Future TOF detectors

J. Va' vra, SLAC

Marina Artuso:
…..would you be willing to give a presentation on challenge of particle identification for future applications, in particular the prospects and applications of new time of flight systems based on picosecond timing.

Content

- Present limits of electronics timing resolution.
- Present limits of detector timing resolution.
- Future developments in TOF detectors:

A few comments before I start

- One needs to know experimental conditions, which tends to eliminate many choices.
- There is a difference in your choices and overall performance goals if you cover an area of a few cm^2 with a few channels, or 10-15 m^2 with 150,000 channels.
- Is the Waveform digitizing electronics better way to go than the analog CFD-based electronics ?

Major limit: experimental conditions

~~SuperB~~ & BelleII:

- L ~ 10^{36} cm^{-2} sec^{-1}

- Total neutron doses: ~10^{12} /cm^2 after 10 years
- Total Gamma doses : ~5x10^{11} /cm^2
- Total charged particle doses : ~5x10^{11} /cm^2
- Bhabha rate per entire detector: ~100 kHz

LHC ATLAS central region

- Total neutron doses: ~10^{14} /cm^2 after 10 years
- Total charged particle doses : ~10 MRads
- Total charged particle rate : ~10^5 /cm^2 sec
- Total photon rate : ~10^6 /cm^2 sec
- Total neutron rate : ~10^6 /cm^2 sec (~1 m from IP)

STAR exp. Au + Au coll.:

- Collision rate: ~ 1kHz
- Multiplicity of tracks: ~10,000/event
- Rate of tracks in TOF detector: ~50-100 Hz/cm^2

ALICE Pb + Pb coll.:

- Multiplicity of tracks: ~10,000/event
- Rate of tracks in TOF detector: ~50-100 Hz/cm^2

TORCH exp. in LHCb:

- MCP-PMT detector rate: ~10 MHz/cm^2
- Total rate per entire quartz detector: ~10^{11} photons/sec

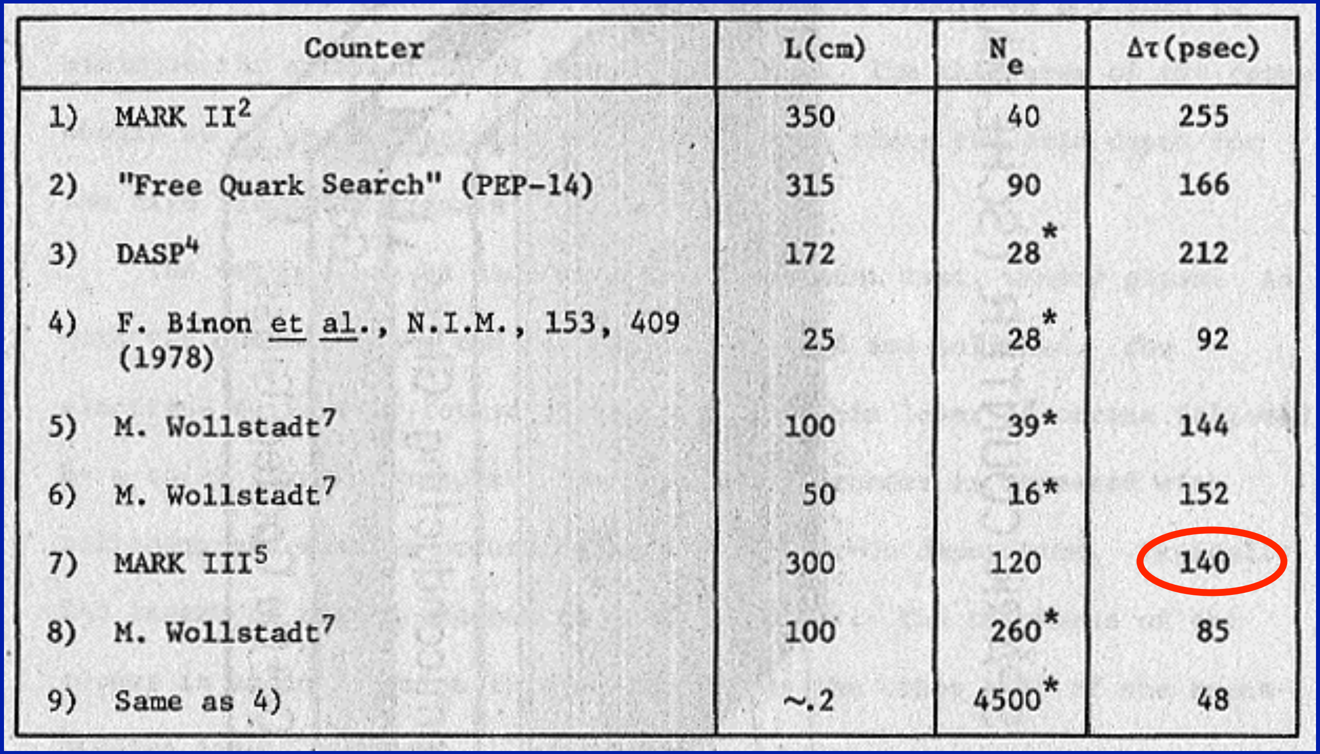
LHC pp diffractive scatt.

- L ~ 10^{34} cm^{-2} sec^{-1}

- Total neutron doses: ~10^{12} /cm^2 /year (???)
- Total charged particle doses: ~10^{14} /cm^2/year
- Proton rate in the inner radiator: ~10-15 MHz/cm^2
- Total charge: < 30 C/cm^2/year in worst pixel
- Expected current: < 3.3 μA/cm^2 in worst pixel

30-years ago …

W. Attwood, SLAC Summer Institute, SLAC-PUB-2620, October 1980.



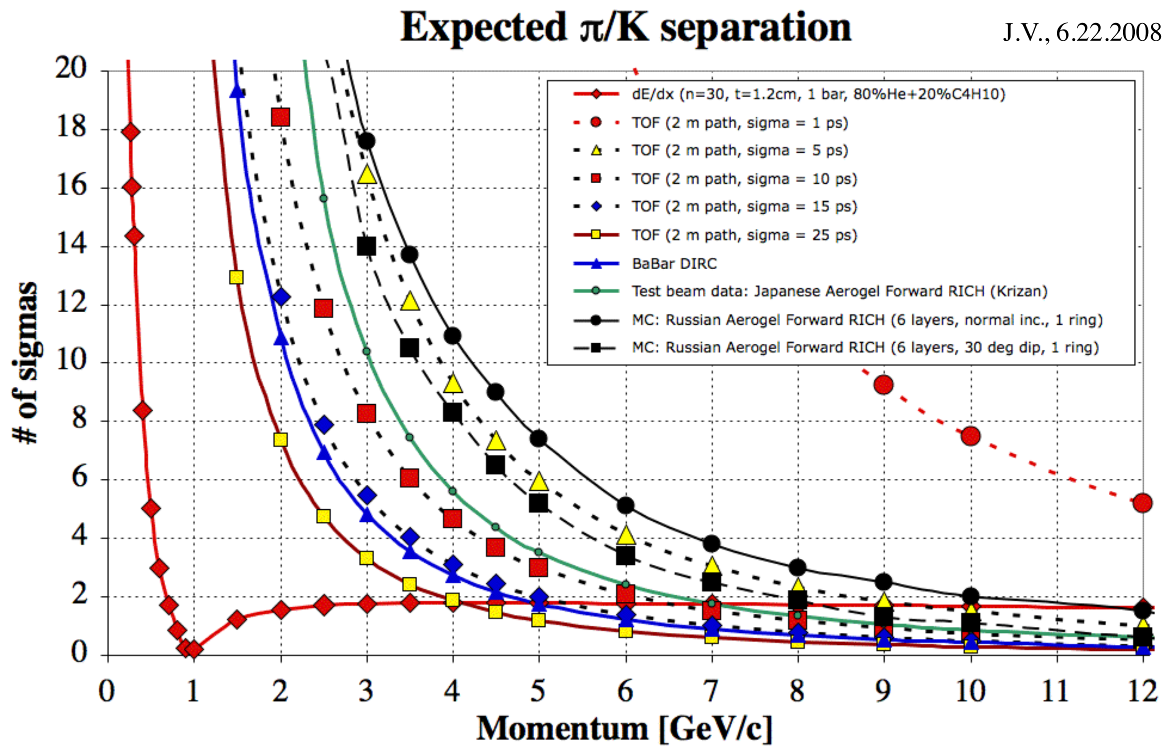
Counter	L(cm)	N_e	$\Delta\tau$(psec)
1) MARK II[2]	350	40	255
2) "Free Quark Search" (PEP-14)	315	90	166
3) DASP[4]	172	28*	212
4) F. Binon *et al.*, N.I.M., 153, 409 (1978)	25	28*	92
5) M. Wollstadt[7]	100	39*	144
6) M. Wollstadt[7]	50	16*	152
7) MARK III[5]	300	120	140
8) M. Wollstadt[7]	100	260*	85
9) Same as 4)	~.2	4500*	48

- 30 years ago TOF detectors used scintillators typically.
- Today, to improve the TOF resolution significantly, one has to use a quartz radiator producing the Cherenkov light. The new "TOF counters" measure a combination of time and photon position, where both time and position are together in the maximum likelihood.

Perspective TOF vs. other PID methods

J. Va'vra, SuperB meeting, 2009, SLAC (file: dE_dx = f(beta_gamma) study.xls)

Calculated for SuperB detector:

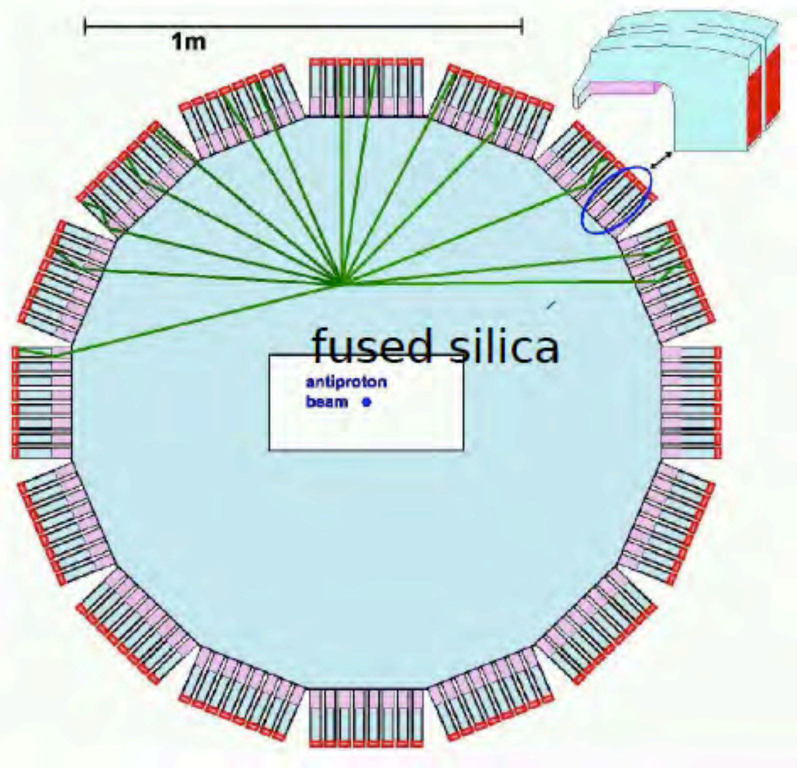


- **<u>For ~2 meter long path</u>, i.e., forward region, a TOF detector needs to achieve a ~ 15 ps timing resolution to compete with the BaBar DIRC, but ~5 ps to compete with Aerogel RICH (FARICH).**
- **<u>For ~1.2 meter long path</u>, i.e., barrel region, a TOF detector needs to achieve a ~10 ps timing resolution to compete with the BaBar DIRC.**
- **To compete with RICH detectors, a TOF counter has to be a DIRC-like.**

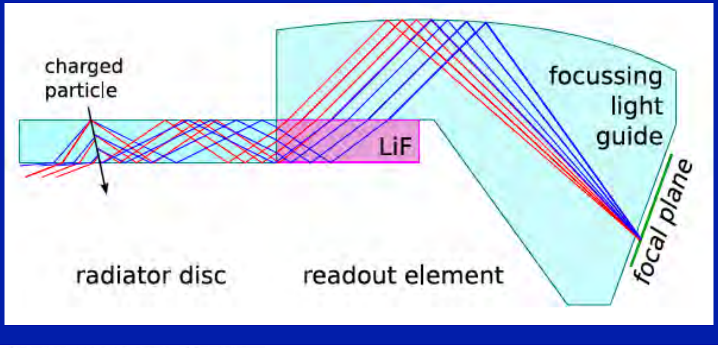
Example of 3D aspect in DIRC-like detector: Panda Disc DIRC

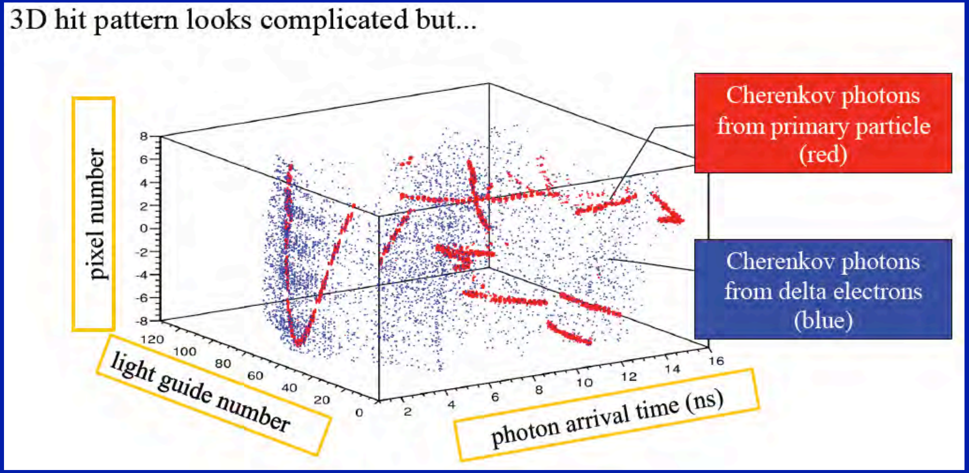
Panda Forward DIRC:

J. Schwiening for Panda collaboration, TIPP 2011



Hardware correction of chromatic broadening:





- **The first DIRC-like detector to correct the chromatic error by optics.**
- **Time is important in these devices to reject background and to do 3D reconstruction. Goal: σ ~50-100 ps. Detector: MCP-PMTs.**

The point

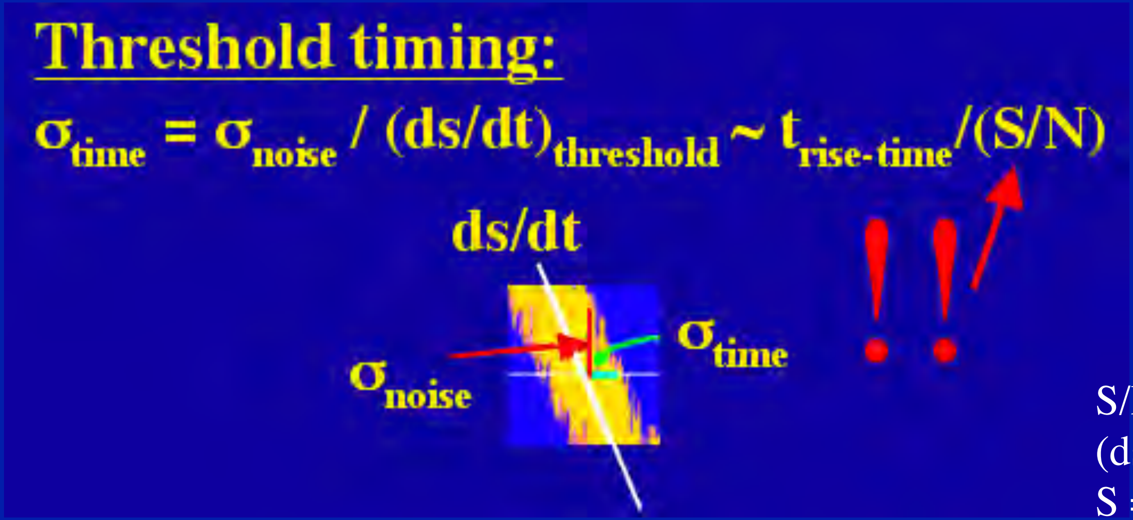
- **Future TOF detectors do not use scintillators ano more. People are moving towards DIRC-like detectors, where one measures x-y coordinate together with time for each photon, and forms a maximum likelihood. In this way one starts approaching a RICH detector performance, and "equivalent" timing performance at a level of 10-15 ps. However, a word of caution: these devices are complicated to use and understand. But many people are working on it !**

- **Pixilated TOF detectors are easier to use and analyze, but they may not reach as high timing resolution, at least presently.**

Present limits of electronics resolution

Timing resolution limit

V. Radeka, RICH 2004 talk,
H. Spieler, Semiconductor Detector systems, Oxf. Univ. Press, 2005, ISBN 0-19-852784-5.
(Jeff Peck: well-known formulas to communication designers for a long time)



Threshold timing:

$$\sigma_{time} = \sigma_{noise} / (ds/dt)_{threshold} \sim t_{rise\text{-}time}/(S/N)$$

$S/N = S/\ \sigma_{noise}$
$(ds/dt)_{threshold} \sim S\ /\ t_{rise\text{-}time}$
S = signal amplitude
$N = \ \sigma_{noise}$

Two requirements, which require a careful investigation:

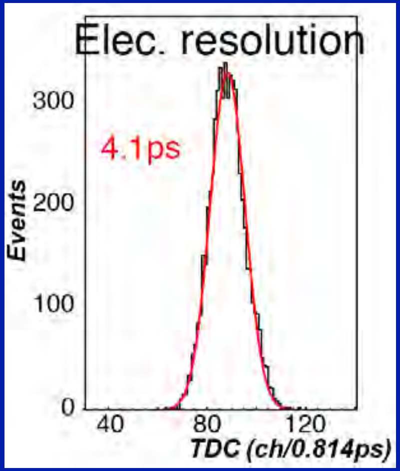
1) The amplifier bandwidth should match the detector rise time.

2) To obtain a good σ_{time} one needs both a good S/N and bandwidth ($t_{rise\text{-}time}$) !

Limit of electronics resolution

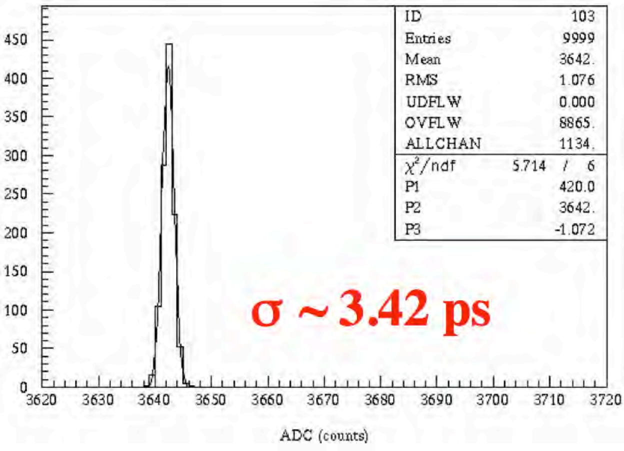
1) Becker&Hickl SPC-134:

(K. Inami et al, NIM A560(2006)303-308)



2) Ortec 9327 1GHz Amp/CFD + 566 TAC + 114 ADC:

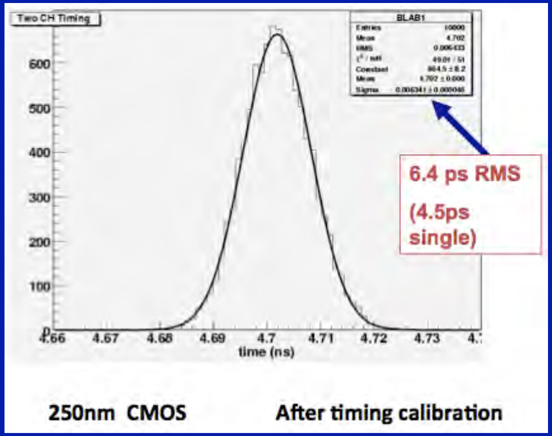
(J. Va'vra, bench top test, MCP log book 4, page 82, 4.4.2007)



σ ~ 3.42 ps

3) Hawaii Labrador-3 waveform digitizer:

(G. Varner et al., NIM **A602** (2009) 438)



6.4 ps RMS

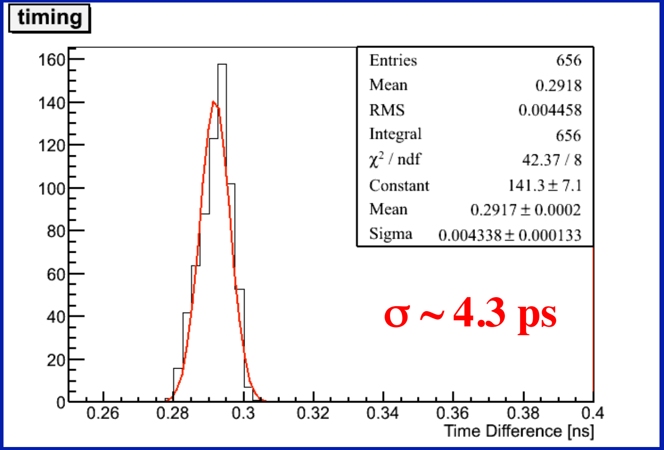
(4.5ps single)

250nm CMOS

After timing calibration

4) LAPPD PSEC-4 waveform digitizer:

(Eric Oberla, U. Chicago, 2012 - obtained from G. Varner)

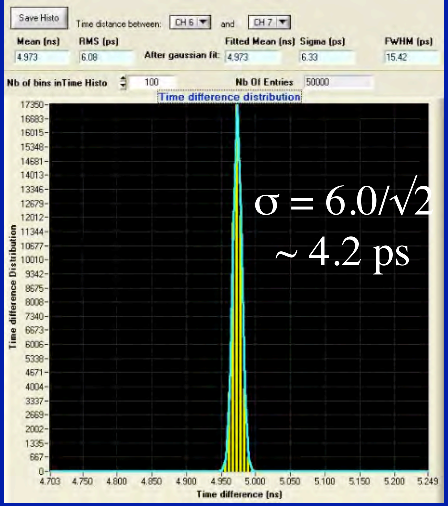


σ ~ 4.3 ps

Limit of electronics resolution

5) WaveCatcher waveform digitizer:

(E. Delagnes and D. Breton, LAL, Orsay, France)



Save Histo

Time distance between: CH 6 and CH 7

Mean (ns): 4.973

RMS (ps): 6.08

After gaussian fit: Fitted Mean (ns): 4.973 Sigma (ps): 6.33 FWHM (ps): 15.42

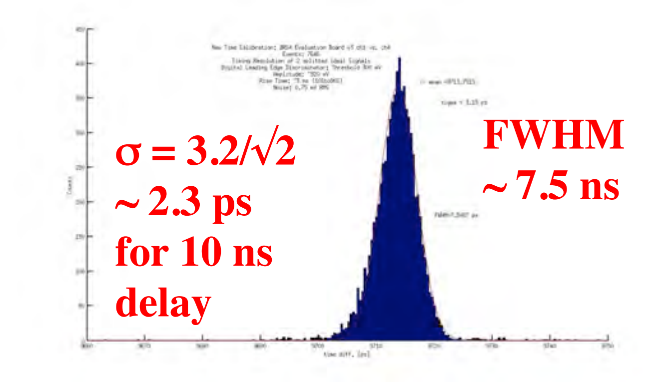
Nb of bins inTime Histo: 100

Nb Of Entries: 50000

σ = 6.0/√2 ~ 4.2 ps

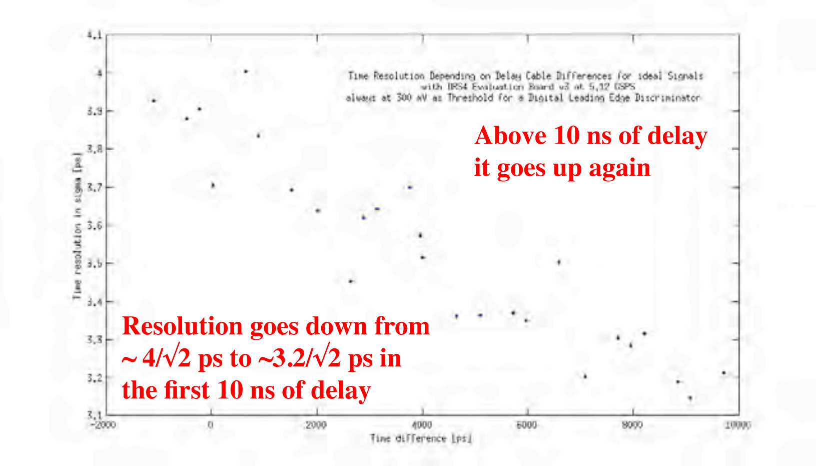
6) DRS-4 waveform digitizer:

(Stefan Ritt, Paul Scherrer Institute, Switzerland, 1/14/2013)



σ = 3.2/√2 ~ 2.3 ps for 10 ns delay

FWHM ~ 7.5 ns

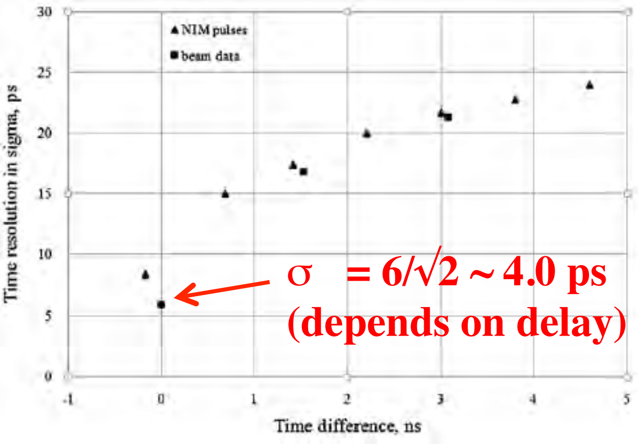


Above 10 ns of delay it goes up again

Resolution goes down from ~ 4/√2 ps to ~3.2/√2 ps in the first 10 ns of delay

7) DRS-4 waveform digitizer:

(A. Ronzhin et al., Fermilab, NIM A 668 (2012) 94–97)



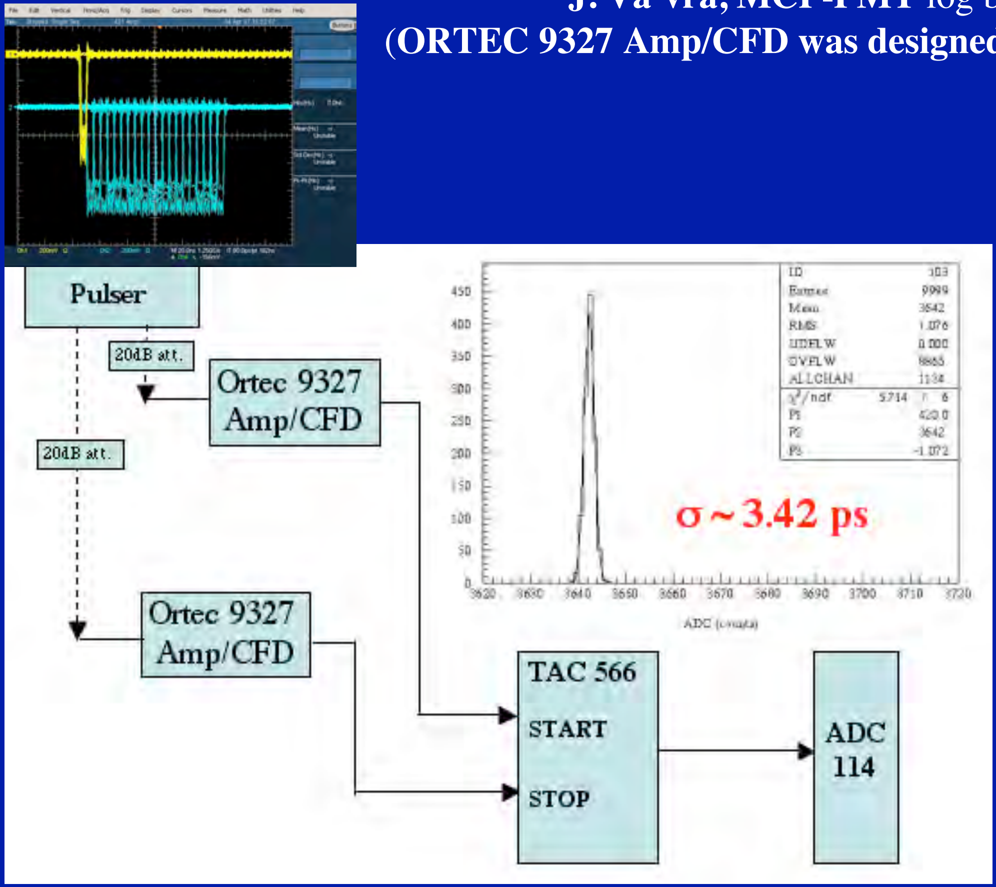
σ = 6/√2 ~ 4.0 ps (depends on delay)

- Waveform digitizing electronics limit seems to be σ ~ 2.3 ps for 10 ns delay at present.

Electronics resolution of 9327Amp/CFD

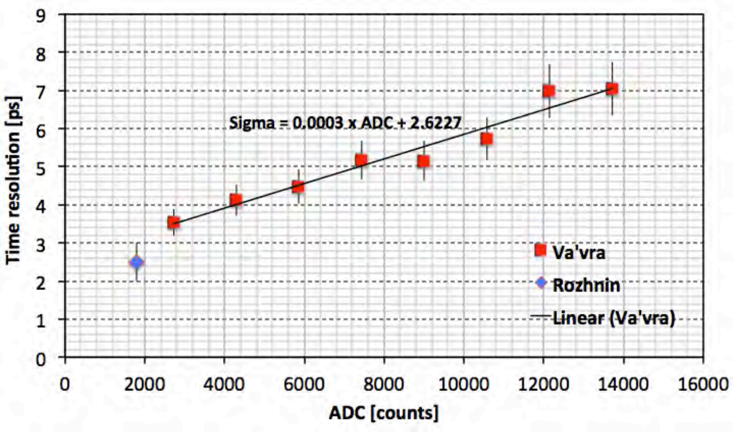
J. Va'vra, MCP-PMT log book #4, page 82

(ORTEC 9327 Amp/CFD was designed in the 1990's by Jeff Peck)



Resolution depends on ADC value:

(Jeff Peck: this indicates the limit is in the TAC/ADC rather than CFD. The TAC architecture integrates a current source over the time interval. The longer the current source is turned on, the longer errors can accumulate and hence the degrading resolution with increasing ADC bin position.)



- **Fermilab people achieved <u>σ ~ 2 ps with this electronics</u> (A. Ronzhin et al., NIM A 623 (2010) 931–941). <u>This makes it the best result I know about.</u>**
- **Jeff Peck: <u>9327 Amp/CFD can reach ~2 ps resolution</u>, if one avoids the TAC and chooses a better pulser.**

Present timing resolution limits

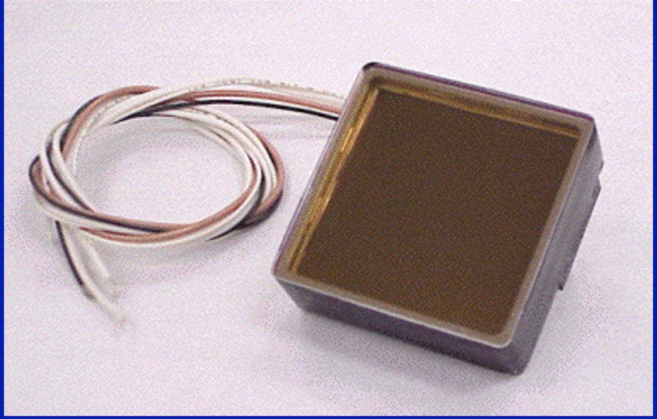
- MCP-PMTs
- HAPD
- SiPMTs

Examples of MCP-PMT tubes used for TOF

HPK-6 (single pad):

Photek 210 & 240 (single pad):

Photonis 10 & 25 (64 pads):



HPK SL-10 (4 pads):

TTS resolution of some MCP-PMTs

Data from Hamamatsu[+], Burle/Photonis, Photek*,
and from K. Inami (Nagoya) [a], J. Va’ vra (SLAC) [b], A.Lehman [c], A.Brandt (Arlington) [δ], A.Rozhnin (Fermilab) [e]

MCP-PMT	# of anodes	# of MCPs	MCP size	Hole [μm]	QE [%]	Photocathode	TTS [ps]	Rise time [ps]
HPK 6	1	2	ϕ11mm	**6**	26	Multi-alkali	**~11 [+]**	**< 150 [+]**
HPK 10	1	2	ϕ25mm	**10**	26	Multi-alkali	**< 35 [a]**	**< 200**
HPK SL-10	4	2	22x22	**10**	24	Multi-alkali	**< 30 [a]**	**< 200**
BINP 8	1	2	ϕ18mm	**8**	18	Multi-alkali	**< 27 [c]**	**< 200**
Photonis 10	64	2	49x49	**10**	24	Bi-alkali	**< 30 [b]**	**< 200**
Photonis 25	64	2	49x49	**25**	24	Bi-alkali	**< 40 [b]**	**< 250**
Photek 110	1	1	ϕ10mm	**3.2**	30	Multi-alkali	**?**	**~70 ***
Photek 210	1	2	ϕ10mm	**3.2**	30	Multi-alkali	**< 25 [d, e]**	**~81 ***
Photek 210	1	2	ϕ10mm	**6**	30	Multi-alkali	**?**	**~95 ***
Photek 240	1	2	40mm	**10**	30	Multi-alkali	**?**	**~180 ***

HPK6 is R3809U-50-11X, HPK10 is R3809U-50-25X,
SL-10 is R10754-00-L4 in Hamamatsu catalog

To get the best out of these tubes one may have to develop a new fast electronics

TTS resolution = f (amplifier bandwidth) for 10 µm Planacon

J.Va' vra, MCP-PMT log book 3, 2006

Amplifier type	Amplifier bandwidth [GHz]	Total voltage gain	Signal /Noise S/N	CFD type	TTS Resolution σ_{narrow}, σ_{wide} [ps]	Comment
Ortec VT120A + 6dB attenuator	0.35	100x	450:1	Phillips 715	32 , 100	The best result
Hamamatsu C5594-44	1.5	63x	300:1	Phillips 715	32 , 136	Very good (a bit worse tail)
Ortec 9306	1.0	100x	50:1	Ortec 9307	43 , 134	Not bad (worse S/N)
THS 4303 (Tandem of 2 chips)	1.8	30-40x	25:1	Phillips 715	38 , 159	Worse
Philips BGA2712 (Tandem of 2 chips)	3.2	10x10	25:1	Ortec 9307	37, 110	Worse

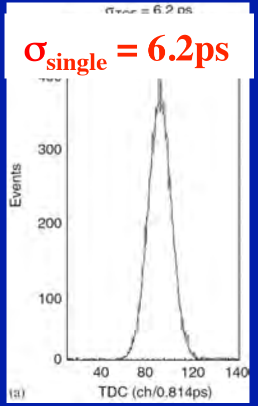
- **In the "~30ps timing resolution domain", and 10 µm hole MCP-PMT, increasing bandwidth did not help as the S/N ratio is worsening.**

Two identical detectors directly in the beam

Two **HPK6** (6 μm holes, vary radiator length)
(K. Inami et al, NIM A560(2006)303-308)

10 + 3mm (radiator plus window)

High gain of ~10^6 :

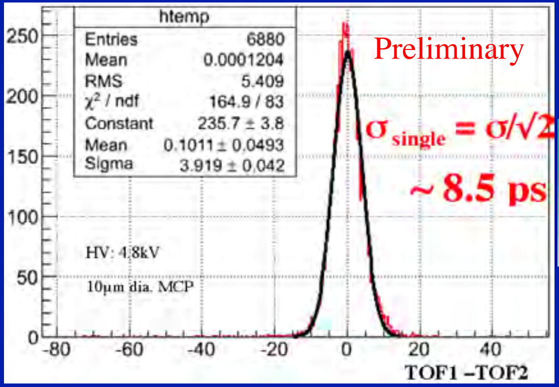


HPK6

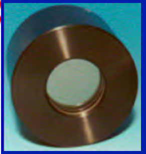
Two **Photek 240** (10 μm holes, window is radiator,)
(M. Albrow, A .Ronzhin, E. Ramberg, to be published)

9.6 mm window only

High gain of ~10^6 :



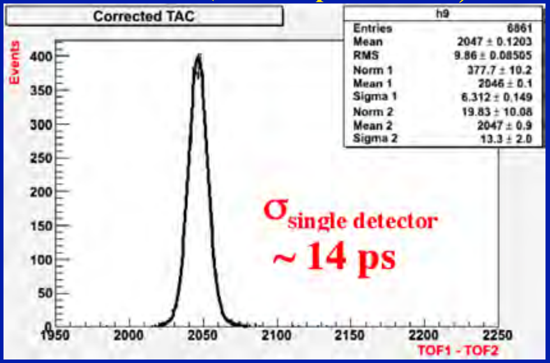
Photek 240



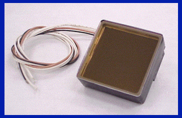
Two **Planacons** (10 μm holes, 10mm long radiator)
(J. Va' vra, A.Ronzhin, et al, Fermilab test, NIM A606(2009)404-410)

10 + 2 mm (radiator plus window)

Low gain of 2x10^4 :



Planacon 10

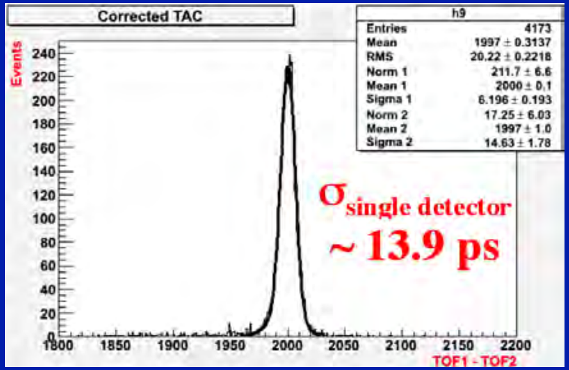


(Low gain to limit the single pe background at SuperB)

Two **Planacons** (25 μm holes, 6mm long radiator)
(A.Ronzhin, E.Ramberg, J.Va' vra et al., Fermilab test, unpublished)

6 + 2 mm (radiator plus window)

High gain of ~10^6 :



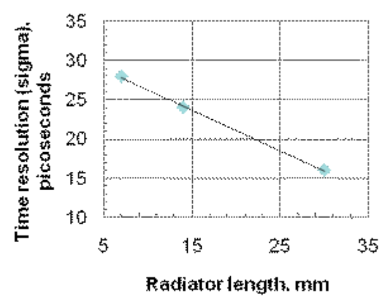
Planacon 25

(This tube had much larger number of photoelectrons)

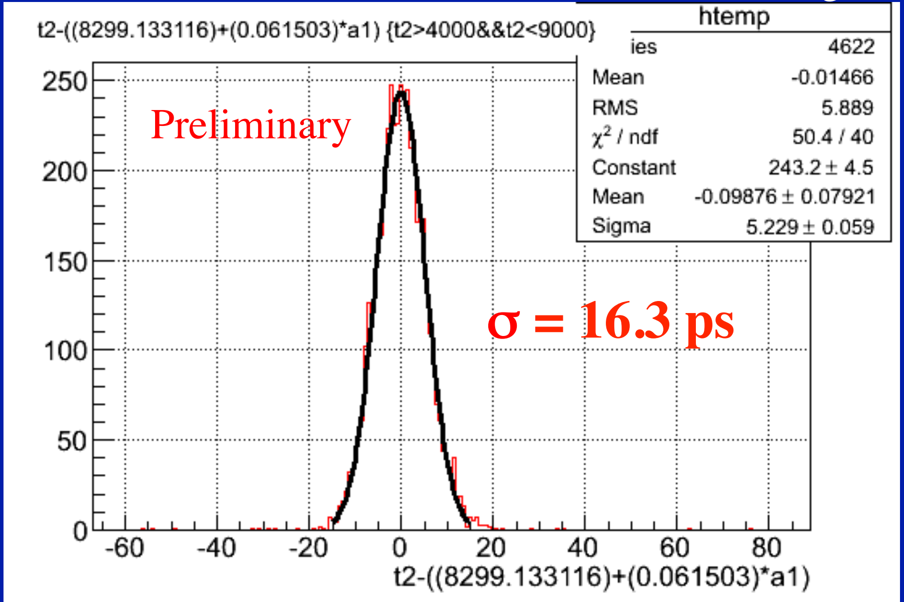
Beam tests with G-APD (or SiPMT)

Anatoly Roznhin, Mike Albrow, Erik Ramberg, et al., Fermilab

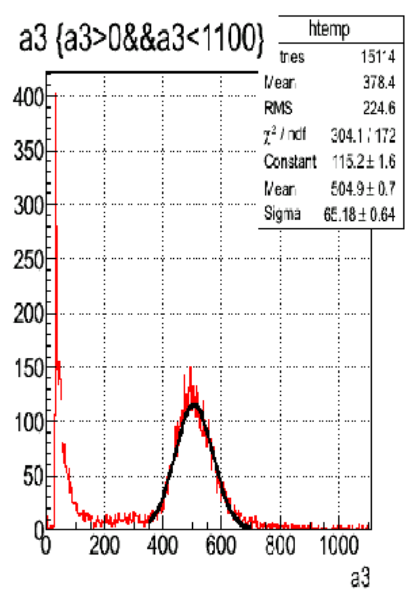
Single 3x3mm^2 G-APD with 3cm-long quartz radiator:



Fused Silica radiator: 3x3mm^2, 3cm long



Npe ~ 60 pe's



- **<u>Timing start</u>: G-APD (Hamamatsu MPPC, radiator is fused silica, 3x3 mm^2 and 30 mm long, all surfaces polished)**

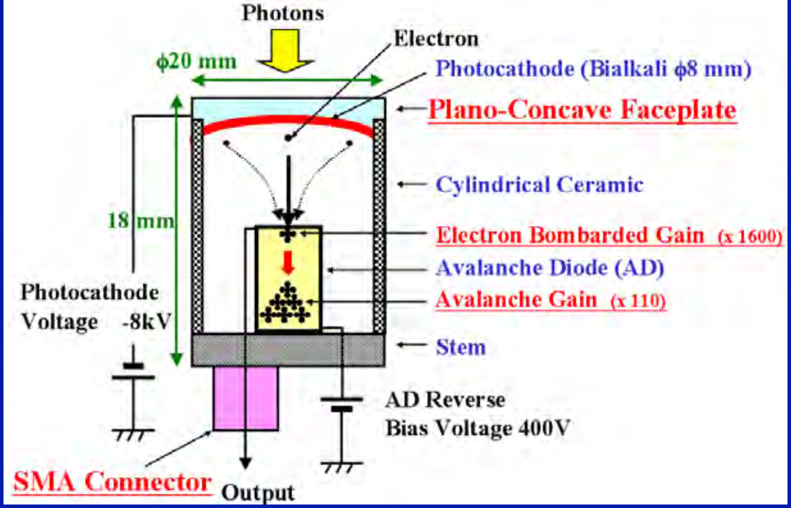
  <u>Timing stop</u>: Photek 240 (radiator is the MCP window, 9.6 mm thick).
- **The MPPC time resolution is <15 ps assuming the Photek 240 time resolution is 7.7 ps. Small pulse height cuts and slewing correction applied.**
- **120 GeV protons used for the test. Normal incidence.**
- **<u>Attention has to be paid to ΔT & ΔV stability</u>: 11.5ps/0.5^{o}C & 6.2ps/10mV !!**

From my AIS instrumentation talk at SLAC, 2007 – 5 years ago !!

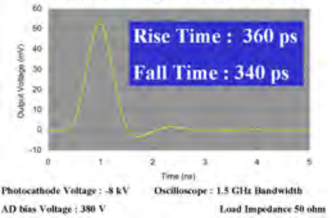
Hamamatsu single-channel HAPD

A.Fukusawa et al., KEK & Hamamatsu, IEEE San Diego, 2006

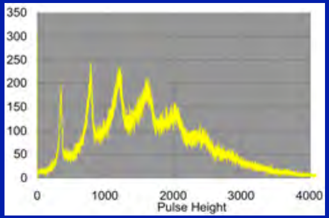
HAPD R10647U-01:



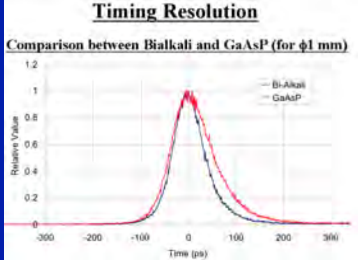
Waveform:



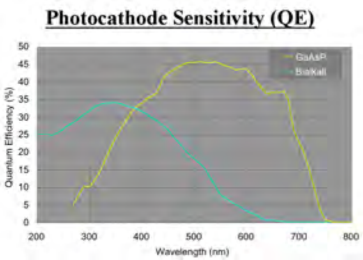
Pulse height spectrum:



Resolution: Bialkali vs GaArP



QE: Bialkali vs GaArP



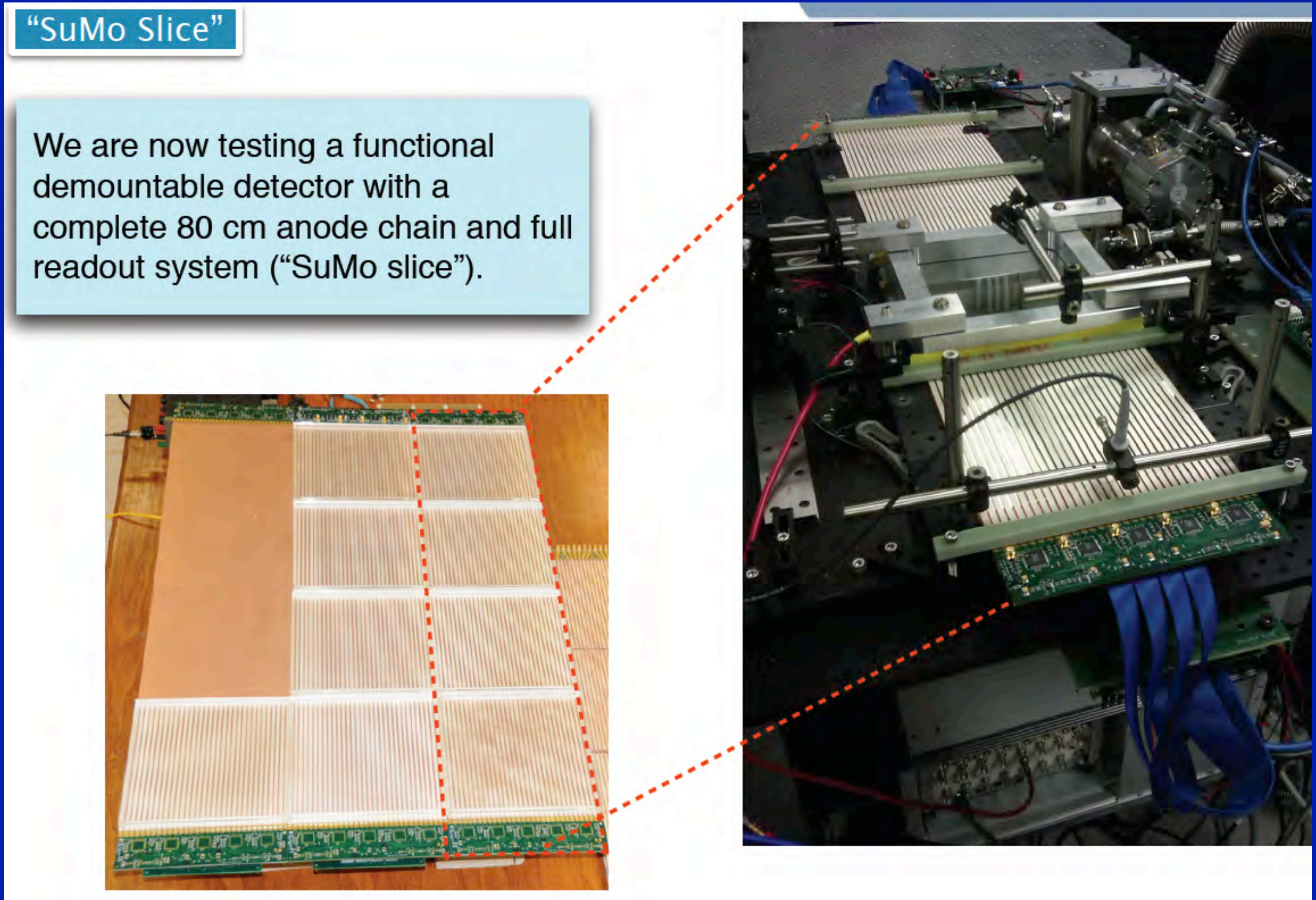
Photocathode	Bialkali or GaArP
Gain @ $V_{photocathode}$ = -8 kV and V_{APD} ~405 V	**~ 1.8 x 10^5**
Raw pulse height	~ 2 mV
Rise time & fall time (1.5 GHz BW scope)	**~360 ps & ~340 ps**
σ_{TTS} (Bialkali & light illumination over ϕ 8 mm)	**~ 28 ps**
σ_{TTS} (Bialkali & restrict light illumination over ϕ 1 mm)	**~ 9 ps**
σ_{TTS} (GaArP & restrict light illumination over ϕ 1 mm)	**~ 28 ps**
σ_{TTS} (GaArP & restrict light illumination over ϕ 3 mm)	**~ 38 ps**

!

New MCP-PMT development

New LAPPD MCP-PMT Development

M. Wetstein, LAPPD DOE review, Dec. 2012



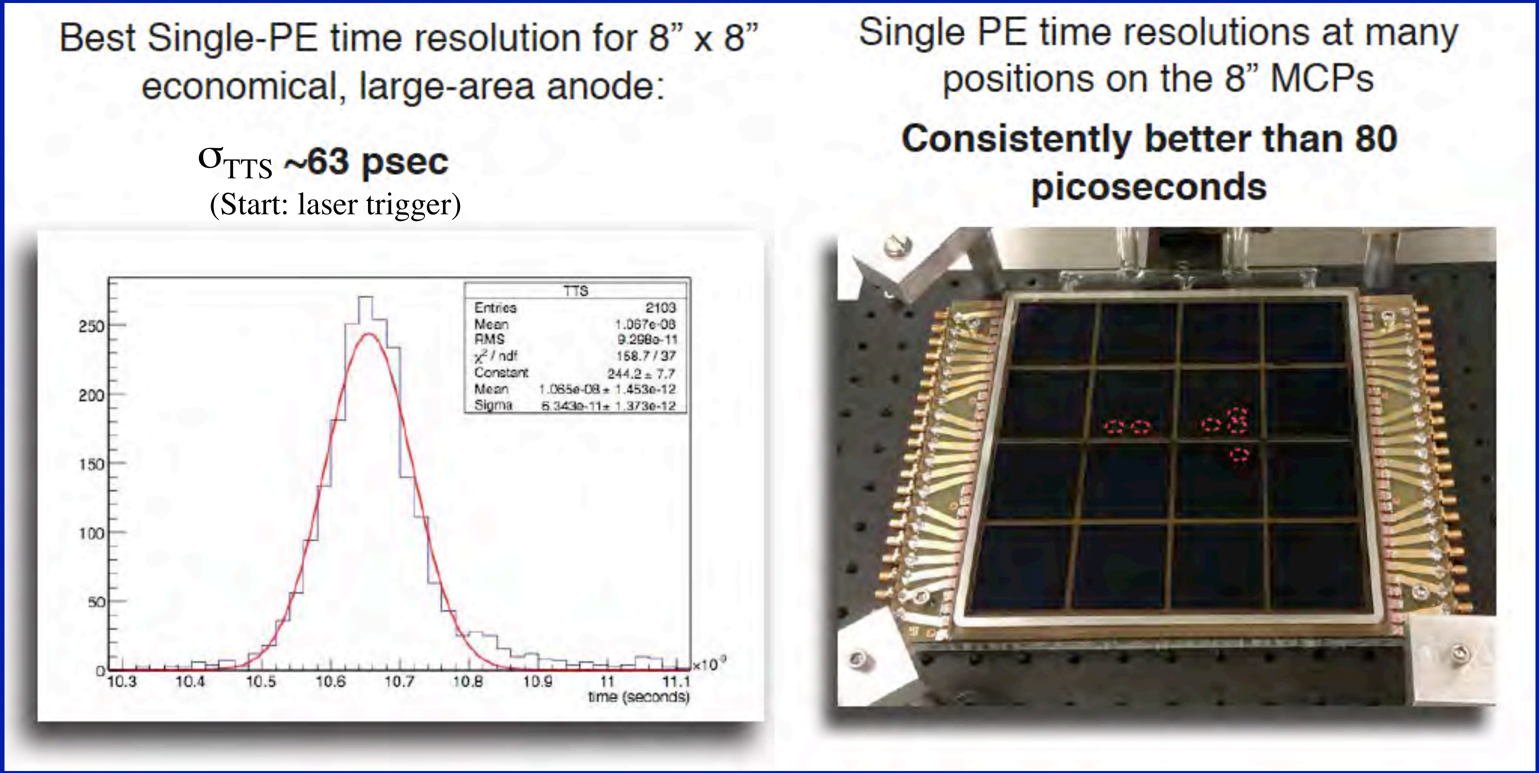
“SuMo Slice”

We are now testing a functional demountable detector with a complete 80 cm anode chain and full readout system (“SuMo slice”).

- **If these detectors will be available and the cost will be lower than Photonis Planacon per the same area, this would indeed make a breakthrough in the detector physics.**

TTS resolution of new 8” x 8” MCP-PMT

M. Wetstein, LAPPD DOE review, Dec. 2012



Best Single-PE time resolution for 8” x 8” economical, large-area anode:

σ_{TTS} **~63 psec**

(Start: laser trigger)

Single PE time resolutions at many positions on the 8” MCPs

Consistently better than 80 picoseconds

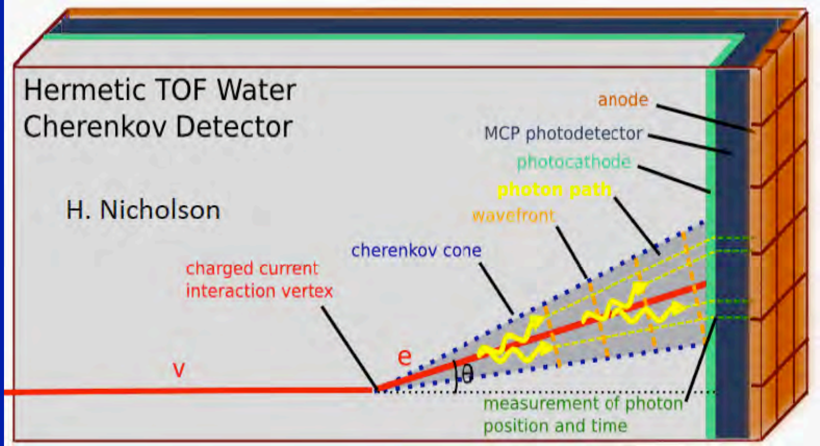
- **Initial single photoelectron timing resolution: $\sigma_{TTS} \leq$ 80 ps.**
- **For a radiator providing ~ 20 pe one could get $\sigma \sim 80/\sqrt{20} < 20$ ps.**
- **Many experiments would gladly take this performance.**

Future detector requiring fast timing

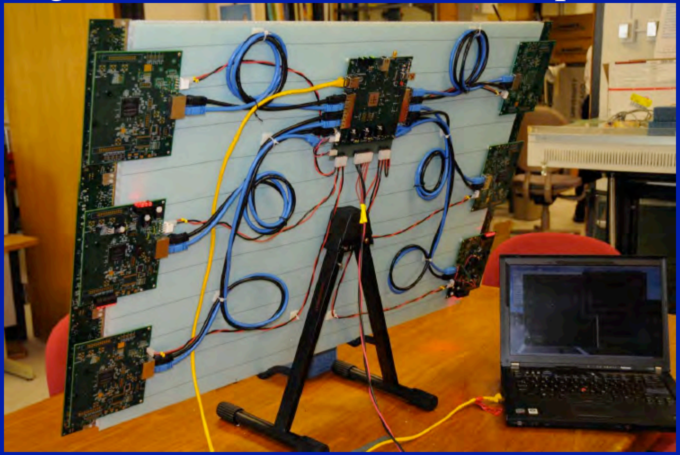
Examples of applications of LAPPD MCP-PMTs

H. Frisch, SLAC talk, 2012

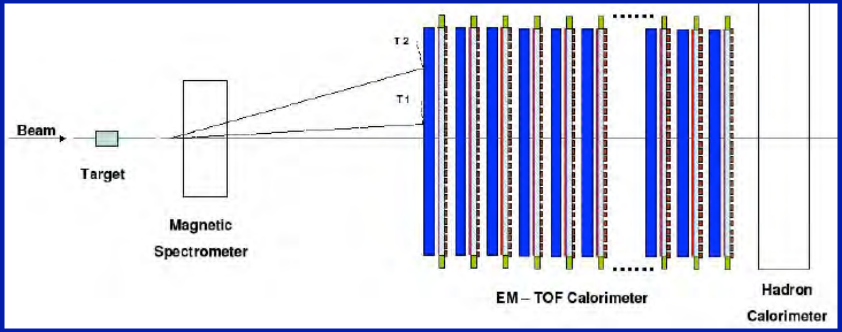
Measure photons & reconstruct the track:



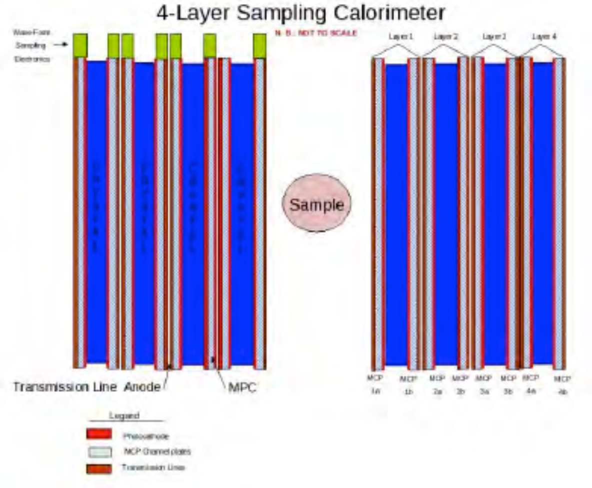
One large MCP-PMT tile with a complete readut:



MCP-PMT based EM-TOF calorimeter:



MCP-PMT based medical imaging calorimeter:

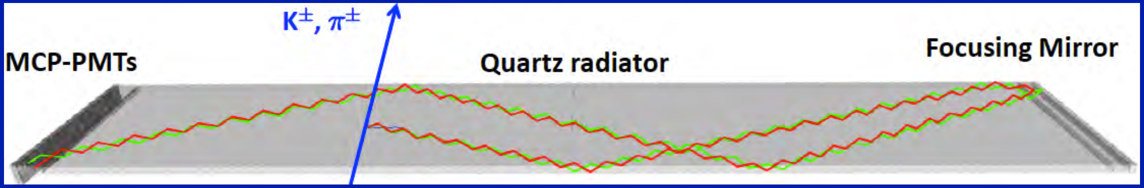


- **There are many possible applications, if these devices are available and have low cost.**

Belle-II TOP counter – a new TOF detector

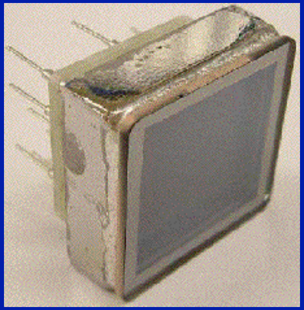
Belle-II Technical design report, 2010 and later updates

TOP counter measure “x , y and time” in its latest form:

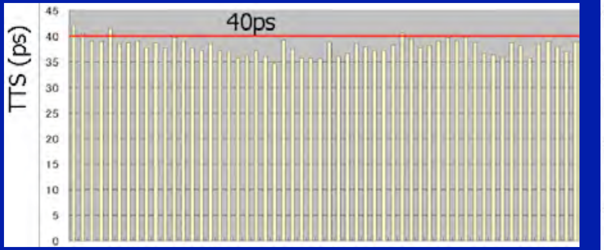


IRS-2 electronics:

SL-10:

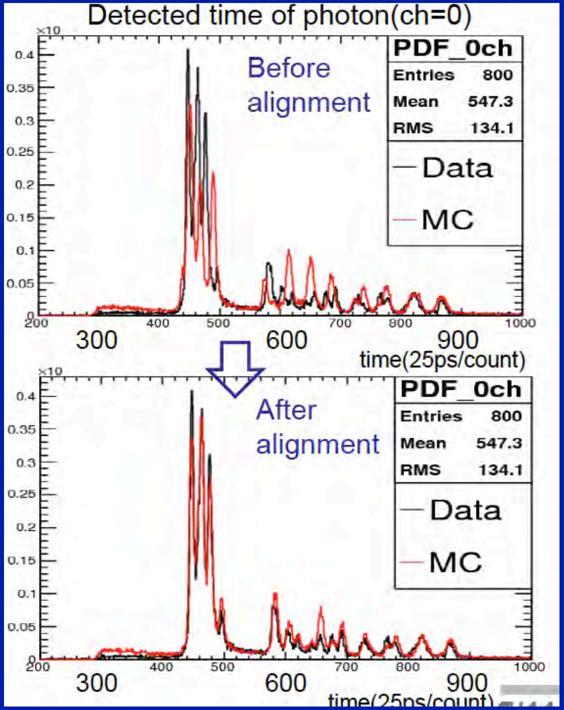


σ_{TTS}:



Tube

PDF

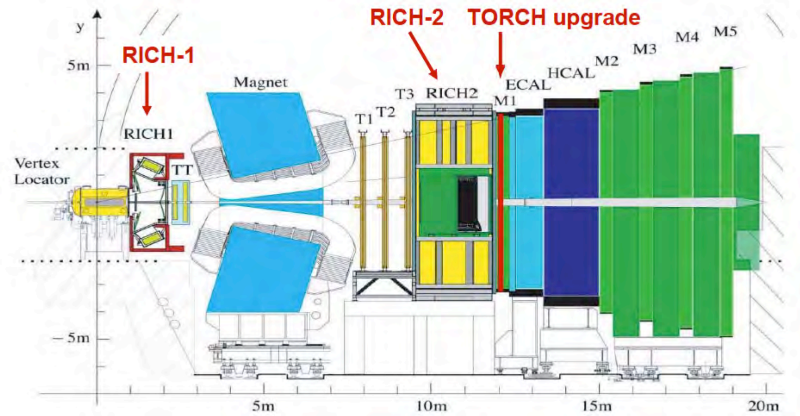


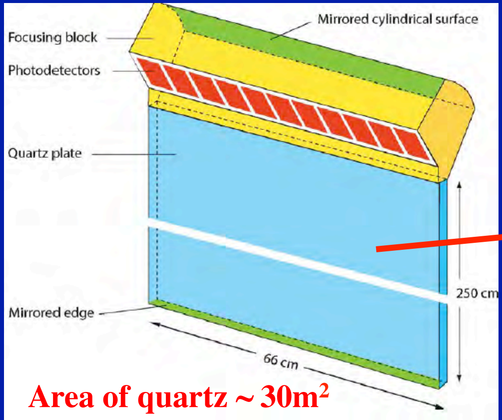
Time

- **Goal: σ ~ 40 ps / photon.**
- **Electronics: IRS-2 waveform digitizing electronics.**
- **The data analysis in these types of DIRC-like detectors is not trivial.**
- **Although time is very crucial in this type of detector, it is not any more a simple TOF counter, but it includes the knowledge that all photons are tied together via the Cherenkov angle geometry. To do PID, you do not show a Cherenkov peak any more, but one forms PDF and determines a likelihood for each particle hypothesis.**

LHCb TORCH – a new TOF detector

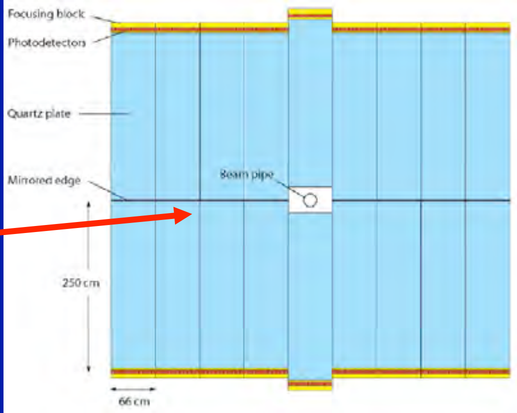
N. Harnew for TORCH collaboration, TIPP 2011 and private communication



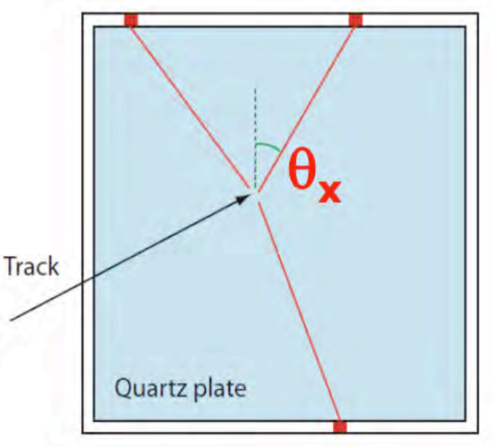


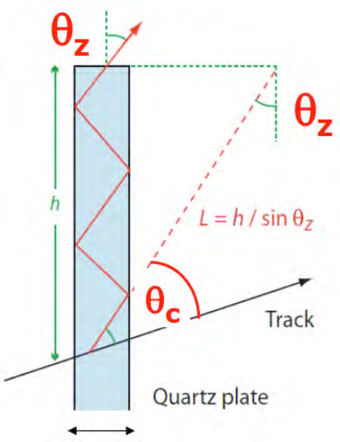
Area of quartz ~ $30 m^2$

Probably segmented:



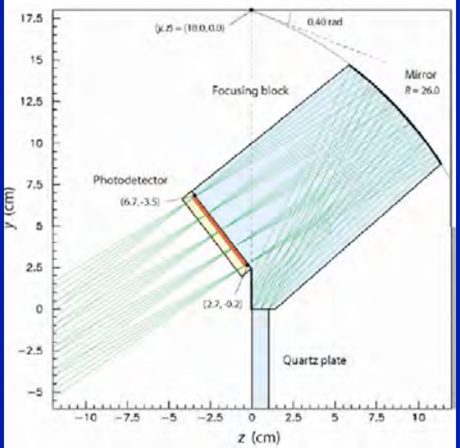
Principle:





Focusing optics:

~200 Planacon tubes (if one instruments top & bottom only)
~360 tubes is one instruments sides also

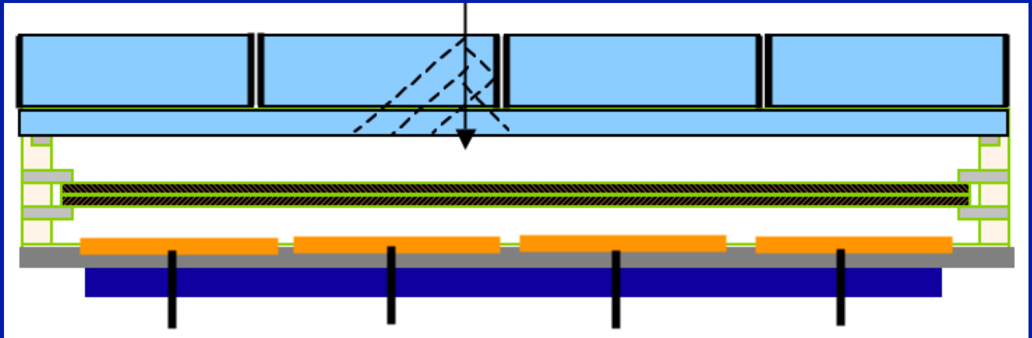


- **Goal: σ ~ 70 ps / photon (dominated by chromatic error).**
- **ΔTOF (π-K) = 35 ps at 10 GeV over ~10 m flight path => aim for σ ~15 ps / track.**
- **Rate ~10^{11} photons/sec per total quartz detector area; Ave. detector rate:** ~10 MHz/cm^2

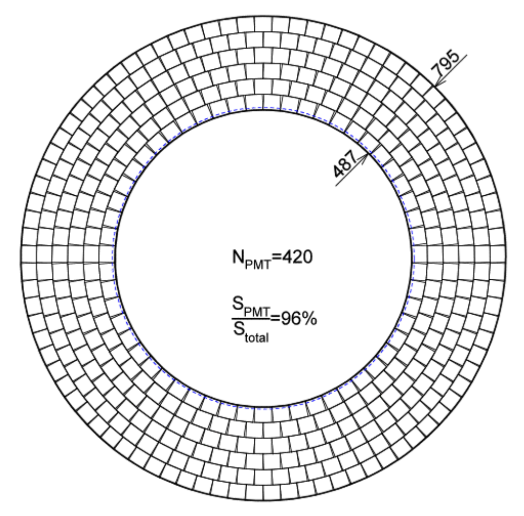
Proposal of pixilated TOF for ~~SuperB~~

J. Va' vra, "Forward PID", SuperB workshop, Orsay, Feb. 2009

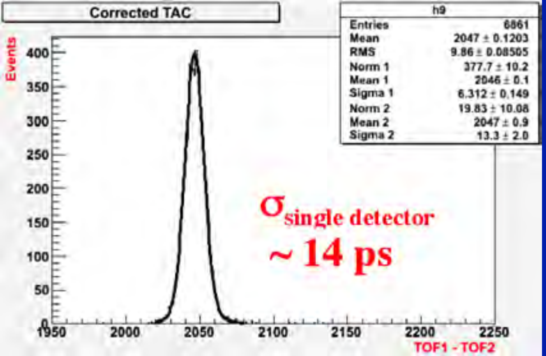
SuperB-related based on the Planacon MCP-PMT:



Forward TOF:



Test beam result:

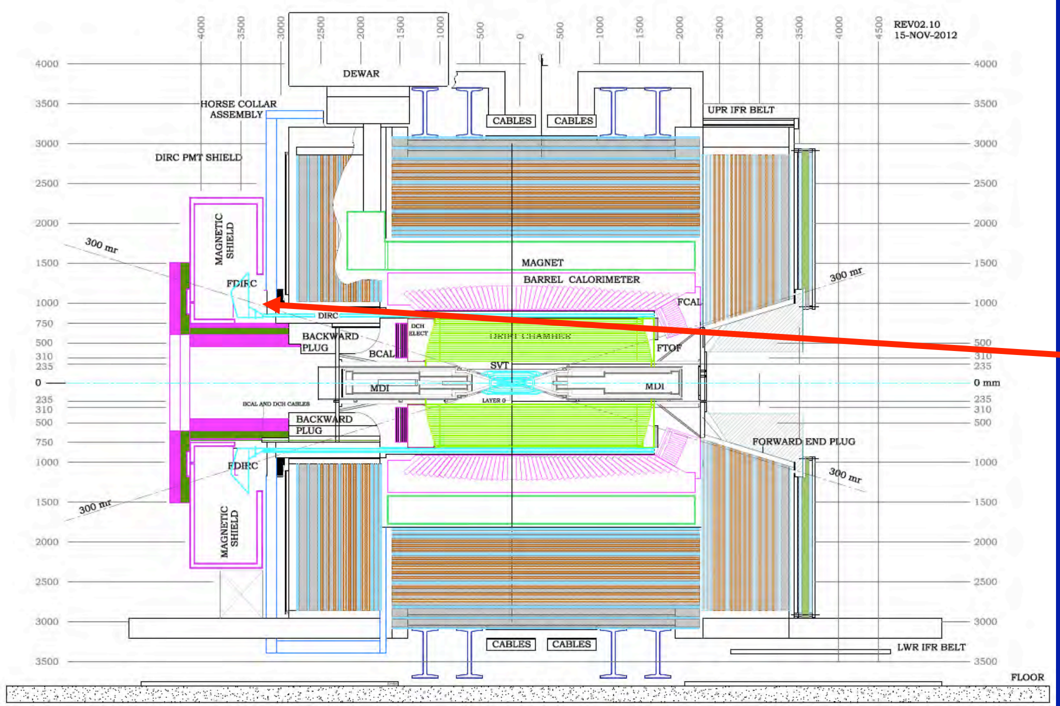


Would need **~550** Planacon 2"x2" MCP-PMTs;
This is area equivalent to **~35** 8"x8" LAPPD tubes

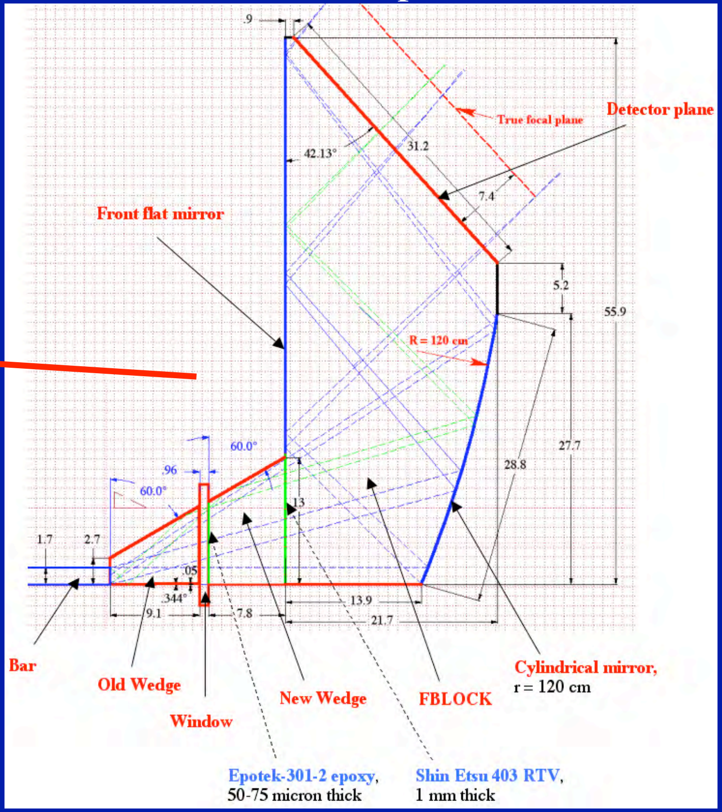
- **Radiator is formed from cubes, each side polished.**
- **This was my proposal for SuperB forward PID.**
- **Decision at that time: MCP-PMTs are too expensive.**
- **But the new LAPPD MCP-PMTs could make such a proposal possible.**

SuperB FDIRC

SuperB Technical Design Report, to be published in 2013 soon



FDIRC photon “camera”:

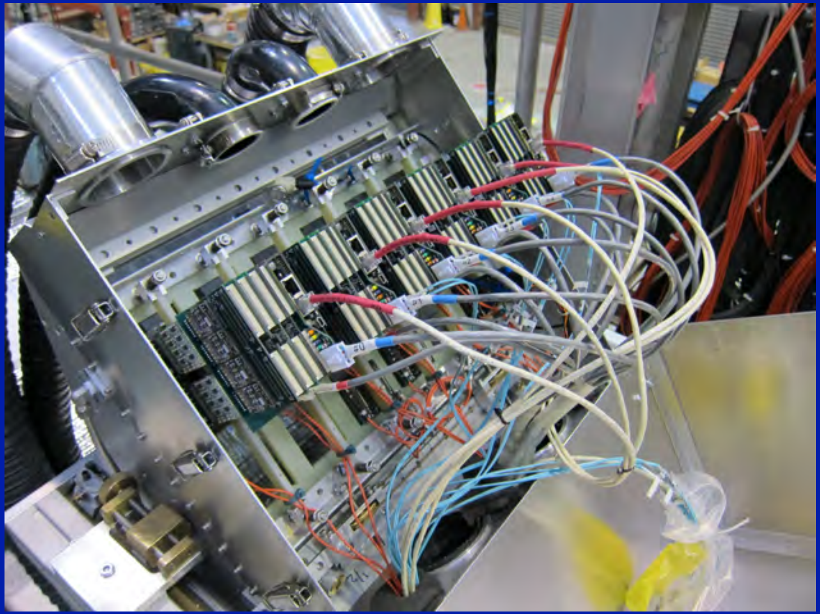


- **SuperB electronics: LAL Amp/CFD/TDC.**
- **Goal: σ ~ 200 ps / photon to be able to reduce background, handle ambiguities and do chromatic corrections.**
- **FDIRC test is under way in SLAC CRT right now with the Hawaii IRS-2 electronics.**
- **JLAB people expressed an interest in FDIRC and bar boxes from BaBar, now that SuperB has been cancelled.**

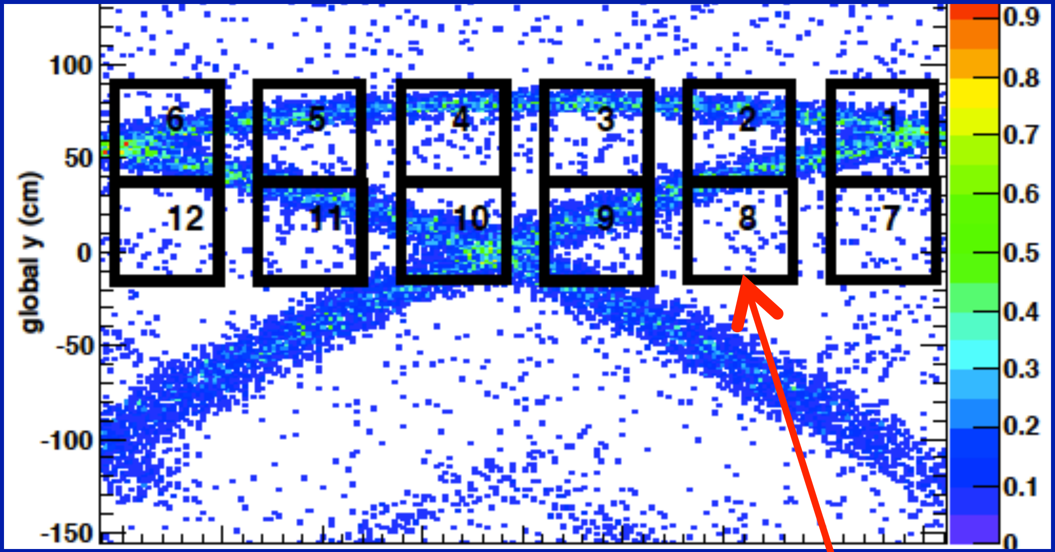
~~FDIRC~~ prototype test in CRT

B. Day, M. Borsato, D. Roberts, K. Nishimura, N. Arnaud, G. Varner and J. Va’vra

FDIRC with H-8500’s & IRS-2 electronics:

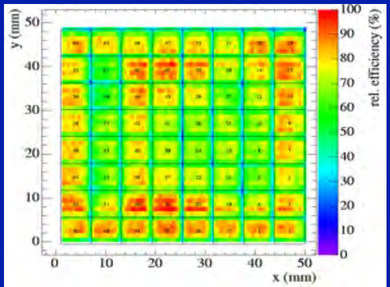


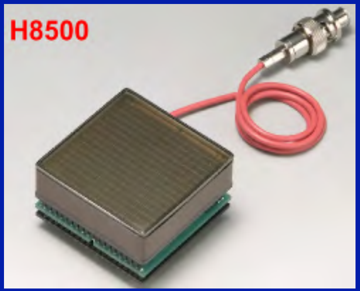
An example of MC ring image:



H-8500 PMTs

- **Presently use SLAC amplifier + IRS-2 packages.**
- **Timing requirement: ~ 200 ps / photon.**
- **12 x 64 = 768 pixels – we are learning that to deal with that many channels of waveform digitizing electronics is a nontrivial task !**
- **Ambiguities complicate the analsyis.**
- **Tests at SLAC cosmic ray telescope (CRT).**

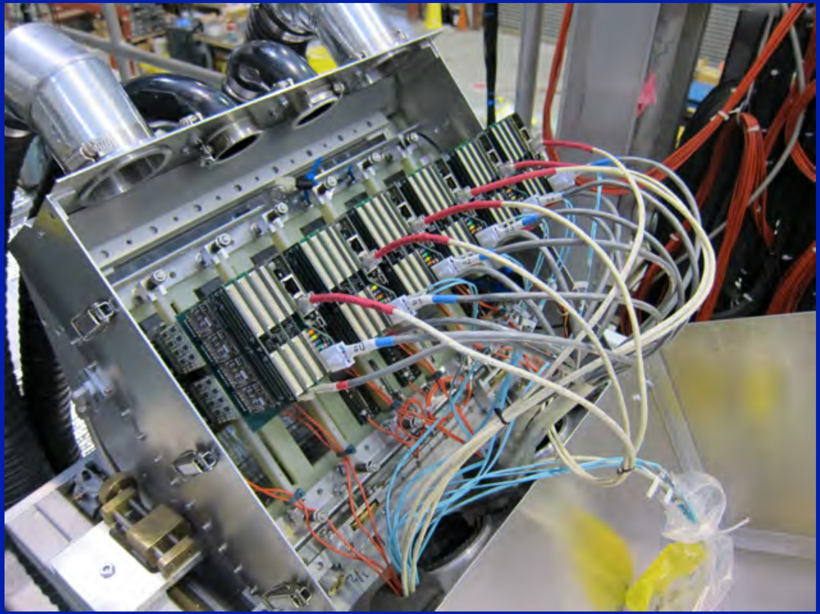




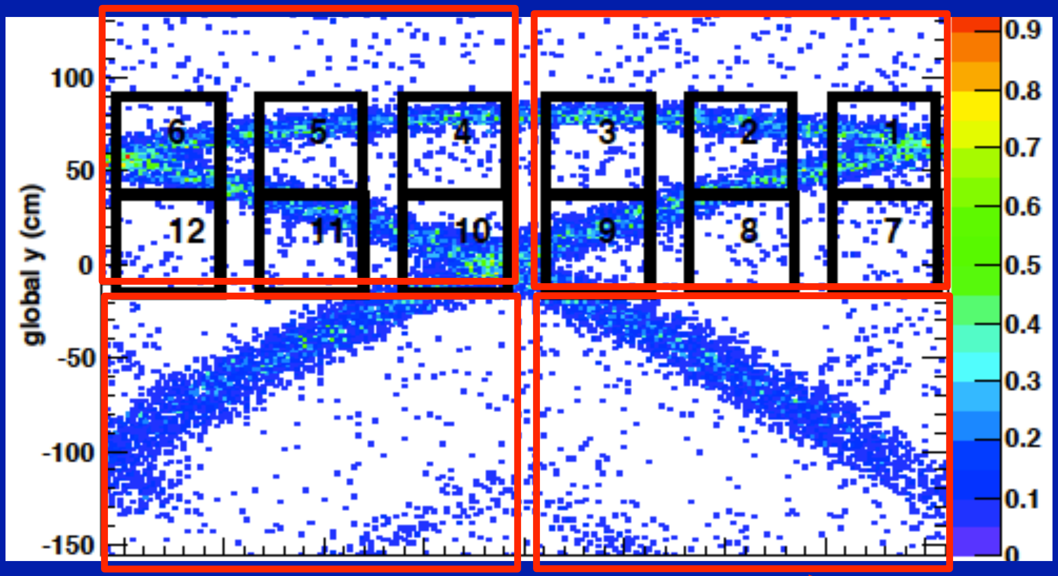
~~Super~~B FDIRC test in CRT

SuperB Technical Design Report, to be published in 2013 soon

FDIRC with H-8500's & IRS-2 electronics:



FDIRC detector plane:



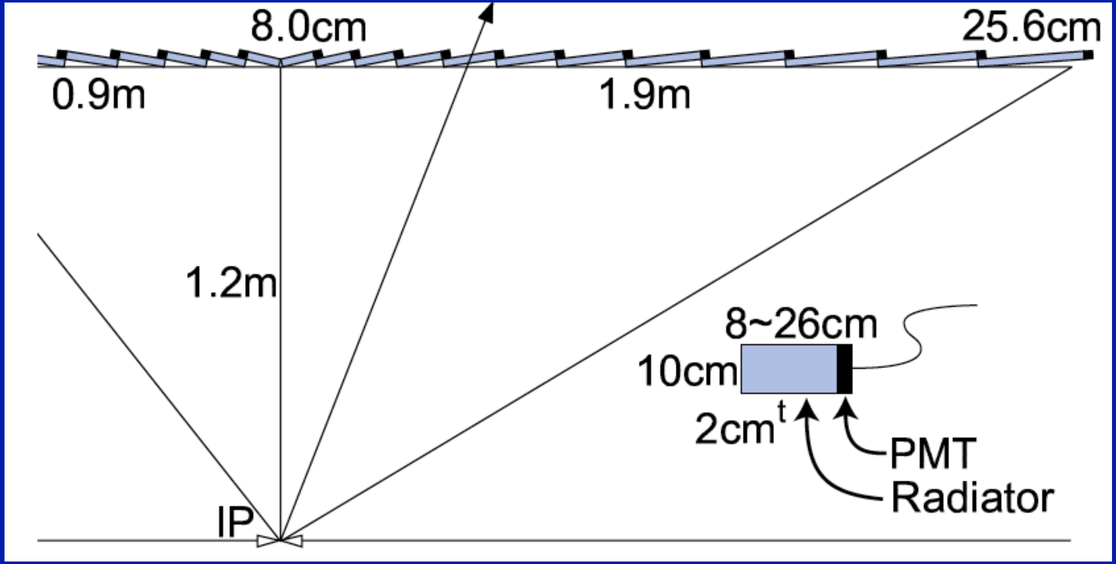
Would need **~576** Planacon 2"x2" H-8500 PMTs;
This is area equivalent to **~36** 8"x8" LAPPD tubes

LAPPD
MCP-PMT

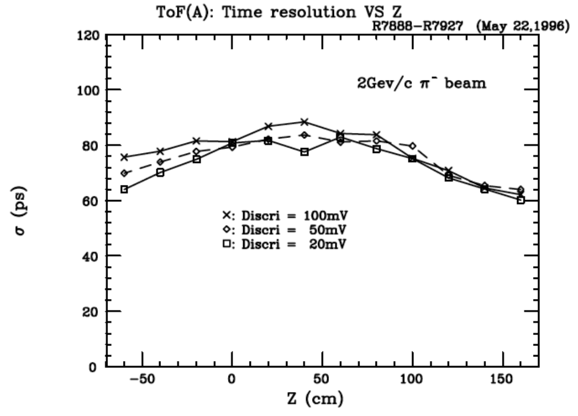
- **Four LAPPD detectors would cover the detector plane in FDIRC.**
- **I hope the detector part would be cheaper.**
- **A better TTS of MCP-PMT would allow a better treatment of ambiguities.**

Belle-II TOP counter – early version

Belle-II Letter of Intent, 2004



Expected resolution:

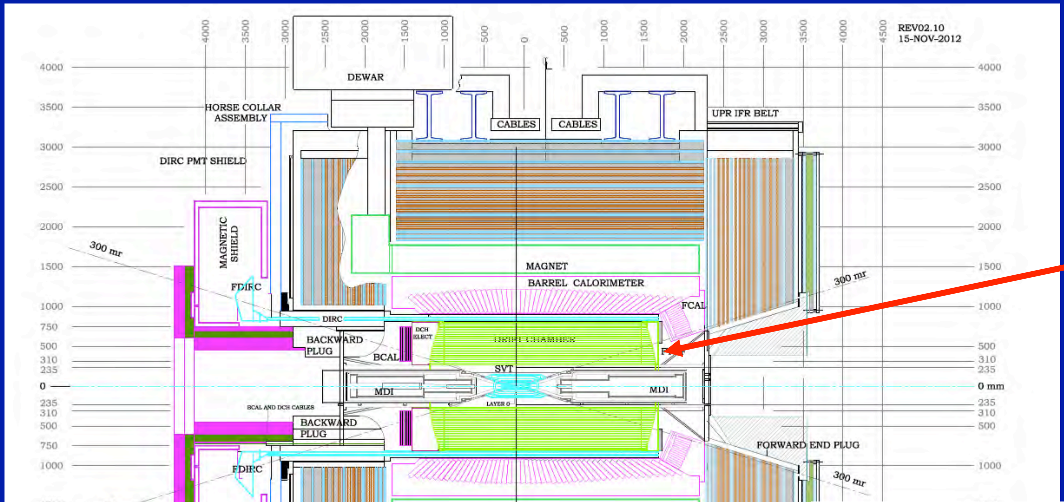


Total area to cover: **~30 m^2**
This would require **~785** 8”x8” LAPPD tubes

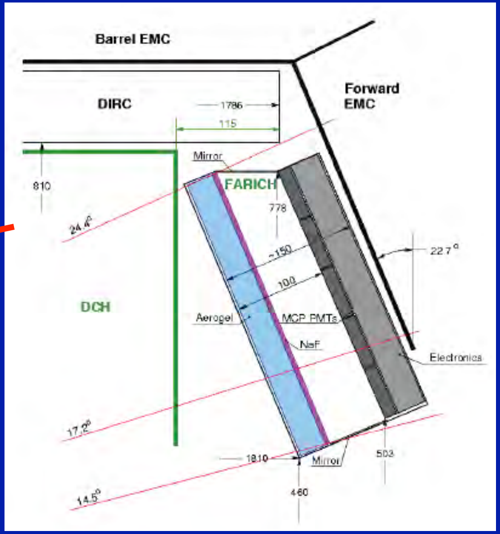
- **This detector was not chosen at the end.**
- **Goal: σ ~ 80 ps / track.**
- **<u>My point:</u> Experience shows that data analysis in these types of DIRC-like detectors is not trivial. Replace them with pixilated detector ?**
- **It would take ~785 LLAPD 8”x8” MCP-PMTs to cover the total area !**

~~Super~~B Forward Aerogel RICH (FARICH)

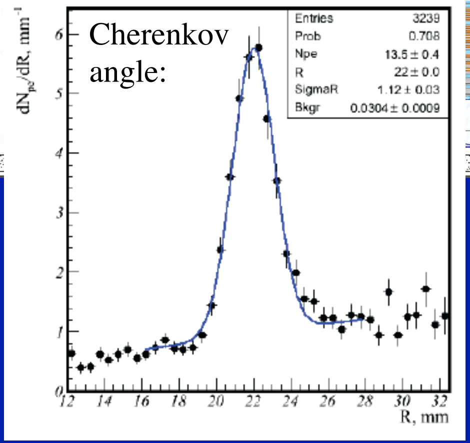
SuperB Technical Design Report, to be published in 2013 soon



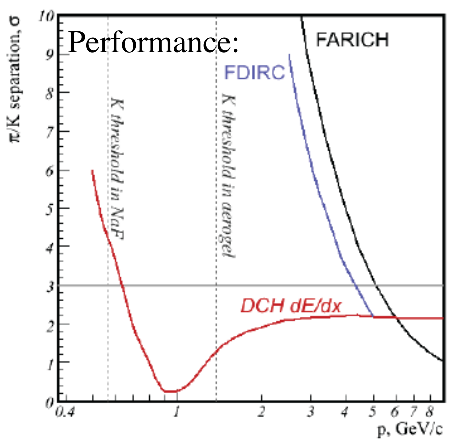
Design:



Cherenkov angle:



Performance:

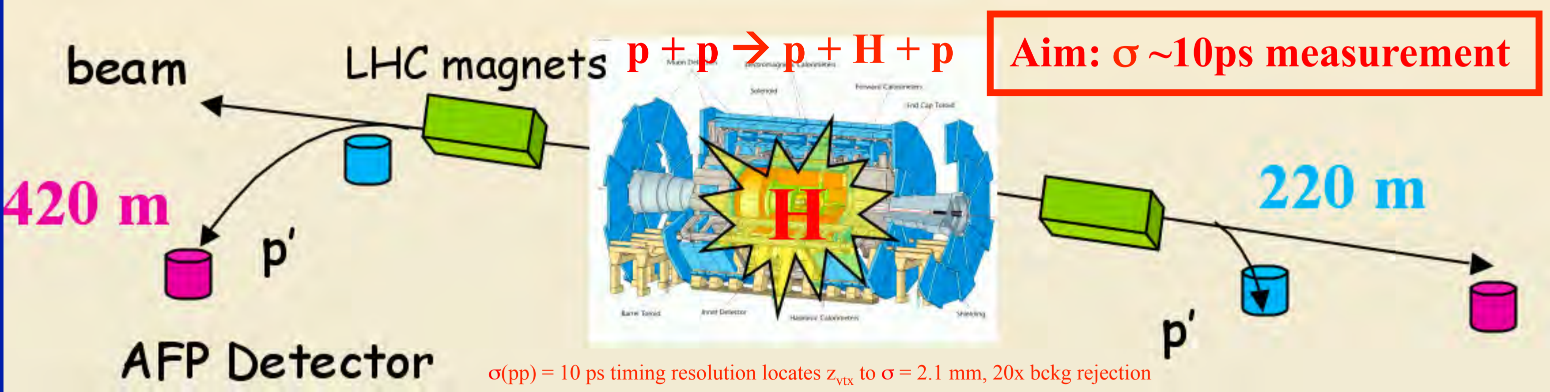


Would need **~550** Planacon 2”x2” MCP-PMTs;
This is area equivalent to
~35 8”x8” LAPPD tubes

- **Good results obtained using a prototype in Novosibirsk test beam with SiPMTs.**
- **It was judged as too expensive for SuperB if one would use Planacon MCP-PMTs.**

ATLAS & CMS: pp-diffraction scattering

Andrew Brandt, Anatoly Roznhin, Mike Albrow, Erik Ramberg, Krzysztof Piotrzkowski, and many others

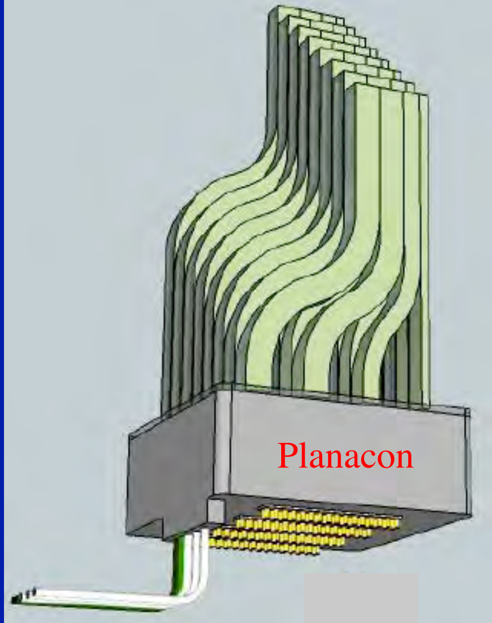


$p + p \rightarrow p + H + p$

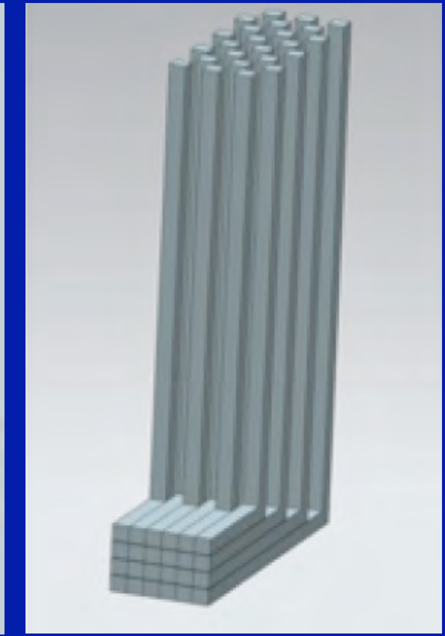
Aim: σ ~10ps measurement

$\sigma(pp)$ = 10 ps timing resolution locates z_{vtx} to σ = 2.1 mm, 20x bckg rejection

Bent bars:



L-bars:



- **Single bar resolution 30-40 ps, resulting in total of ~10ps.**
- **Very challenging environment:**
  (a) High event rate (10-15 MHz/cm^2),
  (b) Running close to max anode current
  (c) Large annual collected charge (~10 C/cm^2).

Not yet decided which detector to use.

ATLAS & CMS: pp-diffraction scattering – another way to do it ?

Sebastian White

a) Light detection using HAPD (with small quartz radiator or Quartic bars ?):

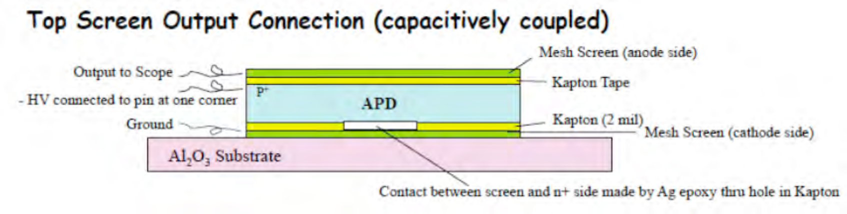
- **Hamamatsu data:** R10647U-06 HAPD can take a charge dose 2-orders of magnitude larger than their best MCP-PMT, I am told by Sebastian.
- **Timing resolution results:** See page 16 for TTS resolution results by Fukusawa
- **HEP experience:** R10647U-06 HAPD was not yet used in a high rate HEP experiment.

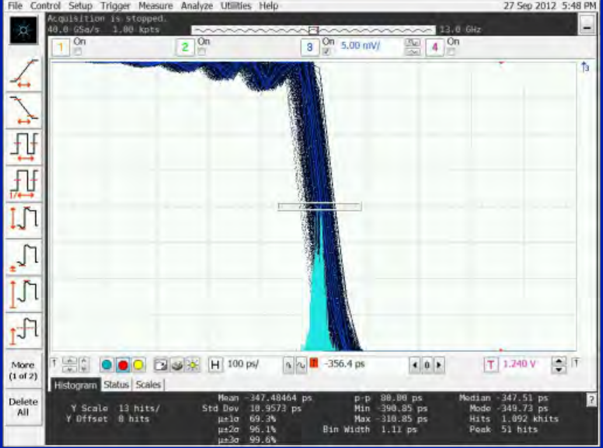
b) Direct charge particle detection by Dynasil APD detectors:

- **Timing resolution results:** A laser test with a cope indicates σ ~ 11 ps.
- **HEP experience:** not yet used in a high rate HEP experiment.

Npe ?

Scope measurements:

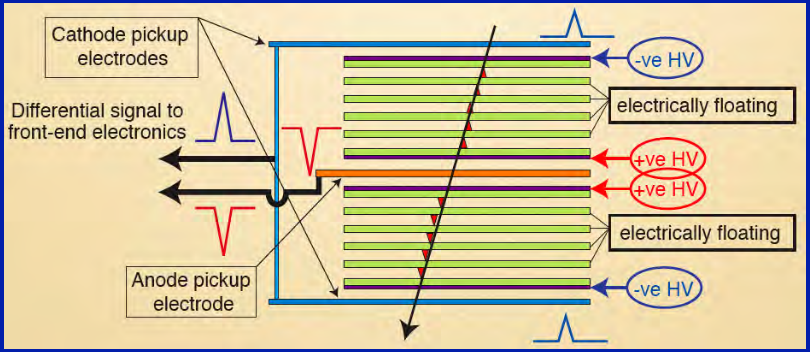




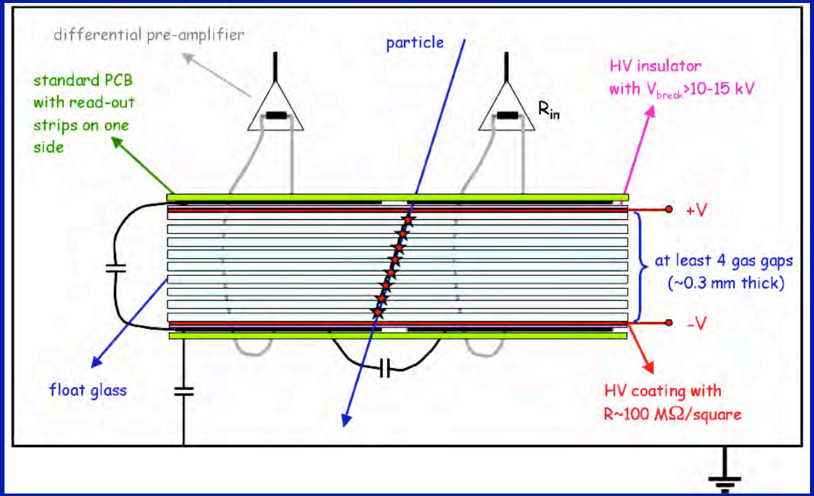
```
Acquisition is stopped.
40.0 GSa/s   1.00 kpts                    13.0 GHz

                      Mean -347.48464 ps      p-p  80.00 ps        Median -347.51 ps
 Y Scale  13 hits/ Std Dev  10.9573 ps        Min -390.85 ps        Mode -349.73 ps
 Y Offset  0 hits     μ±1σ  69.3%             Max -310.85 ps        Hits  1.092 khits
                      μ±2σ  96.1%       Bin Width  1.11 ps          Peak  51 hits
                      μ±3σ  99.6%
```

Present MRPC used for TOF detectors

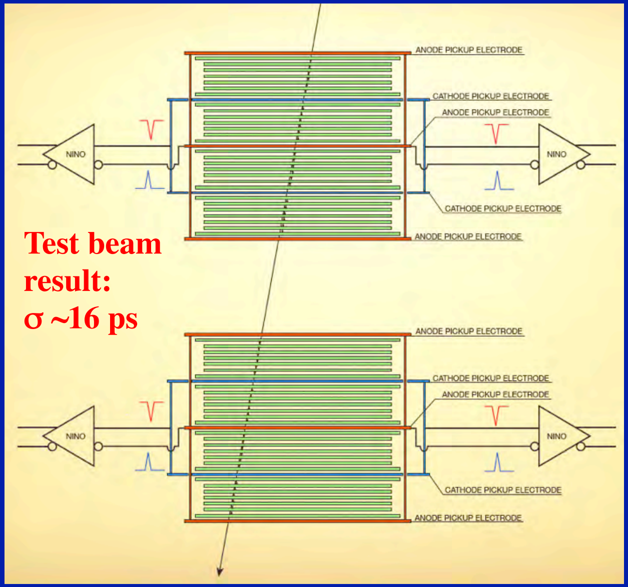
ALICE (10 gaps/MRPC):



STAR (8 gaps/MRPC):



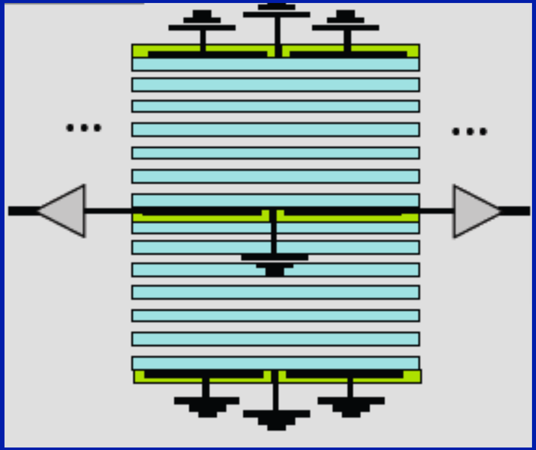
ALICE R&D (24 gaps/MRPC):



Test beam result:
σ ~16 ps

In test beam they achieved ~ 16 ps.

FAIR (12 gaps/MRPC):



~50 m^2 area

- **ALICE is getting σ ~ 86 ps in the total system presently.**
- **It would require ~ 1250 LAPPD 8"x8" MCP-PMTs to cover ~ 50m^2 area.**

My take away points

- For ultimate resolution, can a Waveform digitizing electronics compete with analog electronics a'la Ortec 1GHz 9327 Amp/CFD, which seems to have a limit of 2 ps resolution ? Perhaps work with author of 9327 CFD jeff.peck@impeccableinstruments.com ?
- LAPPD MCP-PMT detector development has a potential to open up new applications requiring fast detectors. But these detectors must be easily available and the cost must be smaller than the cost of Photonis Planacon, normalized to the same area.
- For some applications, one needs to develop a "truly" pixilated LAPPD MCP-PMT at some point in future. For example, RICH detectors.
- Future TOF detectors do not use scintillators ano more. People are moving towards DIRC-like detectors, where one measures x-y coordinate together with time for each photon, and forms a maximum likelihood. In this way one starts approaching a RICH detector performance, and "equivalent" timing performance at a level of 10-15 ps. However, a word of caution: these devices are complicated to use and understand. But many people are working on it !

Appendix

Nagoya test: can a simple calculation explain data ?

J. Va'vra, a simple naïve model for Nagoya timing results on page 14 (K. Inami)

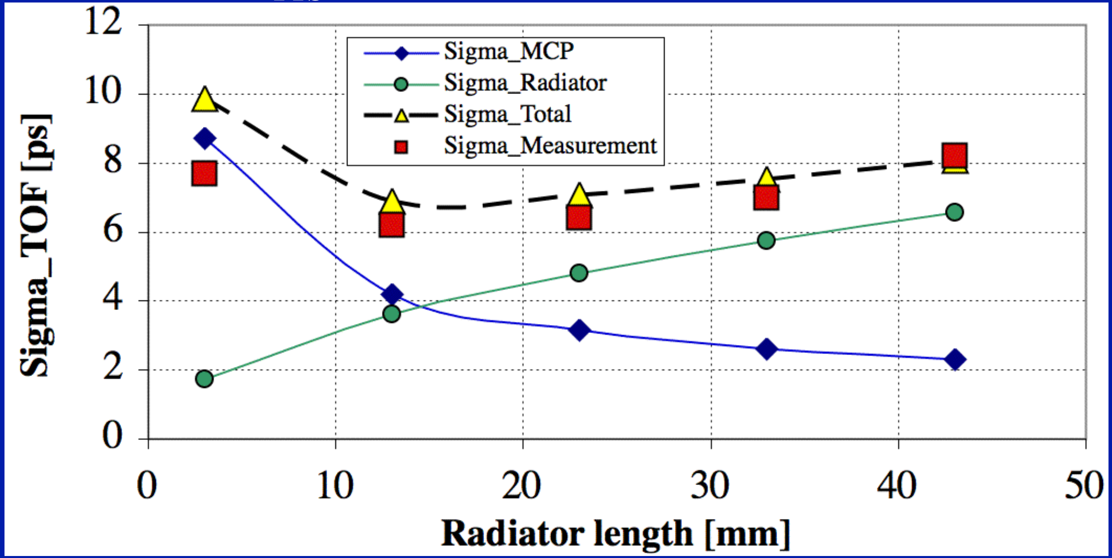
$$\sigma_{TOF} \sim \sqrt{\left[\sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Radiator}} + \sigma^2_{\text{Pad broadening}} + \sigma^2_{\text{Electronics}}\right]} =$$

$$= \sqrt{\left[(\sigma_{TTS}/\sqrt{N_{pe}})^2 + (((L*1000\mu m/\cos\theta_C)/(300\mu m/ps)/n_{group})/\sqrt{(12Npe)})^2 + \right.}$$

$$\left. + \; ((5*1000\mu m/300\mu m/ps)/\sqrt{(12Npe)})^2 + (4.1\ ps)^2 \right]$$

For L = 13 mm: $\sigma_{TOF} \sim \sqrt{[4.18^2 + 3.6^2 + 0.63^2 + 4.1^2]} \sim 6.9$ ps

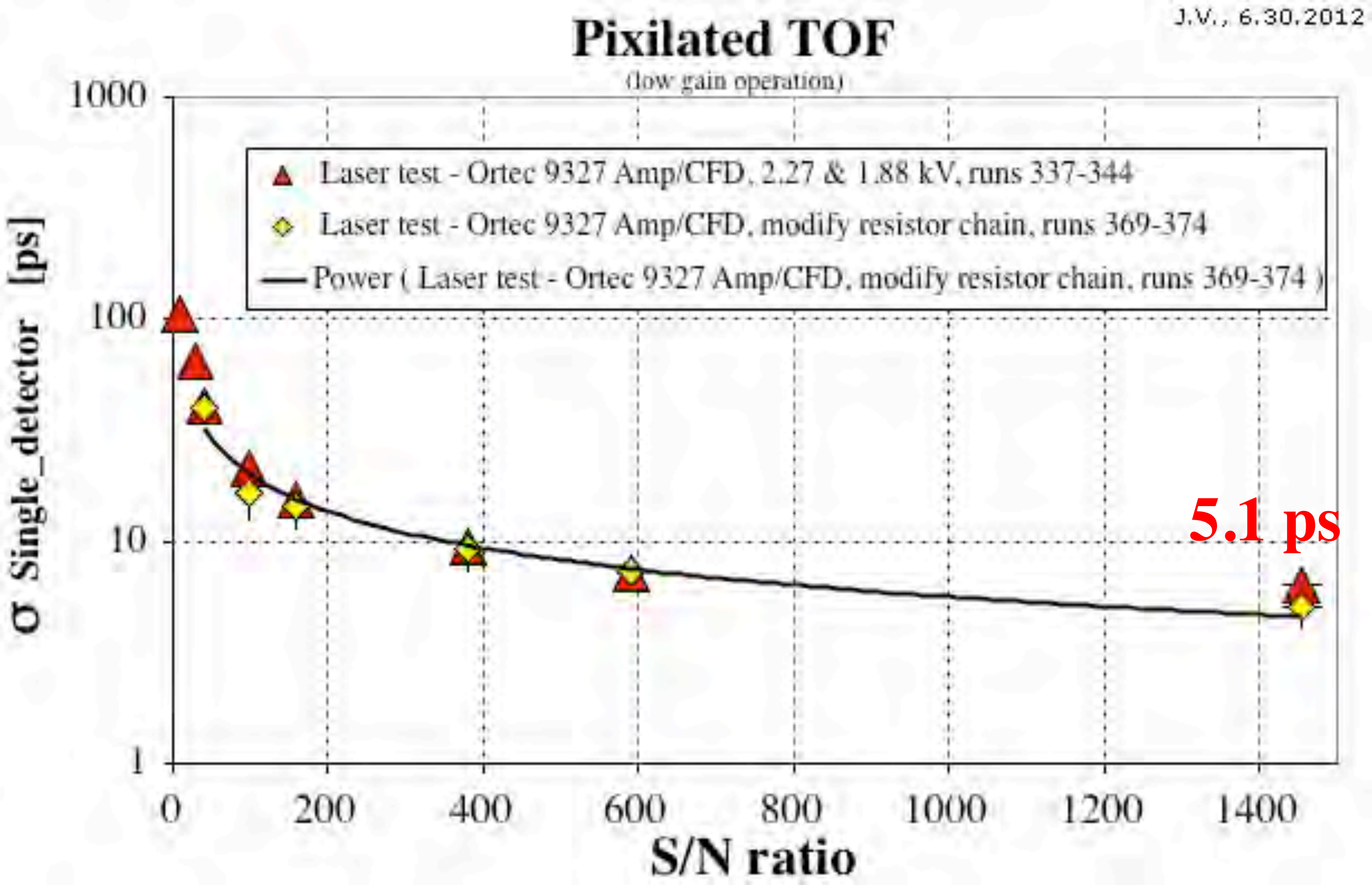
Assume: $\sigma_{TTS} \sim 32$ ps & Npe = 40-50 pe/10 mm



- **A simple model actually does work quite well.**
- **A radiator length of 12-15 mm is optimum.**

Timing tests with MCP-PMT detectors

J. Va’vra, MCP-PMT log book #4, page 82, 2007

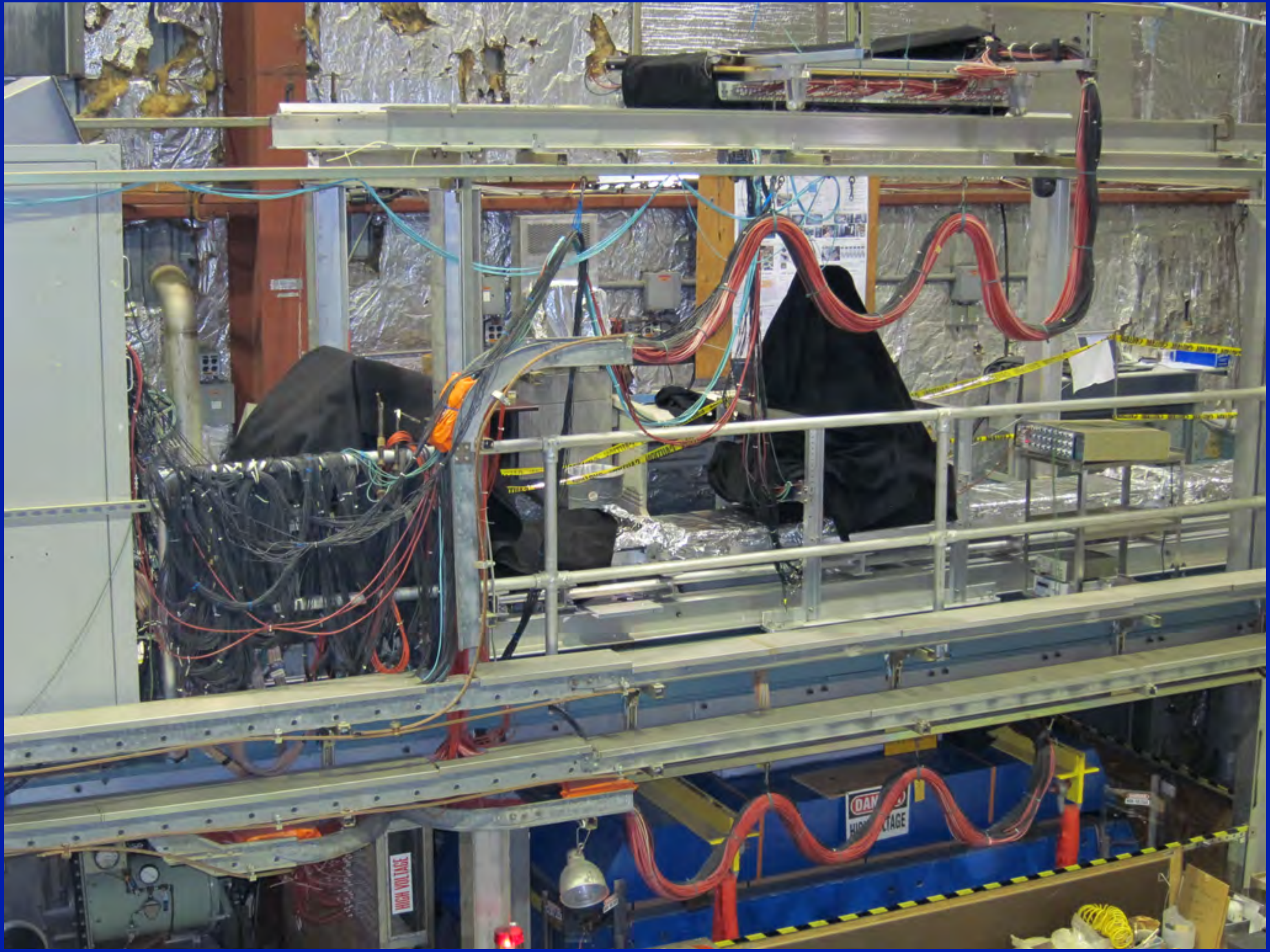


5.1 ps

- If I assume that $\sigma_{electronics}$ ~ 2ps, it means that $\sigma_{detector} \sim\sqrt{(5.1^2 - 2^2)} \sim 4.7$ ps.
- In our laser tests we achieved σ ~ 5.1 psec with Ortec 9327 CFD electronics for S/N > 1000; more realistic S/N in a real application is < 200.

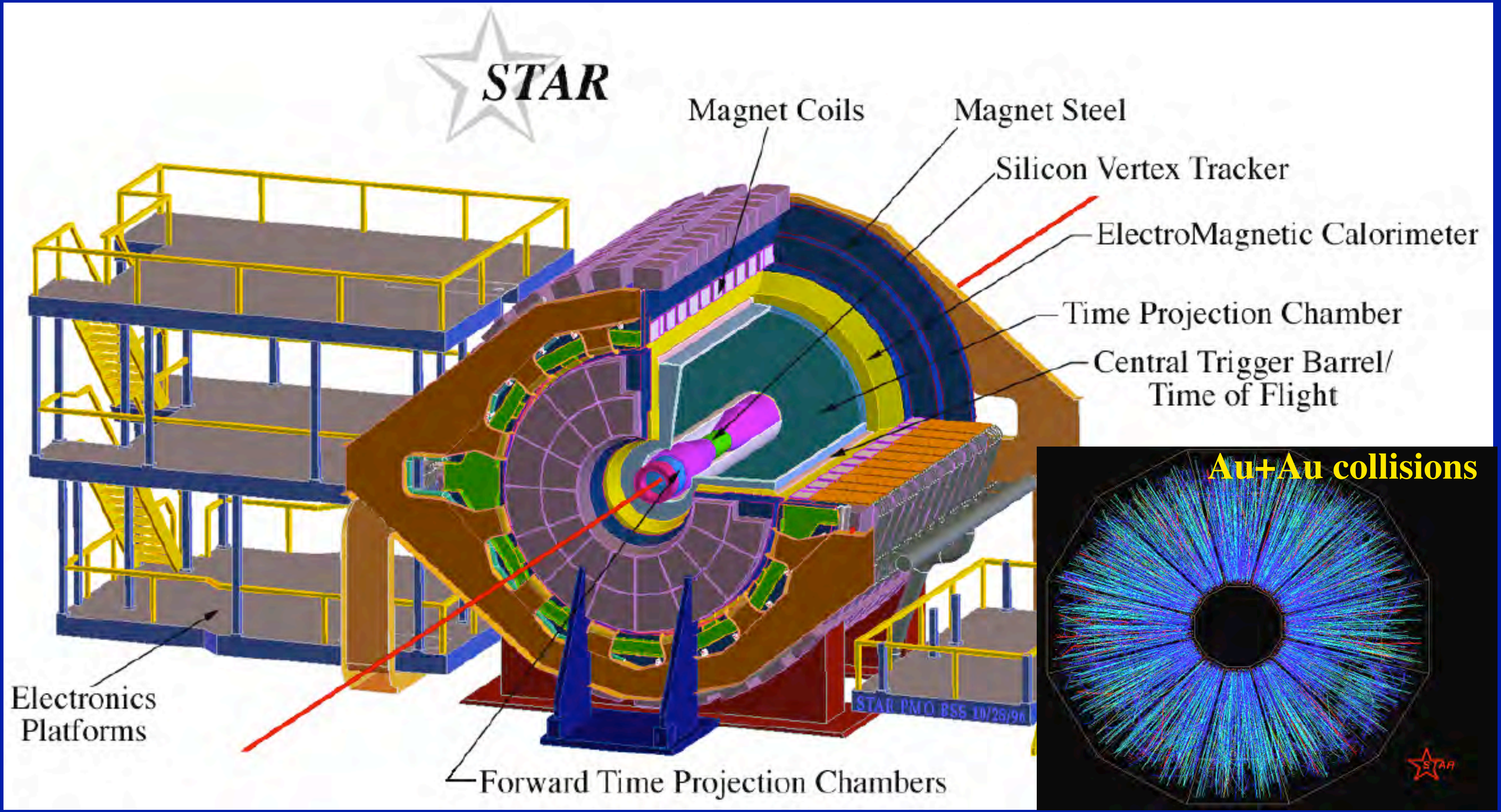
FDIRC test in CRT (cosmic ray telescope)

Description and tests in CRT: SLAC-PUB-13873, and SLAC-PUB-15202



- **Muons of E ≥ 2 GeV, ~1.5 mrads tracking, ~1.5 mrads tracking, dip angles ±15°.**
- **This was extremely good investment; CRTs are much better than test beams.**

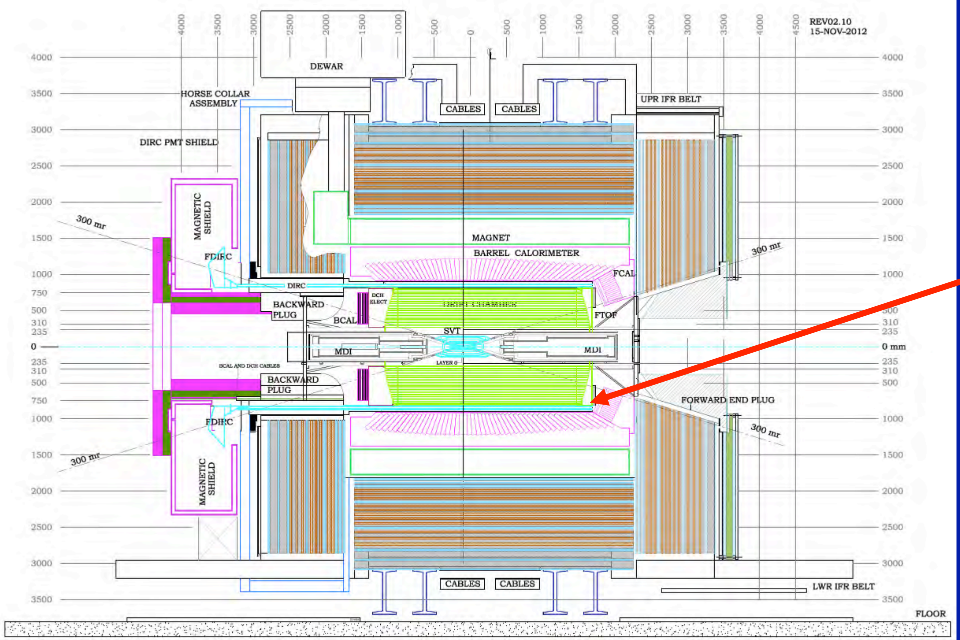
STAR experiment at RHIC



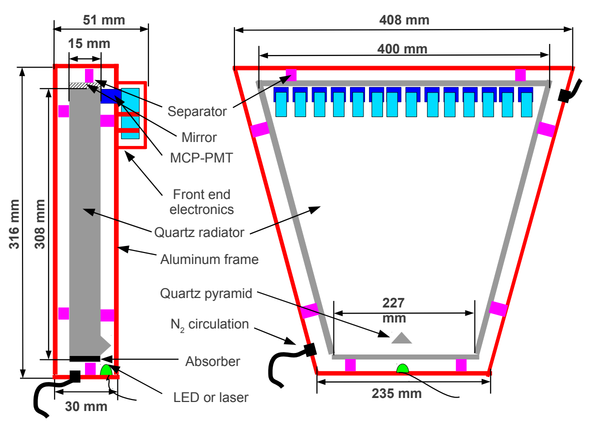
- Total area of STAR TOF system is ~50 m^2. Timing resolution: $\sigma \leq 100$ ps / track.
- It would require ~ 1250 LAPPD 8”x8” MCP-PMTs to cover the same area, if one wants to TOF detector in an e-RHIC experiment in future !!

~~Super~~B DIRC-like TOF in forward direction

SuperB Technical Design Report, to be published in 2013 soon



Sectors of FTOF detector:



This is area equivalent to **~35** 8”x8” LAPPD tubes

- **Goal: σ ~ 60-80 ps / track.**
- **Electronics: LAL WaveCatcher waveform digitizing electronics.**
- **<u>My point:</u> Experience shows that data analysis in these types of detectors is not trivial. This detector is also sensitive to a single electron background (photons like to rattle in radiator back and forth, adding to the background level). A pixilated TOF detector is better because it avoids this and one does not need a single pe sensitivity.**