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→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 $2 \times 10^{33}$ 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 $pp \rightarrow p H p : \ 3-10 \ \text{fb}$

(used to be called double pomeron exchange)

\[
M_{H}^{2} = (p + \bar{p} - p' - \bar{p}')^{2}
\]

$\Delta M = O(2.0) \ \text{GeV}$


``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 ($0.002 < x_{IP} < 0.01$)

• 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

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The Physics case: MSSM h/H

Fig. 6: Figure (a) shows a typical mass fit for 3 years of data taking at $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ (60 fb$^{-1}$). The significance of the fit is $3.5\sigma$ 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 $3\sigma$. The L1 trigger strategy and analysis cuts are described in the text.

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 position
- Trigger and Readout
- **Fast Timing Detector**
Integration of the moving beampipe and detectors
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)

Faceplate

Photocathode

Dual MCP

Gain ~ $10^6$

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

Anode
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 mm² 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 test beam 10-16 October 2007

3D SENSORS “blades”

HAMBURG PIPE

GASTOF

MOVING TABLE MOTOR

QUARTICS
FP420 Timing Setup June 2008 CERN TB

veto

G2

Q1

G1

Amplifiers
First TB Results (Fall 2006)

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

For QUARTIC bar
110 psec
Efficiency 50-60%

For events with a few bars on see anticipated √N dependence
**March 2007 Test Beam**

**Threshold discrimination**

If $G1=G2$ then $\delta t=25$ ps each, but $G1$ (Gastof new) has faster tube (Hamamatsu 6 $\mu$m pore vs 25 $\mu$m Burle) and better mirror than $G2$ (Gastof old); extract resolution $G1=13$ ps $G2=32$ ps, initial estimate 80% efficient.

**CFD algo simulated**

QUARTIC
80 ps/bar (15 mm bar) 80% efficient
Test Beam Electronics

QUARTIC:
Photonis Planacon 10 μm pore 8x8
Gastof:
Hamamatsu 6 μm pore single channel
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
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
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 $n(\lambda)$.
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

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 μm 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:

![Graph showing T2_fit_CFD - T3_fit_CFD {T2_fit_CFD<1 && T3_fit_CFD<1}]

**Photek PMT210**
3 μm pore <100 ps rise time!

Gastof resolution < 10 ps – we are there!
Note: Expect real resolution with Photek ~5 ps...
Components of Fast Timing System

MCP-PMT → Preamplifier → Constant Fraction Discriminator → TDC

QUARTIC:
- Photonis planacon
- 10 μm pore 8x8 or equivalent

GASTOF:
- Hamamatsu 6 μm pore single channel
- or equivalent Photek

HV/LV

Mini-circuits ZX60 4 GHz or equivalent

Louvain Custom CFD (LCFD)

HPTDC board (Alberta)

Reference Timing

Opto-modules/ROD

Manchester/UCL

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

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Alberta HPTDC board

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 $2 \times 10^{33}$ 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 $\times$ number of photo-electrons generated by each proton $\times$ electron charge

**Anode Current** = Cathode Current $\times$ 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)
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

<table>
<thead>
<tr>
<th>Al protection correction eff.</th>
<th>O</th>
<th>X</th>
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<tbody>
<tr>
<td>Effective area</td>
<td>11mm²</td>
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<tr>
<td>Gain</td>
<td>1.9x10⁶</td>
<td>1.5x10⁶</td>
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<tr>
<td>TTS</td>
<td>34ps</td>
<td>29ps</td>
</tr>
<tr>
<td>Photo-cathode</td>
<td>Multi-alkali (NaKsBcCs)</td>
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<tr>
<td>Quantum eff. at 400nm</td>
<td>21%</td>
<td>19%</td>
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<tr>
<td>Bias angle</td>
<td>13deg</td>
<td></td>
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</tbody>
</table>

Lifetime for CT0790 & YA0071

\[ x^2 / \text{ndf} = 23.71 / 52 \]
\[ \text{Prob} = 0.0007 \]
\[ p0 = 0.0007 < 0.01203 \]
\[ p1 = -0.003651 < 0.000003 \]
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 $f(#\text{pe’s})$?
  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)

LeCroy Wavemaster
6 GHz Oscilloscope

Hamamatsu
PLP-10 Laser Power Supply

Laser Box
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

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

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)

75 +/-1ps
75/1.4 =54 ps /channel

0.8x10^5 Gains x40 amp

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

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)

1x10^6 Gain x16 amp
Timing vs. Number of PE’s

Measurement roughly shows expected $\sqrt{N_{pe}}$ behavior for 25 $\mu$m pore tube
Rate Dependence of Amplitude/Timing

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

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

~1pA input current

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Rate Limits as $f(gain)$

Saturation decreases with decreased gain, but not linear.

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)

Scaling of saturation with beam area as expected

Note the last point is $\sim 400$ MHz/cm$^2$ pe rate!
10 pe's at 10 MHz with 0.24 cm$^2$ area at gain of $0.8 \times 10^5$

$2 \times 10^{33}$ at 420m

$10^{34}$ at 220m about 450 MHz pe/cm$^2$
Timing vs Track Rate/cm$^2$

Timing degrades only slowly with rate, but up to 50% efficiency loss at high rate.
Allows us to study all channels ~easily (manually)
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

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.
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)
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 $\mu$m Tube)

- Voltage (50 mv bins)
- Time (2 ns bins)
- Voltage (50 mv bins)
- Time (20 ns bins)

Ringing persists for >100 ns!

(∼400 pe, gain ∼0.8E5)

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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.
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
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: 2\textsuperscript{nd} 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 $\Rightarrow$ Clad Fused Silica Fibre Bundles

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