Fast Timing detectors for Central Exclusive Production

High Precision Spectrometer (HPS) development

Michael Albrow, Fermilab

with mainly:
Anatoly Ronzhin, Sergey Los, Erik Ramberg, Heejong Kim,
Vladimir Samoylenko, A. Zatserklyaniy

Already in 2000 need for fast timing was recognised:

Searching for the Higgs Boson at Hadron Colliders using the Missing Mass Method

Michael G. Albrow,[1] Andrey Rostovtsev[2]

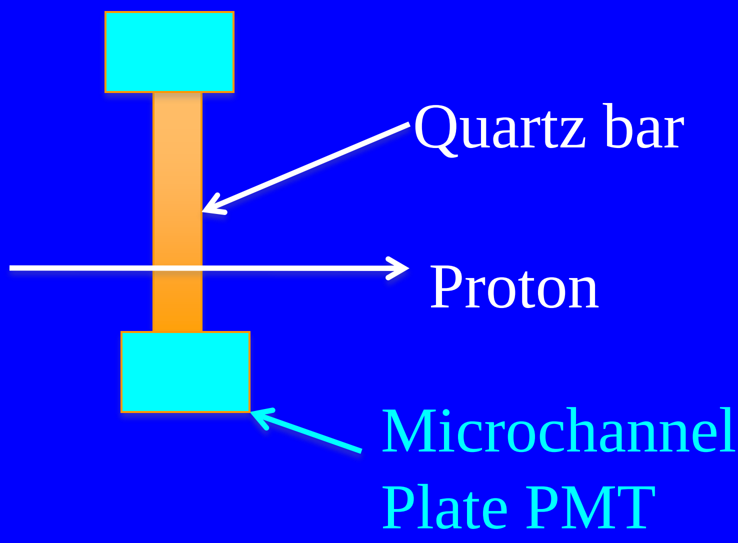
arXiv:hep-ph/0009336v1 28 Sep 2000

With multiple interactions in a bunch crossing a background could come from two single diffractive collisions, one producing the p and the other the $\bar{p}$. One way of reducing this is to require longitudinal momentum balance. However "pile-up" can be reduced by one to two orders of magnitude by backing up the silicon detectors in the pots by counters with excellent timing resolution. A conventional fast detector would be a quartz (for radiation hardness) block producing Cerenkov light viewed by a fast photomultiplier. One can achieve 30 ps timing resolution on the p and $\bar{p}$, much better than the ($\approx$ 1 ns) spread between random concidences. There are ideas [22] for Fast Timing Cerenkov Detectors (*FTCD*) using microchannel plates which might achieve a resolution of a few ps. The sum of the p and $\bar{p}$ times is a constant for genuine coincidences, and their difference Δt is a measure of z_{vtx} at the level of 1 cm (for $\Delta t = 30$ ps).

(apart from event time spread!)

Tevatron!

Pile-up reduction by timing



[pXp] ... good ones
[p][Xp] + [pX][p]
[p][X][p]
} 2 uncorrelated protons -- PU
[pp][X] ... was "good" but wrong X

Original concept (2000)
~ 30 ps expected
σ_z(interactions) ~ 25 cm
PU (μ) ~ 10

Algebra:

Time difference = Δt

$z(pp) = 0.5\ c\ \Delta t$

If time resolution = $\sigma(t)$ = 10ps

$\sigma(\Delta t) = \sqrt{2}\ \sigma(t)$ = 14.1 ps

$\sigma(z(pp))$ = 0.5 c 14.1 ps = 2.1mm

σ_z(interactions) ~ 50 mm == 150 ps

10 ps: not a fundamental limit but achievable goal
Spread in p-path differences <~ 2 ps.

Requirements on timing detectors for HPS

1) Excellent time resolution ($\sigma(t) \sim 10$ ps)
2) Edgeless on beam side ($\Delta x <\sim 200\ \mu m$)
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)

Two detectors developed: **Quartz Cherenkov Counters for Fast Timing: QUARTIC** MGA et al., 2012 JINST 7 P10027

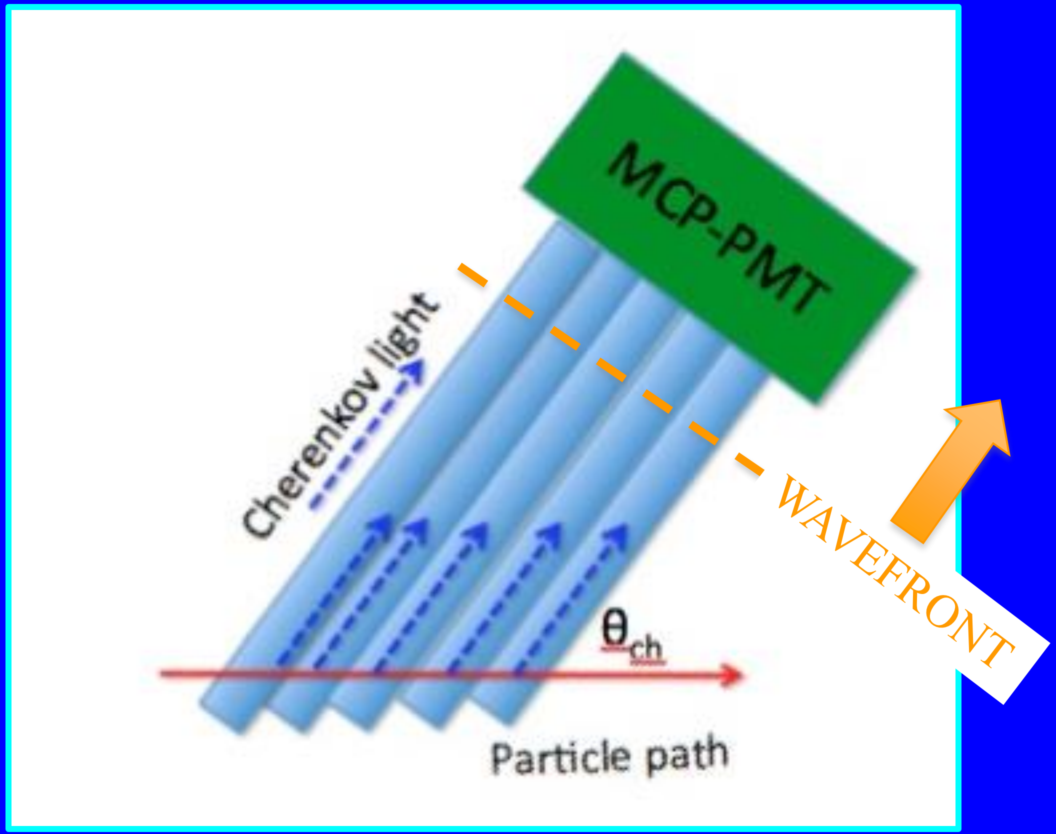
Cherenkov detectors with quartz radiators:
Angled-bar QUARTIC and L-bar QUARTIC
Light detected by MCP-PMTs or Silicon PMs (SiPMs)

Faster and better Q.E. but lifetime issues

Small, cheap, but slower and radiation issues

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

Developments with AFP, Andrew Brandt et al.



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

Single Channel multi-bar QUARTIC-1 Detector

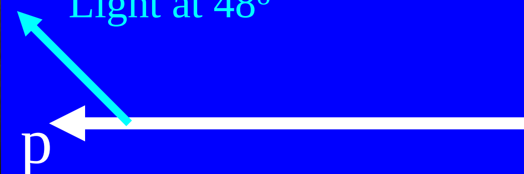
PHOTEK PMT240
(40 mm diam. cathode)
~ $20K !

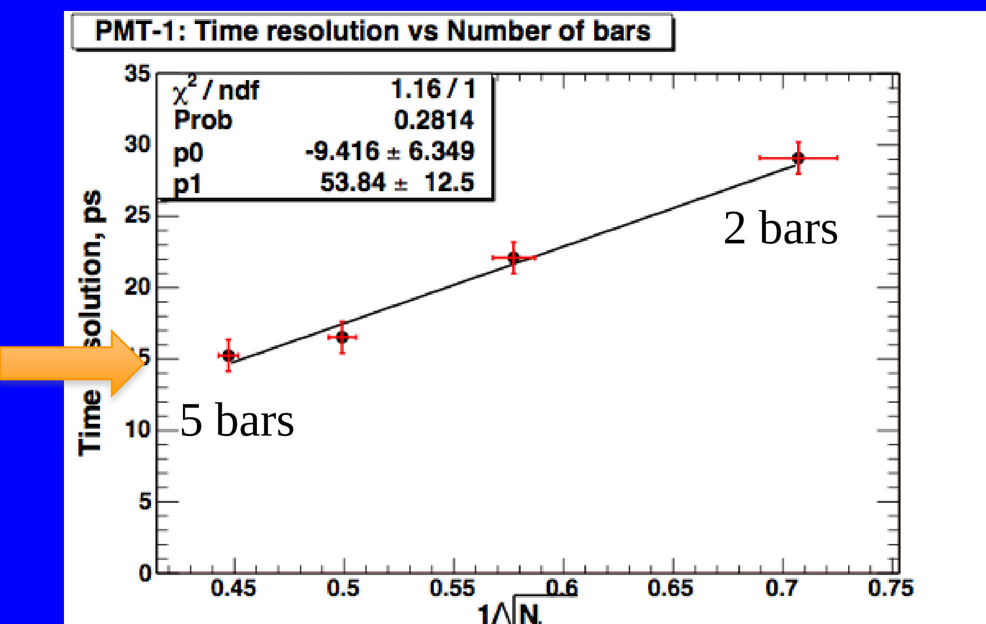
HOUSING, 5mm x 5mm bars
3 rows of 5 bars; springs

This version of QUARTIC: all bars on single 40 mm photocathode (nice isochronous anode design, Δt <~ 2 ps over 40 mm surface)

QUARTIC-1 Beam tests (120 GeV protons at Fermilab)

Same side: t(A) - t(B) independent of x.





Resolution vs Nbars

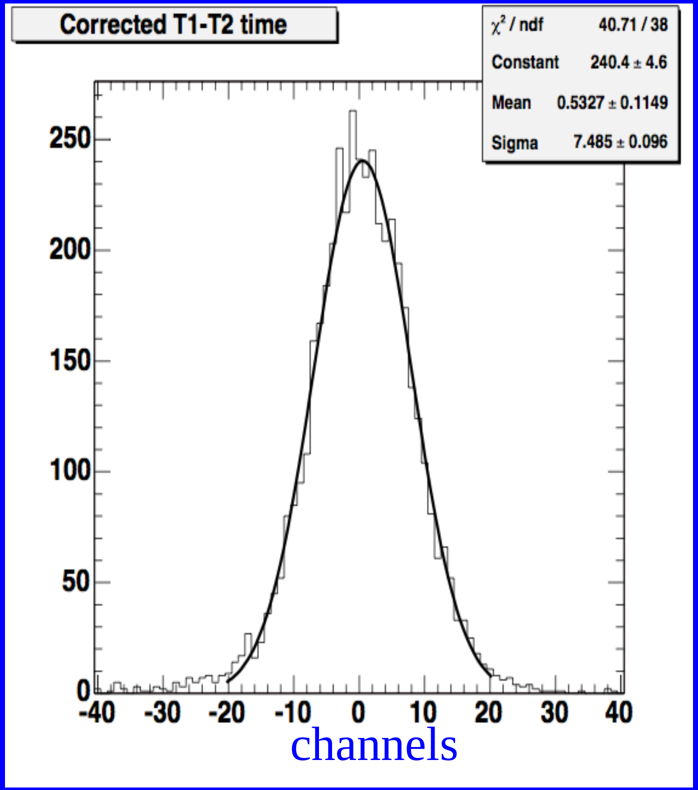
- →Bars contribute about equally
- →Two detectors the same

p.e. ~ 20-25 (5 bars)

Some Results:

Remove tails of PH distributions
(correlated, probably interactions).
Apply time-slewing correction
(CFD needs residual PH correction)
Fit t(1) – t(2) to Gaussians (good fits):

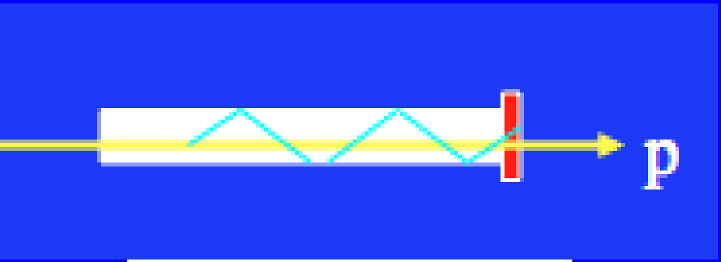
A=15.5 ps B=16.3 ps :
in quadrature combination 11.2 ps
Beam at nominal x and 10 mm closer to PMT



Are we there yet? (11.2 = 10) No, because:
1) Electronics not LHC/25ns compatible
2) Lifetime of MCP-PMTs may be an issue
3) Bars need to be longer, further from beam.
4) No multi-hit capability yet.

Quartz bar in-line + SiPM

We tested with different thicknesses of quartz radiator.



For parallel to axis particles all Ch. light is T.I.R → back.
Front light lags, but helps (bigger pulse)

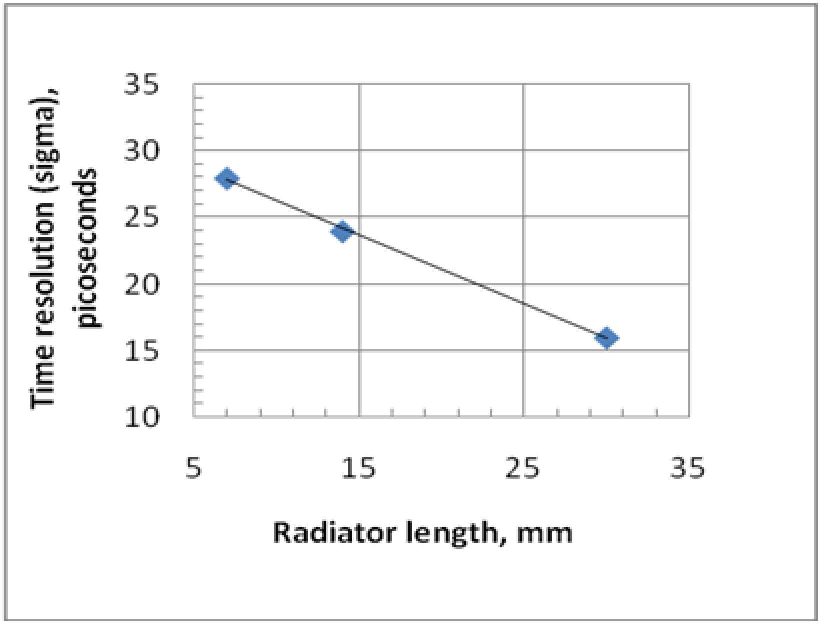
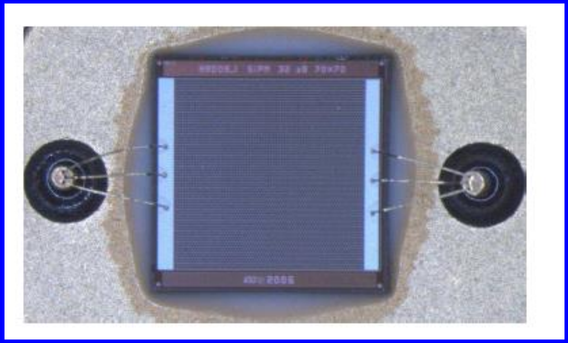


Fig. 25. Dependence of the measured time resolution of the MPPC the Cherenkov radiator (3x3 mm^2 of cross section). The data are no



Longer radiator bar helps!

GEANT simulations concur

Silicon PhotoMultiplier
3 x 3 mm^2 (Hamamatsu)

Not corrected for electronics (3.1 ps) and PMT240 (7.7 ps) …
unfolded **14.4 ps with 30 mm Quartz bar**.

Nice features of SiPM:

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

Demands on electronics less: σ = 25 ns/ channel HPTDC could be used.
Existing HPTDC adequate, but next version should get to < ~ 10 ps
(But we have another solution: 4-threshold discriminator – see later)

Cheap: ~ < $80 each (just detector) = $16K for 200 devices.
Can be quickly exchanged (“cartouche”, if mechanics so designed)
Can be extended with extra layers if z-slot large to improve measurement.
Low voltage (~ 30-60V) gives gain ~ 10^6

CMS gets 1,000’s for HCAL.

QUARTIC 48^o bars + MCP-MPT:
2 give 11 ps but: MCP lifetime issue, multiple measurements
x-segmentation but not in y

QUARTIC 0^o bars + SiPM in line: Radiation damage to SiPM

QUARTIC 48^o bars + SiPM: Tested, but as bars individually
read out, 48^o not necessary … smaller angle → more light, but SiPM closer to beam.

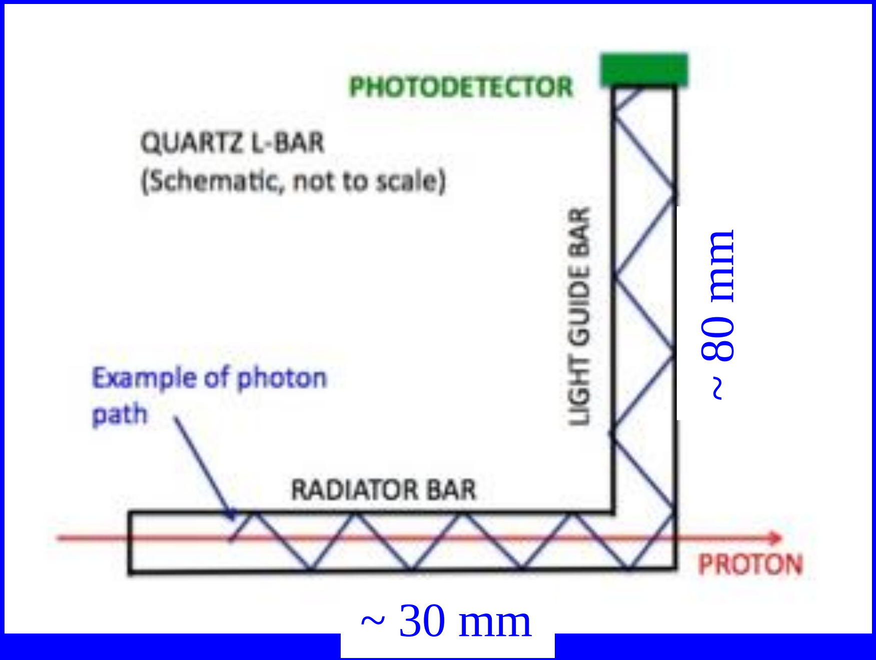
New solution: L-bars + SiPM: 68% collected fast, SiPMs away from beam

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".

Conditions:

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

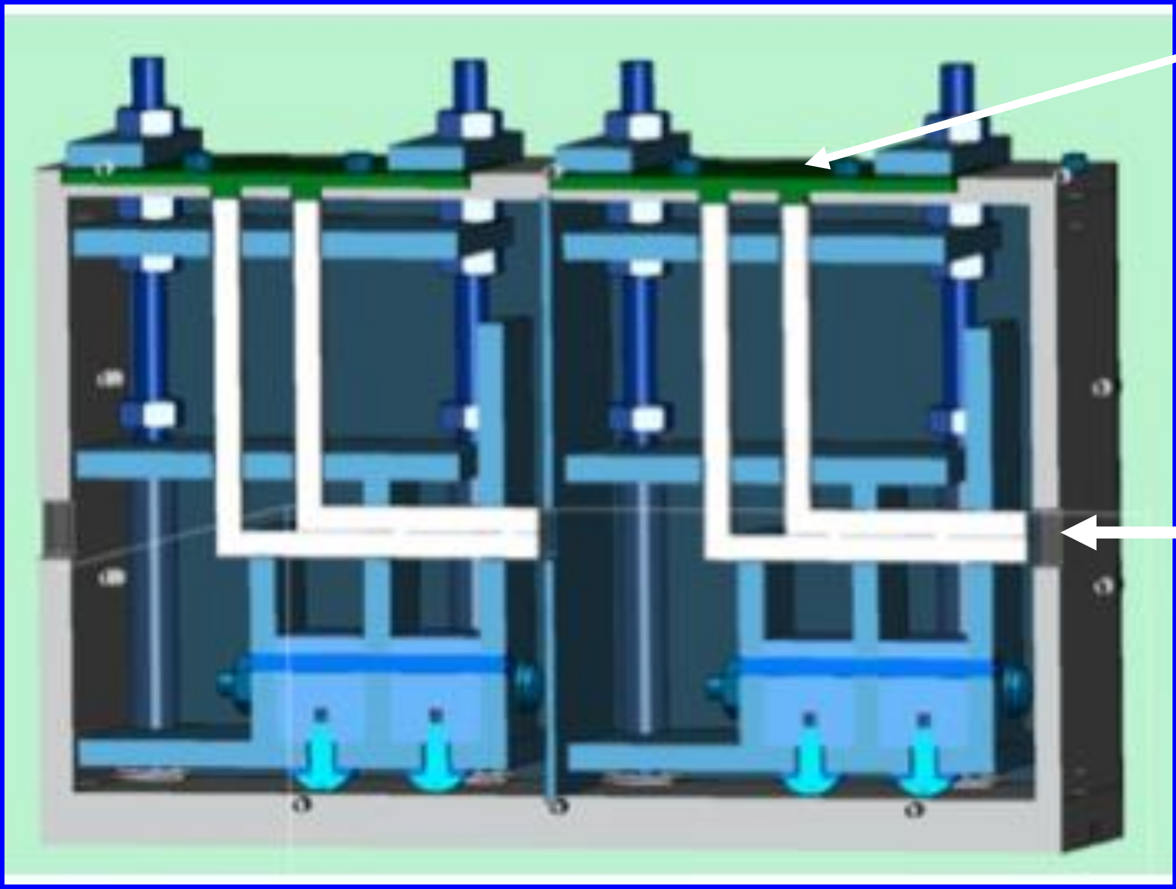


Radiator close to beam while photo-detector remote (and may be shielded)

NO MIRRORS

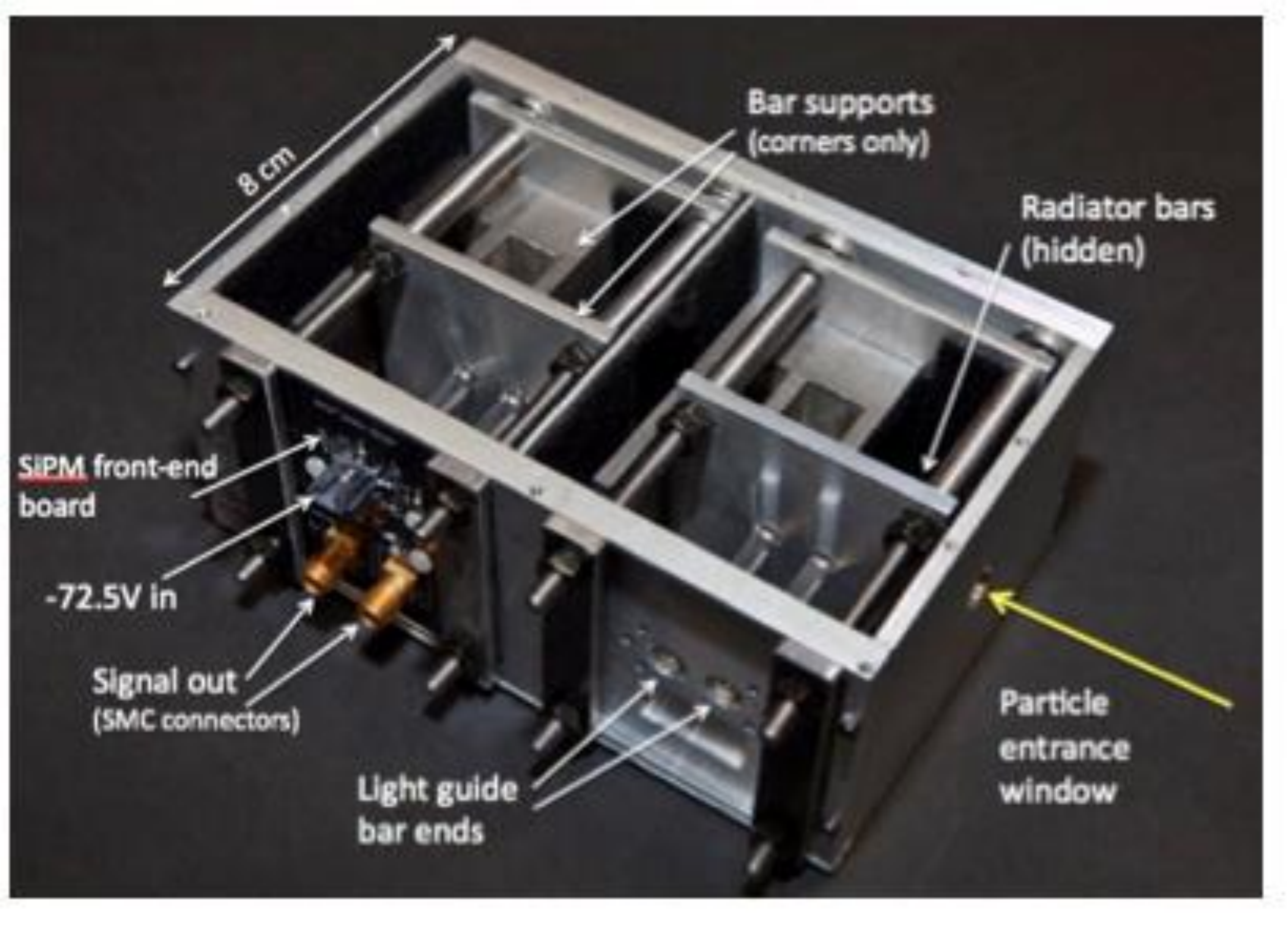
Hodoscope of 3mm x 3mm independent elements
Repeat N times in depth for sqrt{N} improvement (timetrack)
Finer segmentation eg 2x2 mm^2 possible in principle

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

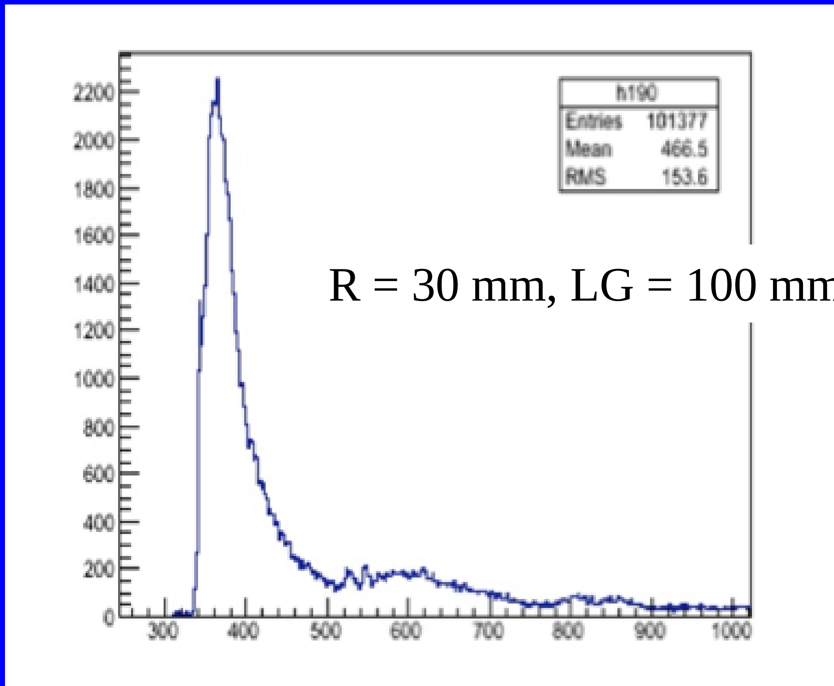


With a pair of these boxes, opened 3 cm gap and measured 100 ps shift

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



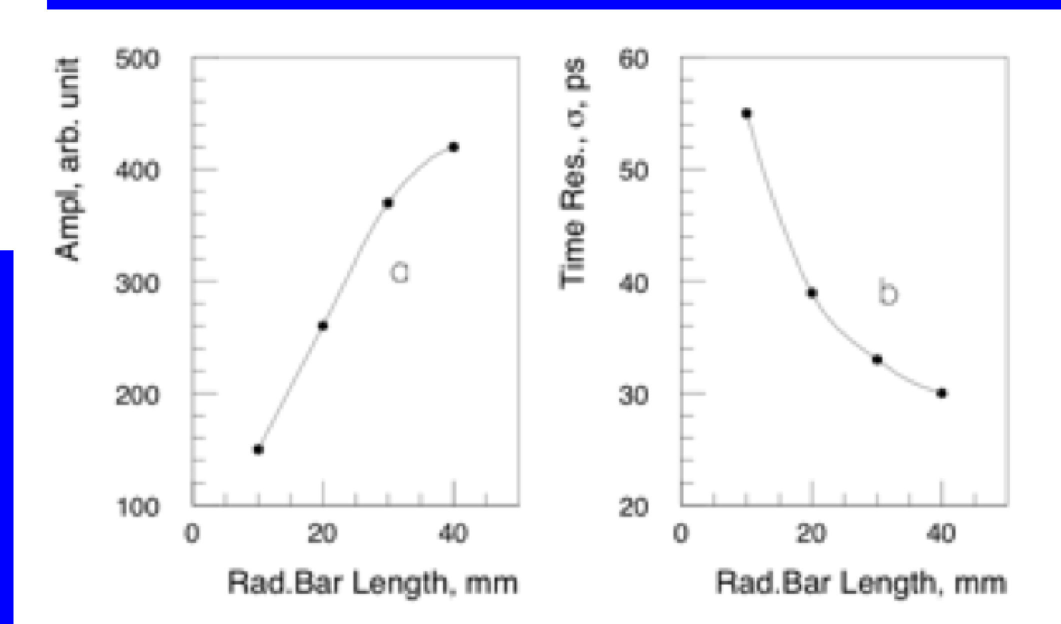
GEANT simulation (Vladimir Samoylenko): photoelectron time distribution



R = 30 mm, LG = 100 mm

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

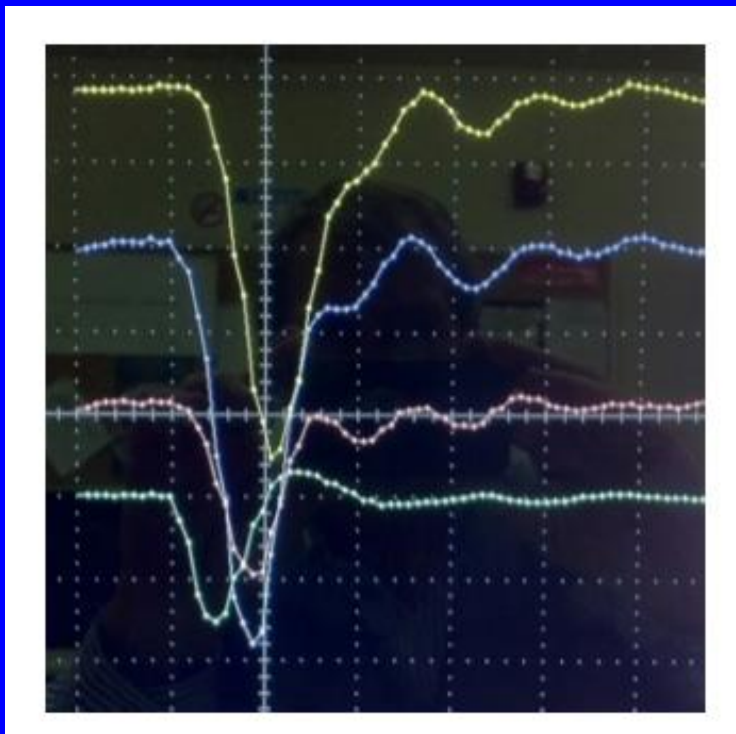
"More light beats more spread"



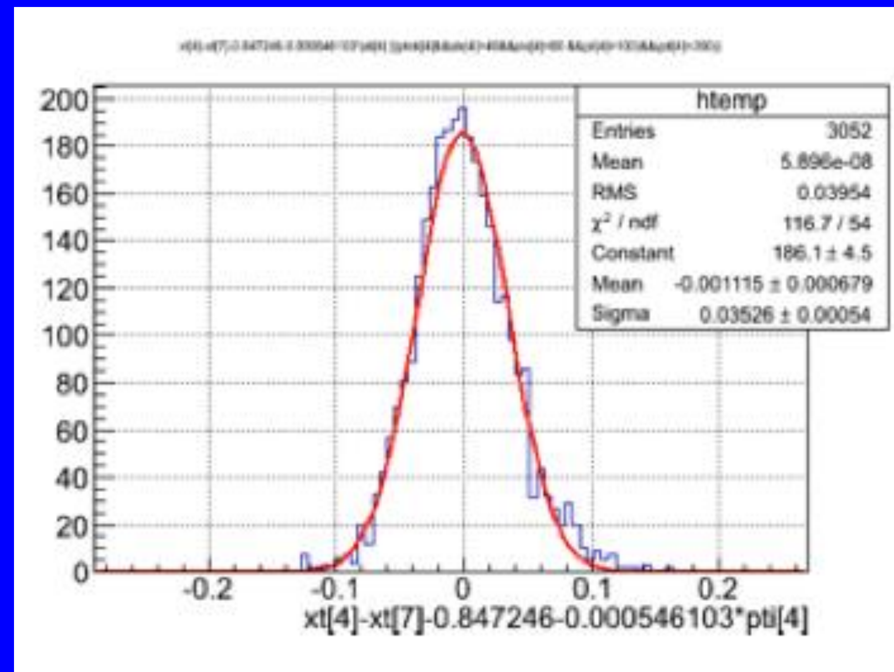
↑

Light back to front and back again. (Will have absorber gluing bars)

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



Δt (30mm bar – PMT240)

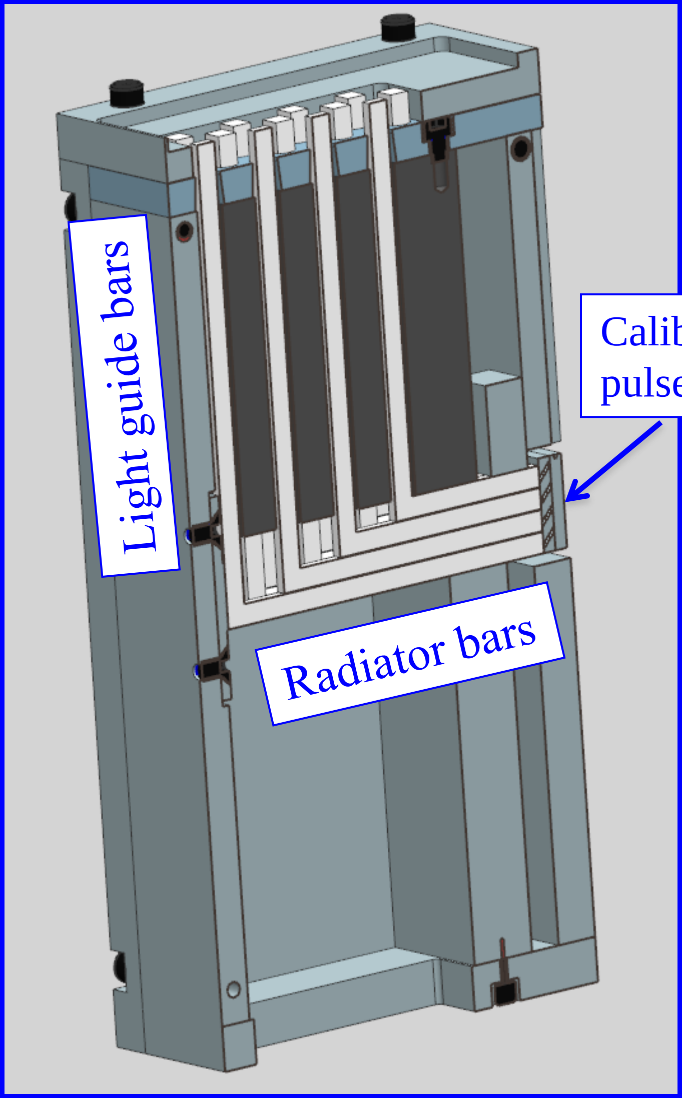


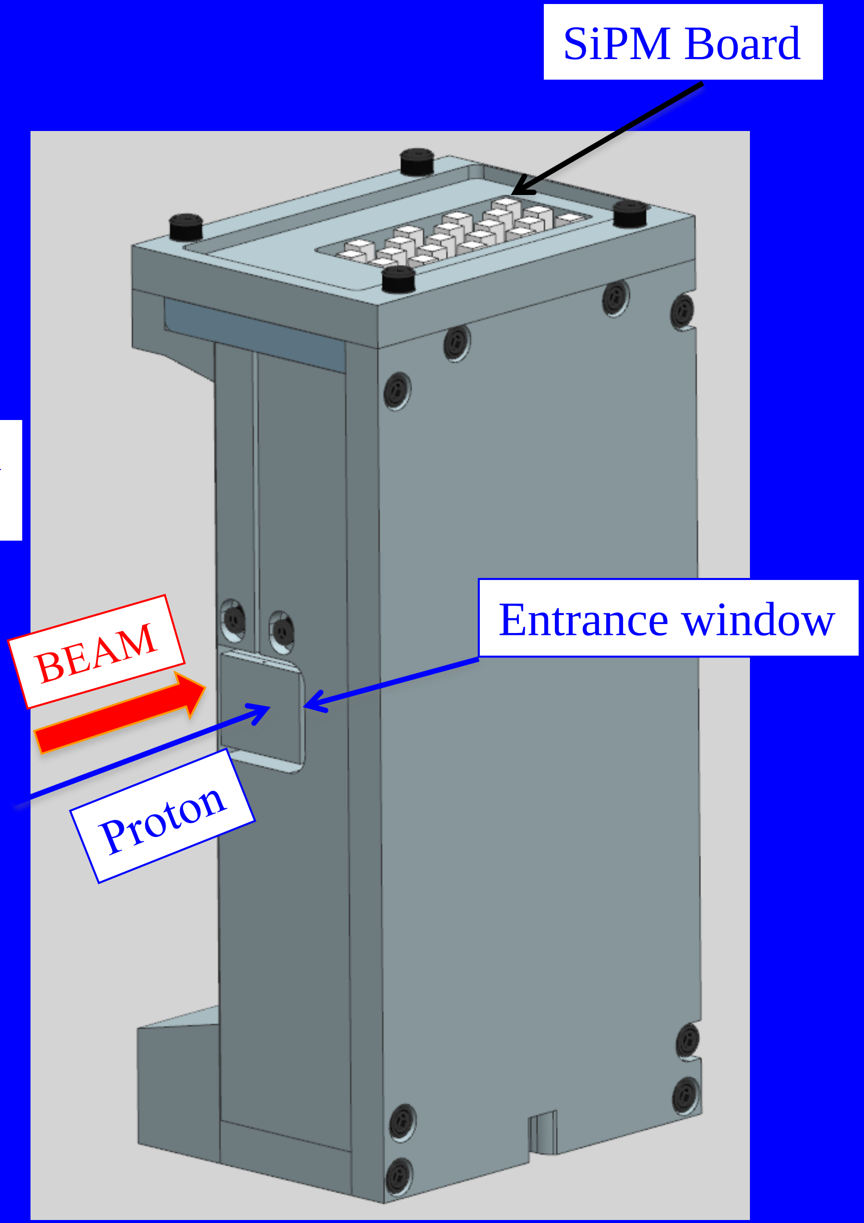
σ(t) = 31 ps for 30 mm bar
Four-in-line → 15 ps

Expected improvements: sapphire bars (+30%) & faster SiPMs (50%?)

QUARTIC: L-bar design, 4x5 channel Module

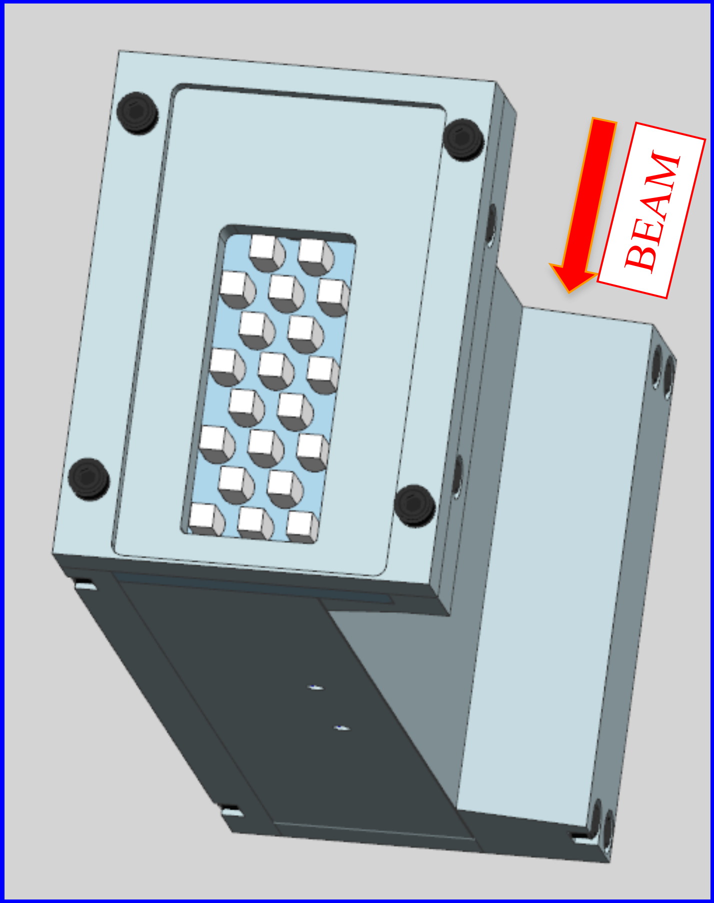
Vertical slice through:



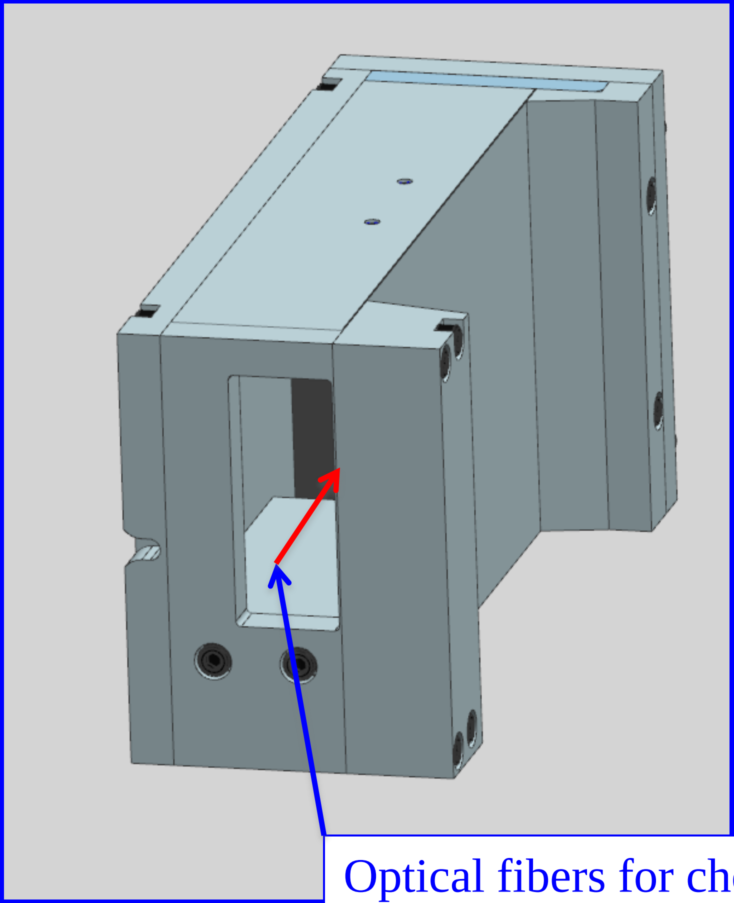


QUARTIC: L-bar design, 4x5 channel Module

Top view, SiPM array

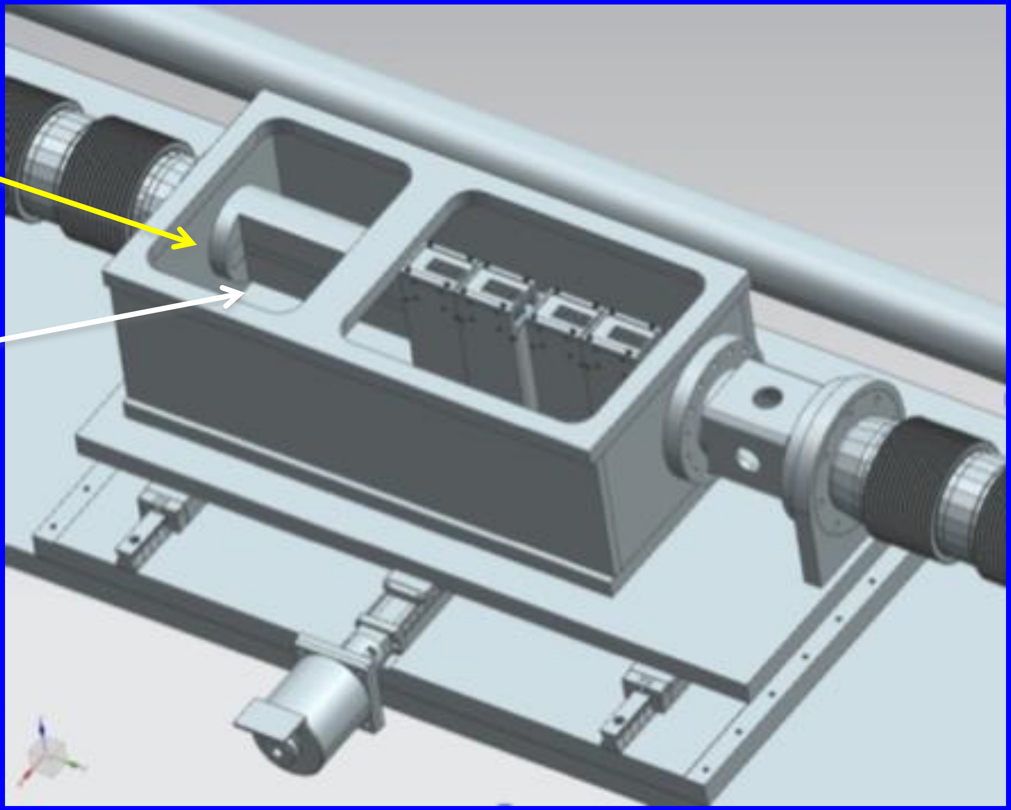


Bottom view, Calibration window



Optical fibers for check of light-guide bars + SiPMs

Arrangement of four QUARTIC modules with moving beam pipe

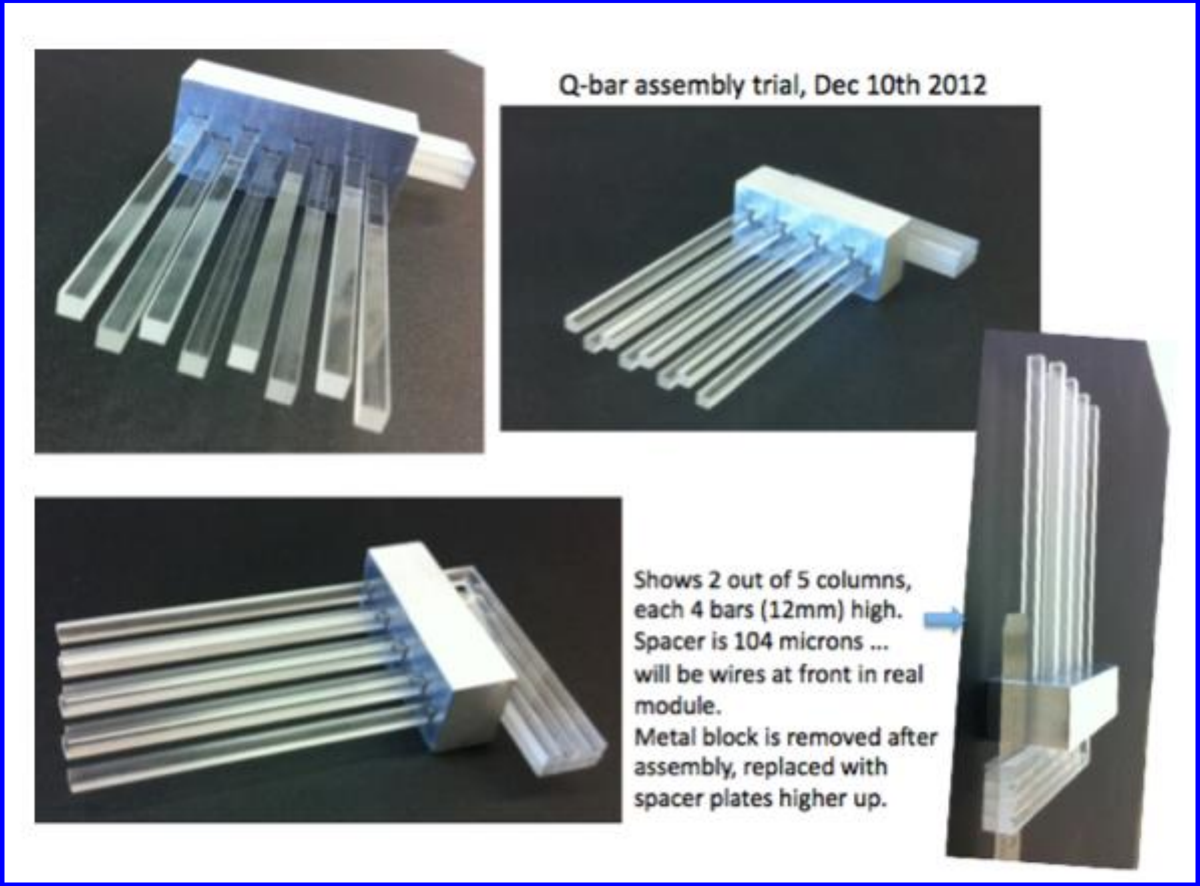


p

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

Construction method with 100 μm spacing and "no" * surface touching established.

* Bars glued at front face, spacers only on front 2 mm.



Light pulse (LED or psec laser) on fiber to glass diffuser plate → distribution to all bars. Monitor performance.

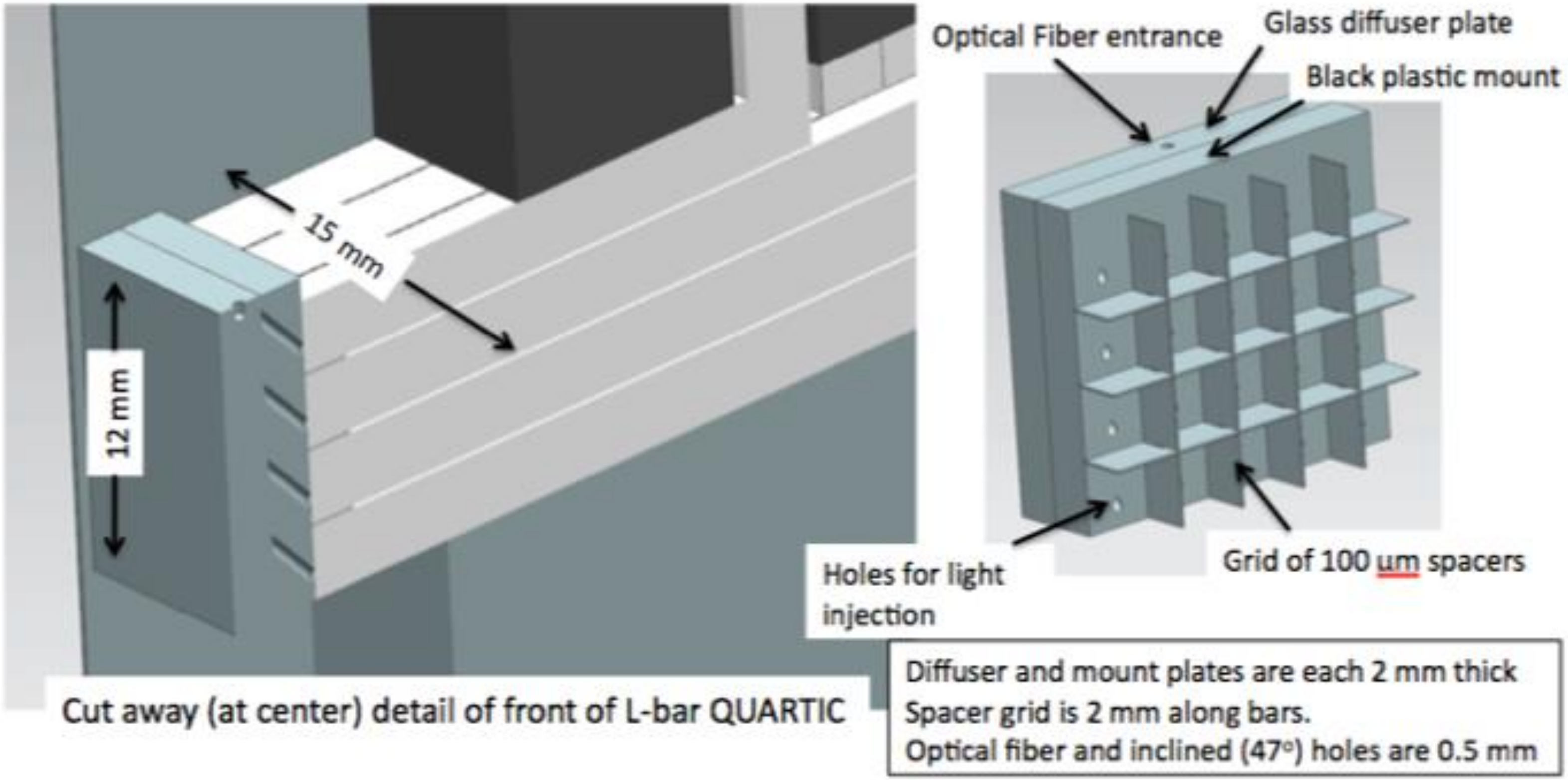


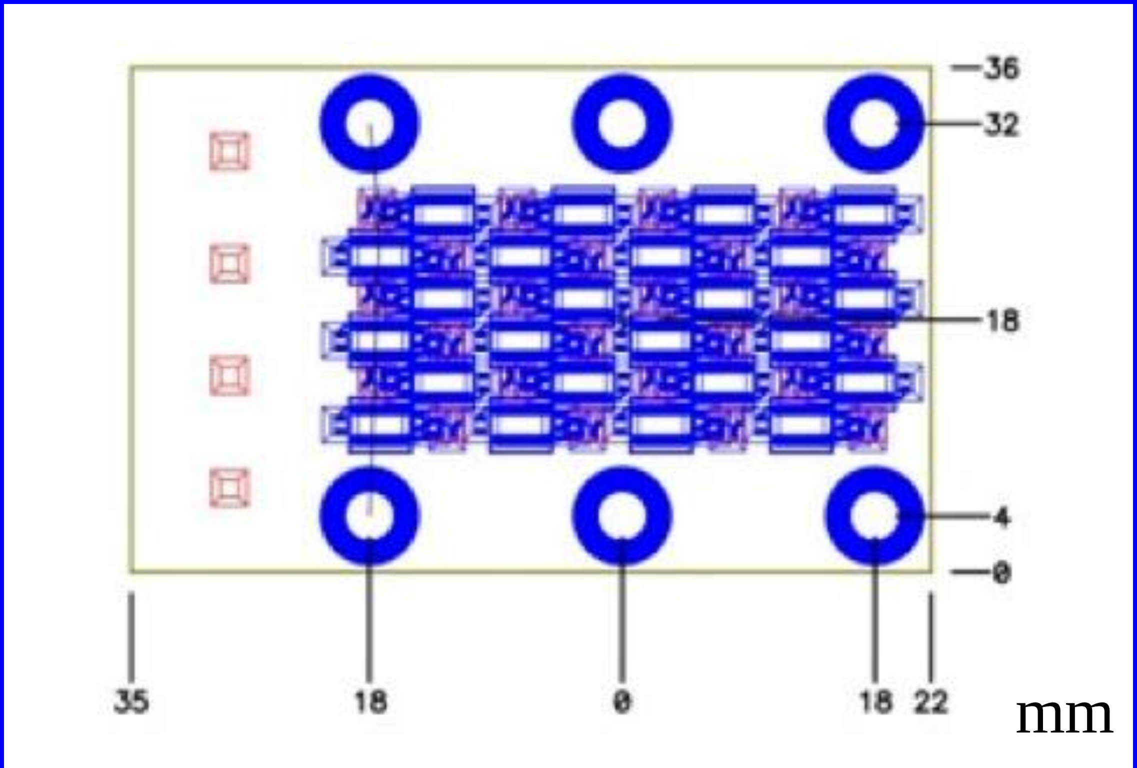
Figure 27: Quartec front end, showing spacer grid and calibration light injection scheme.

Above : R-bar + LG bar + SiPM monitored

Can also do LG bar + SiPM with additional input from below

Outline configuration of SiPMs on board.

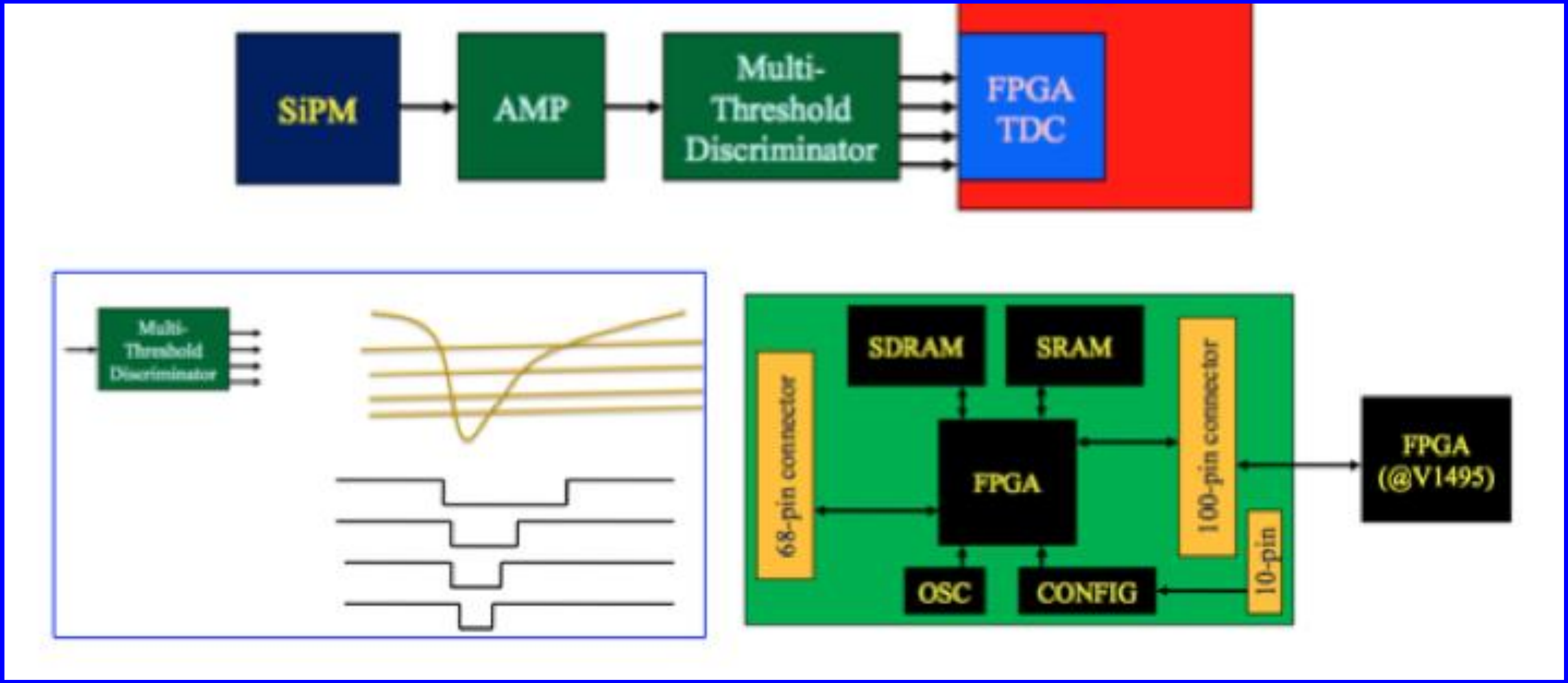
An MCP-PMT with this anode pattern could replace this, iff lifetime issues (# photoelectrons → ion feedback) solved



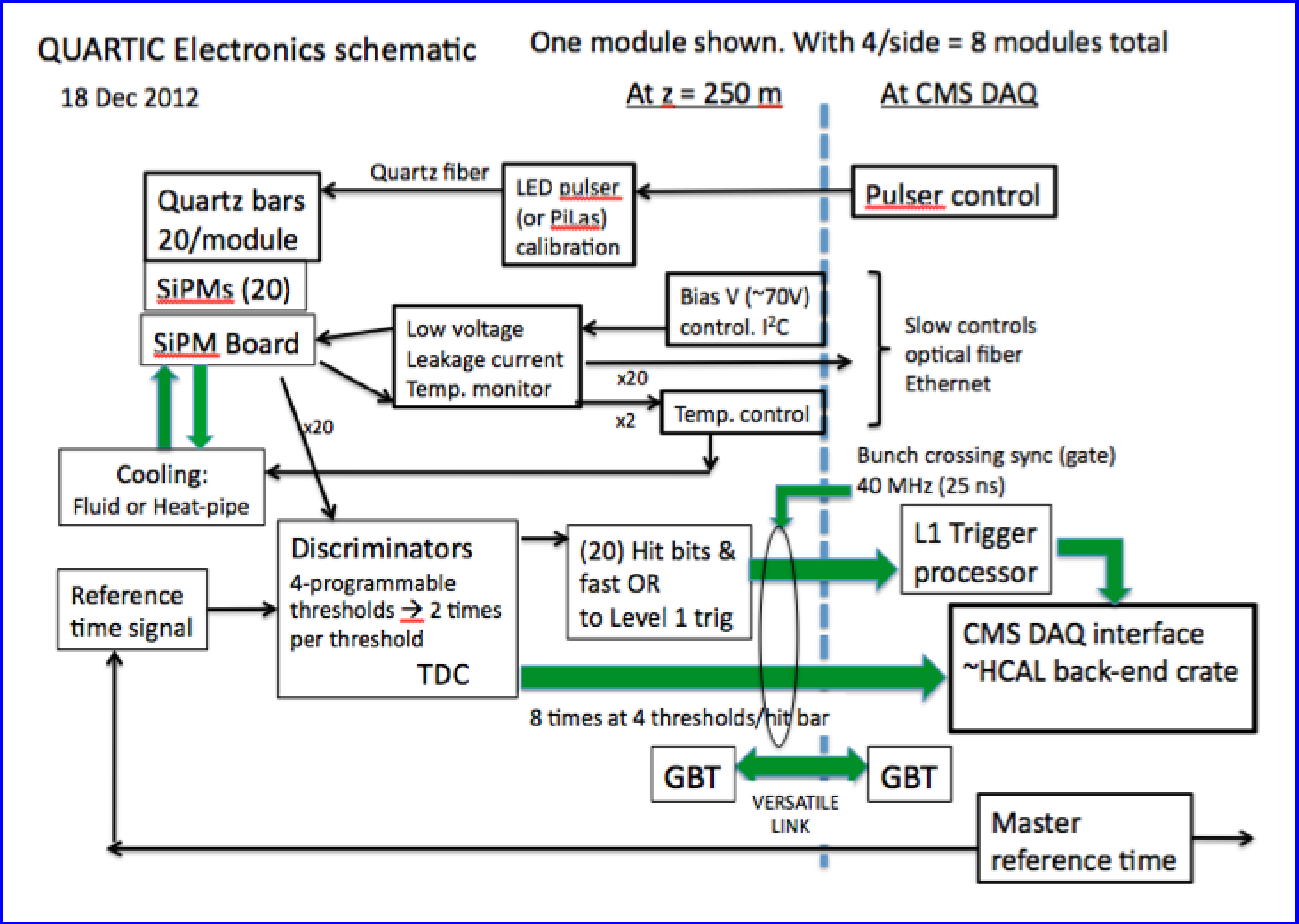
Board being designed (Sergey Los).
Individual SiPM V(~40V) and leakage current monitor, temperature control and readout, fast OR o/p

Fermilab (Jin-Yuan Wu) design: quad-threshold discriminator

Can individually program four thresholds,
recording 4 times on leading and 4-times on trailing edge
Designed and prototype being made. Expect $\sigma(t) \sim 10$ ps



Schematic of QUARTIC DAQ (Ronzhin. Los, Shaw)



Await positive decision from CMS MB, then funding: T_0
Module # 1 Assembly and test beam T_0 + 3 months

Optimization/decisions: quartz/sapphire, SiPM type, ...

Modules # 2(1) – 8 ~ 4 months later (~ 1 week/module)
So could be ready for LS1 installation if funded in time.

Two other PU rejection factors (in principle: futuristic!)

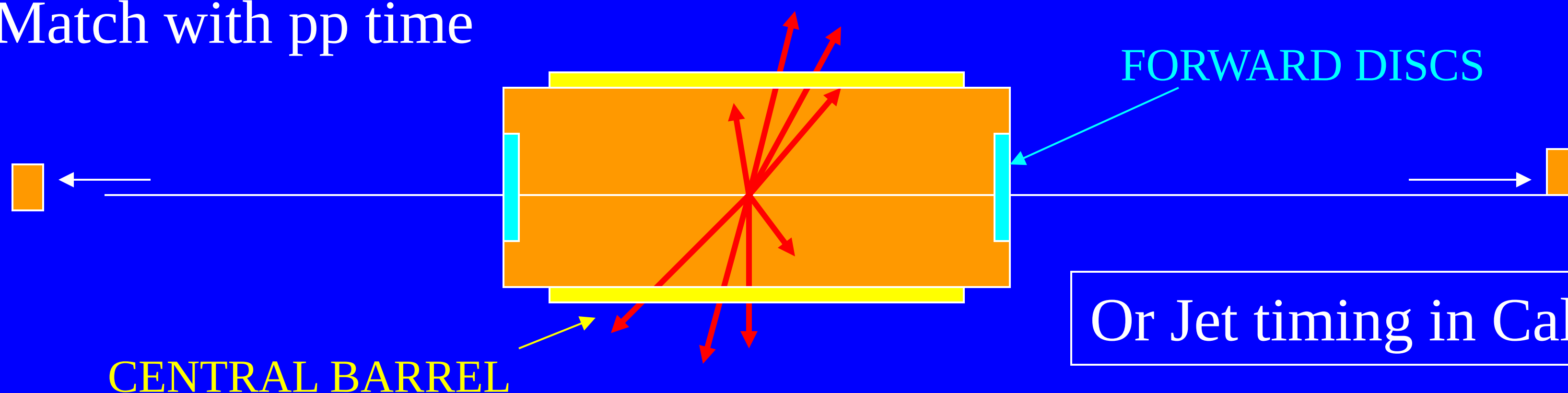
If large areas (many m^2) with ~ cm^2 pads, σ <~ 20 ps and thin

(Goal of ANL-Chicago-FNAL , Frisch inter alia group)

** Forward discs covering HF calorimeters, large $|\eta|$, ~ $1m^2$
e.g. 10^4 pixels of 1 cm^2, timing all tracks that hit it.
Reconstruct collision time of those events.
They are pile-up background : NO tracks from exclusive H go forward

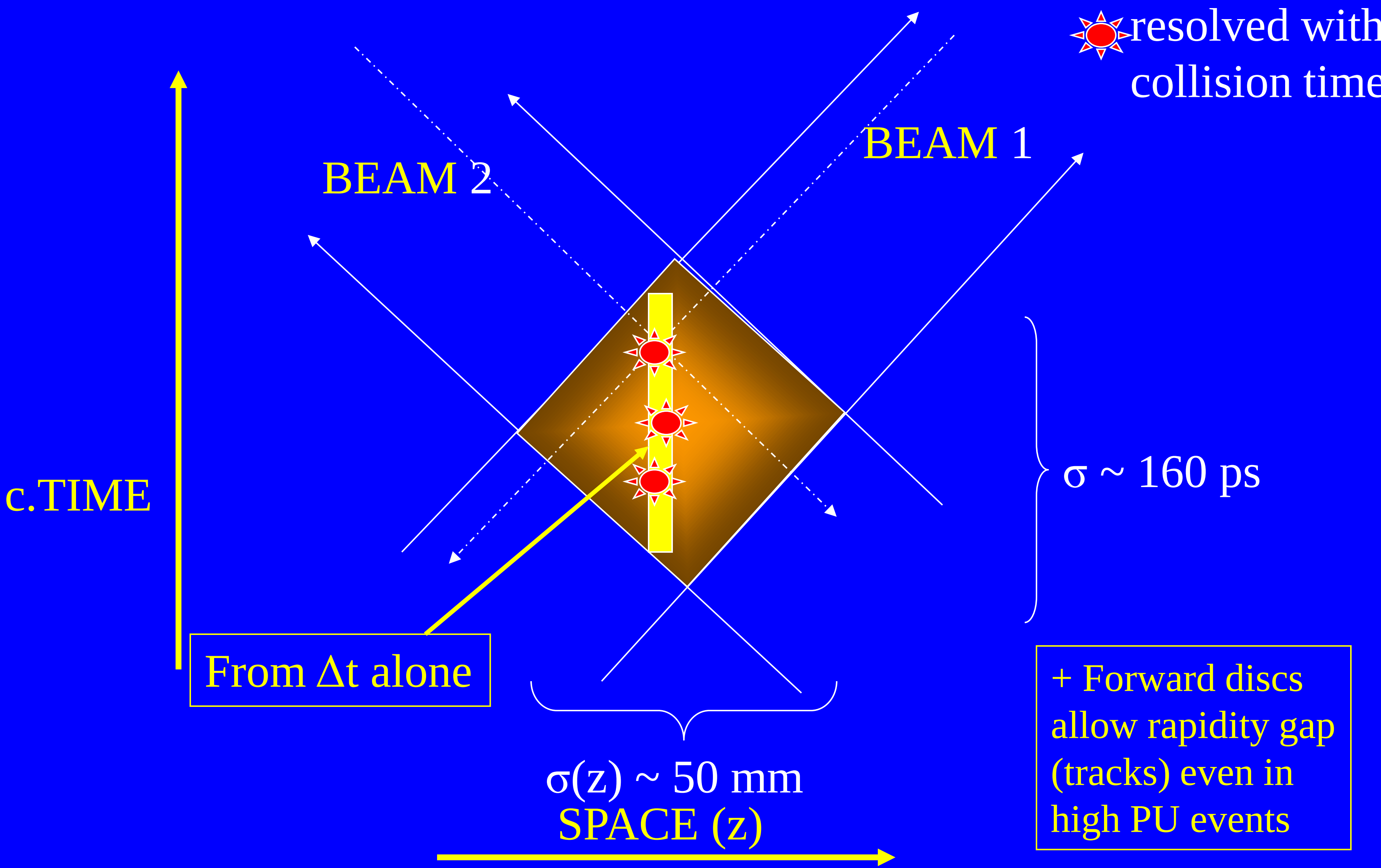
---

Central barrel (much larger)
Reconstruct collision time of dijet candidates
Match with pp time



Or Jet timing in Calo

Three timing techniques each give a good factor in rejecting PU



+ Forward discs allow rapidity gap (tracks) even in high PU events

Summary

Precision timing of protons ($t_L - t_R$) essential for AFP/HPS

Requirements are challenging but we have solutions:

Angled-bar QUARTIC with MCP-PMT
L-bar QUARTIC with SiPM array or MCP-PMT

Four-in-line L-bar is HPS 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.

Thank you

EXTRAS:

Reference Time System (Clock)

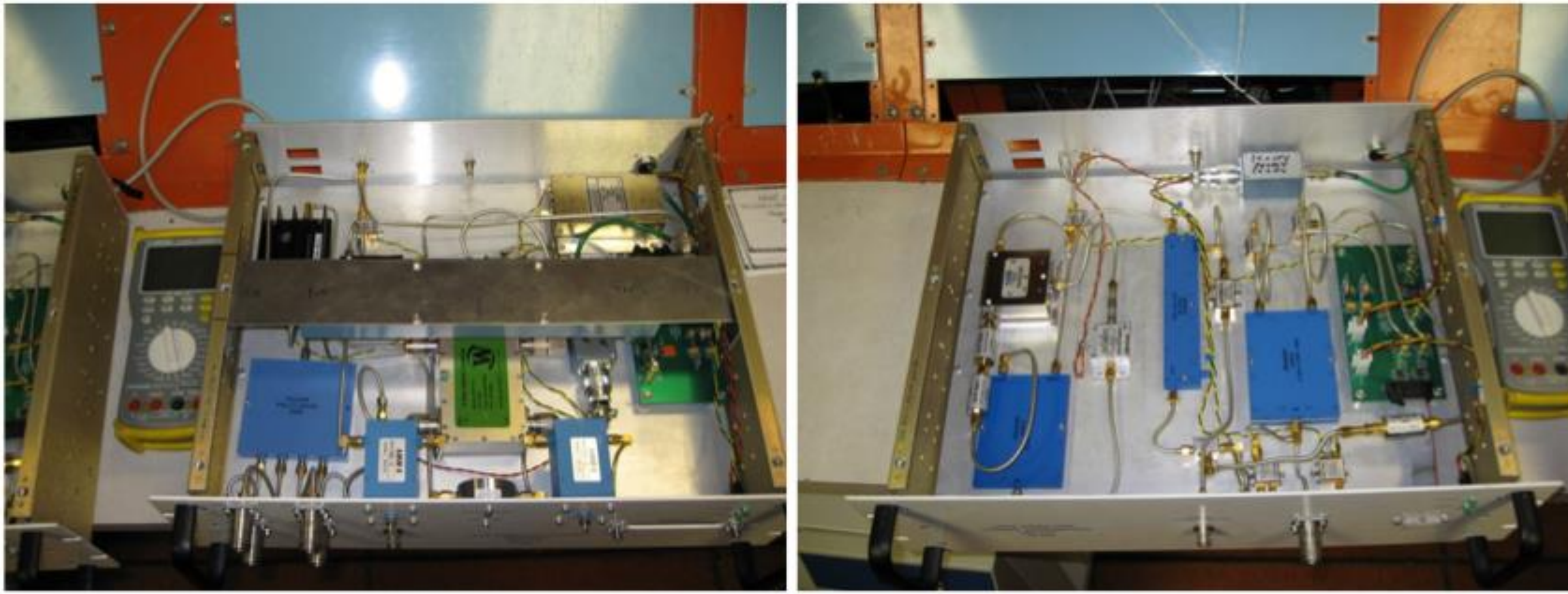


Figure 31: The master (left) and slave (right) RF components.