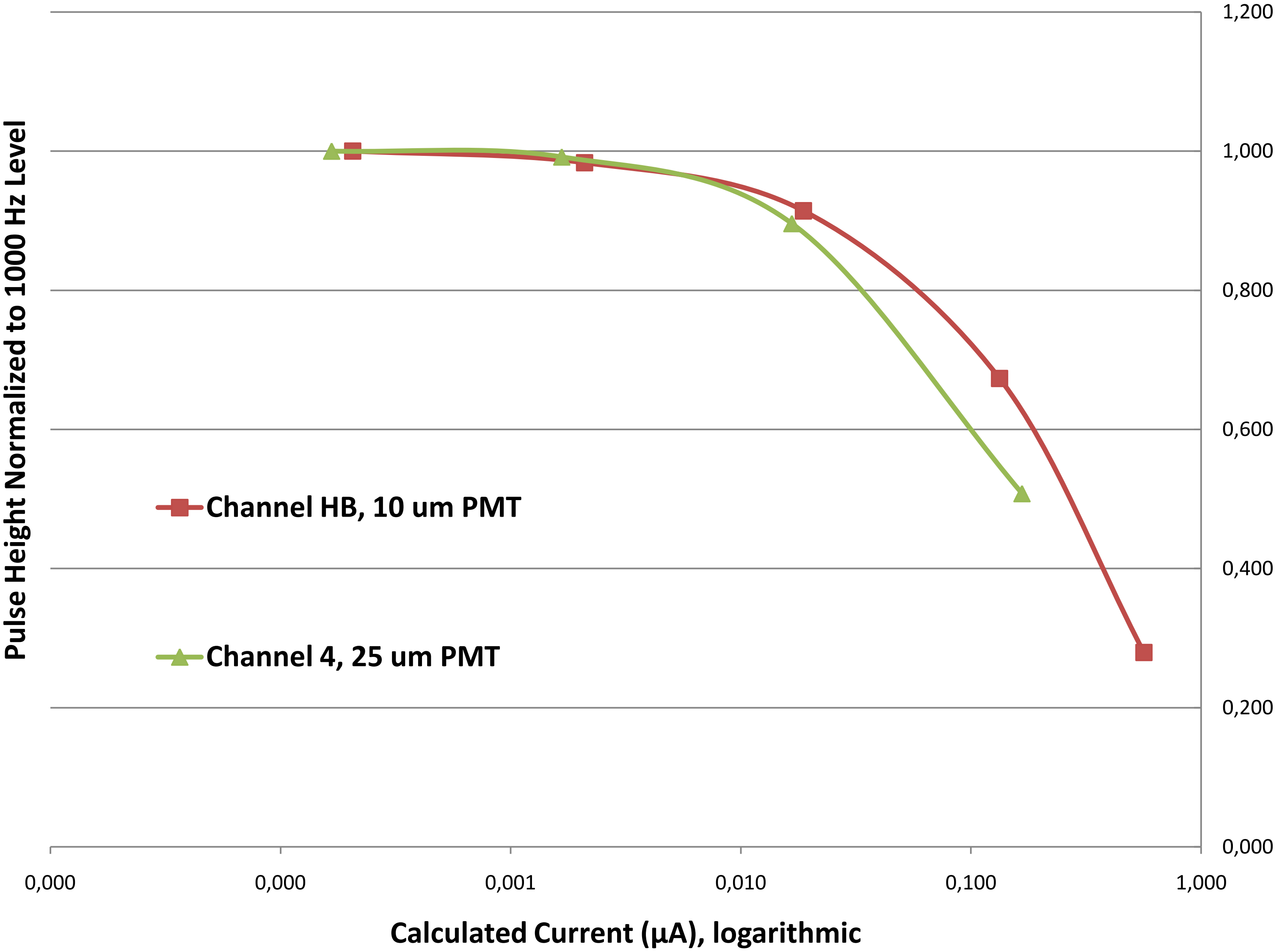
Large light limit with Louvain CFD's show 8.8 ps time difference (including CFD)

Timing as Function of Position



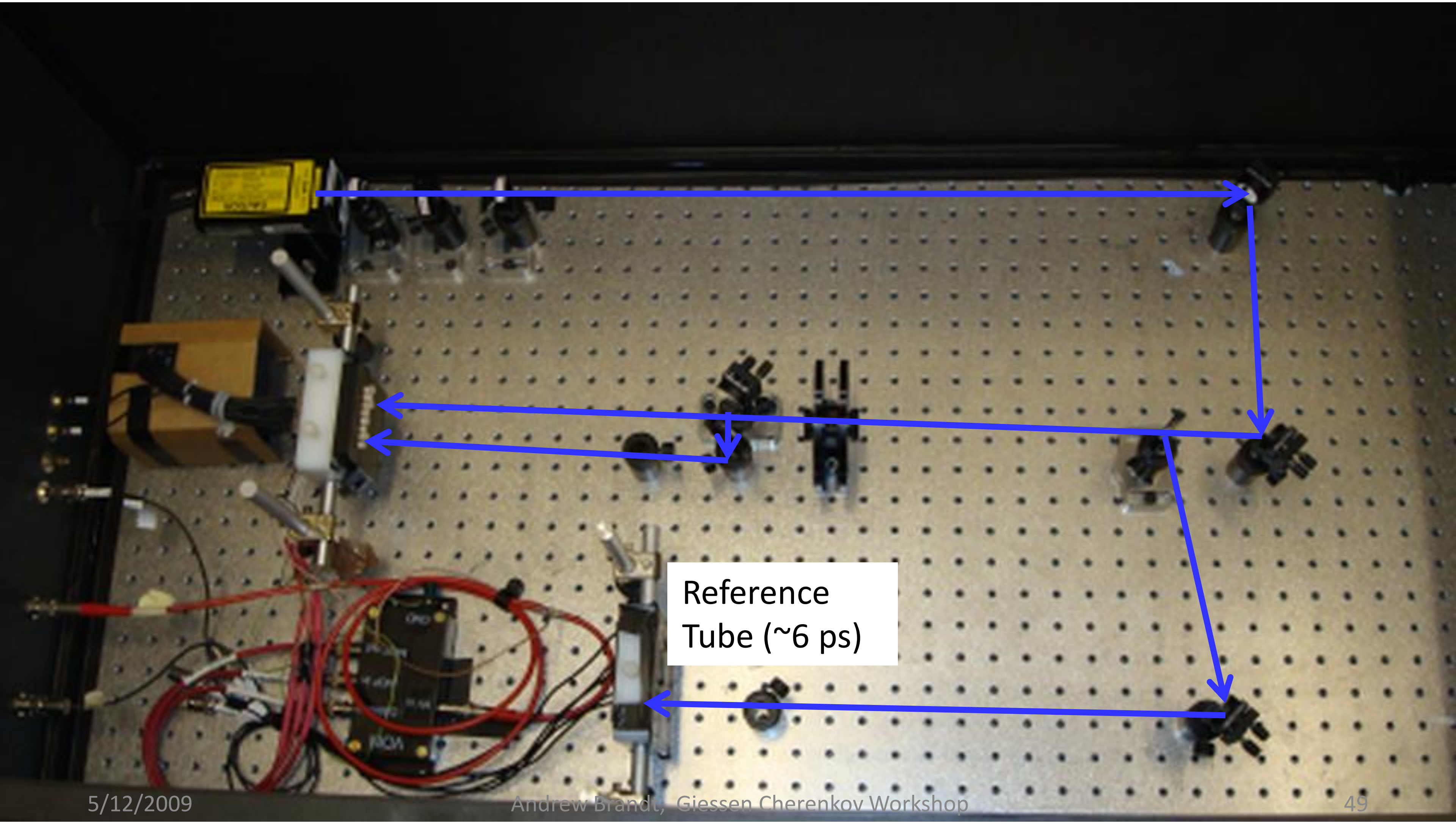
Timing resolution varies with position! Needs further study

Rate Limits as f(pore size)



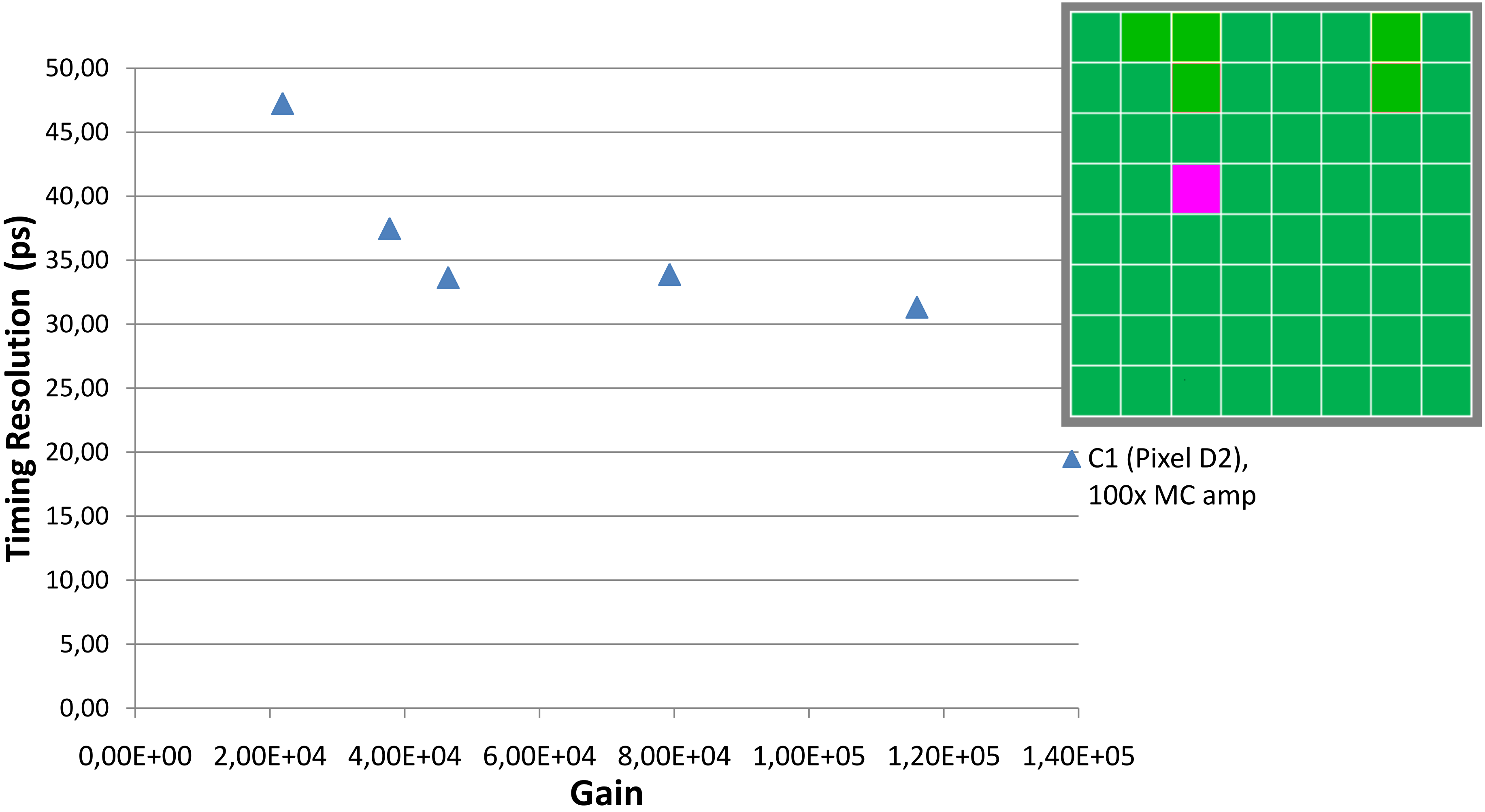
Smaller pore size better for timing and also results in more pores/area reducing saturation

10 μm Laser Setup with Reference Tube (3/17/09)



Reference Tube (~6 ps)

Timing vs Gain for 10 µm Tube

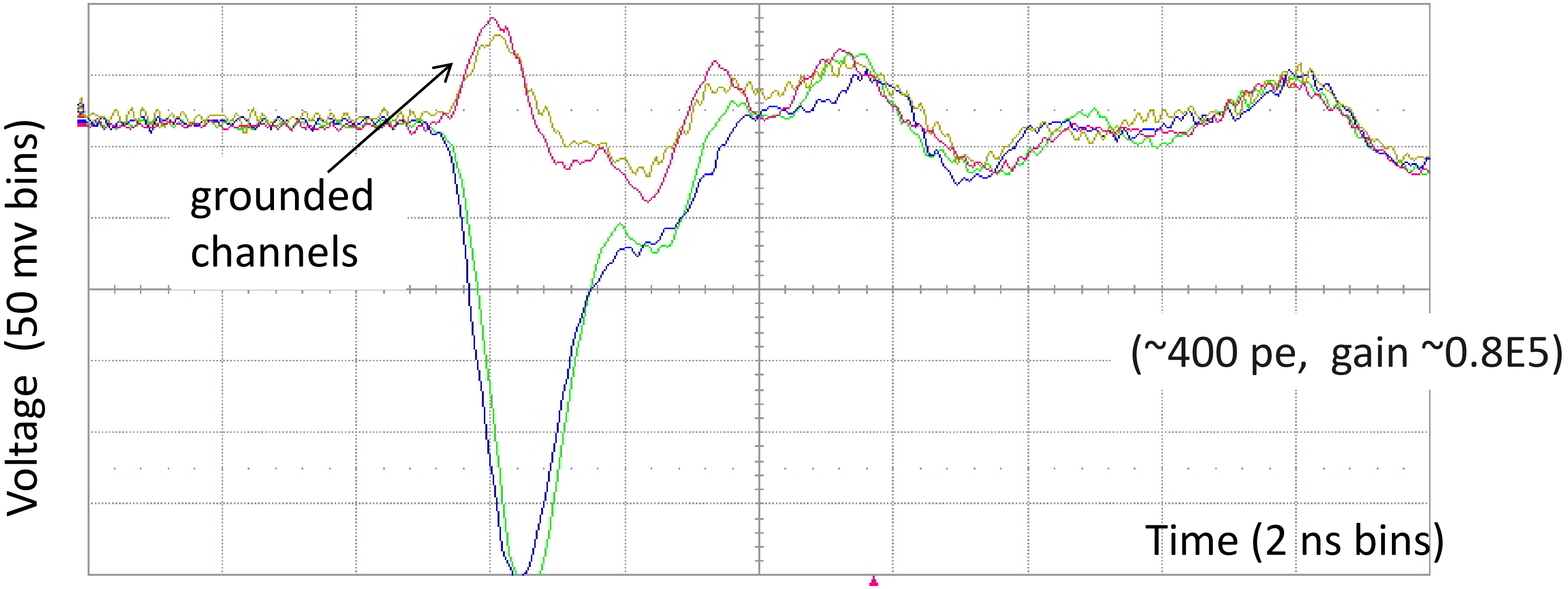


Measured with reference tube using CFD's and x100 mini-circuits amps (performed better than ORTEC VT120, 9306, homemade Phillips amps) ; with 10 pe's can operate at ~5E4 Gain

Wait a Minute!

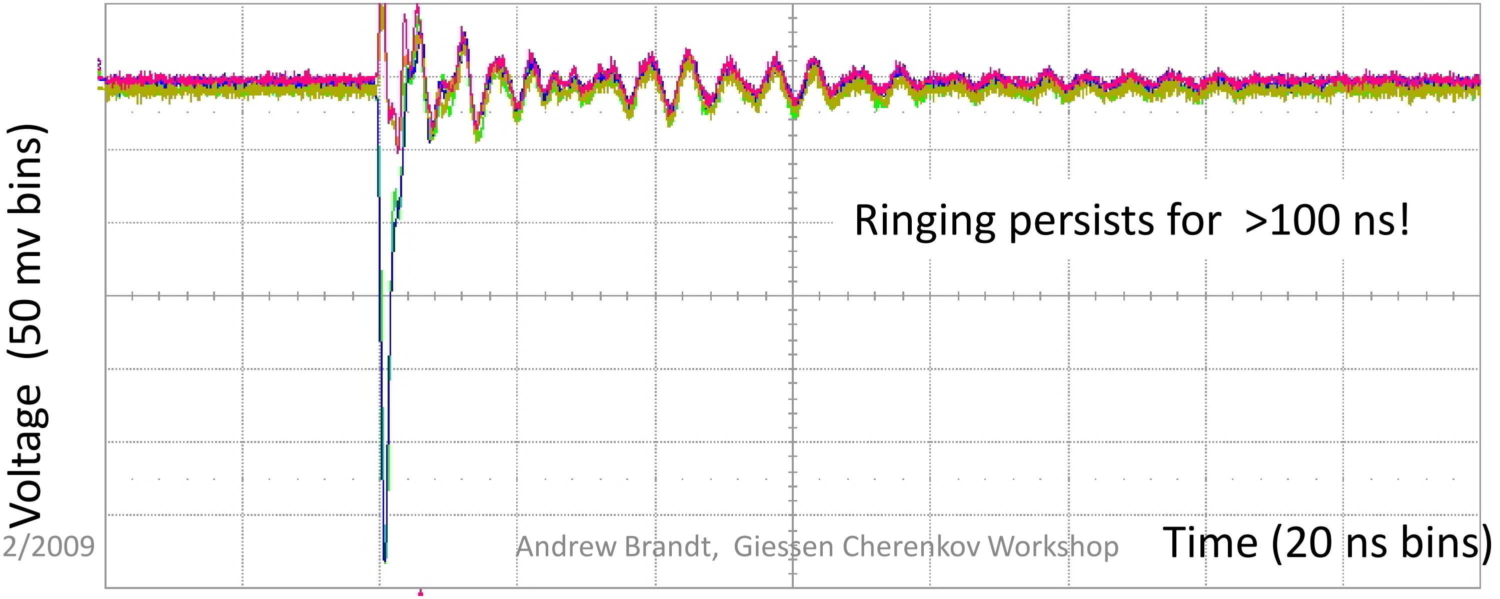
- Jerry Va’vra and others have mentioned TTS of 30-35 ps for single pe ⇒ we should have about 10 ps for 10 pe! Investigating! (of course that ~30 seems a bit suspect as it only applies to 70% of single pe events—first of two peaks)
- Note Jerry grounded all channels except one, we don’t; could be impedance mismatch, noise from cables
- Could be power supply noise or other noise in setup, just bought some low pass filters to test
- Could be residual time walk, not corrected for by LCFD, studying timing as fct. of pulse height

Grounding Issues (25 µm Tube)



grounded channels

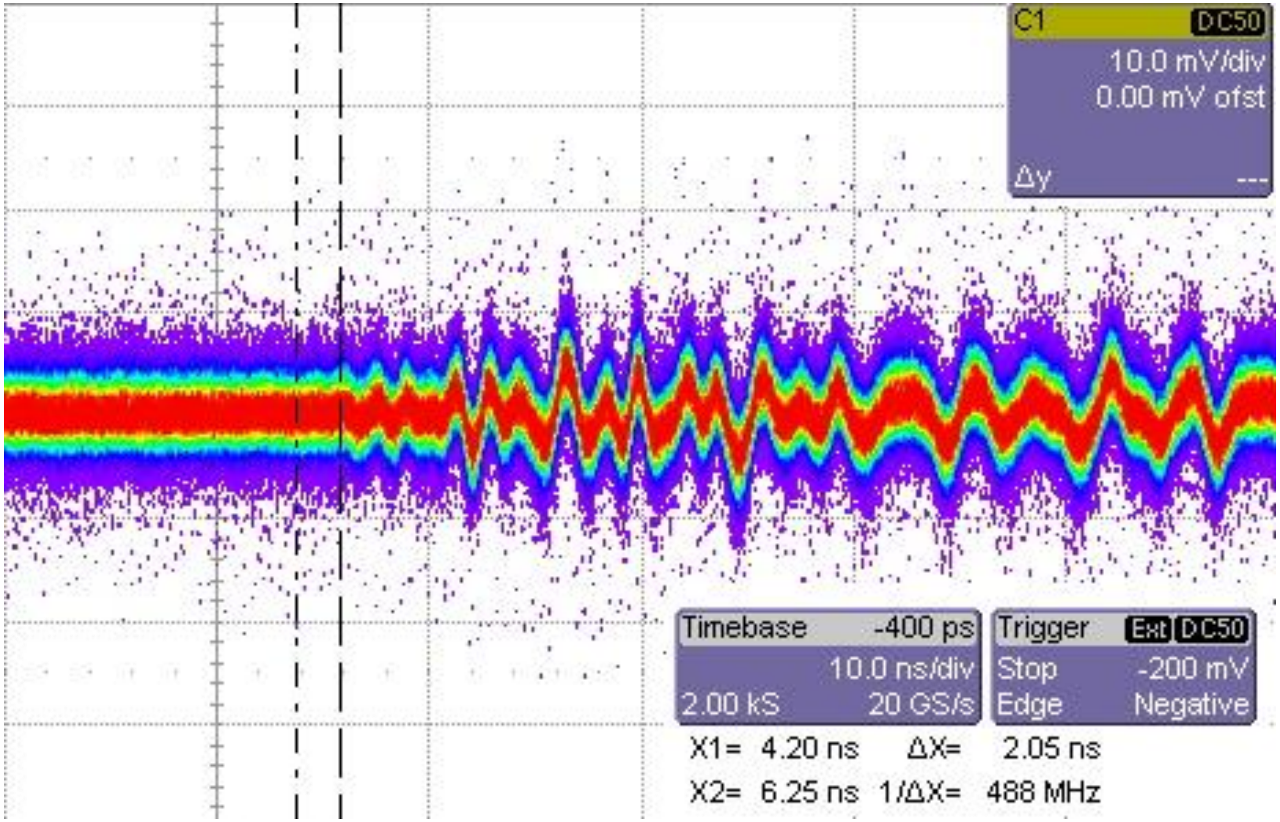
(~400 pe, gain ~0.8E5)



Ringing persists for >100 ns!

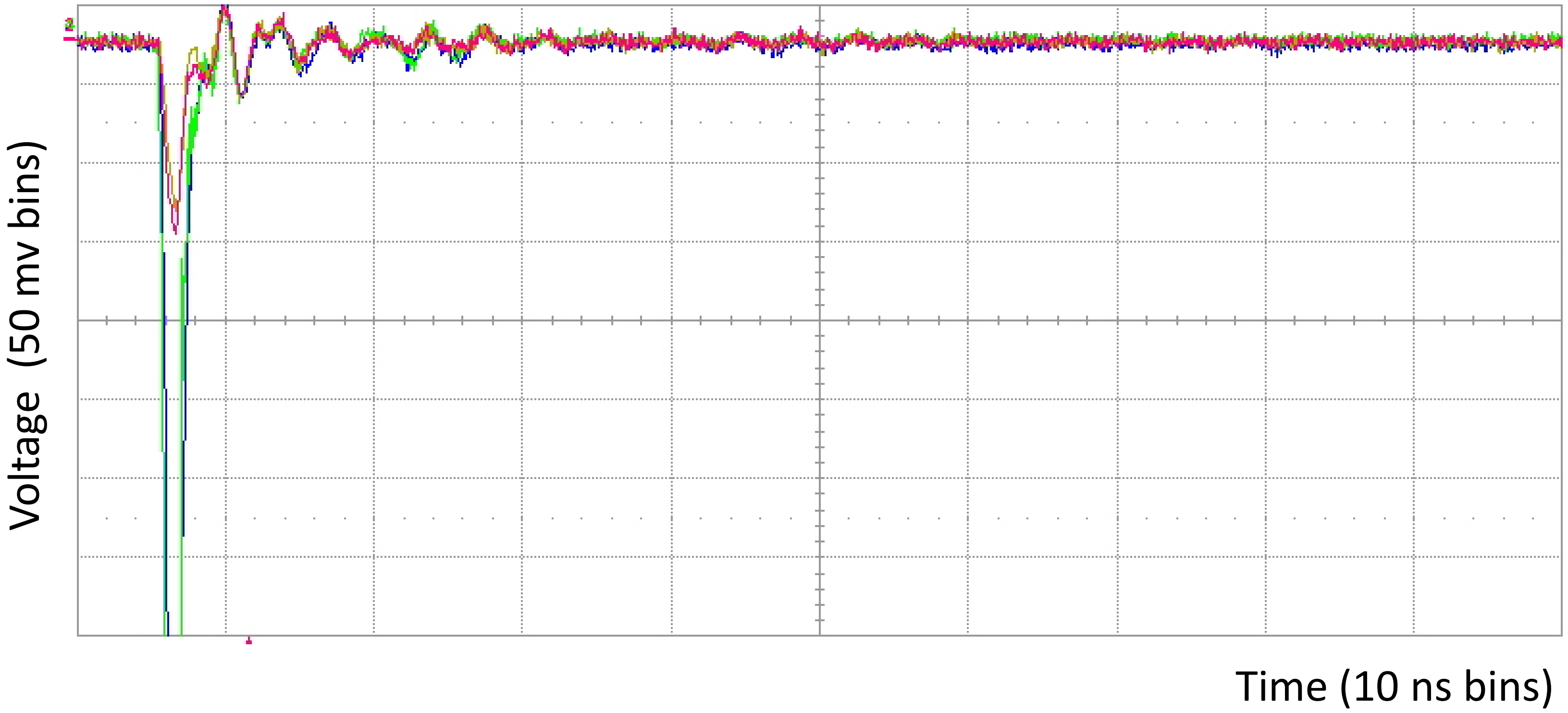
Aside: Measuring Speed of EM Waves

- We noted that ground plane oscillations on reference tube were picked up by second tube
- Used this to do a 3% measurement of speed of light



Moving 2nd tube 2 feet from reference tube shifts pick-up oscillation pattern by 2.05 ns

Grounding Issues (10 µm Tube)



New ground plane dramatically improved ringing both in magnitude and duration

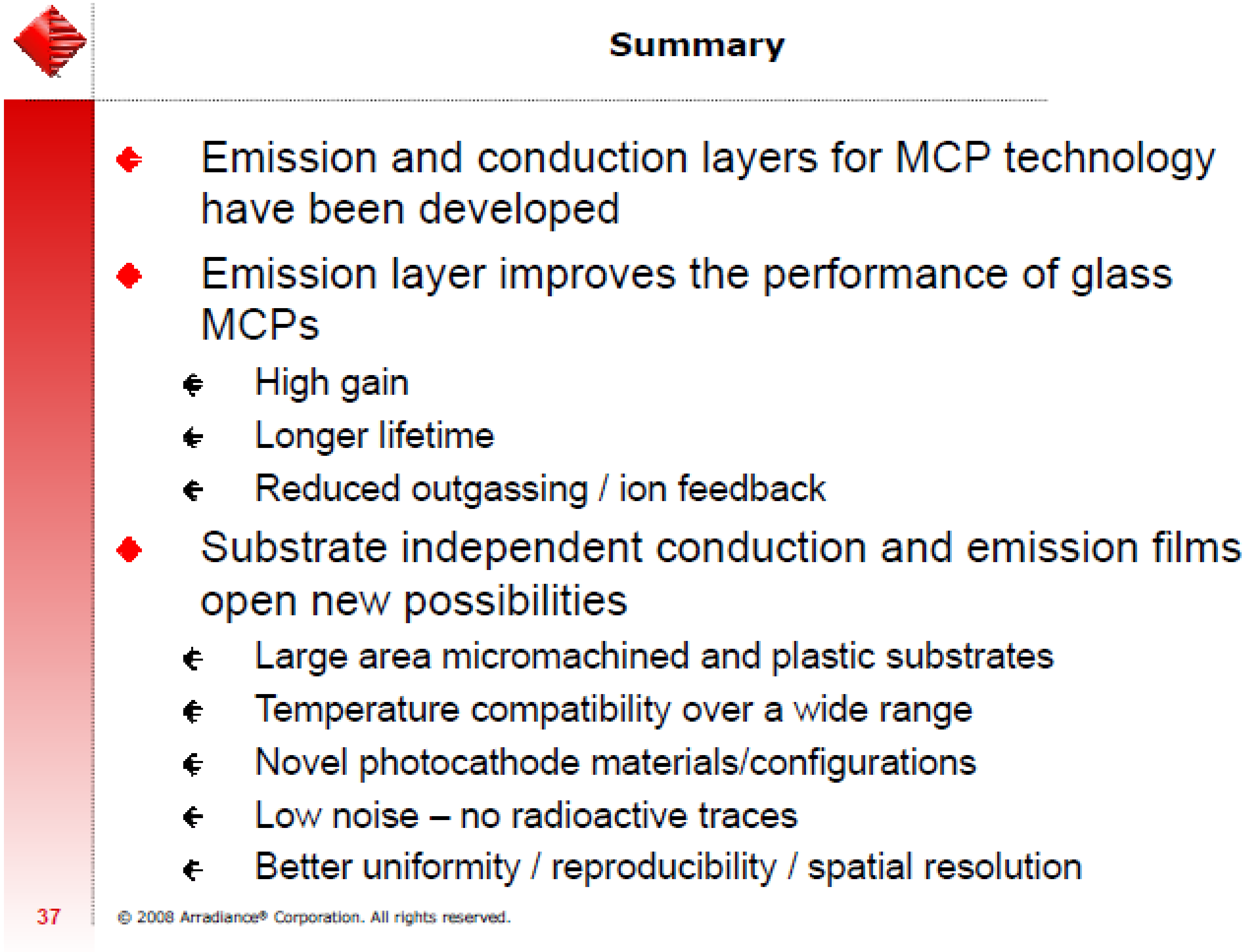
Measuring Lifetime

- We propose to measure lifetime in a controlled manner to establish a baseline of magnitude of lifetime problem (From Paul Hink 50% QE loss after 0.4 mC/cm^2 ; not sure about wavelength dependence)
- Use 5 mm diameter 405 nm laser “beam” centered on a pixel and run at 100 MHz with 10 pe’s at 10^6 gain to see how quickly a pixel deteriorates (monitoring neighboring pixels as well), then repeat for a few pixels. Then repeat with relaxed rate and gain to see if lifetime is linear with gain and rate. (eventually would want to test at operating conditions 10 MHz with 10 pe’s at 5E4 gain)

Improving Lifetime

- Photonis has new electron scrubbing machines: may get x5 to x10 lifetime improvement.
- Ion barrier certainly would help (at cost of x2 in collection efficiency)—used routinely in night vision Gen 3 tubes, and may be a solution on its own, or when coupled with better scrubbing. Would like to test this with Photonis tube.
- Pursuing small business proposal with Arradiance, which has new coatings that have shown promise in extending lifetime. If development promising would like to test in photonis/photek tubes.
- Other ideas more problematic (require more development), using lower gain on first MCP, Z stack, etc.

MCP Development (Arradiance)



Summary

- Emission and conduction layers for MCP technology have been developed
- Emission layer improves the performance of glass MCPs
  - High gain
  - Longer lifetime
  - Reduced outgassing / ion feedback
- Substrate independent conduction and emission films open new possibilities
  - Large area micromachined and plastic substrates
  - Temperature compatibility over a wide range
  - Novel photocathode materials/configurations
  - Low noise – no radioactive traces
  - Better uniformity / reproducibility / spatial resolution

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Exploring collaboration with Arradiance; looking into adding thin film to protect MCP and also improve photocathode lifetime

Conclusions

- Our fast timing R&D has come a long way in 3 years, but still a ways to go

- Rate and lifetime issues are challenging, but likely solvable, given, time, will, and money

- We are willing/eager to collaborate with any and everybody interested in longer life, fast MCP-PMT   (brandta@uta.edu !!!!)

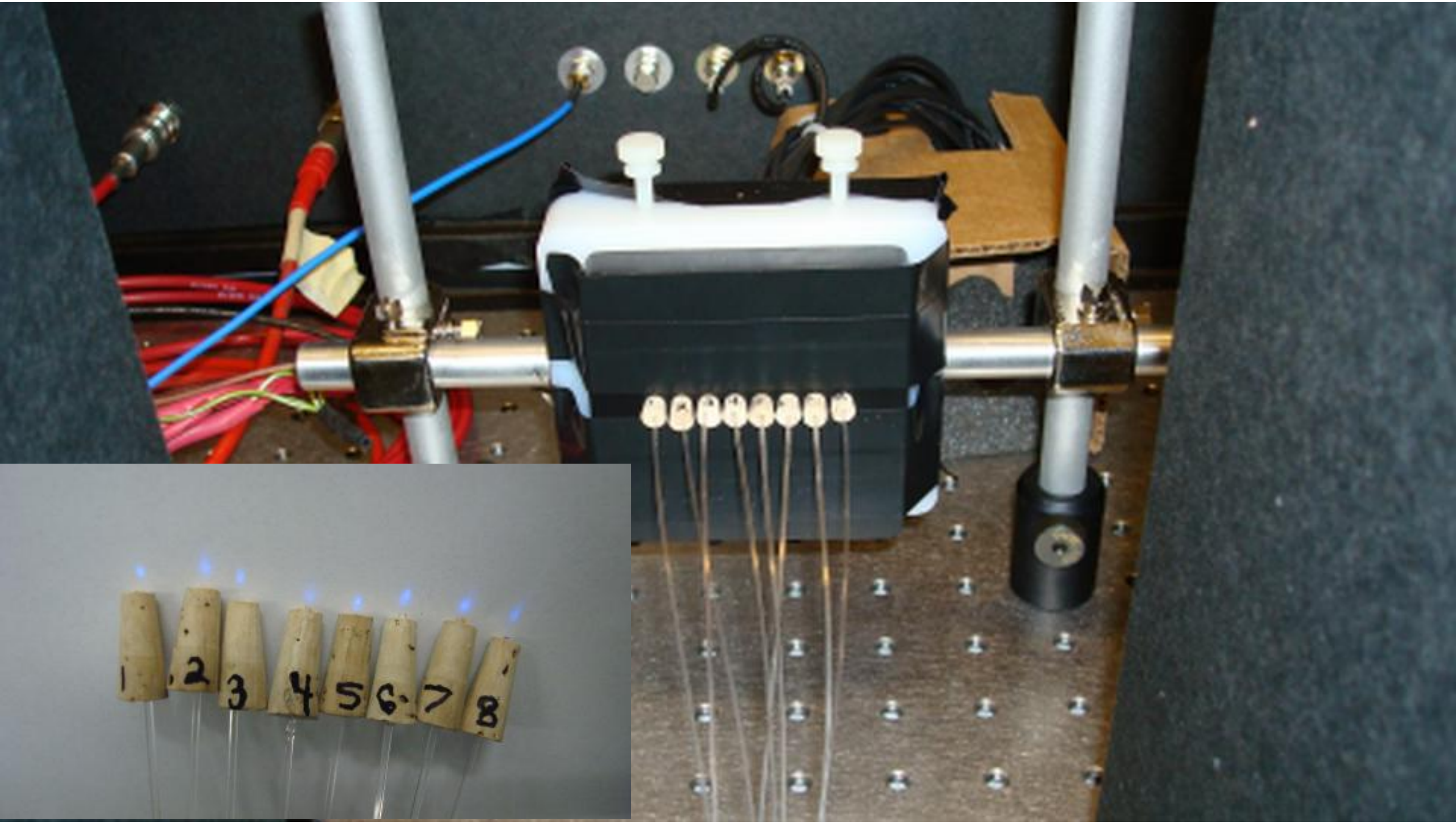
- Laser test stand working well, but still room for improvement

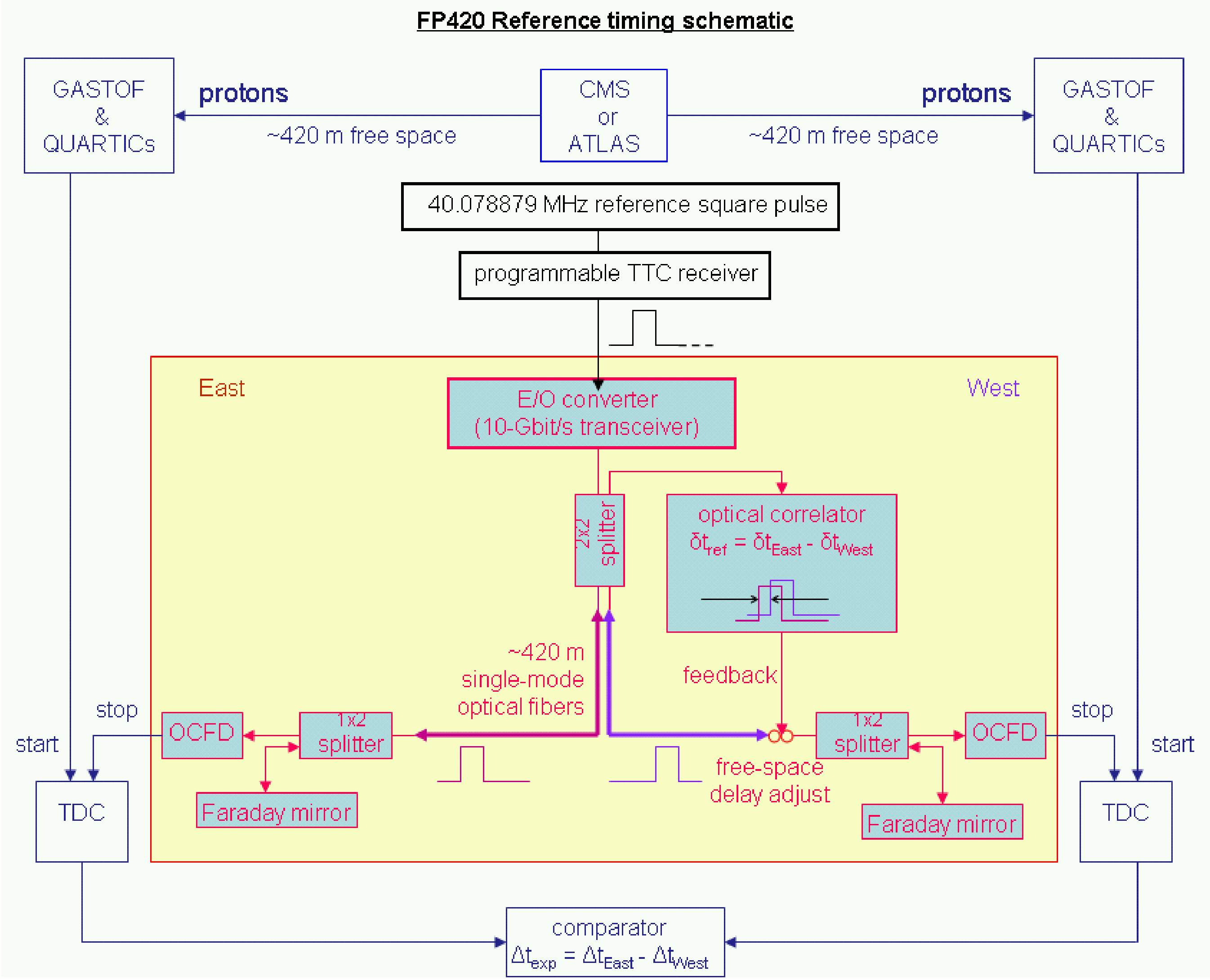
- Working toward ATLAS approval to proceed to TDR, funding for continued R&D

- Next test beam late May at Fermilab

BACKUP SLIDES

New Multi-Channel Laser Setup




FP420 Reference timing schematic

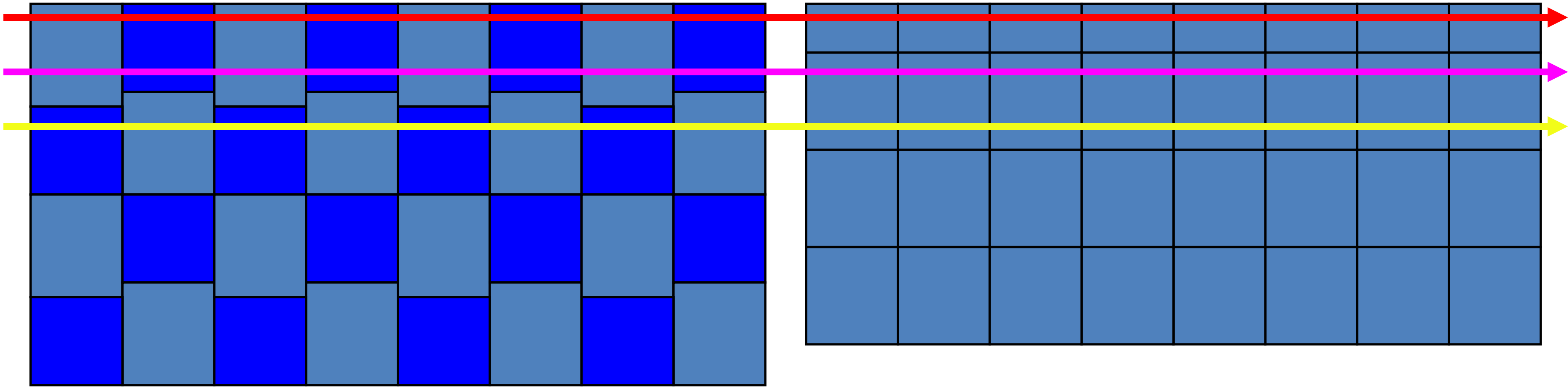
S. White has specified system (presented at Oct. 17 fast timing meeting), I'm sure it will work, but would like to see it tested anyway

Optical CFD dominates performance (< 5 ps)

Provides average time as well for central event comparison

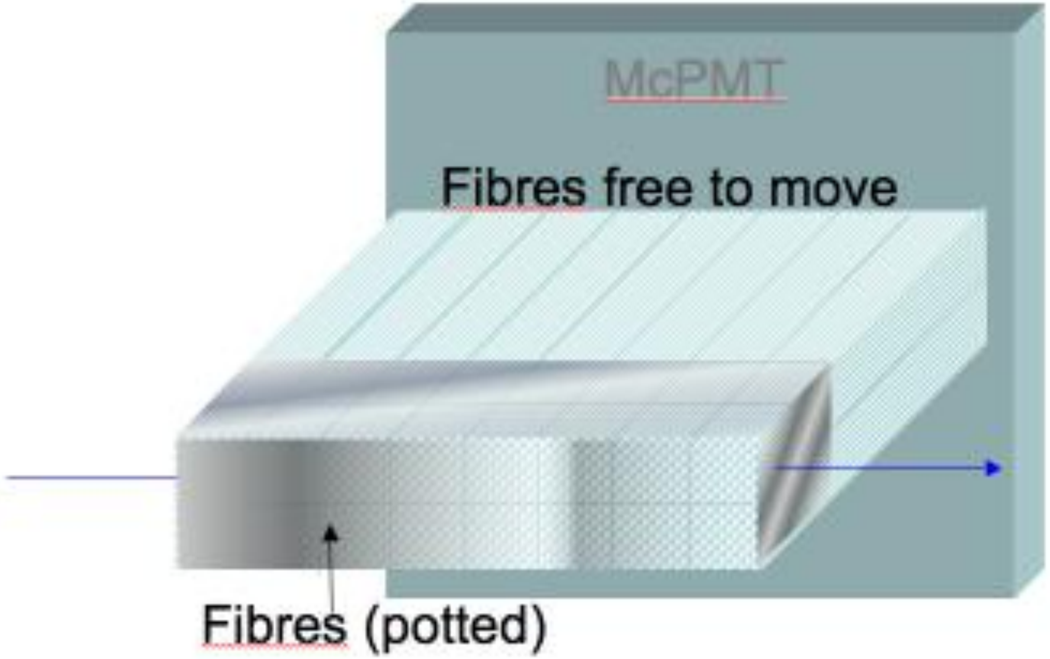
Final QUARTIC Design Considerations

- Multiple proton tracking: 2nd detector could start with 3mm width and be offset by ½ pixel?



Could use Detector 1 to measure yellow and earlier of pink or red
Detector 2 to measure red and earlier of pink or yellow (so if pink earlier than red or yellow, measure all 3). For 2 track event would measure both tracks in at least one detector if tracks separated by more than 3 mm, and sometimes if < 3 mm)

Fused Silica Blocks ⇒⇒ Clad Fused Silica Fibre Bundles



Jim Pinfold

Fiber timing?
Advantages, can avoid cracks, use larger region of pmt