Fast Timing detectors: QUARTIC

Michael Albrow, Fermilab

For PU rejection at high Luminosity

Most events with X (e.g. JJ) & two forward protons are pile-up: (p + X) & (Y + p)
Precision proton timing → z(vertex) IFF (p + X + p)

$$\sigma(\Delta t) = \sqrt{2}\,.\sigma_t$$

$$z_{pp} = \frac{1}{2}.c.\Delta t$$

$$\sigma(z_{pp}) = \frac{1}{2}.\,c.\sqrt{2}\;\sigma_t = c.\frac{\sigma_t}{\sqrt{2}} = 2.1mm\ for\ \sigma_t = 10\,ps$$

Fast Timing detectors: QUARTIC

Requirements:

1) Excellent time resolution ($\sigma(t) \sim 10$ ps)
2) Edgeless on beam side ($\Delta x <\sim 200$ μm)
3) Radiation hard close to beam ($\sim 10^{15}$ p/cm^2)
4) Fast readout (25 ns crossings) --- & trigger signal
5) Segmentation (multi-hit capability)

Baseline for PPS (CMS&TOTEM) project with CMS:

Cherenkov detectors with quartz radiators:
Angled-bar QUARTIC and L-bar QUARTIC
Light detected by MCP-PMTs or Silicon PMs (SiPMs)

Faster and better Q.E. but lifetime issues

Small, cheap, but slower and radiation issues

News on Quartic timing detectors

Designed & tested "quartz" bar Cherenkov detectors for timing:
Angled-bar QUARTIC with MCP-PMTs, adopted by ATLAS AFP as baseline
L-bar QUARTIC with SiPMs, baseline for PPS

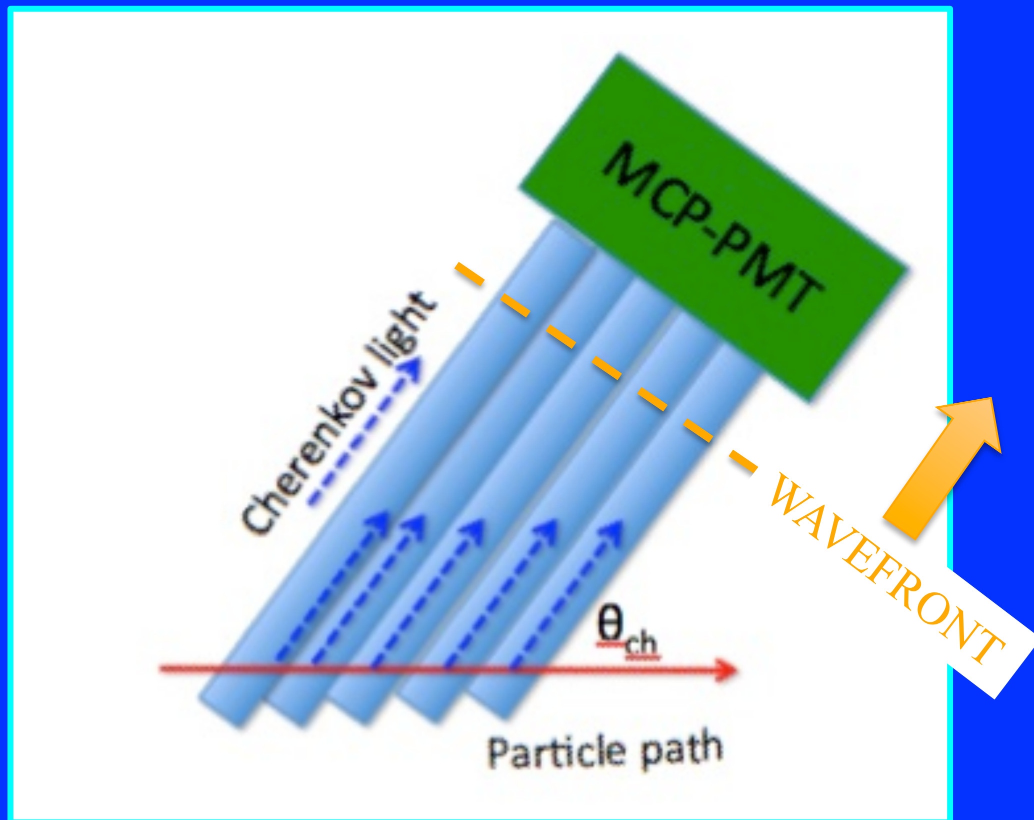
Quartz Cherenkov Counters for Fast Timing: QUARTIC
M.G. Albrow (Fermilab), Heejong Kim (Chicago U., EFI), S. Los (Fermilab), M. M
(Fermilab), A. Zatserklyaniy (UC, Santa Cruz). Jul 2012. 24 pp.
Published in **JINST 7 (2012) P10027**
FERMILAB-PUB-12-418-E

L-bar QUARTIC designs different for Moving Beam Pipe and Roman pot mechanics.
At Fermilab have concentrated on MBP design.
Q-20 bar module with 15mm (x) by 12mm (y) in 3x3 mm^2 elements made
Beam tests at Fermilab test beam (Dec 2013+Jan 2014).
We have learnt how to solve known issues (edgelessness, granularity, cross-talk, SiPM assly) and will learn:

(a) Sapphire vs quartz
(b) R-bar length dependence for 20 mm to 55 mm
(c) Any cross-talk between bars?
(d) Is light in light-guide bars useful?
(e) monitoring SiPMs with LED or PiLas laser schemes.

Angled multi-bar QUARTIC. Multi-anode or single anode

Developments with AFP, Andrew Brandt et al. This is AFP baseline, not excluded



Cherenkov light cone $\theta_{ch} = 48^o$, 360^o in Φ

Direct light propagates as wavefront – isochronous

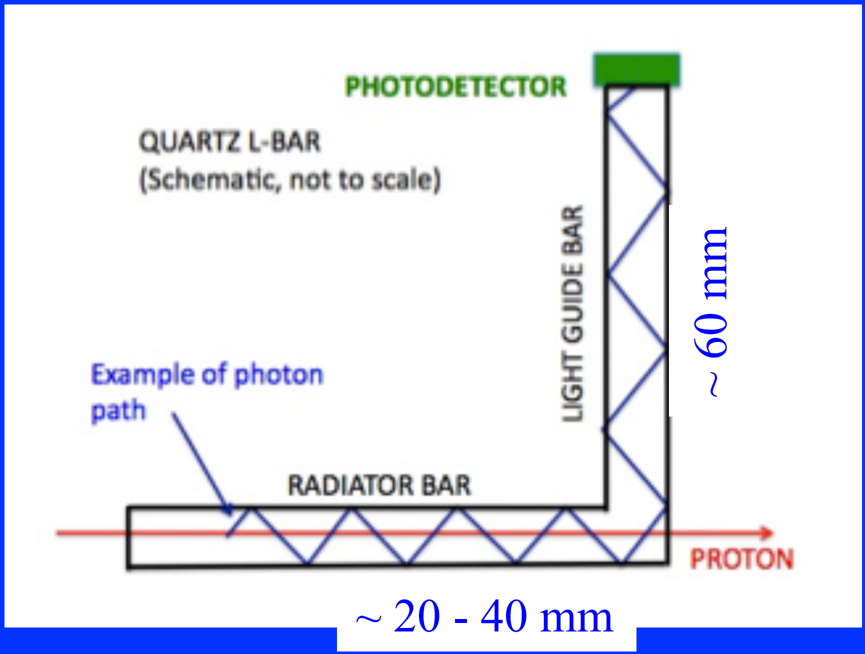
Light emitted at "wrong" Φ ... longer path or exiting

L-bar QUARTIC principle

All Cherenkov light is totally internally reflected along radiator bar and about 66% goes promptly along light guide to SiPM or segmented MCP-PMT.
No light "leaks out".

If conditions satisfied:

1) protons are parallel to radiator
2) n (refractive index) > √2
   so TIR maintained in LG-bar

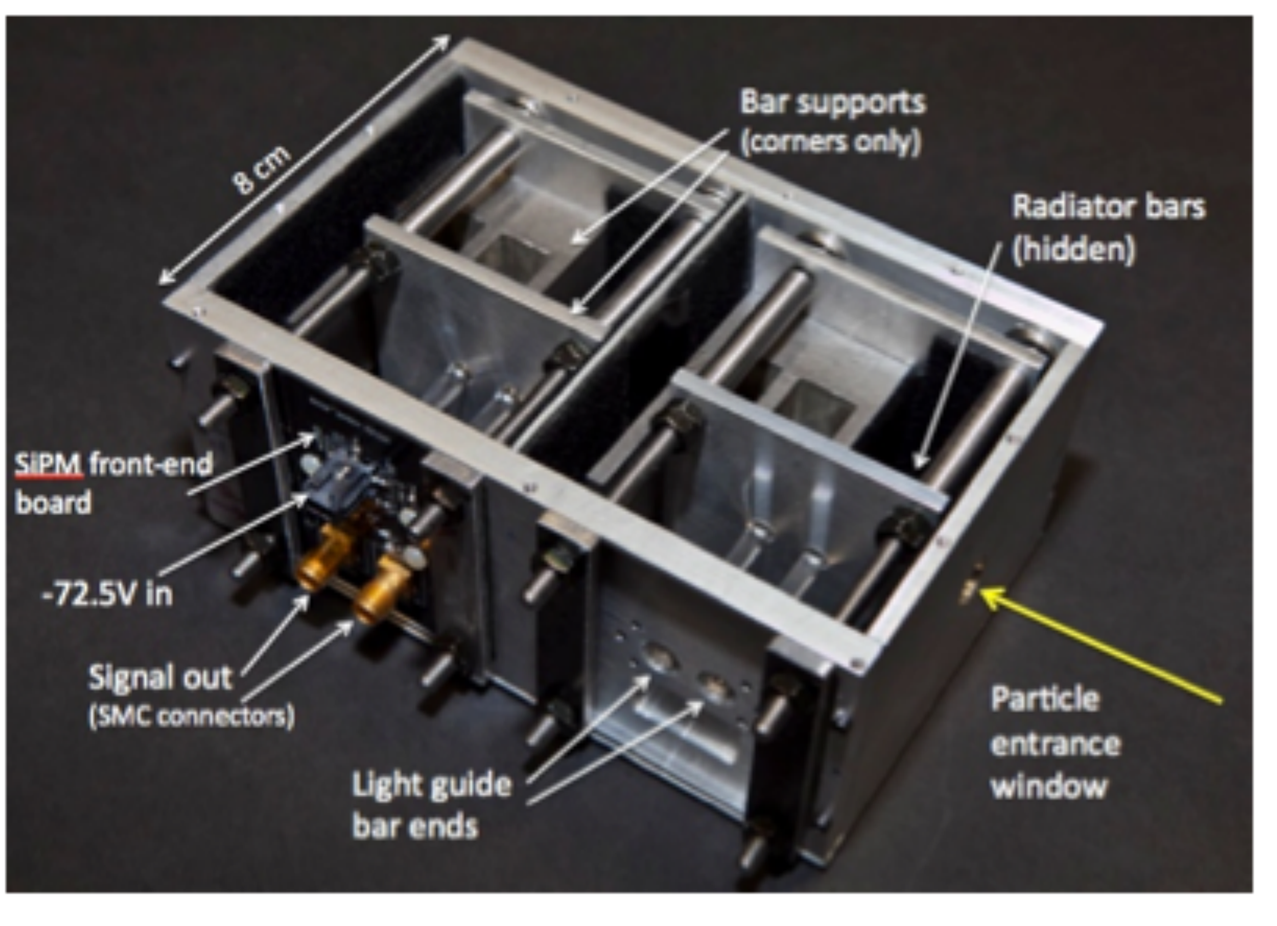


Radiator close to beam while photo-detector remote (and may be shielded)

NO MIRRORS

Hodoscope of 3mm x 3mm independent elements
Repeat 4 times in depth for x2 improvement (timetrack): material concern
Finer segmentation eg 2x2 mm^2 ,even 1x1 mm^2, possible in principle

Test beam modules made: Four in-line radiators, 3 cm and 4 cm

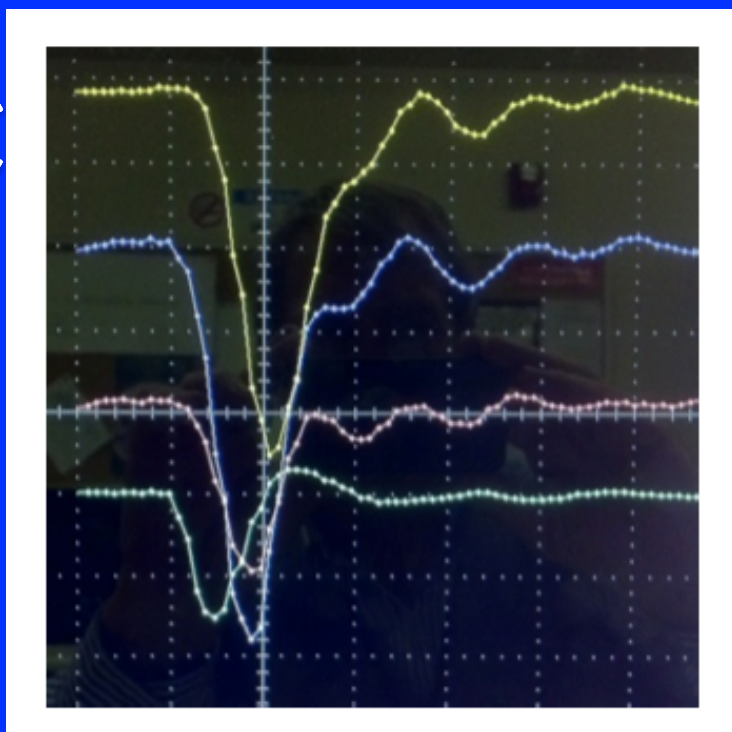


Beam tests 2012 at Fermilab, 120 GeV p's, 2mm x 2mm

Since 2005: **Quartz Cherenkov Counters for Fast Timing: QUARTIC** MGA et al., 2012 JINST 7 P10027

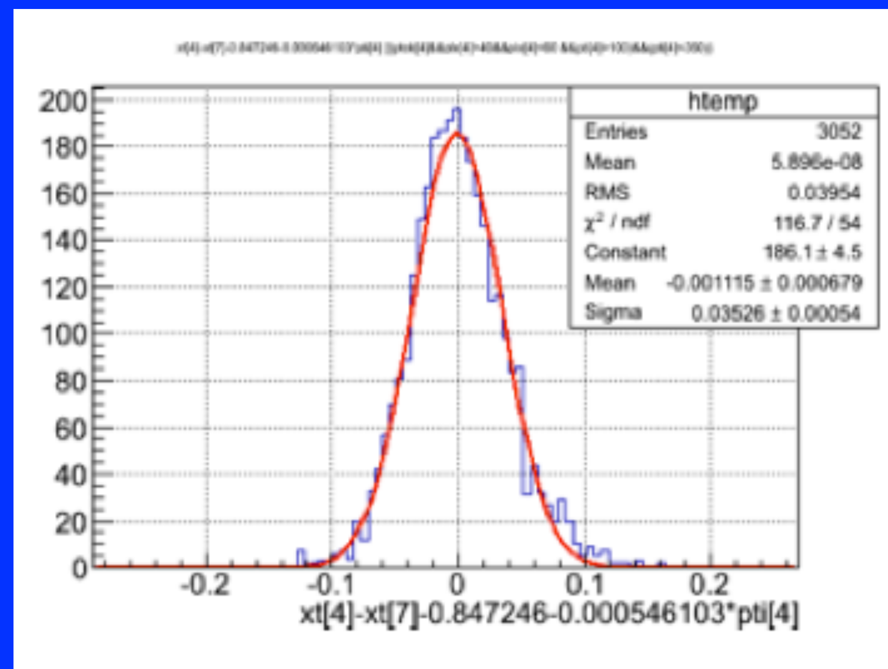
Typical event (120 GeV proton) in 3 radiator bars
and (bottom) PMT240 in line. 200ps/sample, DRS4 scope
Signal rise times ~ 800 ps

20mV/div



2ns/div

Δt (30mm bar – PMT240)



σ(t) = 31 ps for 30 mm bar
Four-in-line → 15 ps

Expected improvements: sapphire bars (+30%) & faster SiPMs (30%?)

Good features of SiPMs with several modules in-line:

Many measurements – “timetrack” – robust – self calibrating
Resolution and offsets of each detector monitored by data.

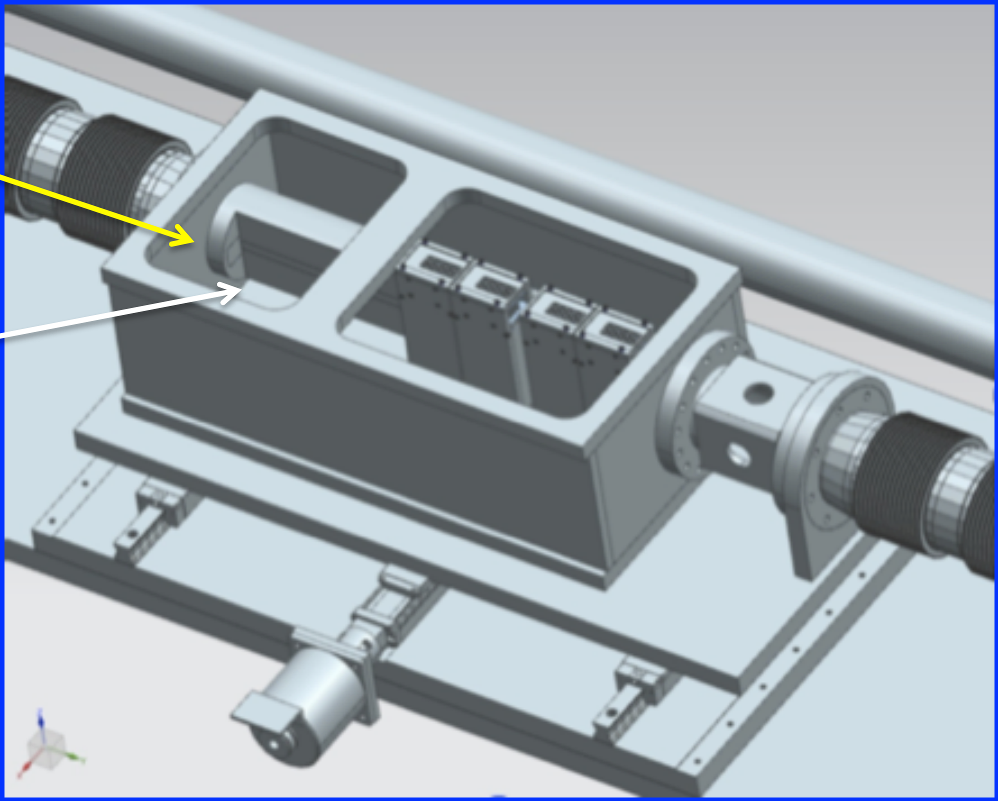
Demands on electronics less: σ = 25 ps/ bit HPTDC could be used.
Existing HPTDC adequate, but next version should get to < ~ 10 ps
Quad threshold discriminator development: Jin-Yuan Wu (Fermilab)

Cheap: ~ < $80 each (just detector) = $16K for 200 devices.
Can be quickly exchanged (“cartouche”, or drop-in design)
Low voltage (~ 30-70V) gives gain ~ 10^6

CMS gets 10,000’s for HCAL.

[MCP-PMT with 24 anode pads matching bars: interesting alternative ... would like $ for development]

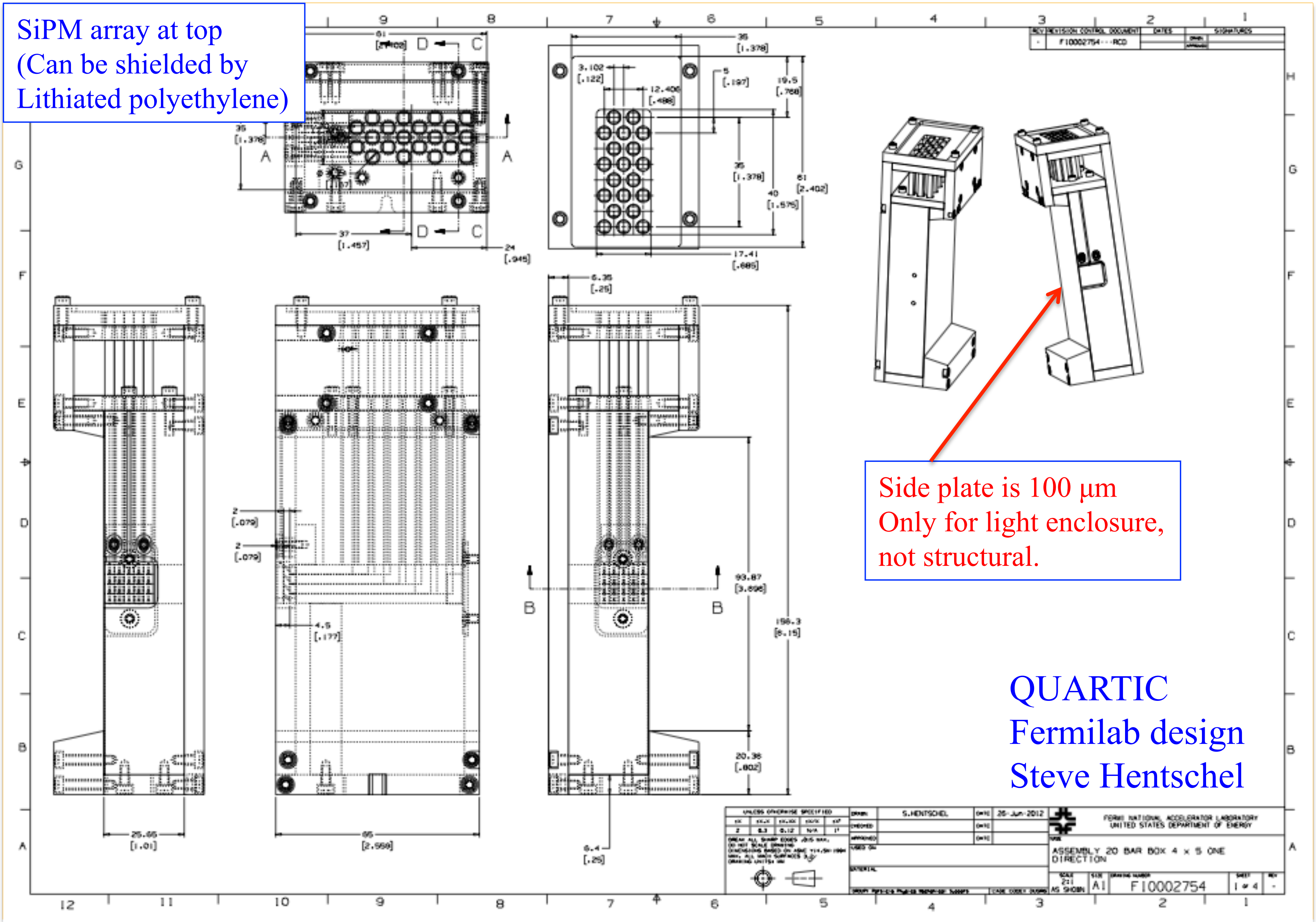
Arrangement of four QUARTIC modules with moving beam pipe



p

Space for tracking:
2+2+2 planes 3D Si

SiPM array at top
(Can be shielded by
Lithiated polyethylene)



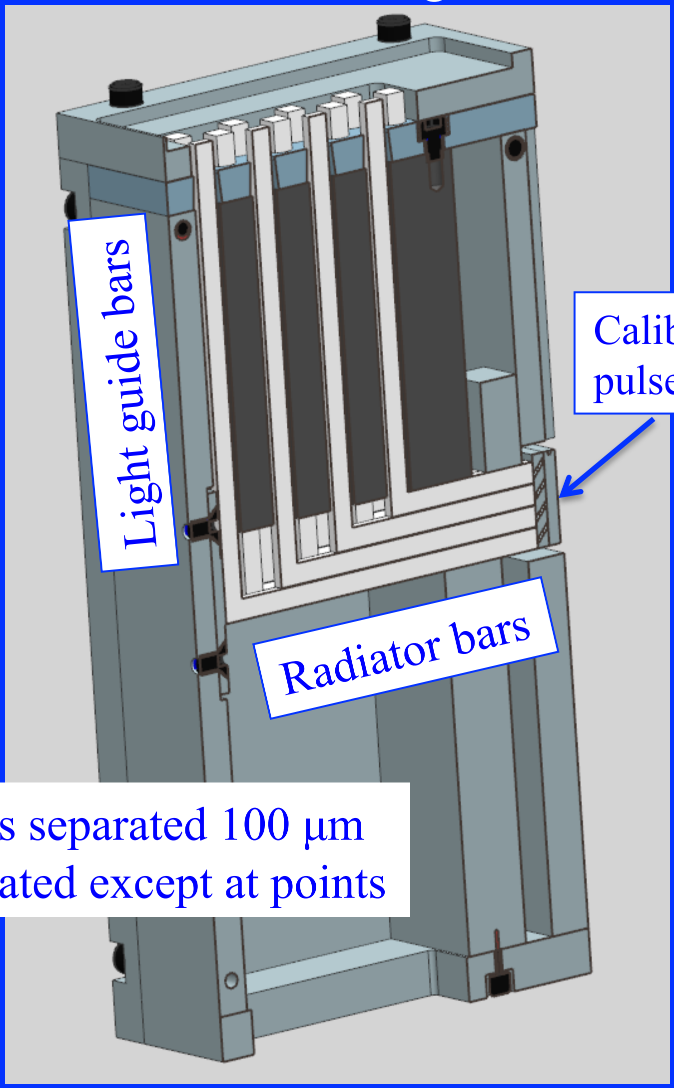
Side plate is 100 µm
Only for light enclosure,
not structural.

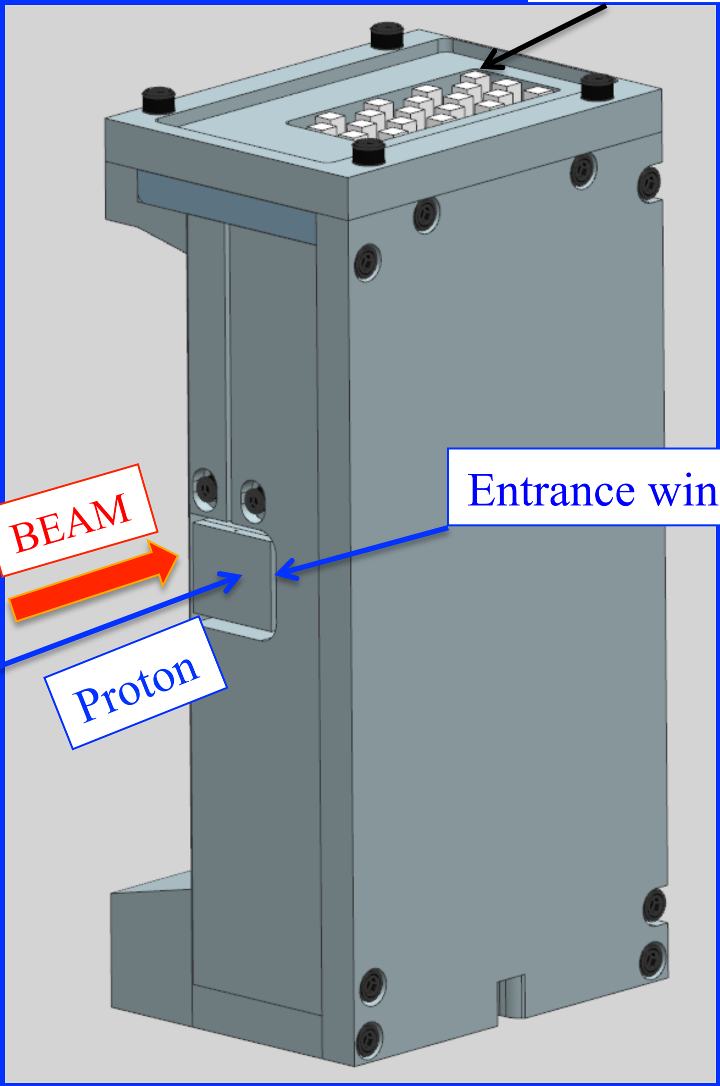
QUARTIC
Fermilab design
Steve Hentschel

QUARTIC: L-bar design, 4x5 (→ 6) channel Module

Increasing x-coverage (hor) unlimited (only cost) – Want to minimize y-coverage (12mm – 9mm?)

Vertical slice through:

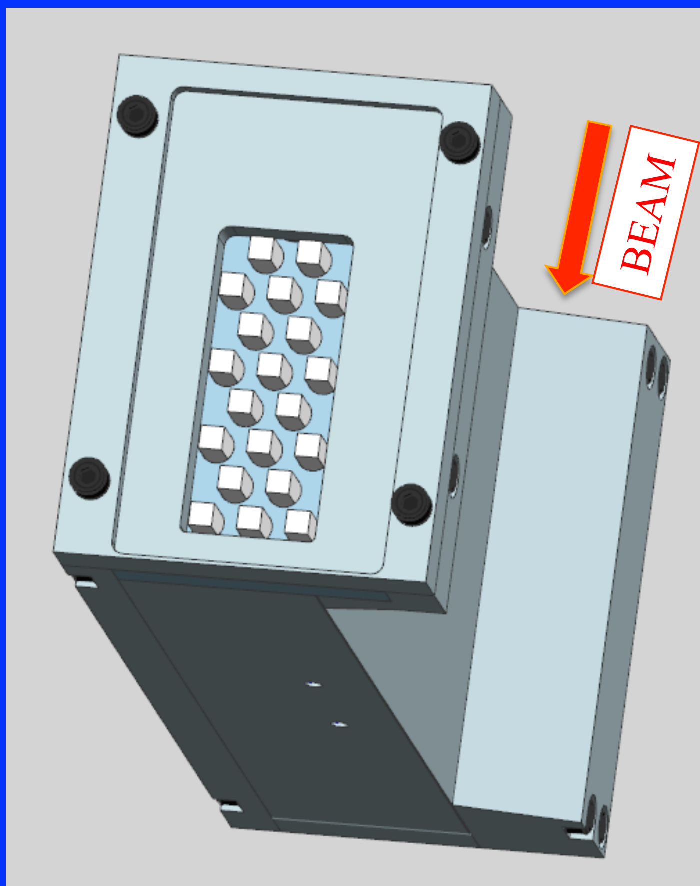




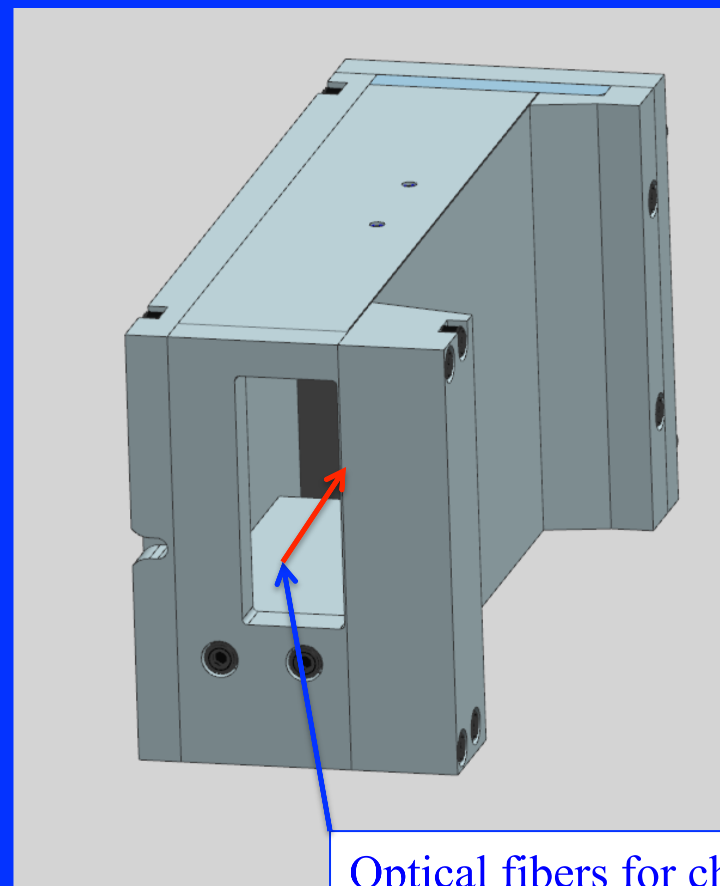
QUARTIC: L-bar design, 4x5(→ 6) channel Module

20-channel Module made for Dec-Jan beam tests

Top view, SiPM array



Bottom view, Calibration window



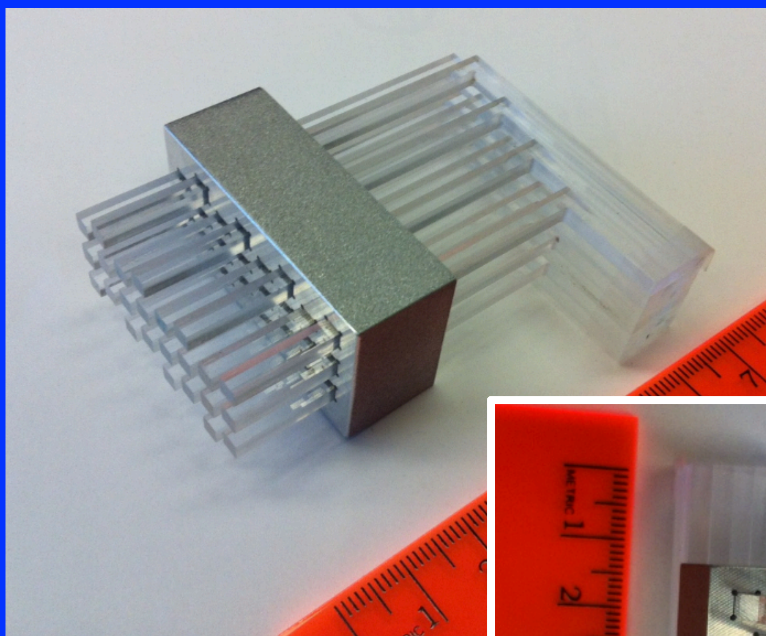
Optical fibers for check of
light-guide bars + SiPMs

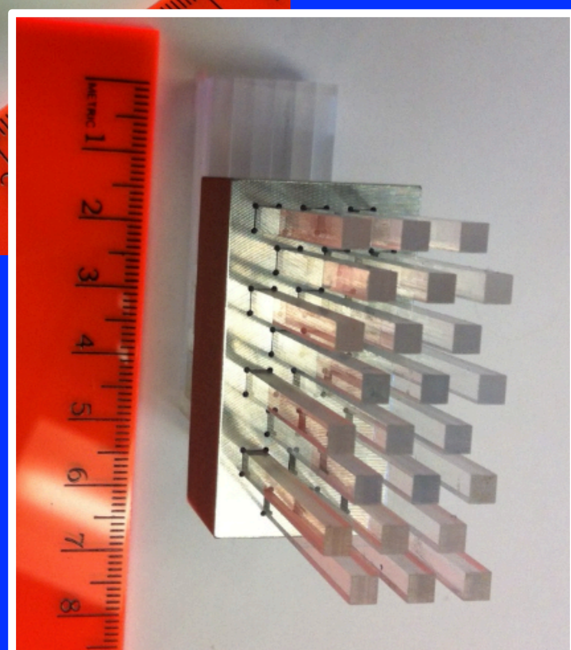
Test assembly (with plexiglas bars).

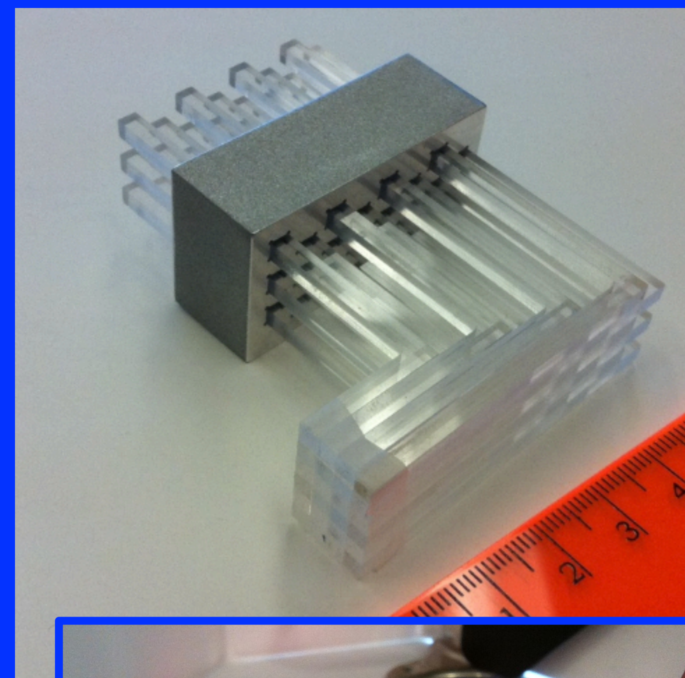
100 μm spacing between adjacent bars.

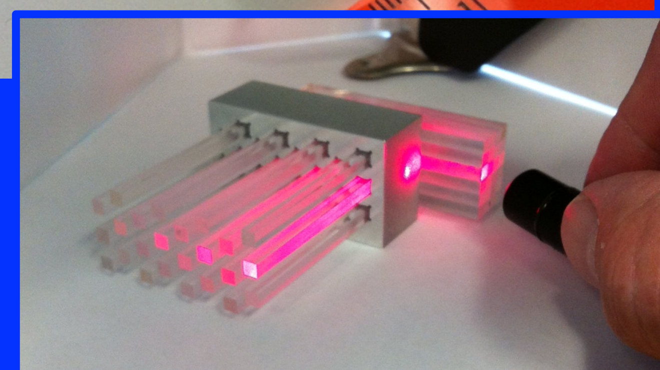
Precision block is a “jig”, removed after front of array glued to black plate

Module #1: 4 columns quartz and 2 columns sapphire.

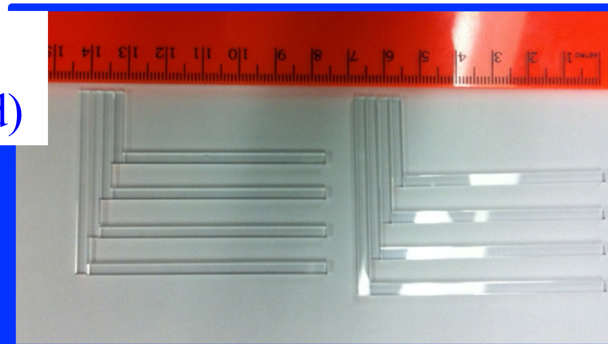








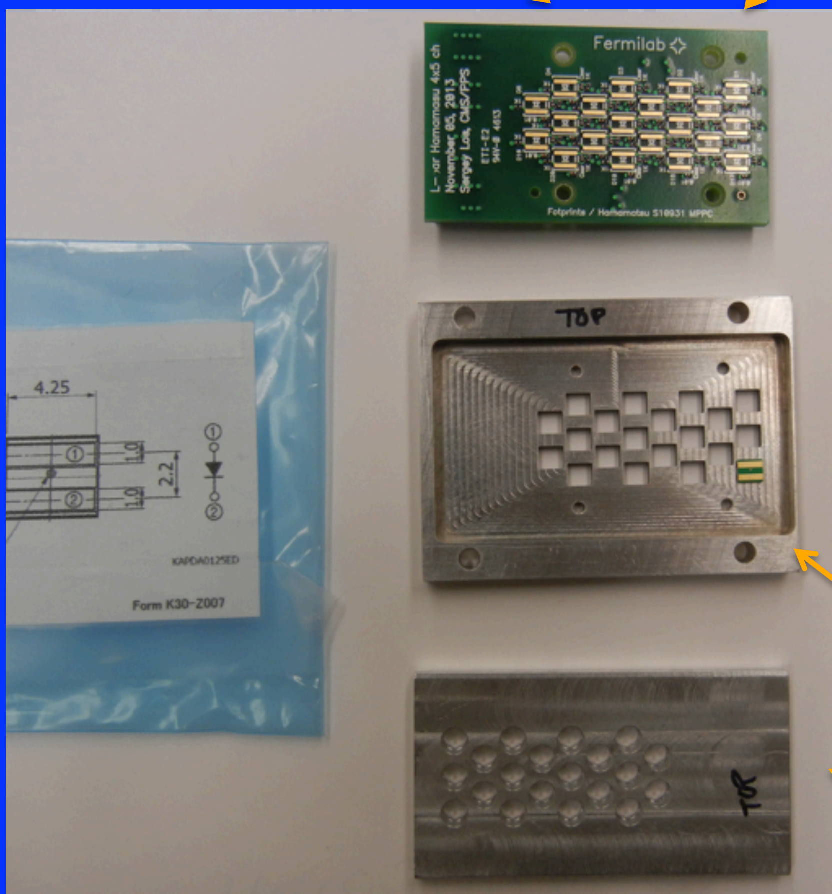
Sapphire bars (glued ...
need to be fused/machined)

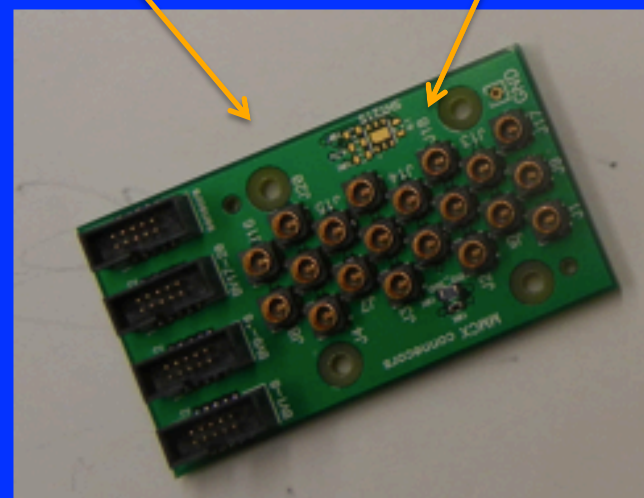


Pressure contacts to SiPMs
through F-B conducting film

20-channel SiPM readout board

Signal cable connectors



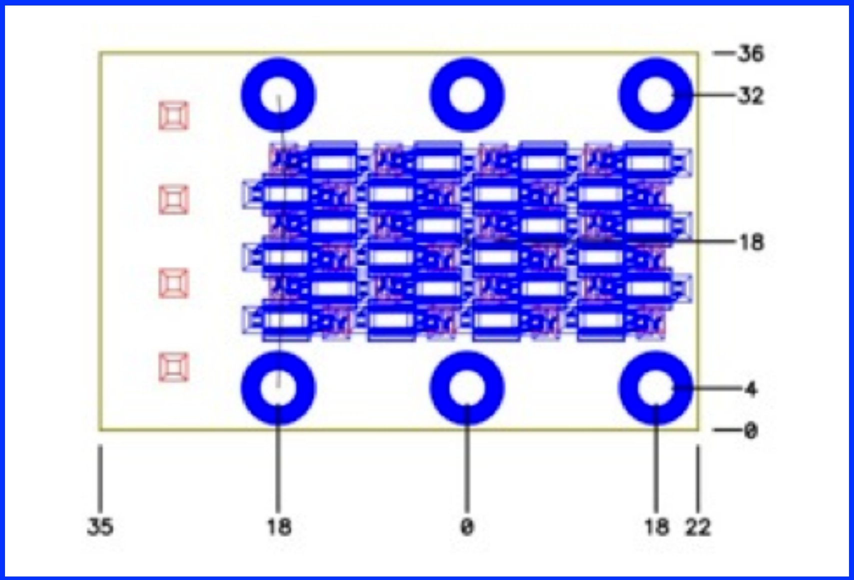


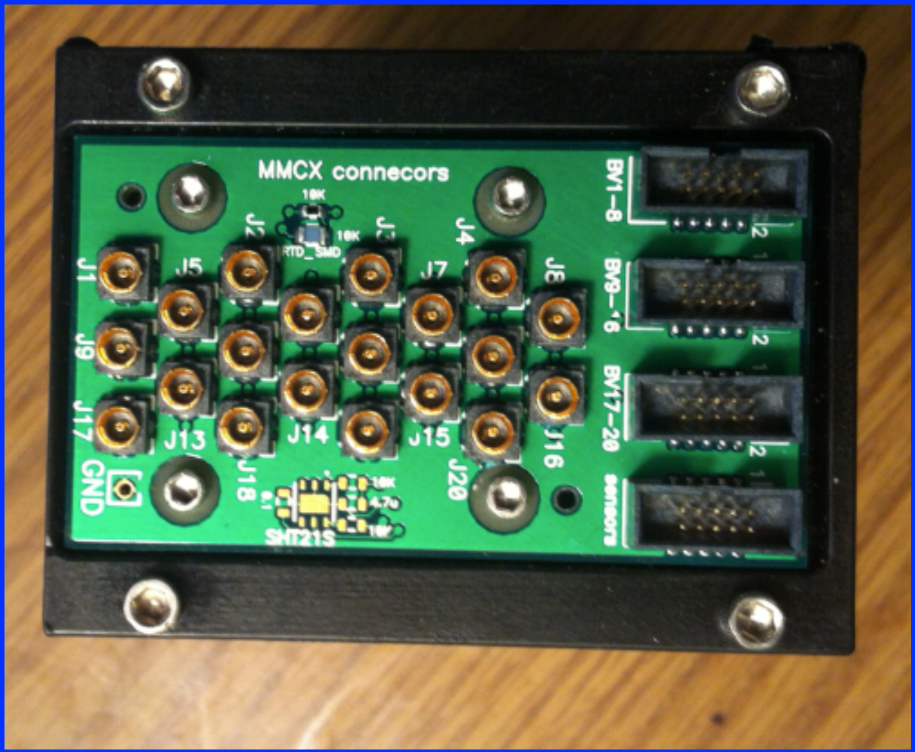
SiPMs drop in rectangular holes

Round-hole plate (countersunk holes)
aligning bars to SiPM assembly

Configuration of SiPMs on board.

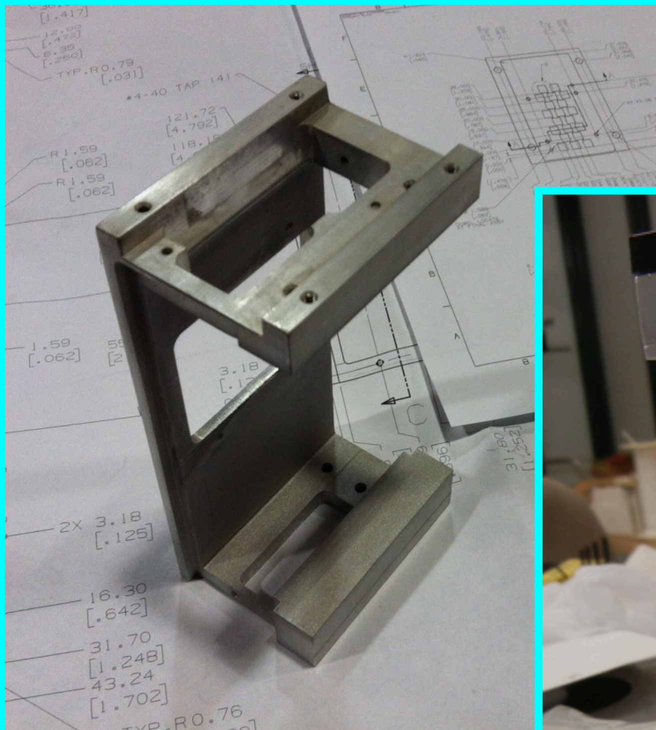
An MCP-PMT with this anode pattern could replace this, iff lifetime issues (# photoelectrons → ion feedback) solved



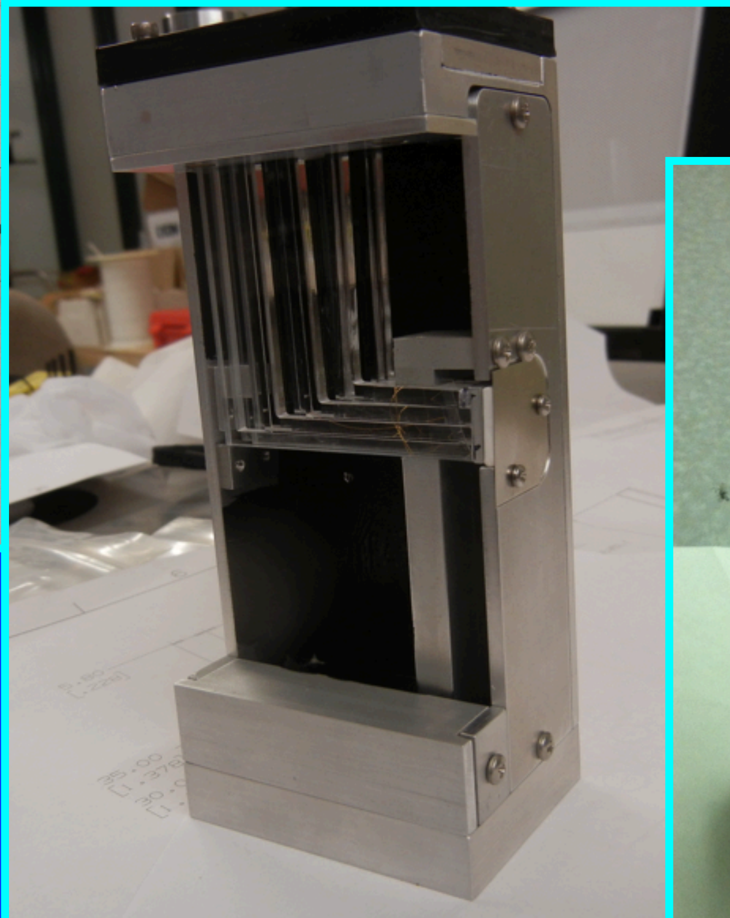


SiPM readout board (Sergey Los).
Individual SiPM V(72V) and leakage current monitor, temperature control and readout (fast OR o/p can be added)

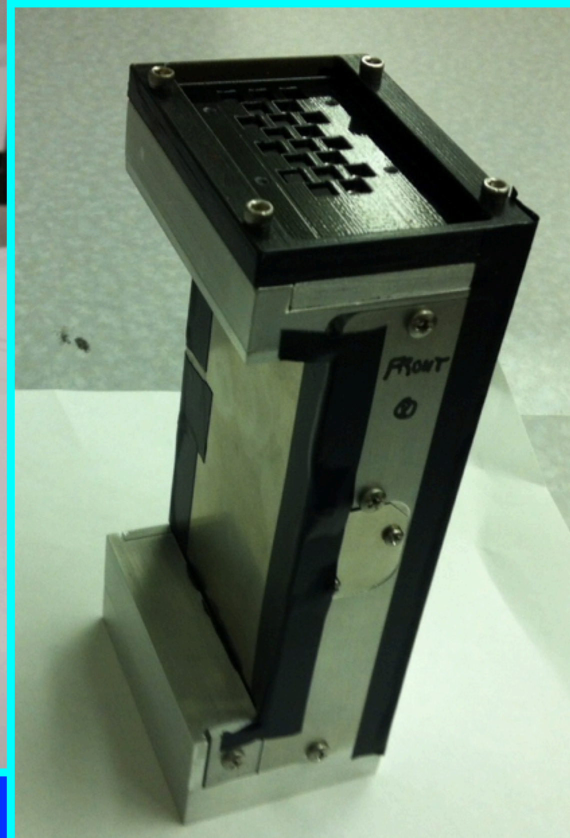
Box machined (electro-erosion) from one Al. block
(Could be 3D-printed)



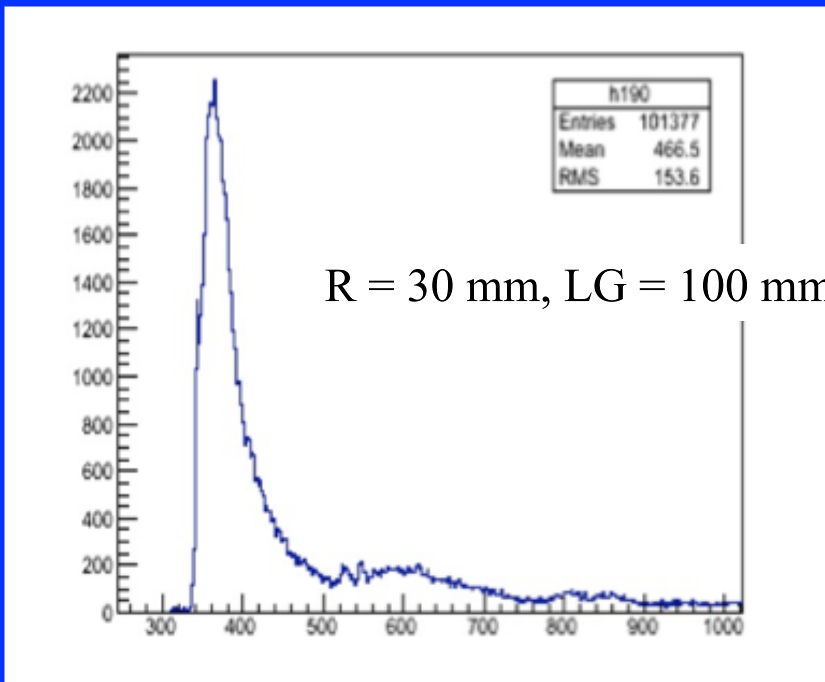
With L-bars assembled



Before SiPM insertion
(Black plate is 3D-printed)



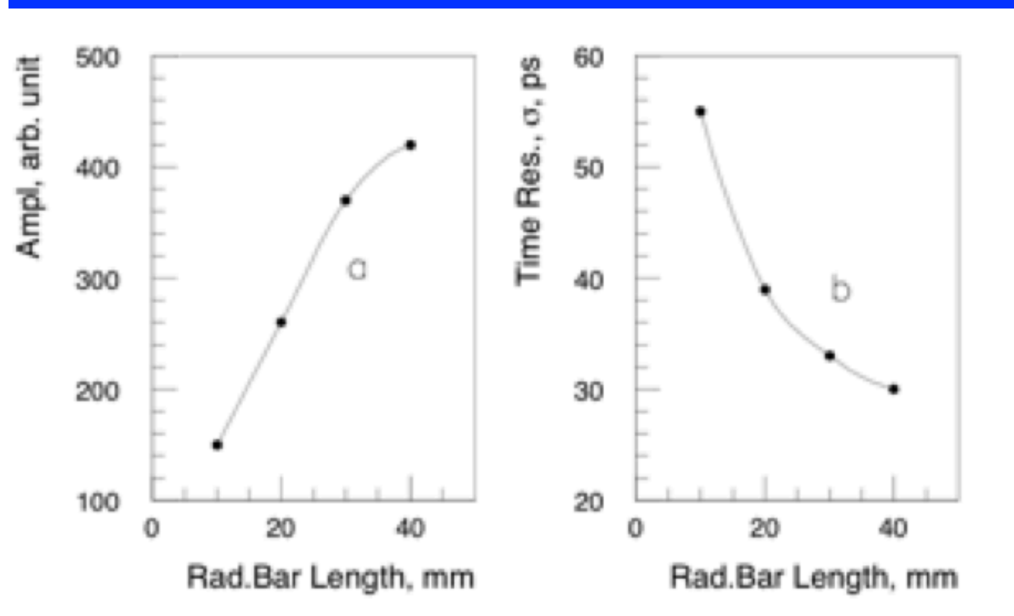
GEANT simulation (Vladimir Samoylenko): photoelectron time distribution



R = 30 mm, LG = 100 mm

Time resolution actually improves with radiator length up to 40 mm.

"More light beats more spread"



↑

Light back to front and back again. (Will have absorber at front end of bars)

Developments

We have the design achieving requirements, but σ(t) = 15 ps with 4 modules.
Good, but any improvement is useful
Before full production, & in parallel with Module #1 assembly and testing, study of two possible improvements:

Radiator bar material:
Sapphire Al_2O_3 replacing quartz? Higher n(λ) = 1.75 – 1.80
> More Cherenkov light /cm but more chromatic dispersion, absorption, surface quality etc to be studied. GEANT (v. preliminary) ... need beam tests

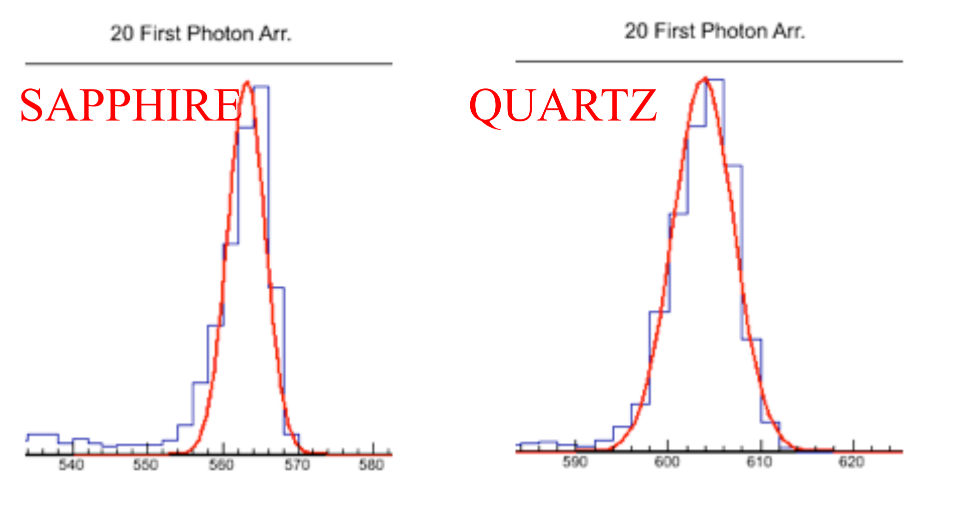


Fig.4 The time distribution for first 20 photoelectrons from Sapphire(left) and quartz(right).

SiPMs: faster (better single photon time resolution SPTR) are made.
E.g. HAM S12652-050C is better
(Used S10931-050P)
Big markets, e.g. ToF-PET so rapid developments

Status, March 2014

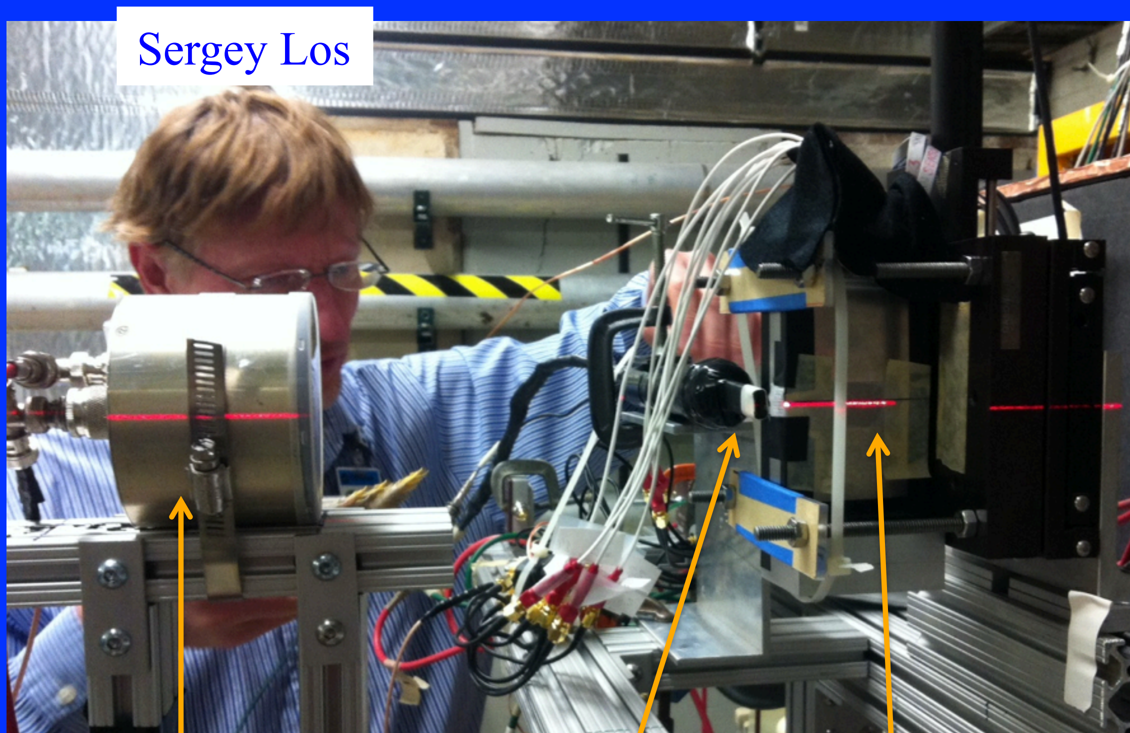
Detector with 5 x 4 = 20 bars 3mm x 3mm constructed.
Hamamatsu S10931-050P SiPMs “dropped in rectangular holes”
104 μm (4 thou”) wire separators.
104 μm sideplate (distance radiator bar – outside)
3D-printed holder near read-out end.
Only 3 x 3 = 9 quartz bars (Specialty Glass) ($$)
2 x 4 Sapphire bars planned ... glued in L ... bad idea, some broke
Need cut in L-form, or invisibly fused. {V.Samoylenko}

Test beam 120 GeV p’s at Fermilab, Dec 2013 & Jan 2014.
{MGA + A.Ronzhin, S.Los, A.Zatserklanyi, E.Ramberg}
MWPC telescope to project track to bars.
DRS-4 Waveform digitisers (200 ps sampling scope)

Analysis ongoing

More test beam at Fermilab end May 2014

At Fermilab test beam, Dec-Jan 2014

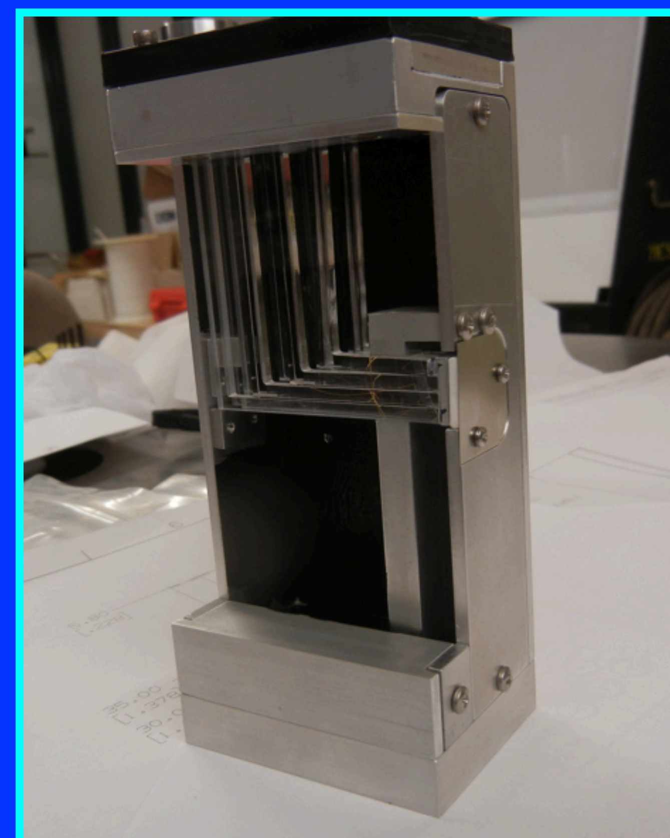


MCP-PMT240
ref.time σ <~ 10ps

Trigger counter
(scint. 10x10 mm^2)

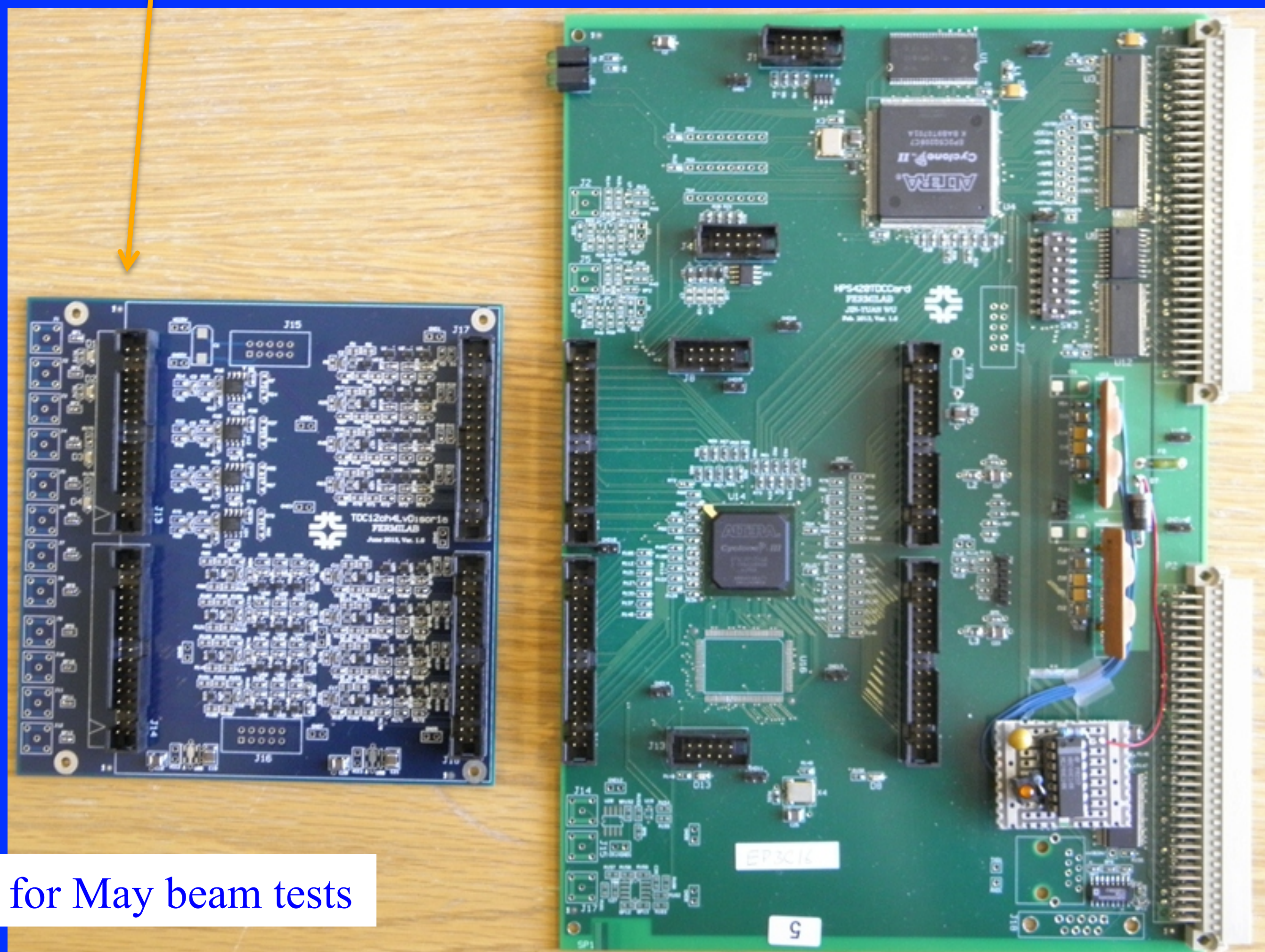
Q20 box on
moving stage

Sideplate removed



Quad-threshold discriminator board (Jin-Yuan Wu, Fermilab)

TDC board (8 times per signal, 4 programmable thresholds)
4 times on rising edge & 4 on trailing edge.
25ns capability. Resolution expected <~ 10 ps.



To be ready for May beam tests

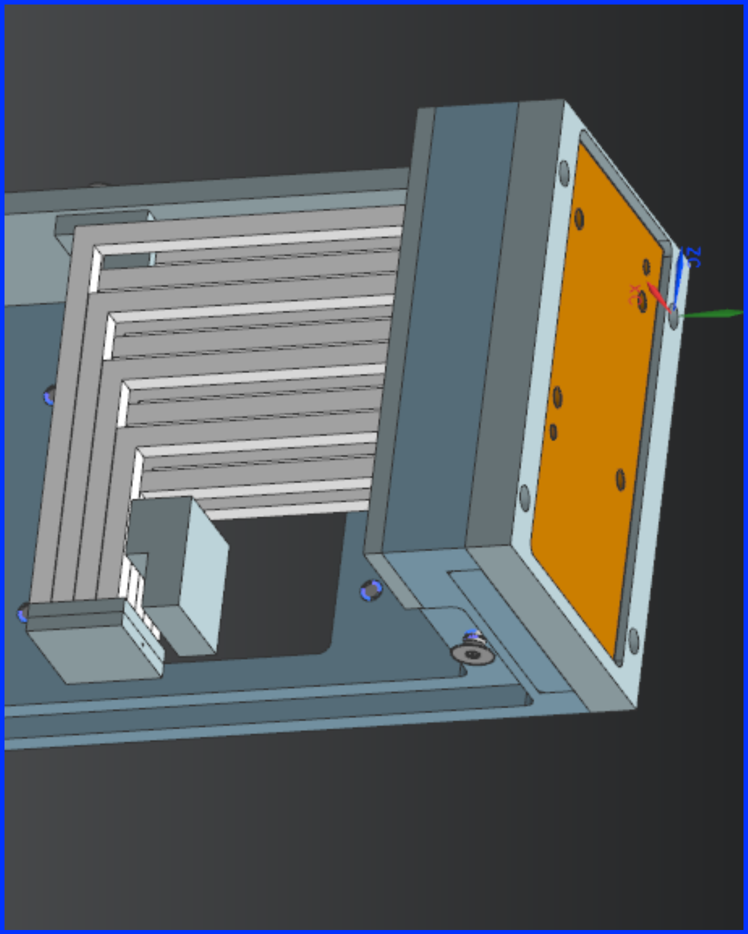
Comments:

IF time resolution is still best with longest (or shortest) radiator bars,
a pair of modules can be “bars-up” and “bars-down” (in MBP scheme)
so protons at all-y traverse same total radiator bar length.

Design can be modified for finer x,y segmentation near beam if desired.
E.g. replace 2x2 block of 3mm x 3mm bars with 3x3 block of 2mm x 2mm bars.
Need experience with 2x2 mm^2 bars, even 1mm x 1mm ... very fragile?
More reflections/cm
Smaller SiPMs, faster.

Want to try with MCP-PMT with 3x3 mm^2 anode pads replacing SiPM array:
Shorter Single photoelectron time spread, better QE in blue.
:
Photonis has a Planacon with 32 x 32 anodes of 1.7 x 1.7 mm^2

Horizontal version of L-bar Quartic for Roman pots ?



Simply turned and with thin foil cover
along bottom of bars (rather than side)
area would be 12mm in x and 15mm in y.

y-coverage does not cost anything in z, but
increasing x-coverage costs in z and gives
larger differences in Radiator bar lengths.
Already here, from 20 mm – 55 mm.
Also Light Guide bars get longer.
Can SiPMs be inside R-pot to keep short,
and can they be surrounded by shielding?
>> Need detailed study of Rad, shielding
Beam tests will measure differences
in timing performance vs R-bar length.
Closest to beam (densest part) has longest bars.

What is x,y area we need to cover (a) for high-β runs for large σ physics w/TOTEM
(b) for low-β runs with high (full) luminosity ?
Can the same detector be good for both scenarios?

Summary

Precision timing of protons ($t_L - t_R$) essential for p+X+p at high pile-up. (Not for special low PU running)

Requirements are challenging but we have solutions:

Angled-bar QUARTIC with MCP-PMT (AFP baseline)
L-bar QUARTIC with SiPM array (CMS baseline) or MCP-PMT

Four-in-line L-bar is baseline. ~ Meets requirements but:

1) so far 30 ps/$\sqrt{4}$ = 15 ps. Improvements expected: faster SiPMs, better radiator (sapphire?), or custom multianode MCP-PMT.
2) Radiation "soft", can shield n's. Can replace > 1/year.

Other solutions welcome ... if beam-tested!

Thank you