Quartz Cherenkov Timing Detectors *Revisited*

Workshop on Picosecond Timing Detectors for Physics
9-11 September 2021, University of Zurich

Quartz (Fused Silica) Cherenkov Timing Detectors: ([1], [2])

- instantaneous source of almost isochronous photons
- transmission by total internal reflection (TIR) with little time spread
- photodetectors with negligible transit time spread (TTS) and high gain

Quartz radiator block + MCP-PMT $\longrightarrow \sigma_t \approx 5$ps ([3])

Non-negligible material budget:

  - Multiple (independent) measurements problematic;
  - showering produce correlations?

- Fused Silica are radiation-hard (≈ 20 Grad) :
- various (high η) detectors of LHC experiments are based on quartz technology, f.i. CMS forward calorimeters (HF, CASTOR, ZDC); can they aim at precision timing ?

A. Penzo – 10 Sept 2021

Acknowledgements, Credits & References

(Essential contributions by B. Kaynak and S. Ozkorucuklu)

(Inspiring discussions with: M. Albrow, A. Mestvirishvili, Y. Onel)

Research described here has been carried out as technical development R&D work within the CMS Collaboration teams engaged in the Forward Hadron Calorimetry (HF) and in the Proton Precision Spectrometer (PPS) and belonging to CERN, FNAL, IPM – Teheran, Istanbul Universities, the University of Iowa and IHEP – Protvino.

Persons involved: M. G. Albrow, O. Atakisi, J. Baechler, A. Baud, S. Cerci, D. Druzhkin, M. Kaya, B. Kaynak, M. Khakzad, S. Los, F. D. Ingram, A. Mestvirishvili, Y. Onel, S. Ozkorucuklu, A. Penzo, V. Samoylenko, C. Simsek, C. Snyder, R. Stefanovitch, D. Sunar Cerci, M. J. Wagner

Photodetectors : MCP-PMT Hamamatsu, Photek, Photonis, Katod

MCP PM UFK-5G-2D produced by KATOD [4]

Quartz (fused silica) radiators : Specialty Glass Products; Russian company Alpha-TM

[1] J. Vavra et al., Beam test of a time-of-flight detector prototype, NIM-PR 299 A 606 (2009) 404

[2] M. G. Albrow et al., Quartz Cherenkov Counters for Fast Timing: QUARTIC, JINST 7 (2012) P10027

[3] K. Inami et al, A 5-ps TOF-counter with an MCP-PMT, Nucl. Instrum. Meth. A560 (2006) 303–308.

[4]http://katodnv.com

Why picosecond timing ? Why Cherenkov ? Why Quartz?

Picosecond Timing:

- TOF → PID
- High Pile-Up
- PET upgrade

} Essential for HL-LHC; also for BSM searches: Long Lived Particles, Dark Matter, ….

Cherenkov Signal:

- Prompt (suited for precision timing)
- Directional (background suppressed, well defined path)
- Blind to neutral/low energy particles (suppress background)

Quartz Radiator:

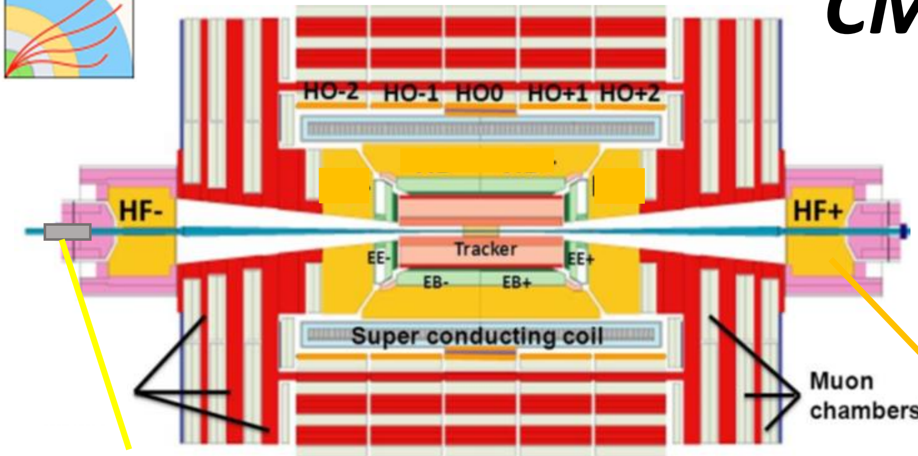
- High optical grade
- Radiation hard
- Fiber technology

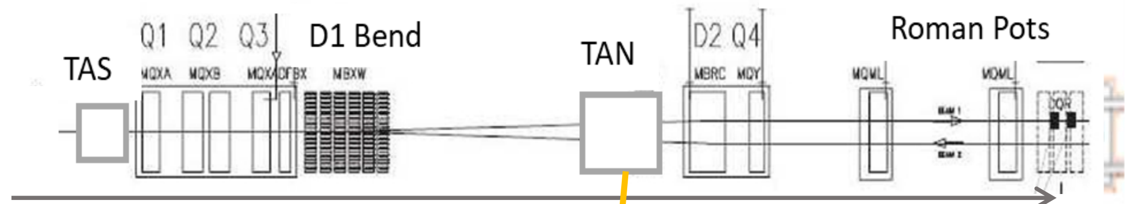
Fast Photodetectors:

- Short transit time
- Low spread (TTS)
- High gain

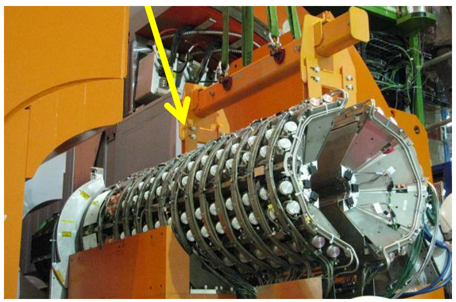
> Is it really such a good idea?
>
> - Few photons…going where they want!
> - Calorimetry use neutral/low energy particles…
> - Radiation tolerance/recovery complicated….
>
>   …..
>
>   …..
> - Photodetectors with good timing have relatively short lifetimes….

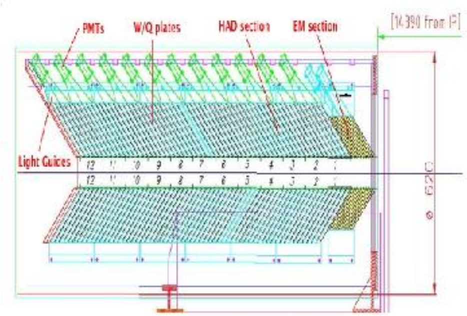
CMS – *LHC Point 5*



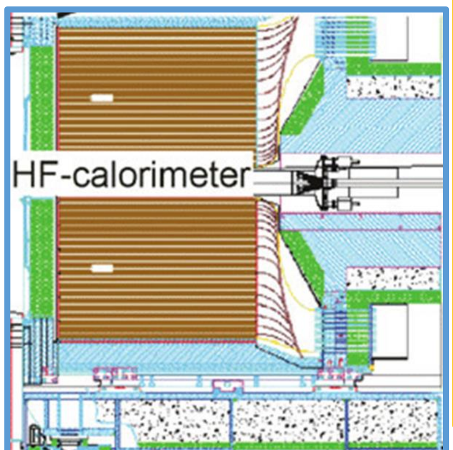


CASTOR





CASTOR (14m)
Quartz Plates
(-5.2 > η >-6.6)

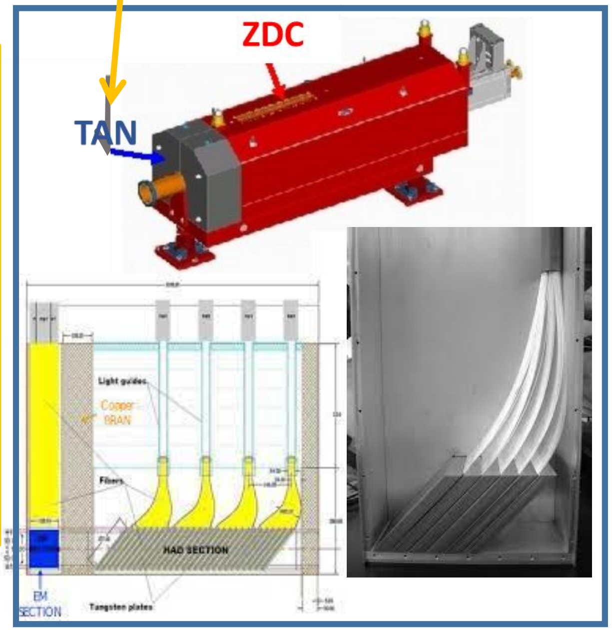


HF (11m)
Quartz Fibers
(3 < |η| < 5.2)

~ 250 tons iron absorber (8.8 λ_I)

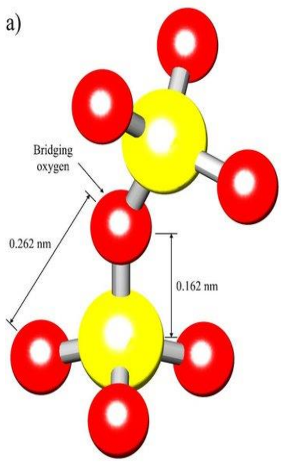
~ 1000 km quartz fibers (0.8mm)

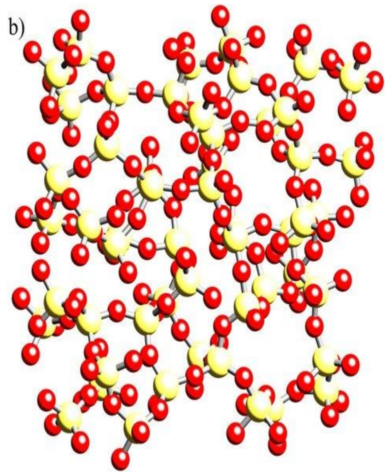
~ 2000 PMT read-out



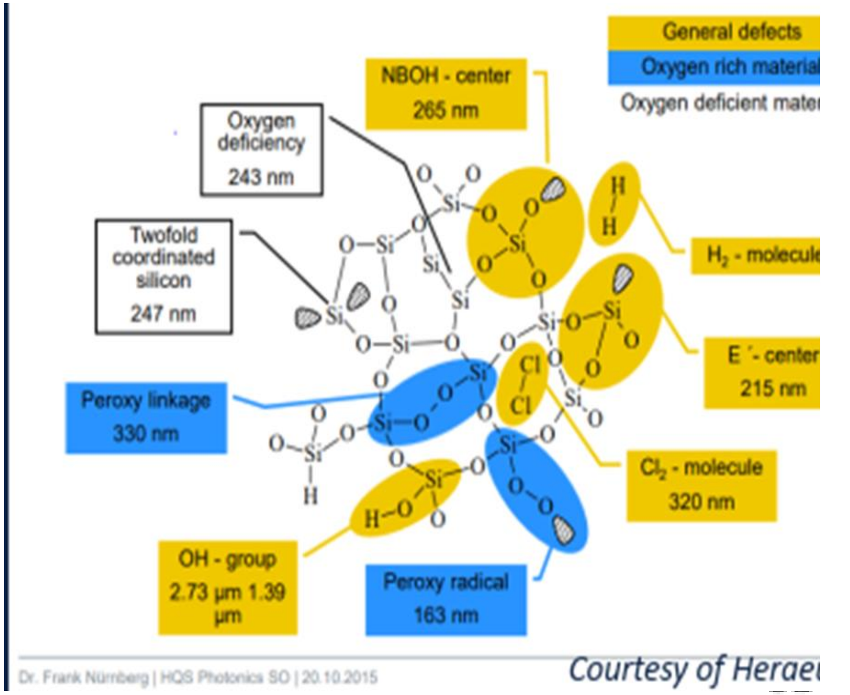
ZDC (140m)
Quartz Fibers
(|η| > 8.0)

Fused Silica: Structure and Defects

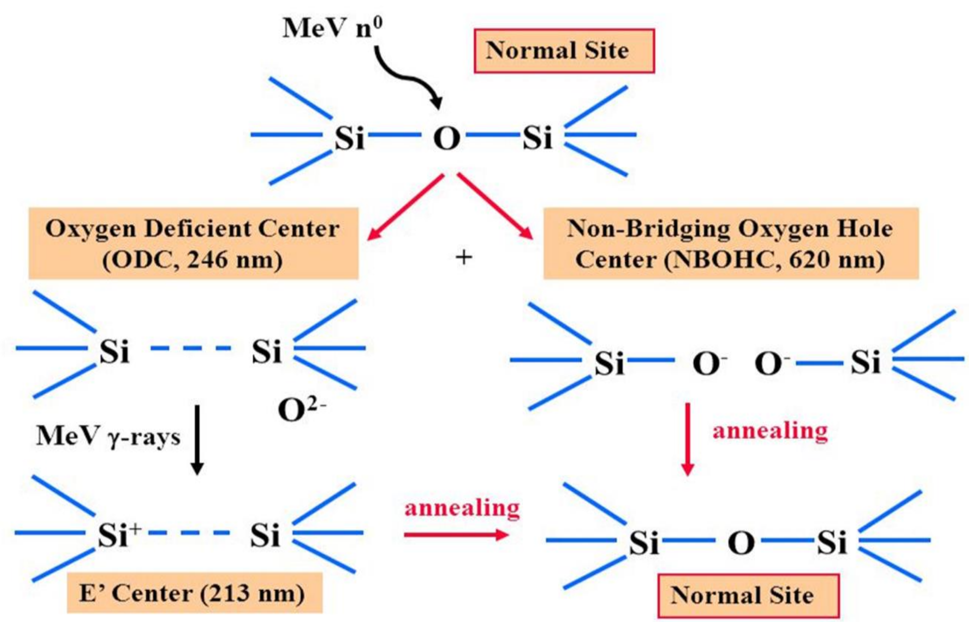


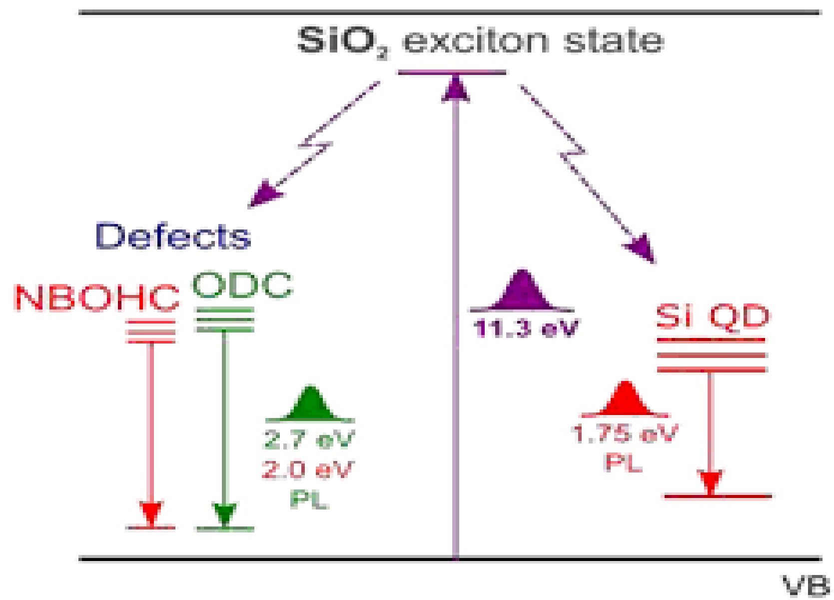


- Amorphous SiO_2
- Impurities < 10^{-8}
- Optical grade
- UV transmission
- Thermal resistance
- Radiation hard

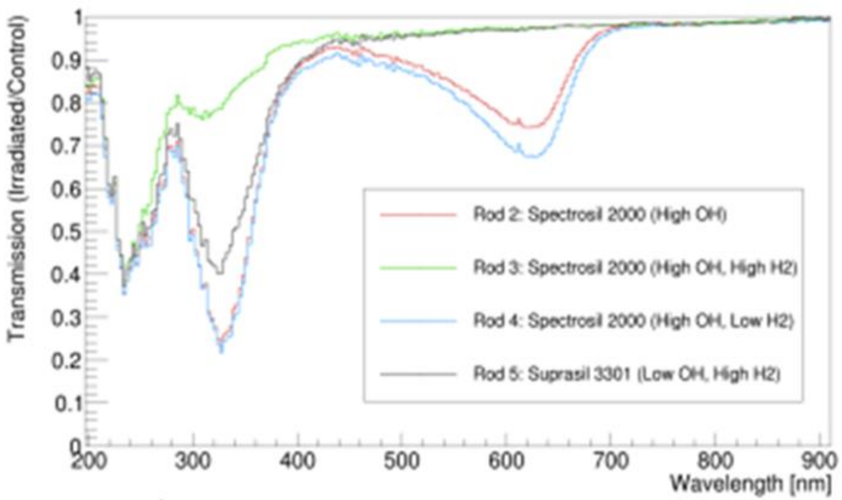


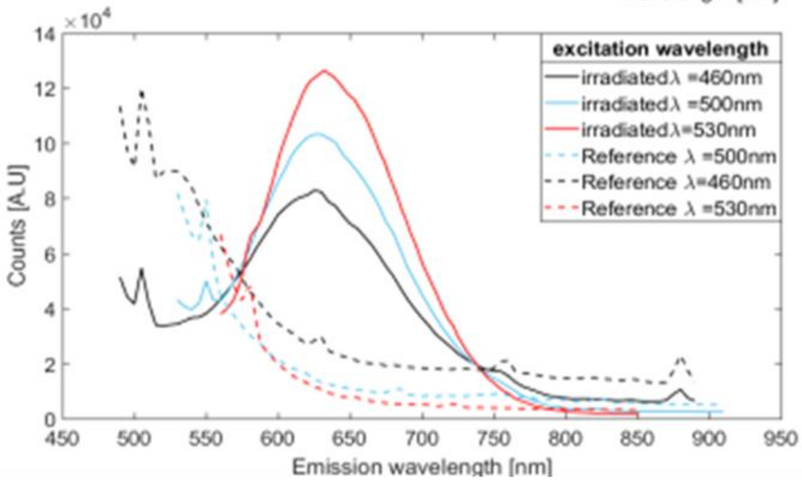
Neutrons and γ-rays create defects in SiO_2 which result in photon absorption

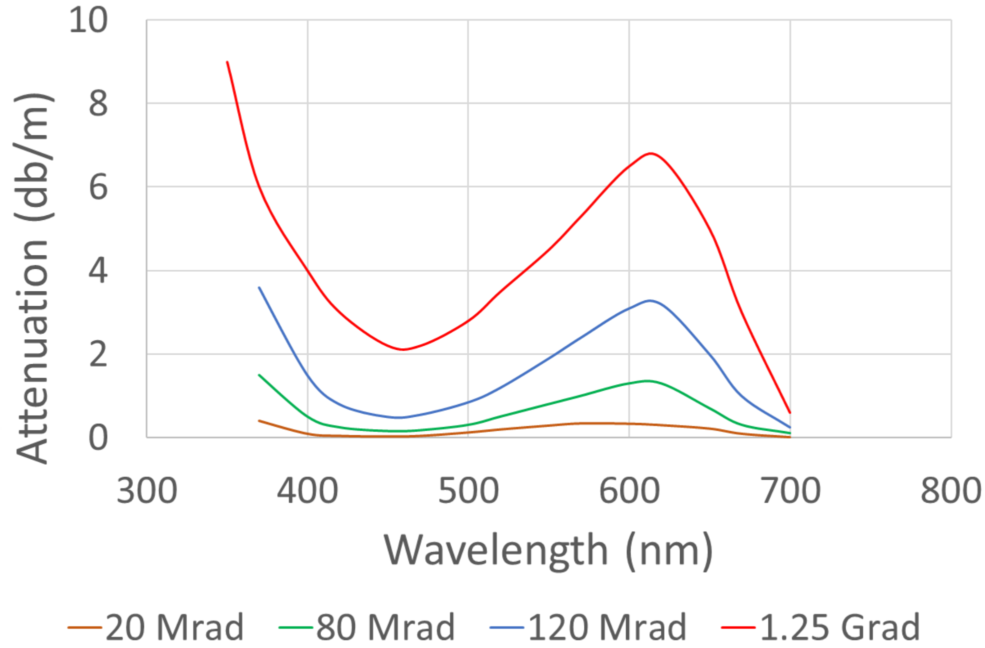




Radiation-induced transmission losses in Fused Silica



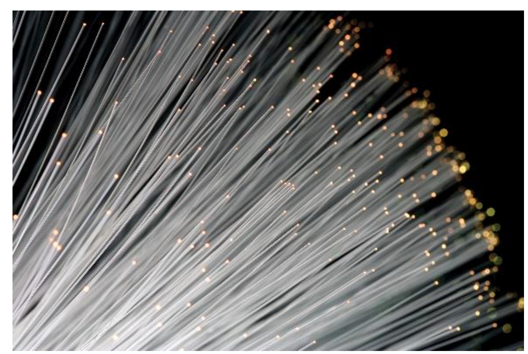




HF “quartz” fibres

Polymicro FSHA600630800 (OH- 500ppm)

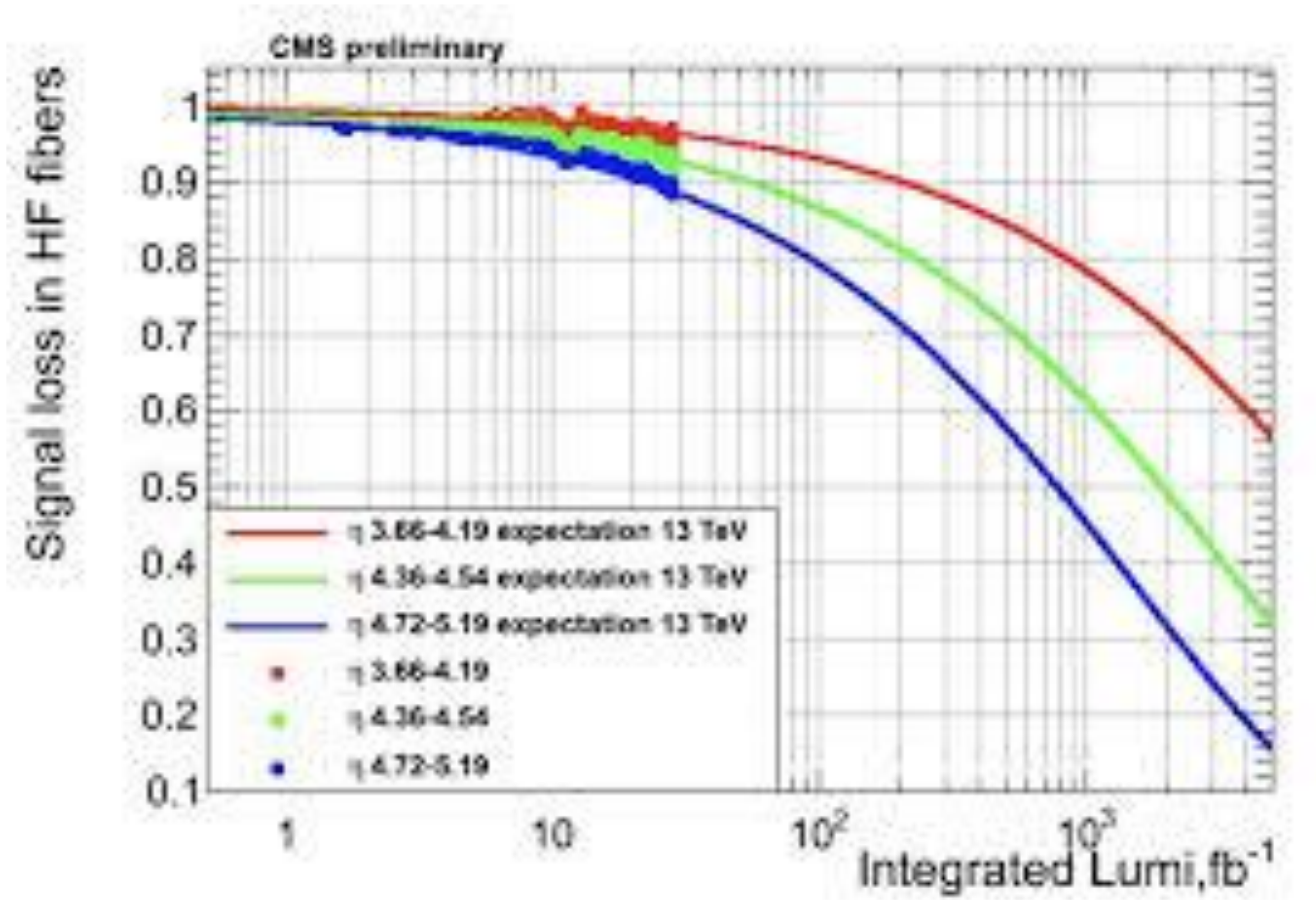
Heraeus Suprasil Rods



HF Longevity

QQ Fibers (fluorine-doped silica clad) should stand ~20 Grads, with ≤ 10% light loss;
QP Fibers (plastic-clad) may have ~75% losses after 5 years of LHC luminosity at high η
PMT Photodetectors (low B) PK windows: 30% transmission loss at 420 nm (glass)

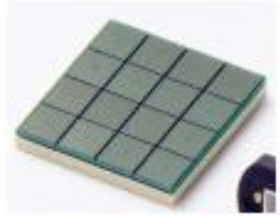
Recovery mechanisms may reduce the effects of radiation damage, either in natural way (self-repair in quiet periods after exposure), or artificially, for instance like thermo- (or photo-)bleaching.
Need to be understood to describe accurately the behaviour of the detector, and its history.
Robust enough for survival of detectors in extreme SLHC radiation conditions…???

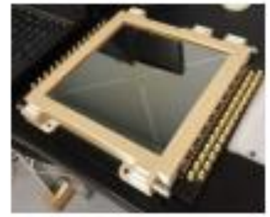


PHOTOSENSOR OPTIONS

Junqi Xie (ANL)
RD14 EIC-PID review meeting,
Sep 19, 2019

Commercial products | R&D only

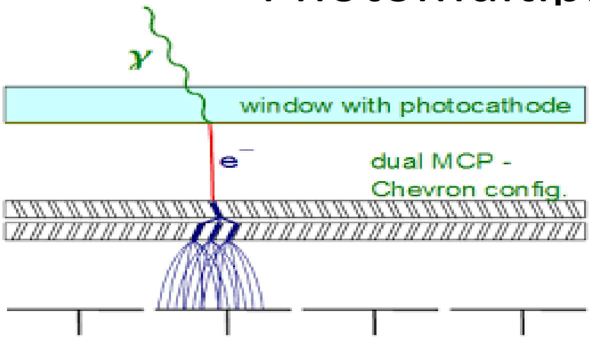


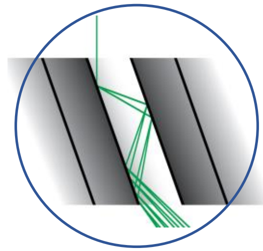


	Planacon	SiPM	LAPPD	Argonne MCP-PMT
Area	6cm x 6cm		20cm x 20cm	6cm x 6cm
Pixel	3x3 mm available	3x3 mm available	25x25 mm available 3x3 mm needs test	3x3 mm demonstrated, needs full device validation
Magnetic field	Yes	Yes	0.7 T, needs 10um MCPs for > 1.5 T	> 1.5 T
Radiation	Yes	Need test	Expect good	Expect good
Availability	In-stock	In-stock	In-stock for 20 um, in 2 years for 10 um	Mar 2020
Price	\$15-20 k/each, Significant cheaper in large unit	\$1 /mm^2 ?	\$50 k/ each now \$25 k/ each 4 years later based on Incom	-
Unit price	\$12.5k /25cm^2 Cheaper in large	\$2.5k /25cm^2	\$3.125k /25cm^2 now or \$1.56k /25cm^2 future Gen-III unknown	-
Concerns	No, except expensive for R&D	Radiation hardness	Cross talk, integration availability	-
Risk	No risk	No risk if radiation is OK	Achievable with risk, Gen-II, III LAPPD design	R&D only

*Photek MCP-PMT is also a potential option for commercial small-pixel MCP-PMTs although not listed in details here.

Micro Channel Plate Photomultipliers

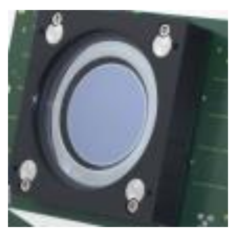




Hamamatsu

Photonis

Photek



KATOD UFK-5G-2D:

2-stage MCP 0.3 mm thick 6 µm pores at 6^{o}

Gain >10^{6} and dark current < 1 nA

Window : 1.2mm thick glass (US-49)

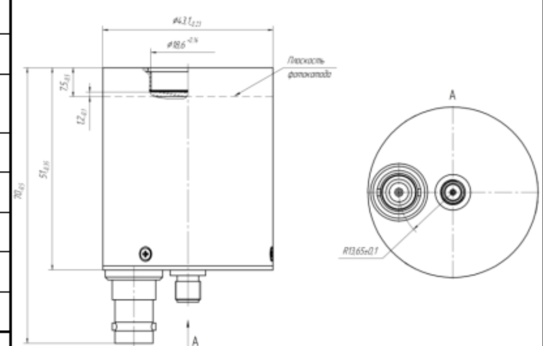
Transit time spread (TTS) 30 -50 ps

ООО КАТОД

Photomultiplier Tube UFK-5G-2D

General

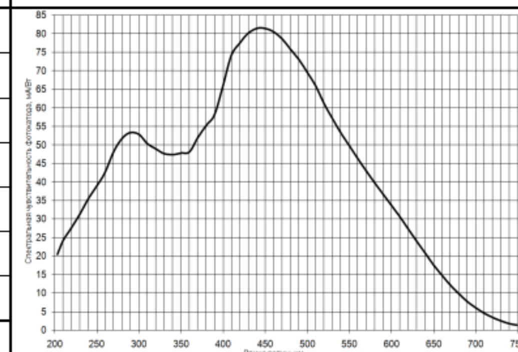
Input Window Material	glass US-49
Photocathode Material	$(Na_2KSb)Cs$
Effective Photocathode Diameter, mm	18
Housing Material	Metal
Connector Types anode output power supply	SMA-R SHV-R
Intensification System	microchannel
MCP quantity	2
Diameter, mm	43,1
Length, mm	70
Weight, g	< 100



Dimensional Outline

Electrical Characteristics

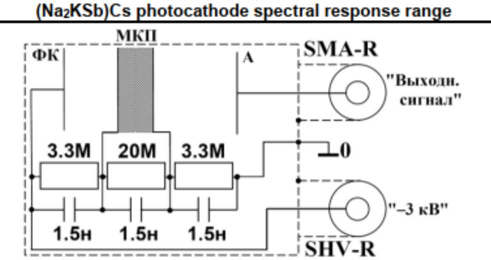
Spectral response range, nm	200-750
Radiant photocathode sensitivity at λ=450 нм, mA/W	> 70
Gain	$1 \cdot 10^6$
Dark Current at gain $1 \cdot 10^6$, A	$< 1 \cdot 10^{-9}$
Max anode current, nA	300
Supply Voltage, kV	< 3,1 negative
Divider Resistance, MOhm	26,5



$(Na_2KSb)Cs$ photocathode spectral response range

Operational Conditions

Sinusoidal Vibration	within frequency range 1÷500 Hz acceleration amplitude 5g
Multiple Shock	15g, (2÷15) ms
Single Shock	300g, 1 ms
Operational temperature	± 50 °C
Transportation temperature	+ 70, - 60 °C
Reliability: MTTF, h	10 000



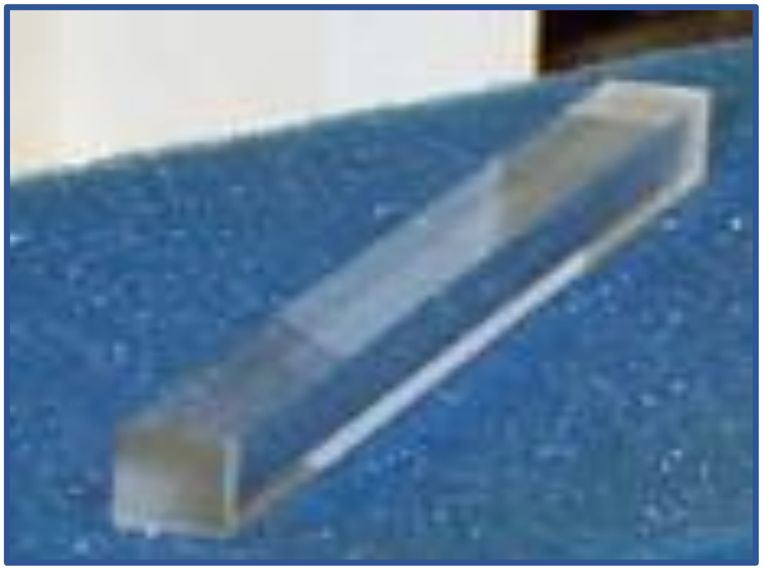
Block Diagram

3 Padunskaya St., Novosibirsk 630047, Russia
tel. +7 (383) 227-22-00 fax +7 (383) 227-21-50 e-mail: sales@katodnv.com

Quartz (Fused Silica) Radiators

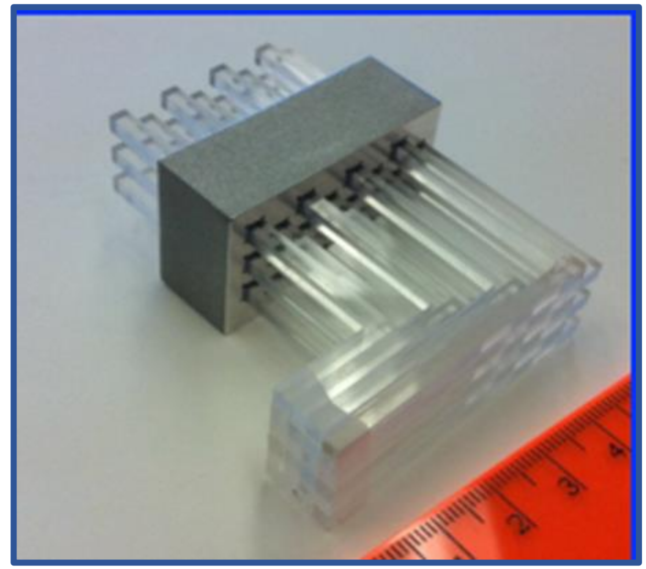
The L-bars were used for the QUARTIC modules (tested at CERN)

For DESY measurements:
The block is KU-1 (Russian Standard) used for TRC is characterized by UV transparency, high radiation hardness and absence of fluorescence
Quartz bars produced by Speciality Glass Ptoducts (USA) were used for SB counters.



Speciality Glass Products (USA)

KU-1 (Russian Standard)



(Alpha-TM)

GEANT4 Simulations (courtesy Berkan Kaynak)

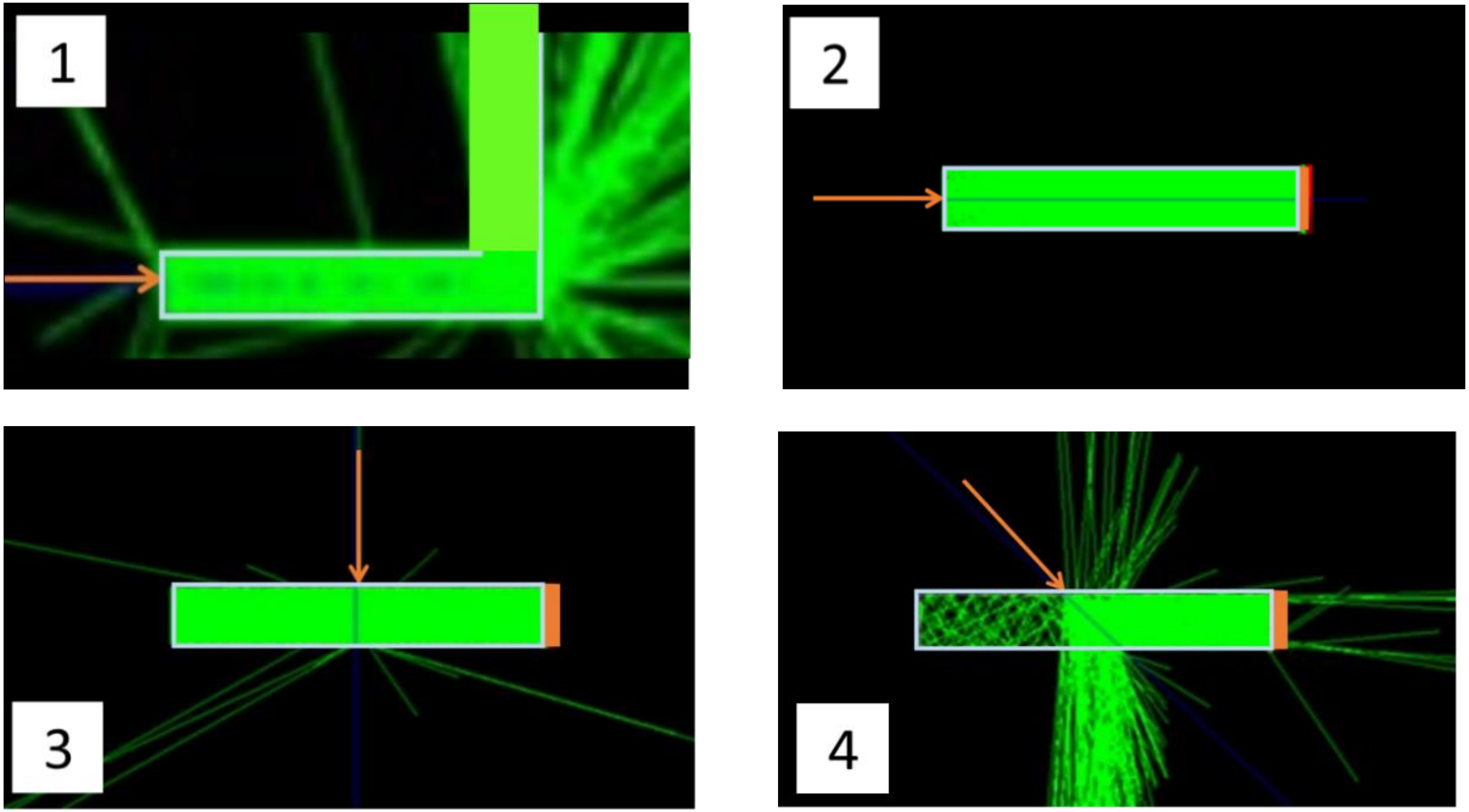


Fig. 4 : Simulations with GEANT4 of four cases : on-axis L-bar (1) and head-on S-bar (2), 90° transverse S-bar (3) and 45° inclined S-bar (4). For case 1 the vertical part of the L-bar has been cut away to emphasize the large losses occurring at the right-angle corner.

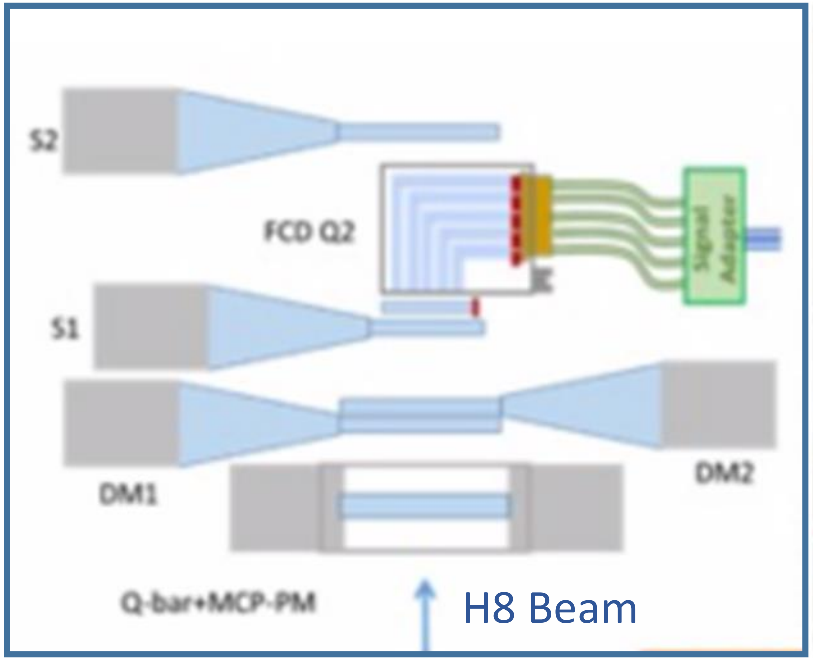
QUARTIC Tests at CERN

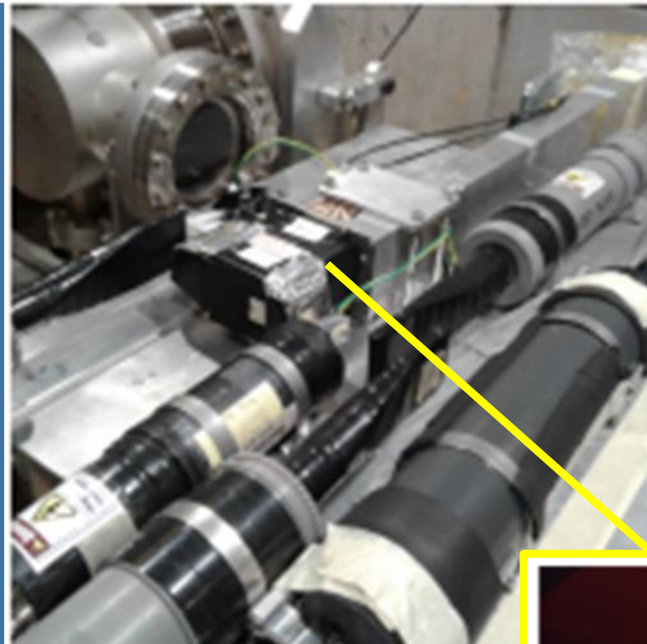
SPS North Area

7 beam lines

total length 5.8 km

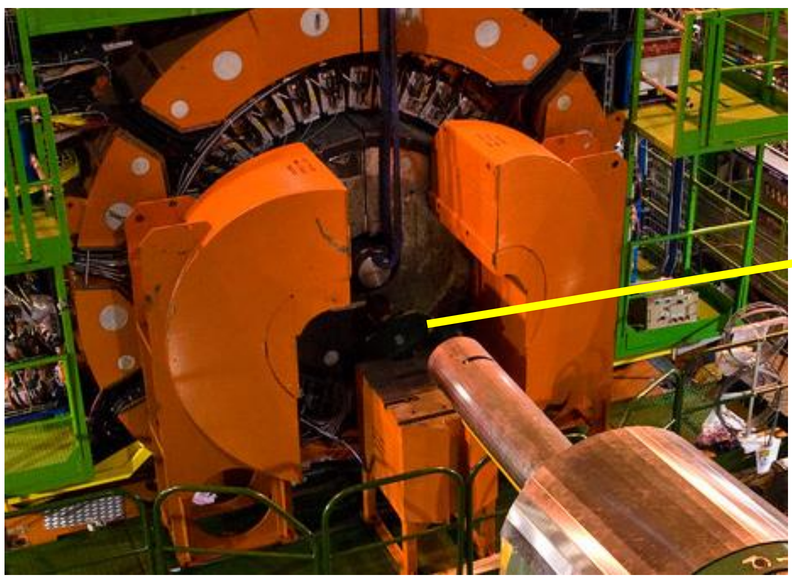
Three experimental halls : **EHN1**, EHN2, ECN3





4 November 2009

CMS HF$^-$



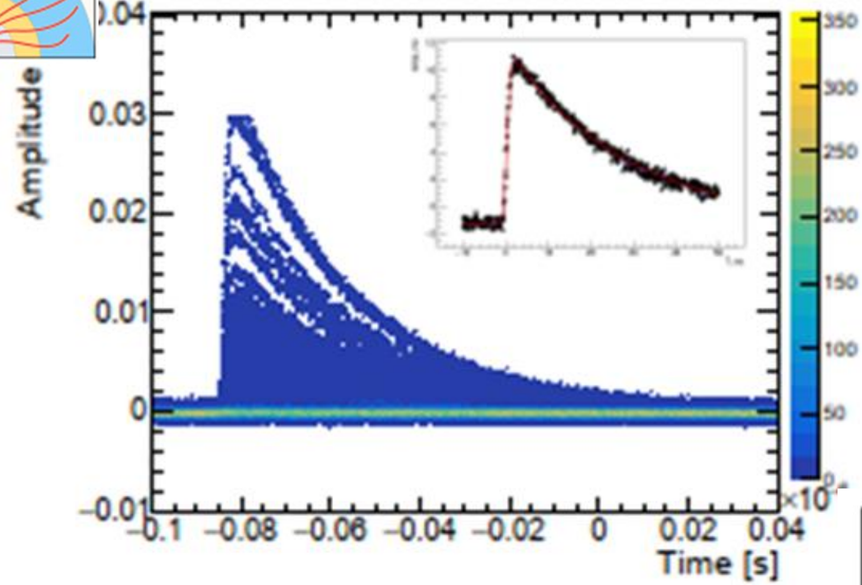
Early Results

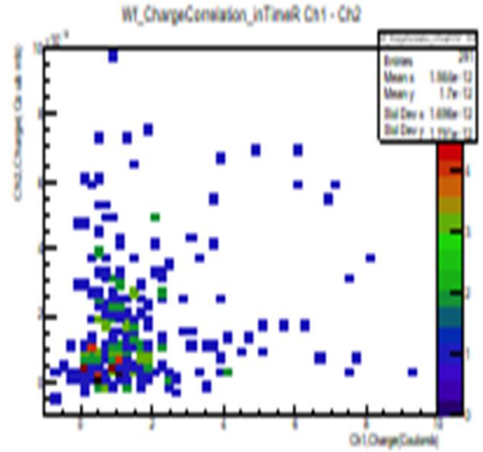
Table 1

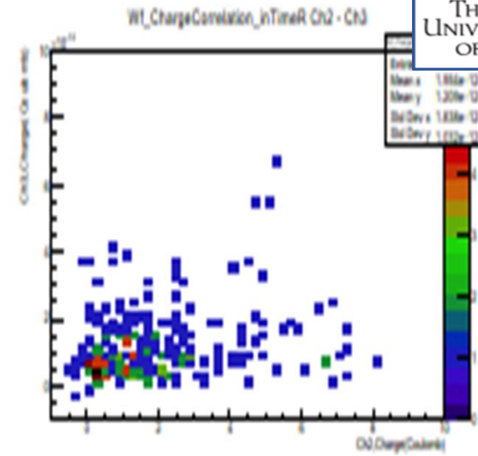
Radiator	Configuration	Photodetector	DAQ	Single-ch. σ_t [ps]	Multi-ch. σ_t [ps]	Ref.
10mm Quartz	Straight bar in-line	Photonis 85011 MCP-PMT (10μm) 8x8 anode pads (6x6mm2)	ORTEC NIM+TAC+ADC 1 GHz BW	$\sigma_t \approx 16$ ps		[1]
(6x6mm²) 80mm Quartz	Inclined ($\Theta_C \approx 48°$)	PMT210 (10mm Ø) MCP-PMT (Photek?)	ORTEC NIM+TAC+ADC 1 GHz BW	$\sigma_t \approx 16$ ps	$\sigma_t \approx 12$ ps for pair	[2]
30mm Quartz	Straight bar in-line	HPK MPPC S10362-330050C 3600 pixels 50μm	DRS4 (5 GSPS) Waveform Digitizer	$\sigma_t \approx 30$ ps		[2]
30mm Quartz	L-bar (40mm LG)	HPK MPPC S10943-0035 (3x3 mm²)	DRS4 (5 GSPS) Waveform Digitizer	$\sigma_t \approx 33$ ps	$\sigma_t \approx 17$ ps for quartet	[2]

[1] J. Va'vra et al., Beam test of a Time-of-Flight detector prototype, NIM-PR A 606 (2009) 404
[2] M.G. Albrow et al., Quartz Cherenkov counters for fast timing: QUARTIC, JINST 7 P10027 (2012)
[3] L. Bonnet,J. Liao,K. Piotrzkowski, GASTOF- 10ps resolution timing detector,NIM-PR A762 (2014) 77

QUARTIC detectors with 20 L-bars were completed in 2015. One critical point was the production of L-bars as single crystals. A Russian company (Alpha-TM) produced 80 (40 Sapphire and 40 Quartz) L-bars with the required parameters and dimensions. The L-bars have a surface polishing of optical quality, tested by Atomic Power Microscope in NIC "Kurchatov Institute“

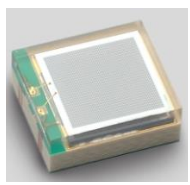




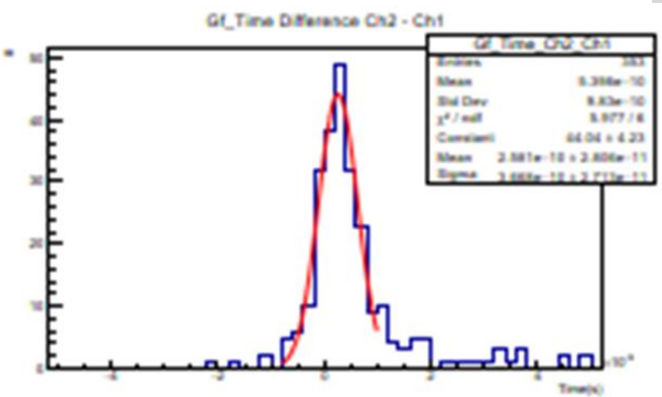


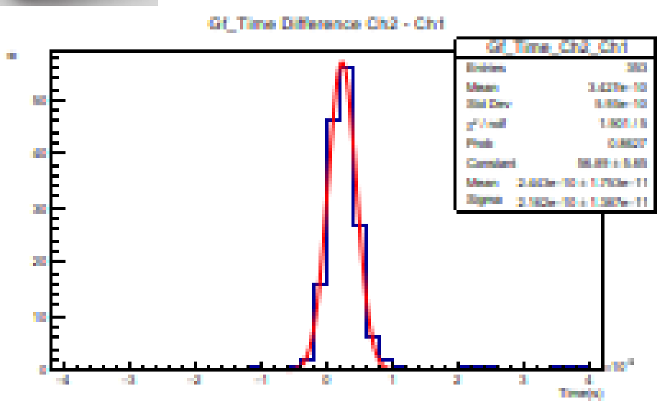
H8 Test Beam

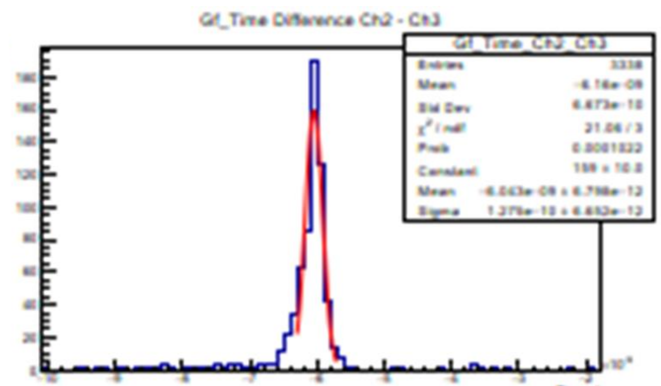
SiPM readout (S. Los) :
MPPC S12572-100P



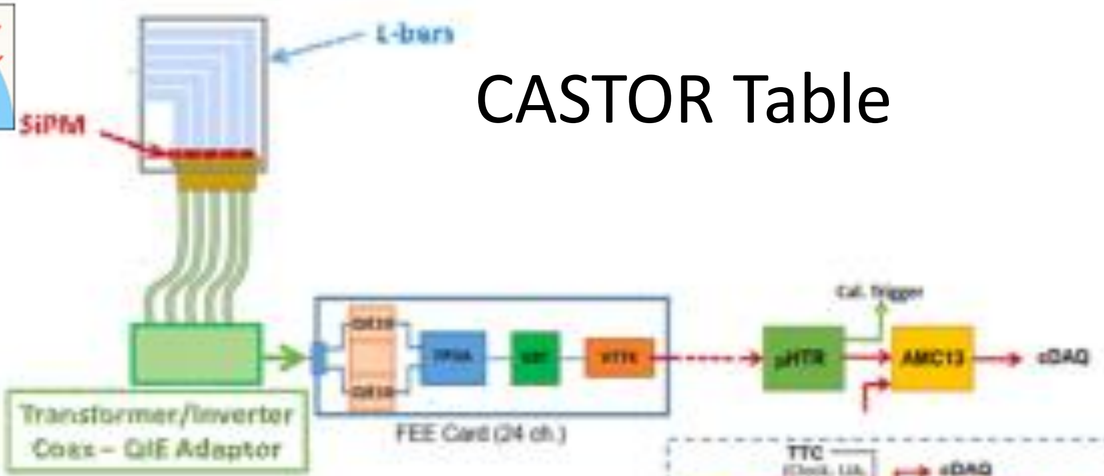
DSO Inputs	QUARTIC Q2 ch.	Trigger (N)= [(DM1*DM2)*S1*S2]	Trigger (S7) [#7>3mV]
Ch.1	# 2	$\sigma_2 = 169(\pm 20)$ ps	
Ch.2	# 7	$\sigma_7 = 216(\pm 20)$ ps	$\sigma_7 = 78.55(\pm 10)$ ps
Ch.3	# 12		$\sigma_{12} = 100.4(\pm 40)$ ps
Ch.4	MCP	$\sigma_{MCP} = 82(\pm 20)$ ps	$\sigma_{MCP} = 88.71(\pm 30)$ ps

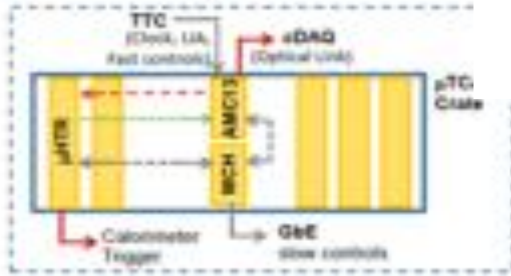


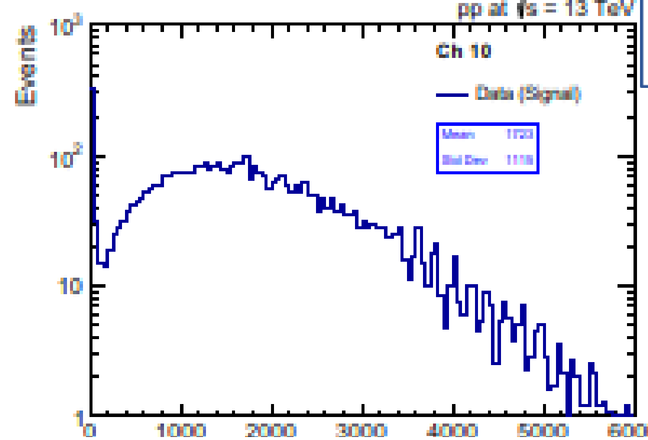


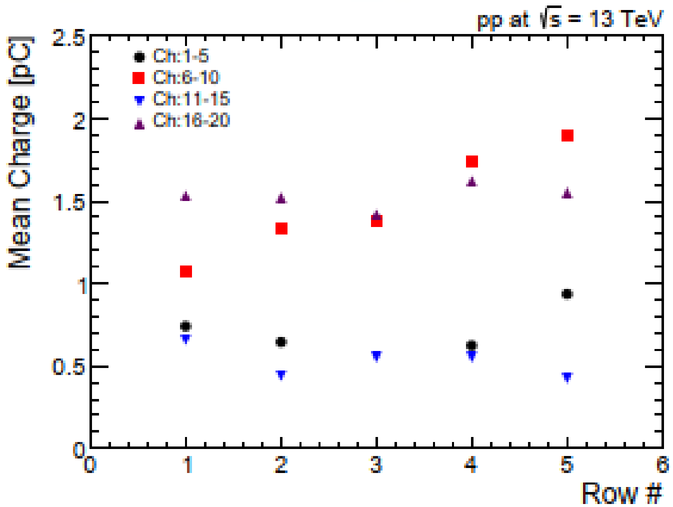


CASTOR Table

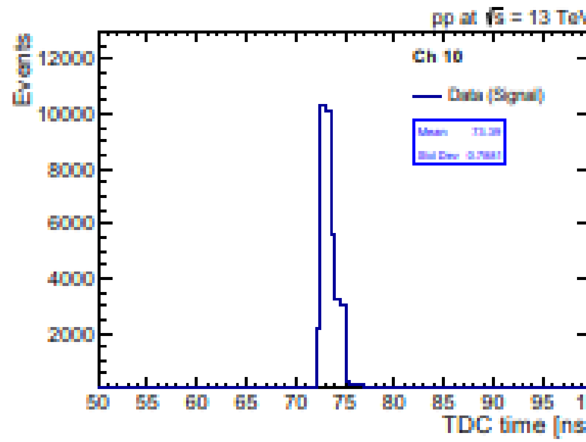


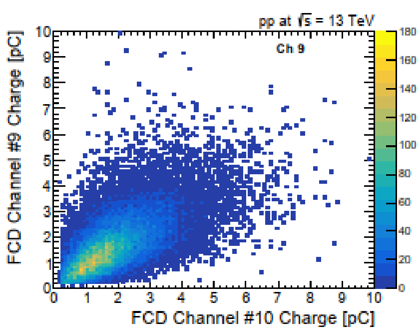


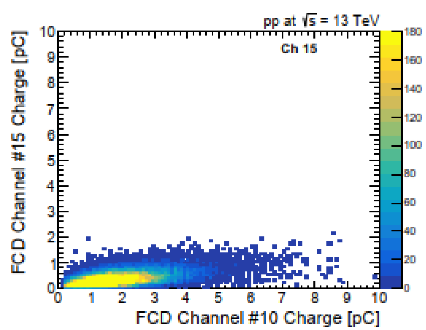


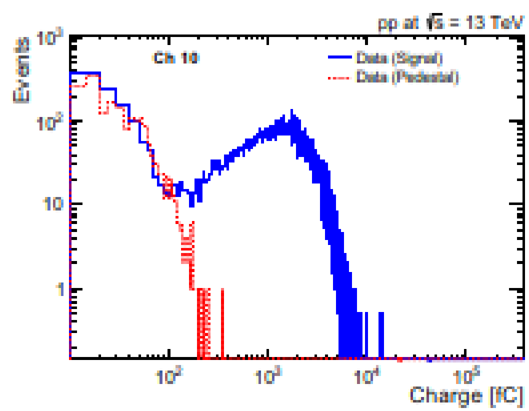


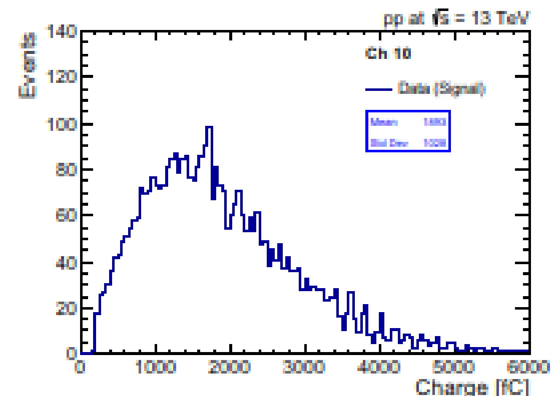
HF- QIE readout



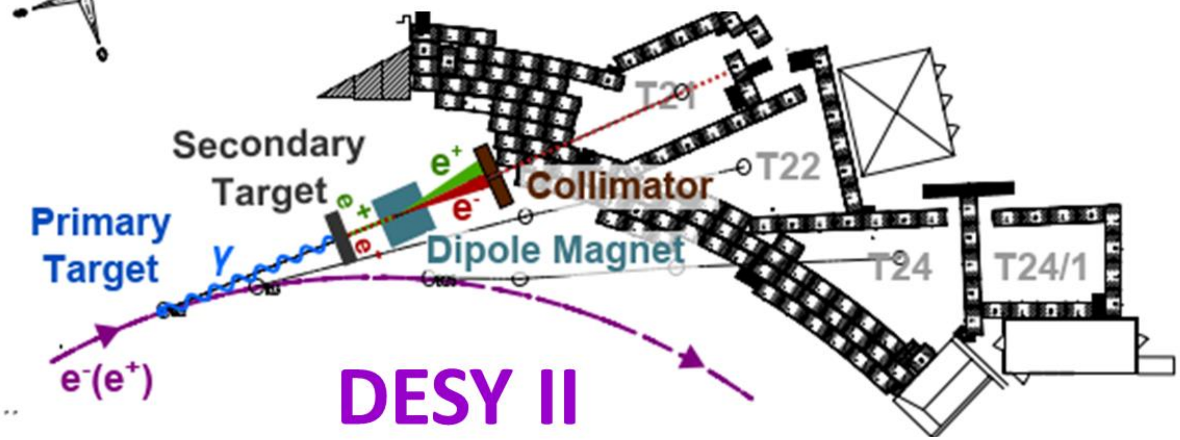






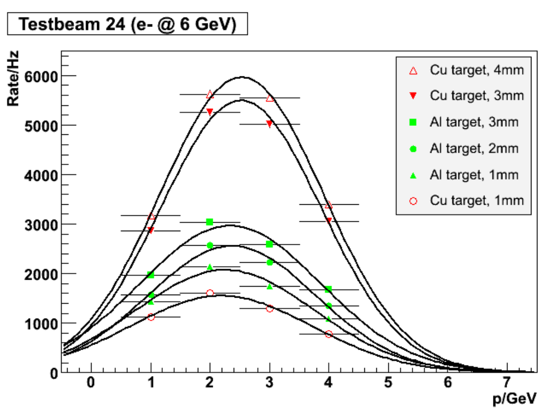


TEST BEAM AREAS

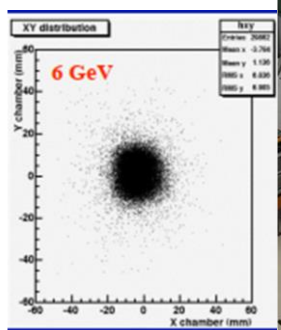


- Bremsstrahlung γ beams
  - converted to e+ e- pairs,
  - momentum/charge selected in magnet – collimator setup
- 3 Beam lines : T21, T22, T24
- Energy : 1 – 6 GeV
- Energy spread : 5%
- Divergence : ≈ 2mrads
- Flux : ≈ 0.3 – 1 kHz/cm2

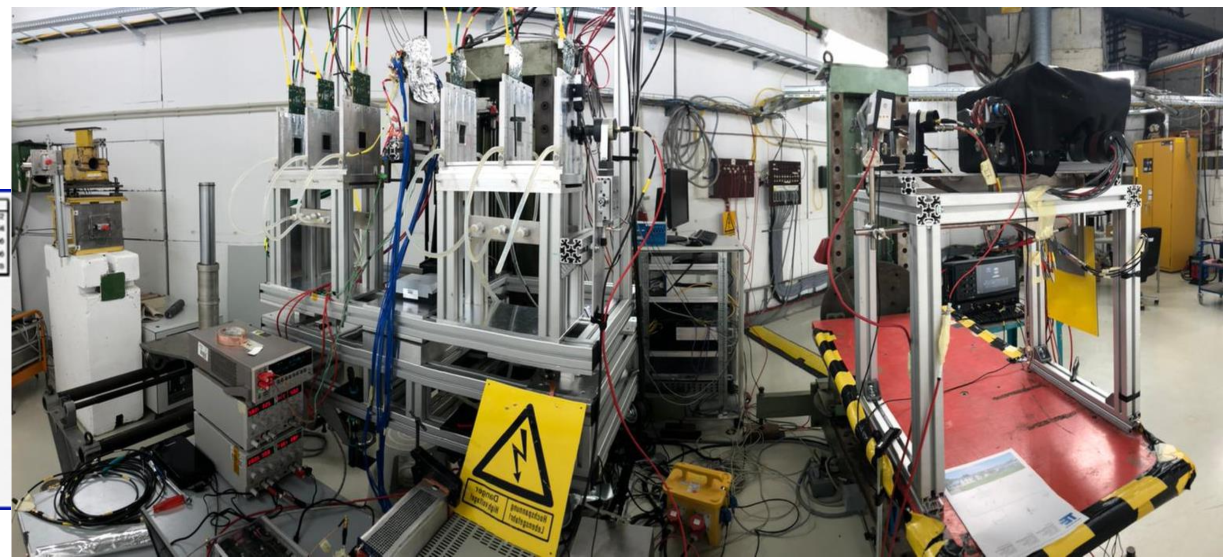
T24 Beam Line



Rates vs Energy



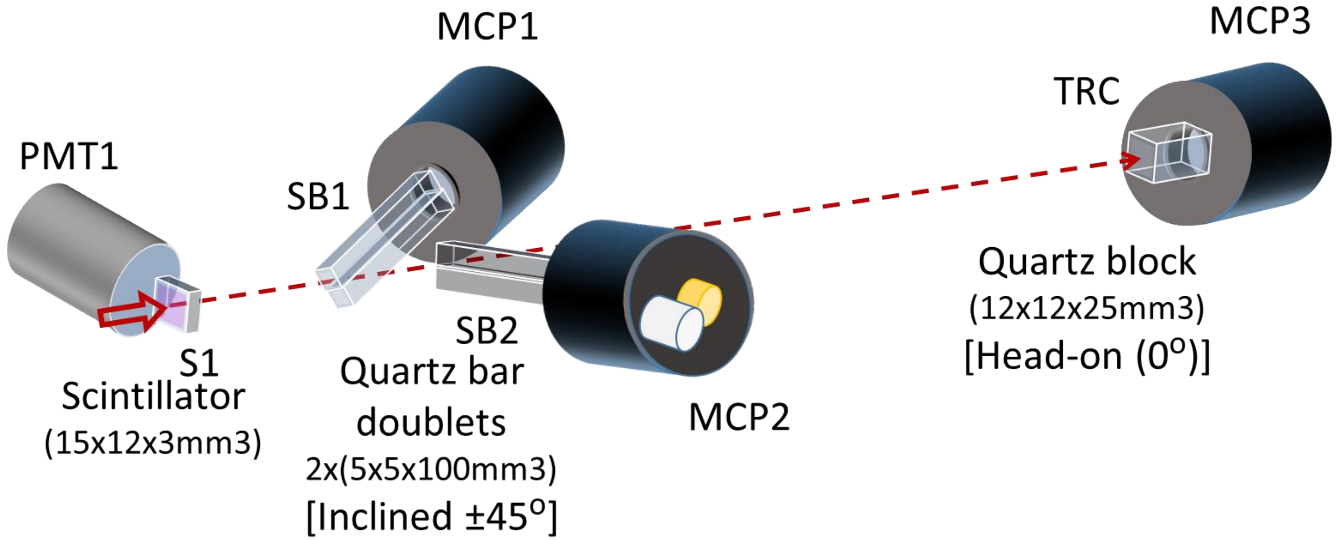
Beam spot

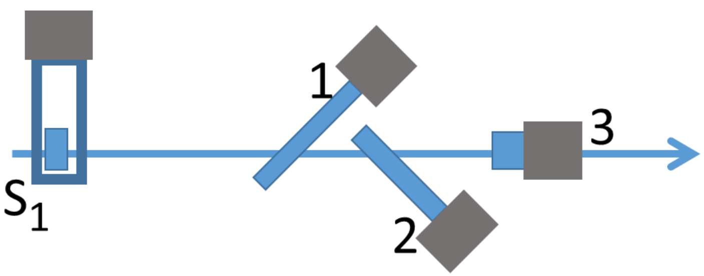


Tracker + DUT1

DUT2

DESY : Setup for CTD Tests

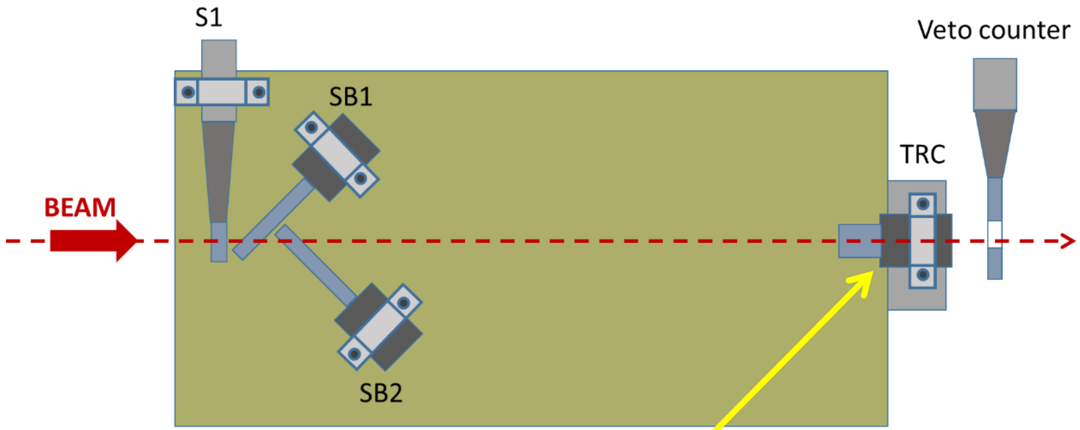




$$\sigma_{12}^2 = \sigma_1^2 + \sigma_2^2$$
$$\sigma_{13}^2 = \sigma_1^2 + \sigma_3^2$$
$$\sigma_{23}^2 = \sigma_2^2 + \sigma_3^2$$

IF Time Measurements are INDEPENDENT variables!

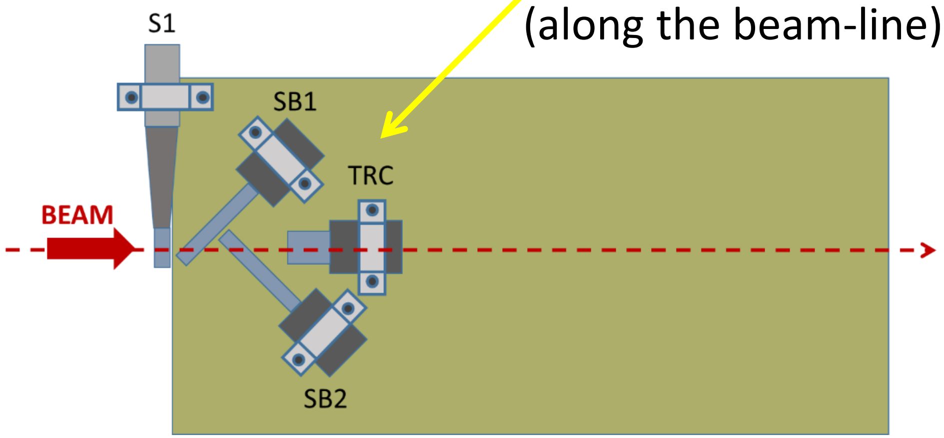
DESY Setup Phases



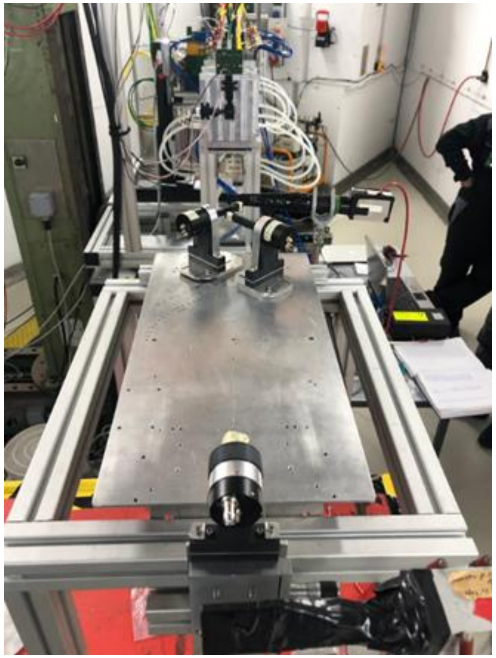
Phase 1: Initial setup

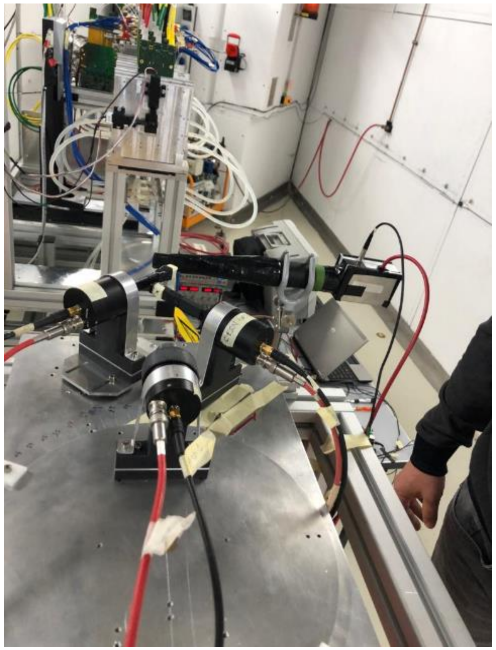
TRC moved by 438 mm

(along the beam-line)

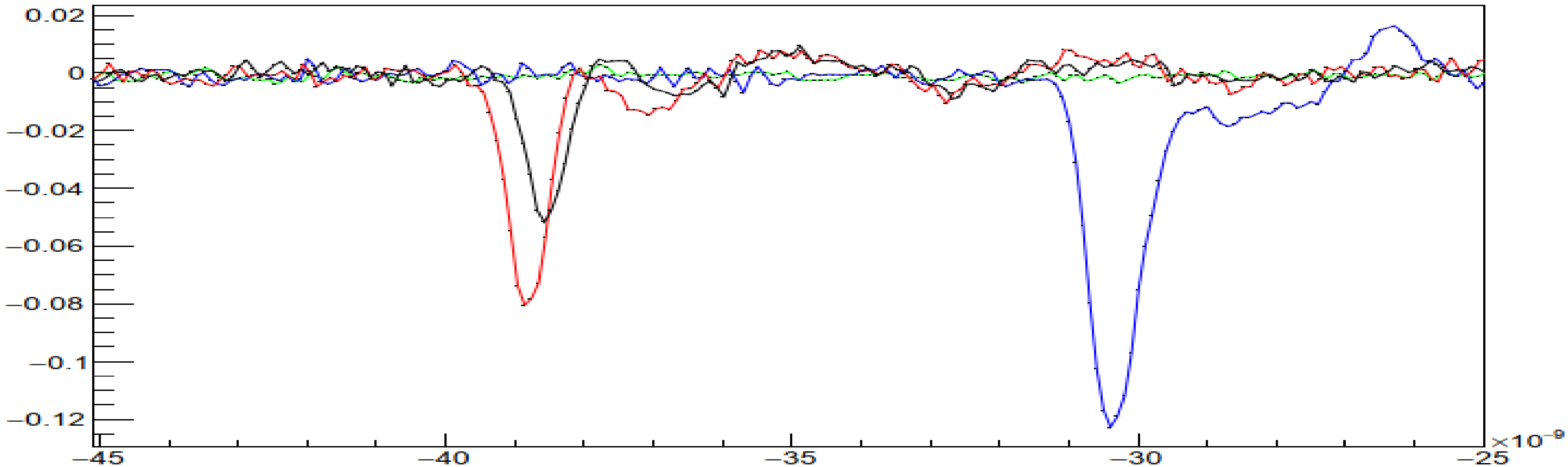


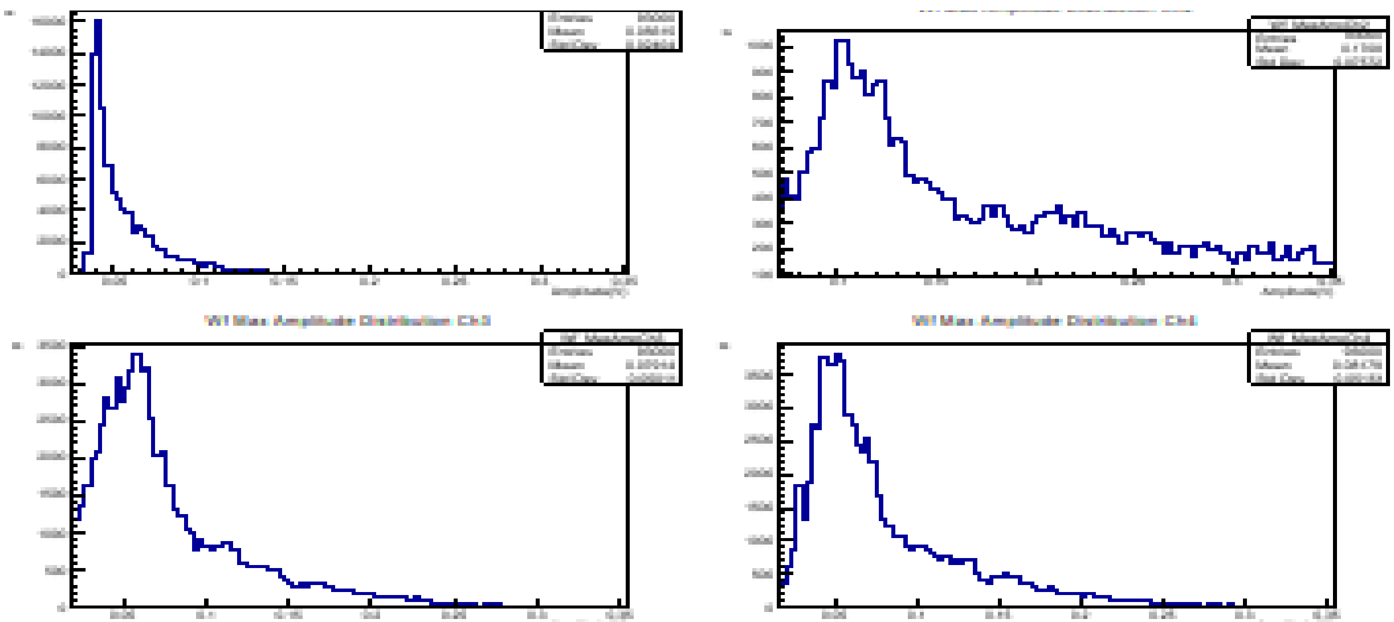
Phase 2 : more compact configuration



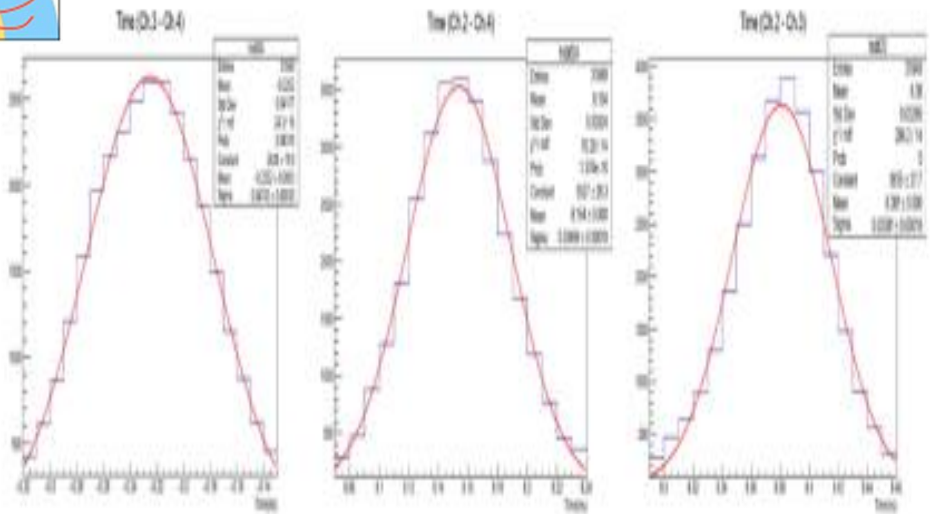


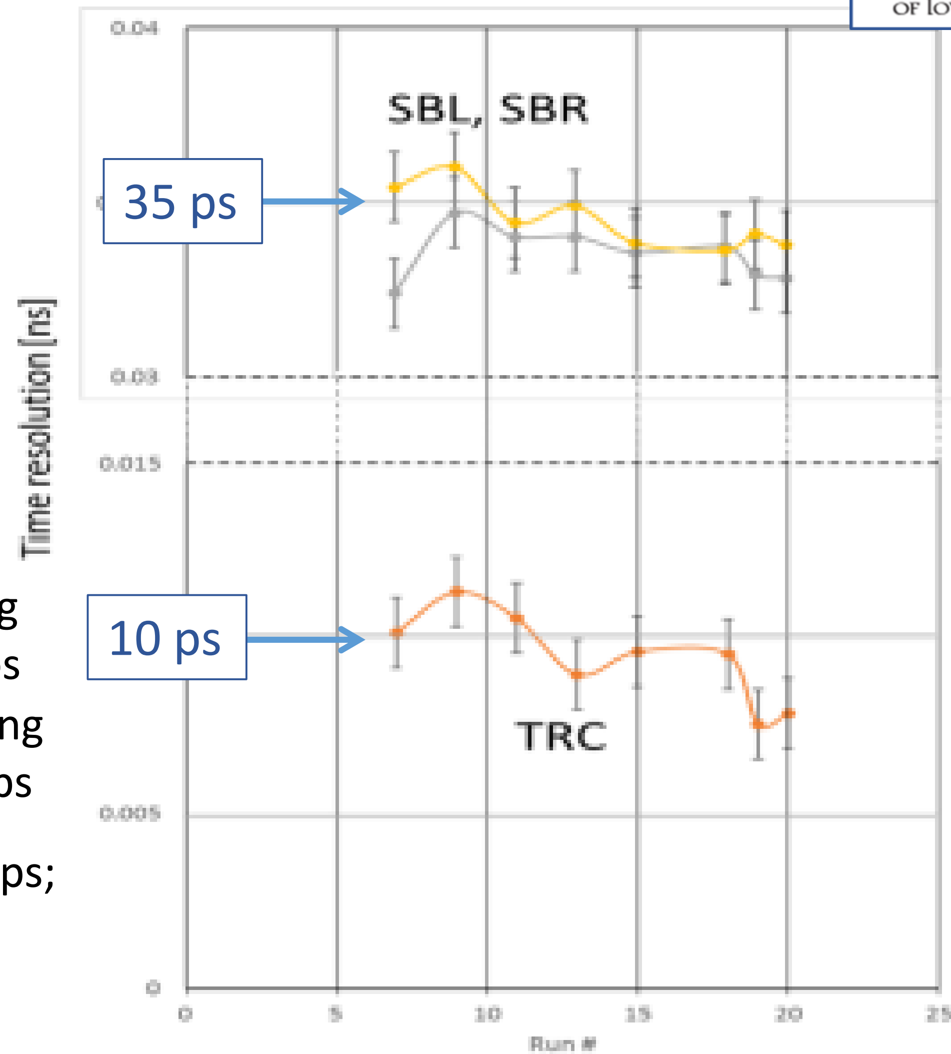
Signals on LeCroy Wave Runner 8104 (1GHz, 10 Gs/s)





Signal Amplitude Distributions





Run 7 σ_{RL} = 49ps, σ_{TL} = 34.5ps, σ_{TR} = 37.8ps, giving σ_{TRC} = 10.2ps, σ_{SBL} = 33ps and σ_{SBR} = 36.4ps

Run 19 σ_{RL} = 48.7ps, σ_{TL} = 35.2ps, σ_{TR} = 35.9ps, giving σ_{TRC} = 8.8ps, σ_{SBL} = 34.1ps and σ_{SBR} = 34.8ps

Statistical error ≈ 0.455 ps and systematic ≈ 1.025 ps; in right figure error bars correspond to ±1.15 ps.

Hierarchy in the configurations:

1. Head-on systems: $\sigma_T \approx$ 10ps → thin quartz/sapphire pads on top of (multipixel) MCP
2. Inclined bars : $\sigma_T \approx$ 35ps → quartz/sapphire bars with (multipixel?) MCP
3. Transverse : $\sigma_T \approx$ 50 – 70ps → quartz/sapphire bars with (multipixel?) MCP

Executive Summary and Interim Conclusions

Large quartz systems are used at LHC and elsewhere.
Excellent timing is possible with quartz specific detectors and photodetectors
Can the criteria found for the latter be extended to the former?

The tests at DESY were successful to establish :

1) A permanently calibrated reference counter (TRC) for the beam (downstream)
2) Confirming GEANT4 simulations
3) getting confidence in the UFK-5G-2D KATOD MCP-PMT

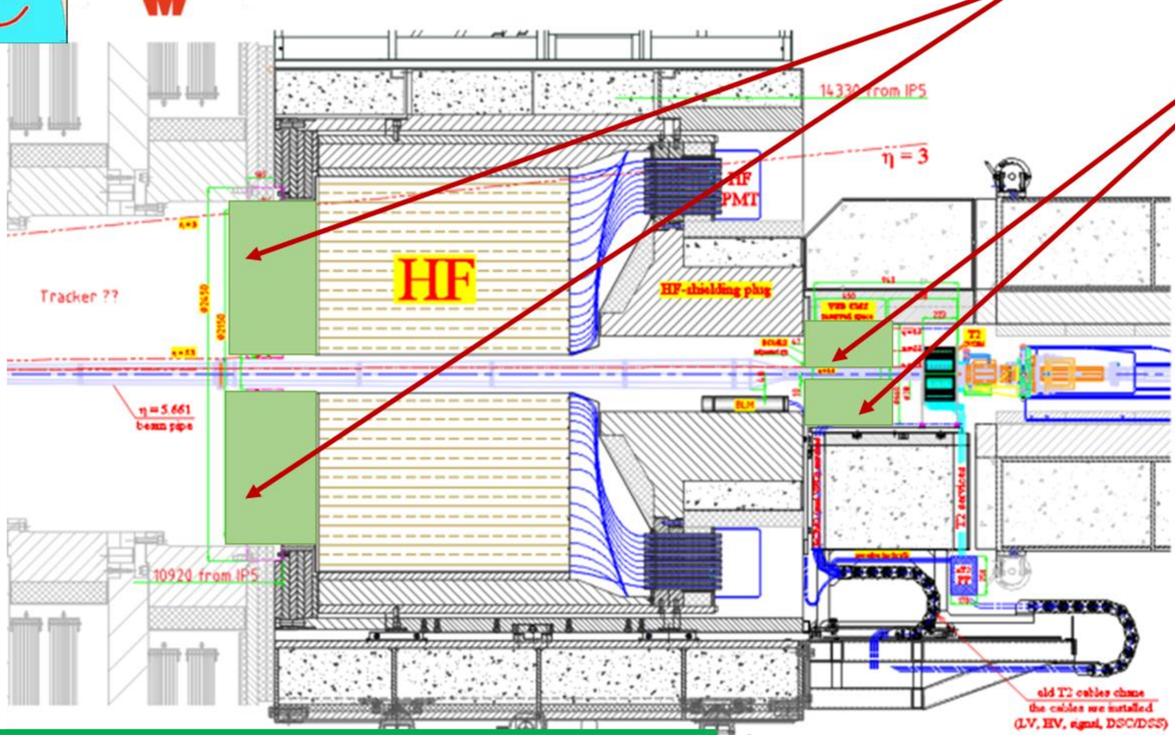
Moving the TRC counter at a certain moment of the run, gave an oppurtunity to check not only the resolution results, but also the good precision (and absence of biases) of the ToF measurements: the change of ToF between runs # 9 and # 11 corresponds to the displacement of TRC by 438mm (0.438 x 3.336 ns/m = 1.461ns); the measured ToF difference is 1.460 ns for TTR = (tTRC − tSBR) and 1.462 ns for TTL = (tTRC − tSBL).

Furthermore the residual of TTR - TTL - TLR (1.02 ps average value) gives an estimate of the systematic error. For the statistical error the average value is 0.455 ps.

Perspective applications

Discussed within the "HCAL Forward Region Task Force" (chair A. Skuja)

High Eta Timing Device



A borderline area in CMS forward region between Endcap Calorimetry and PPS/TOTEM very forward detectors.

- $3 \leq |\eta| \leq 5.3$ interval:
  - HF territory
- $5.3 \leq |\eta| \leq 6.5$ interval:
  - legacy of T2 (TOTEM) and CASTOR

FPC: Forward Preshower Calorimeter

FTL: Forward Timing Layer

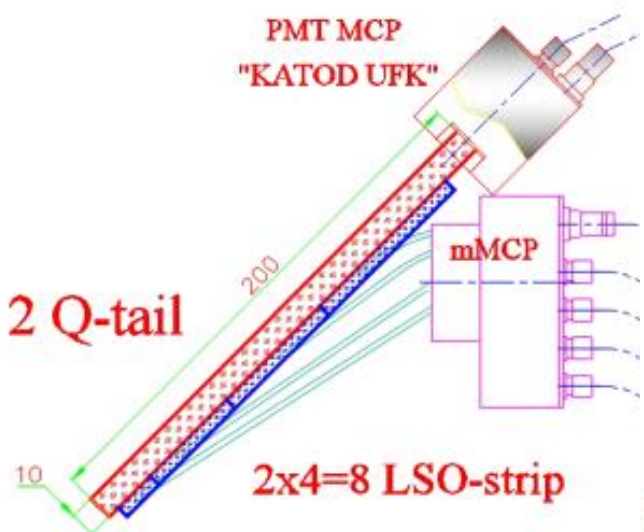
VFD: Very Forward Detector

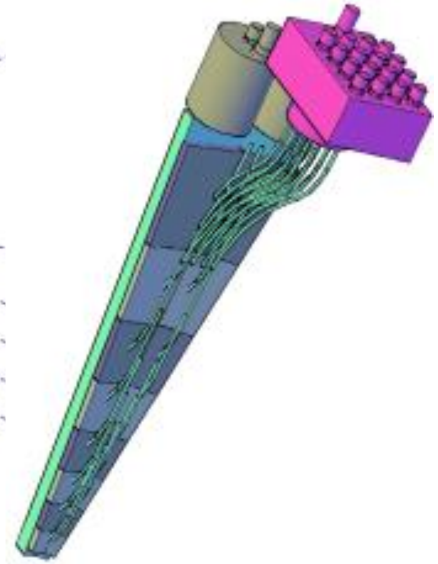
S. Özkorucuklu,
25/09/2019

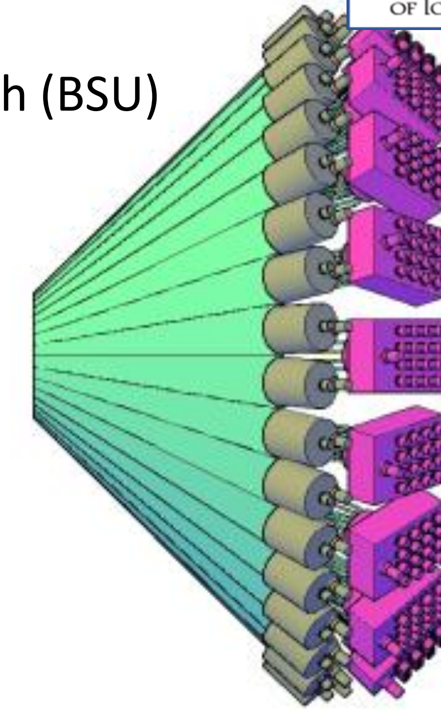
1

Timing Wall Detector for HF CMS(*)

D. Druzhkin(CERN), V. Samoylenko(NRC-IHEP), R.Stefanovich (BSU)





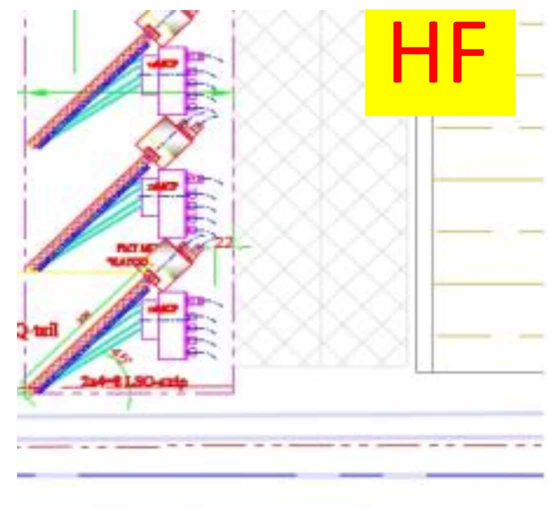


TWD consists of two parts:

1. Timing Part – Quartz Tile with PM MCP Readout (direct Cherenkov light), ϕ=10° (matching with HF), $4.8 < \eta < 6.4$

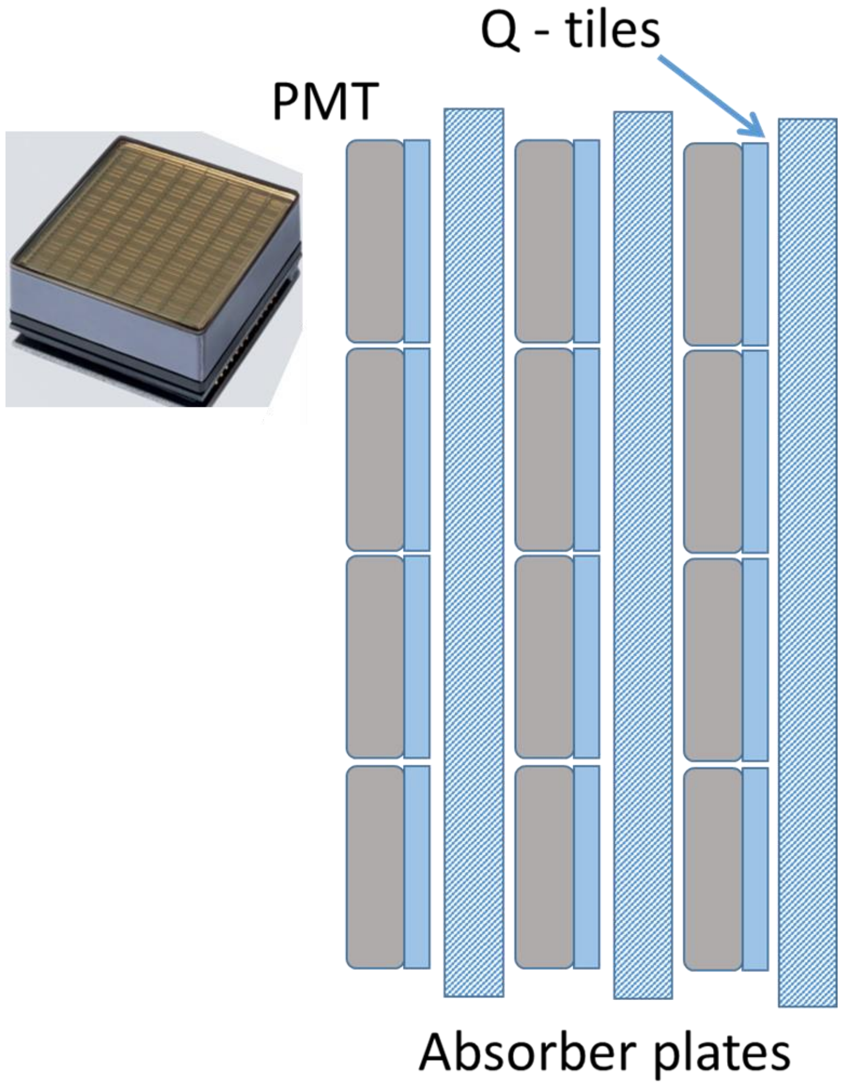
2. R-spatial Part – for R measurement and Time correction (scintillator LSO/GAGG + quartz fiber).

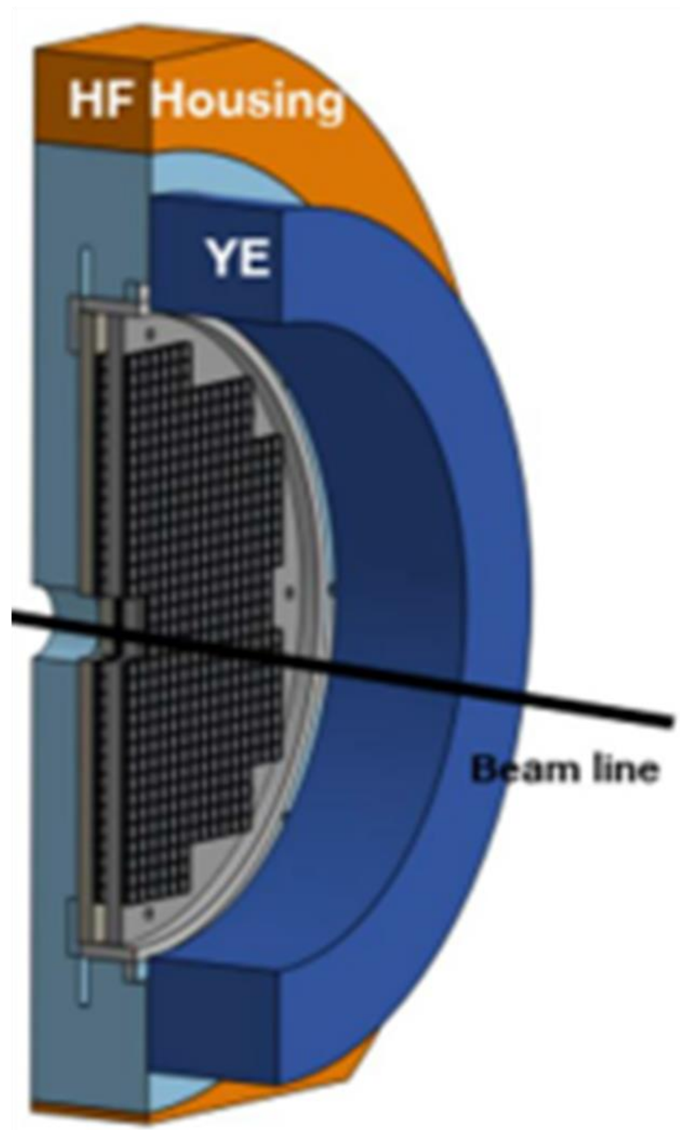
Repeats Quartz Tile geometry with equal rapidity interval η= 0.2 or with equal time spread.



(*) INSTR2020, Novosibirsk

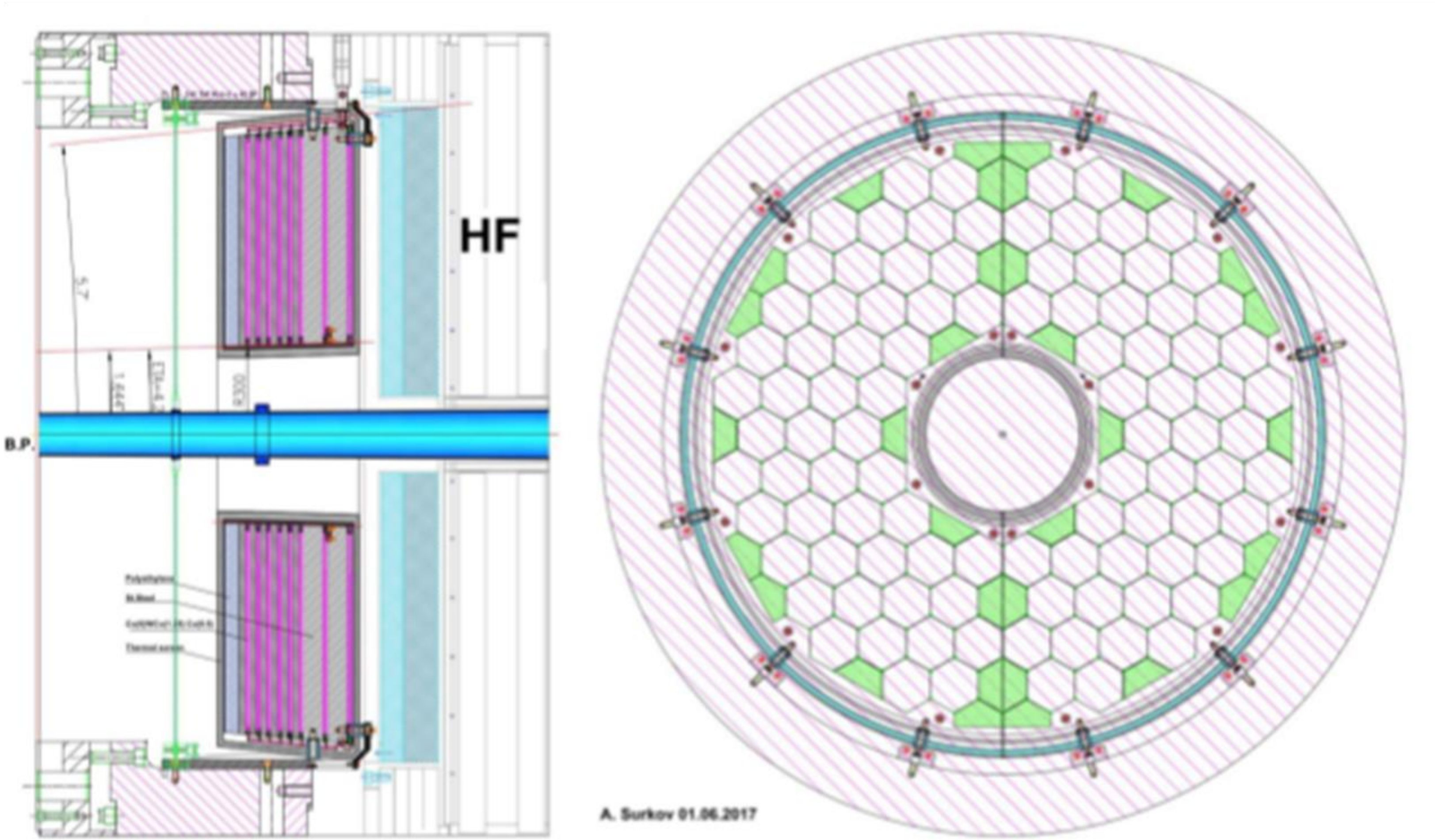
PMT(+Q-tile) Wall   IOWA Team (Y.Onel et al.)





HF-n: HGC-style Si calorimeter

M. D’Alfonso et al. (based on an idea of T.S. Virdee)



A Proposal…

Extrapolation of HF technology to a preshower module, doubled as timing wall, using quartz fiber bundles, coupled to suitable photodetectors (PMTs, MCPs or SiPMs). A similar concept could be used also for the VFD module behind HF

Good example[1]: ***H1 Very Forward EM calorimeter*** (Luminosity Monitor): 25 X0 of W- Quartz fiber planes at 45°, alternating horizontal and vertical fibers, divided in 10 mm strips, to determine x, y impact point.

H1 Very Forw.-EM calorimeter (Luminosity monitor)

$\sigma(E)/E = 0.19/\sqrt{E}\ (\mathrm{GeV}) \oplus 0.5\%$
$\sigma(x,y) = 5\ \mathrm{mm}/\sqrt{E}\ (\mathrm{GeV})$
Filling factor (FF) : ≈ 50%
70 plates (≈1mm) Tungsten (W)
Quartz arrays at 45°

For preshower (<20 Xo)
Fe – Q fibers (FF ≈ 30%)
expect $\Delta E/E \approx 0.30\ E^{-0.5}$

Fibers allow to carry signals far from beam region, in shielded environment.

(1) V. Andreev et al., The new H1 luminosity system for HERA II; NIM-A494 (2002) 45-50
G. Mavromanolakis, HEP-Cavendish/04/34,UA-NPPS/06/2003, 20 Dec 2004 – arXiv:physics/0412123v1 [physics.ins-det

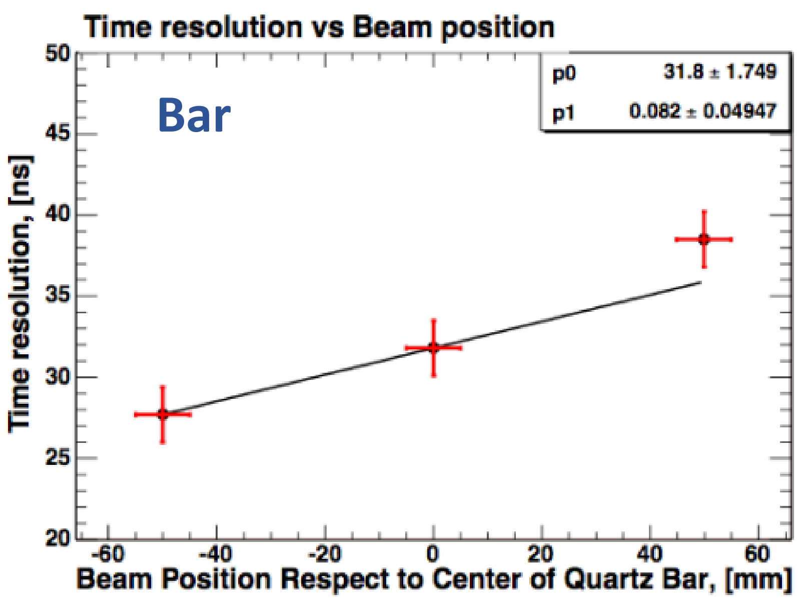
(M. Albrow -2010: Tests with bar and fiber bundle)

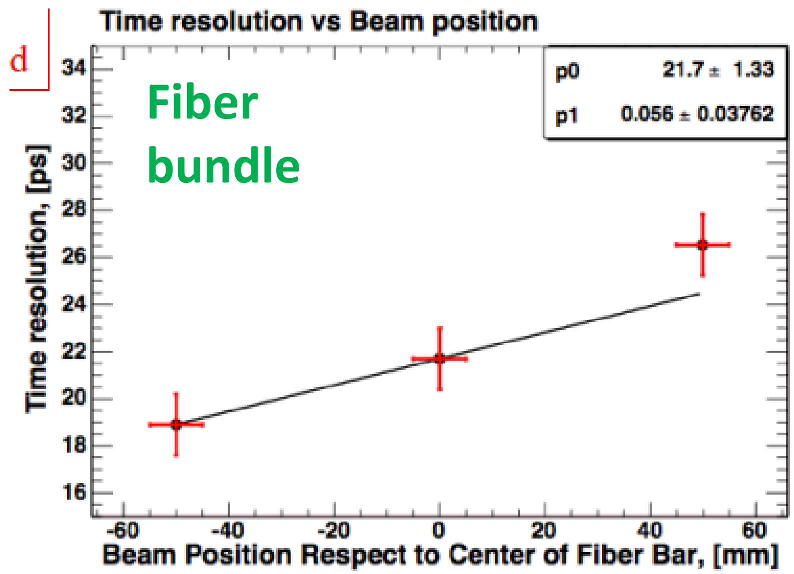
Bar

Pmt-1	17.1 ps	15.5 ps	17.3 ps
Pmt-2	18.0 ps	19.8 ps	16.5 ps
Pmt-3	27.7 ps	31.8 ps	38.5 ps

Fiber bundle

Pmt-1	17.1 ps	17.0 ps	16.1 ps
Pmt-2	16.8 ps	17.6 ps	17.8 ps
Pmt-3	18.9 ps	21.7 ps	26.5 ps





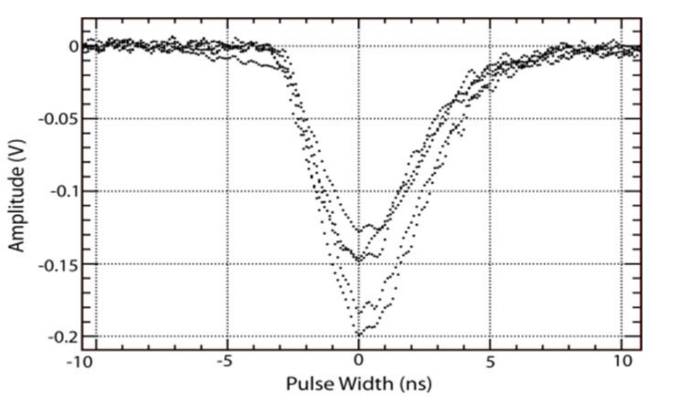
Signals from HF

- The signals of HF PMTs were measured for:

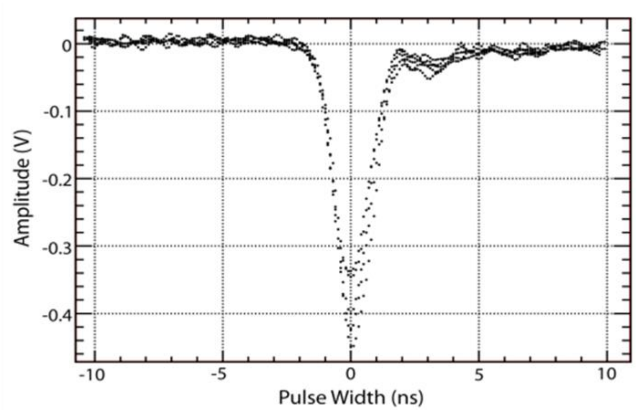
a) Showers produced in HF fiber bundles

b) Muon traversing the PMT windows

- Samples of these signals are shown below
- Try to estimate the expected $\sigma_t \approx t_R /(S_{max}/\sigma_N)$



Standard HF Pulses



Muon PMT Pulses

a) Showers

$S_{max} \approx 0.2$ V
$t_R \approx 2$ ns
$\sigma_N \approx 0.002$V
$S_{max}/\sigma_N \approx 100$
$\sigma_t \approx 20$ ps

b) Muons

$S_{max} \approx 0.4$ V
$t_R \approx 1.4$ ns
$\sigma_N \approx 0.001$V
$S_{max}/\sigma_N \approx 200$
$\sigma_t \approx 8$ ps

New DESY Test Beam Studies

Assembly of 2 orthogonal MCP + Quartz Bar.

Each bar is inclined 45^{o} to the direction of the beam