PANDA experiment

and

Forward ToF wall

detector

С.Белостоцкий   УС ОФВЭ 26. 12. 2018

FAIR accelerator facilities and experiemnts

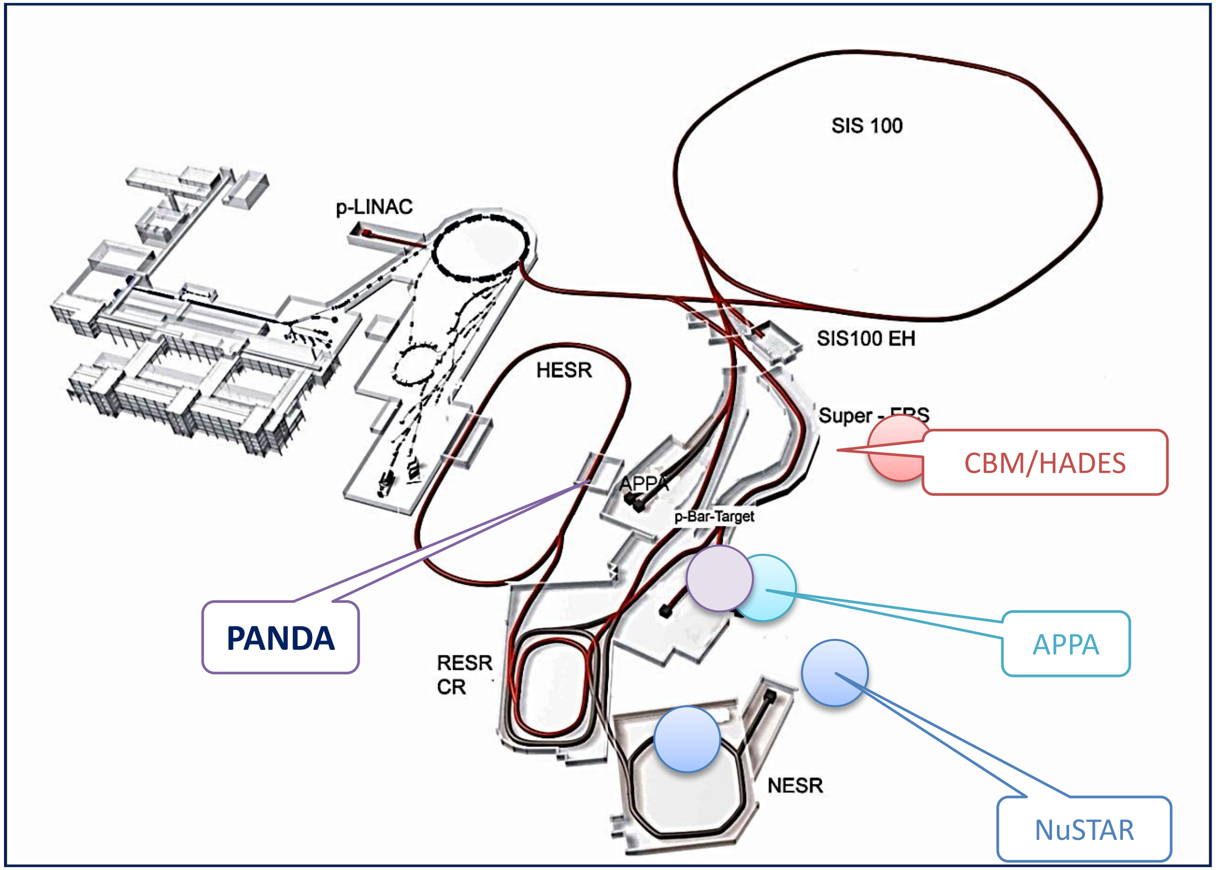
Experiments

APPA

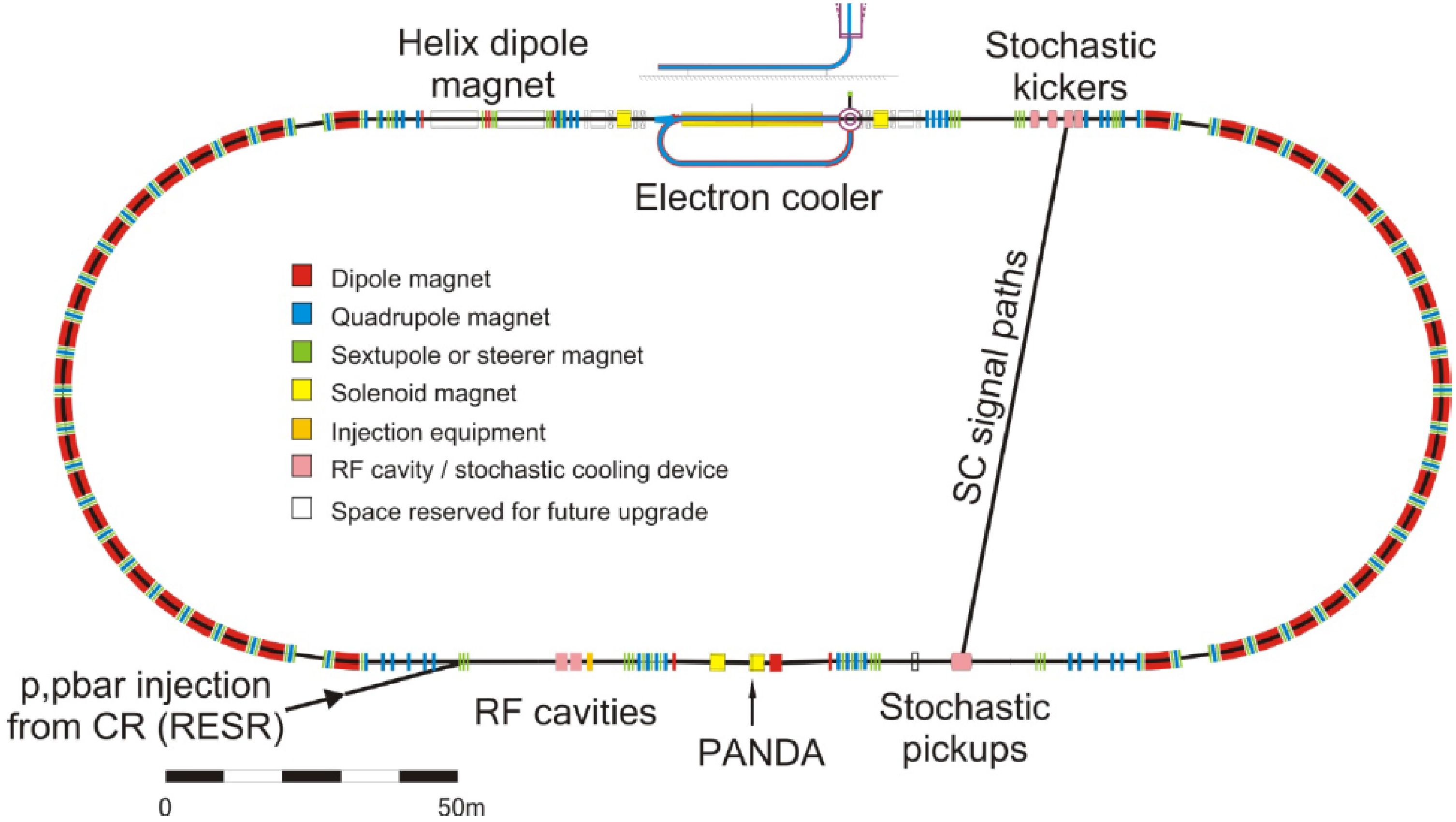
CBM/HADES

NuSTAR

PANDA



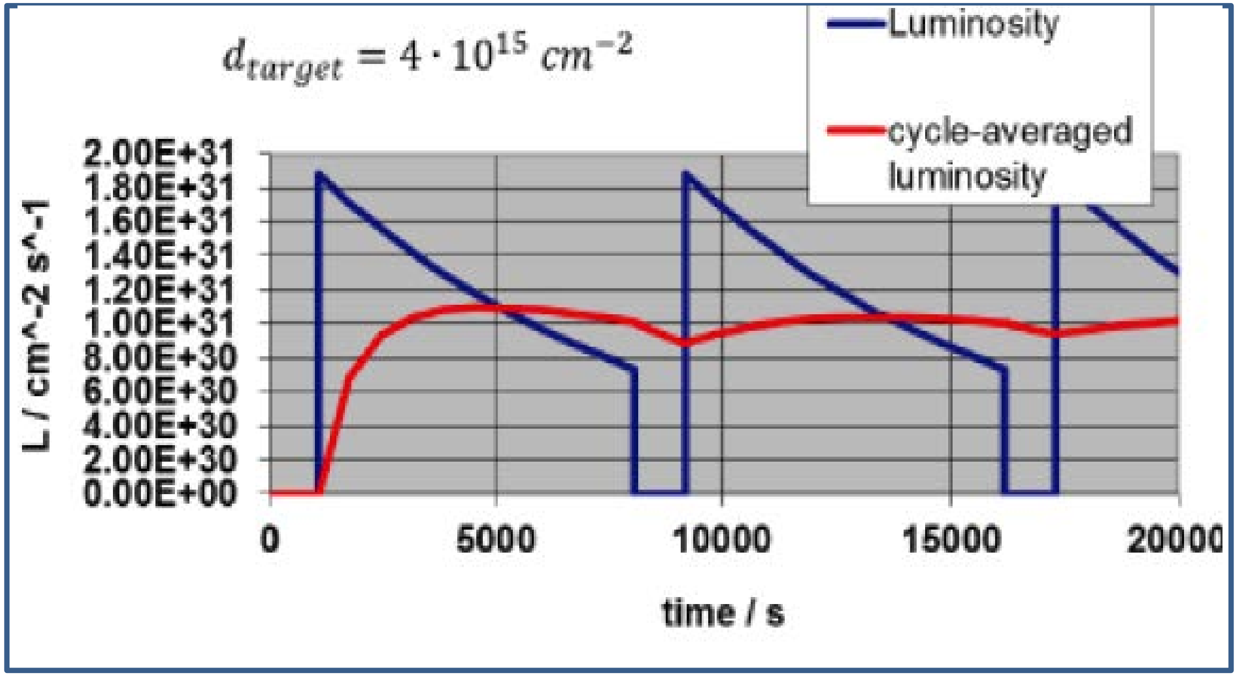
High Energy storage Ring HESR
from 1,5 to 15 GeV



Pbar Injection at 3.8 GeV/ momentum range 1.5-15 GeV/acceleration/ deceleration

HR regime momentum resolution 10^{-5} (!!) Lumi $2x10^{31}cm^{-2}s^{-1}$
HL regime momentum resolution 10^{-4} Lumi $2x10^{32}$ $cm^{-2}s^{-1}$

HESR luminosity vs time



Ring circumference 574 m

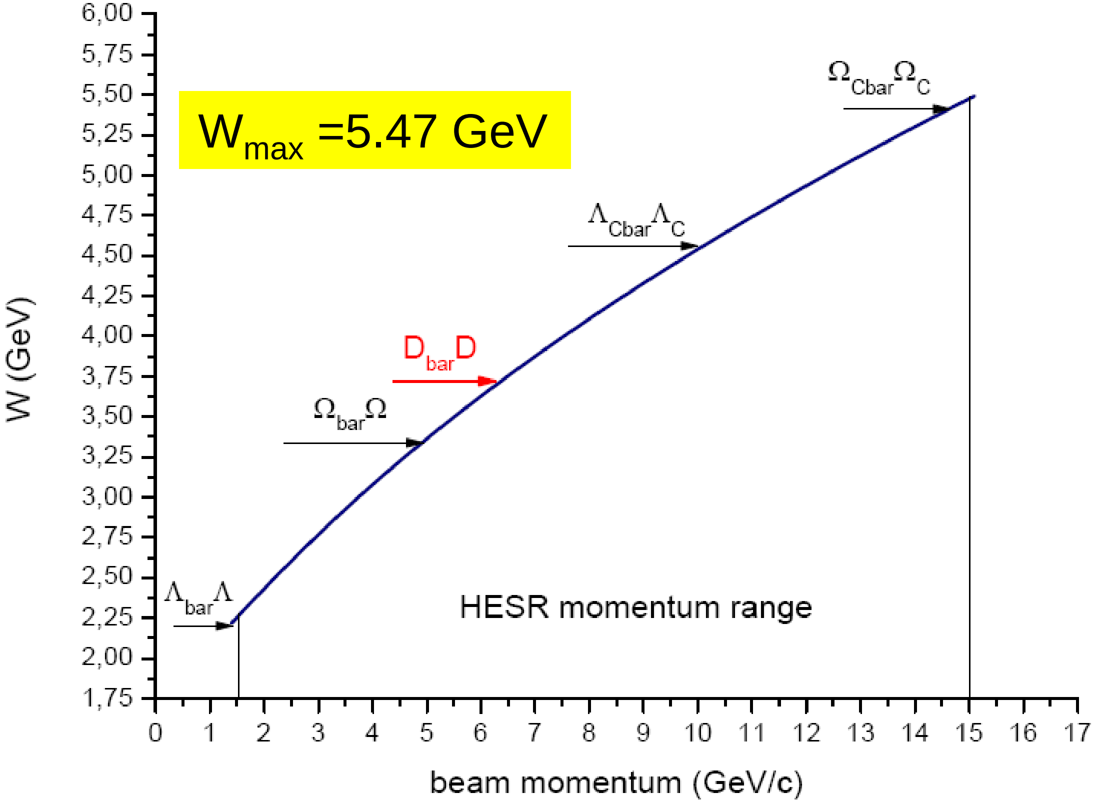
revol. time 1913 ns

in HL regime 2×10^7 interactions/s

$\overline{p}$ production rate	$2 \cdot 10^7$ /s ($1.2 \cdot 10^{10}$ per 10 min)
Momentum / Kinetic energy range	1.5 to 15 GeV/c / 0.83 to 14.1 GeV
Number of particles	10^{10} to 10^{11}
Target thickness	$4 \cdot 10^{15}$ atoms/cm^2 (H_2 pellets)
Transverse emittance	< 1 mm · mrad
Betatron amplitude E-Cooler	25–200 m
Betatron amplitude at IP	1–15 m

The PANDA Physics Program

Thresholds for $\bar{h}h$ production



Charmonium Spectroscopy. Precise study of all states below (8 states) and above (X,Y,Z) the open charm threshold.
Competitors e^+e^- colliders **1**$^{--}$ state (BES, Belle,.). LHCb

Search for gluonic excitation, glueballs, hybrids.

Multiquarks.

Proton FF in time-like region
Q^2 from 8 to 28 $(GeV/c)^2$ to be investigated

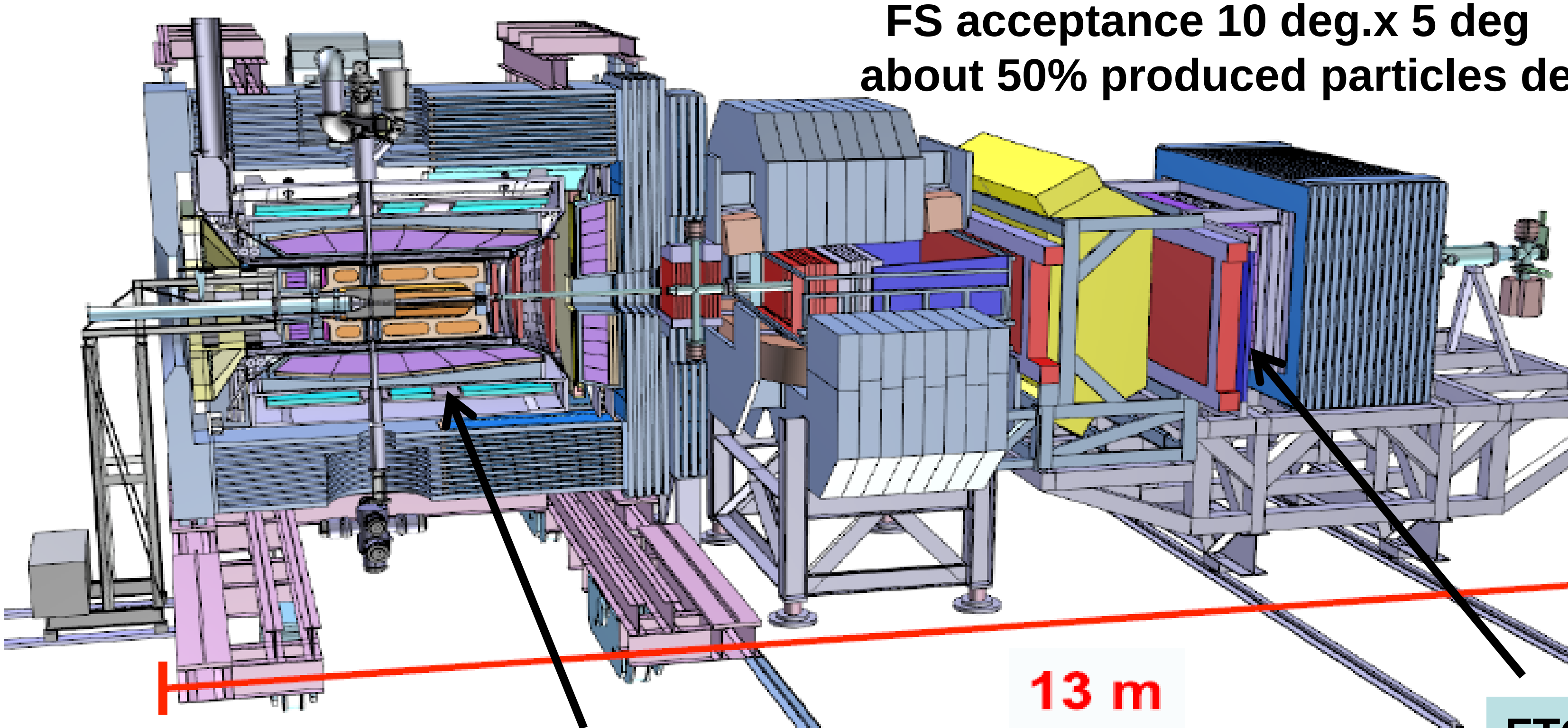
Study of Hadrons in Nuclear Matter.
Large effects (mass shifts ~ 100 meV for charmonium states

Double-strange nuclei

PANDA detector

Panda detector at
HESR. Momentum range from 1.5 to 15 GeV
HL mode dp/p=10^{-4} 1.6×10^{32} /cm^2 s about 10^7 int./s
HR mode dp/p=10^{-5} 1.6×10^{31} /cm^2 s up to 8.9 GeV (15GeV)

FS acceptance 10 deg.x 5 deg
about 50% produced particles detected



Time resolution better 100 ps

Forward TOF wall functions

PID of forward emitted particles using time-of-flight information for low momentum hadrons

protons < 4.GeV/c, kaons < 3. GeV/c, pions < 2.5 GeV/c

close to or below forward RICH threshold

provided

time resolution is about 50-100 ps

FS momentum resolution must be not worse 0.01,

FT reconstruction $\delta L_{track} \sim$ few mm

Event start stamp reference time T_0

provided a particle independently identified

e.g. with FRICH or EMC(FSC) or Forward muon system

Energy deposition information

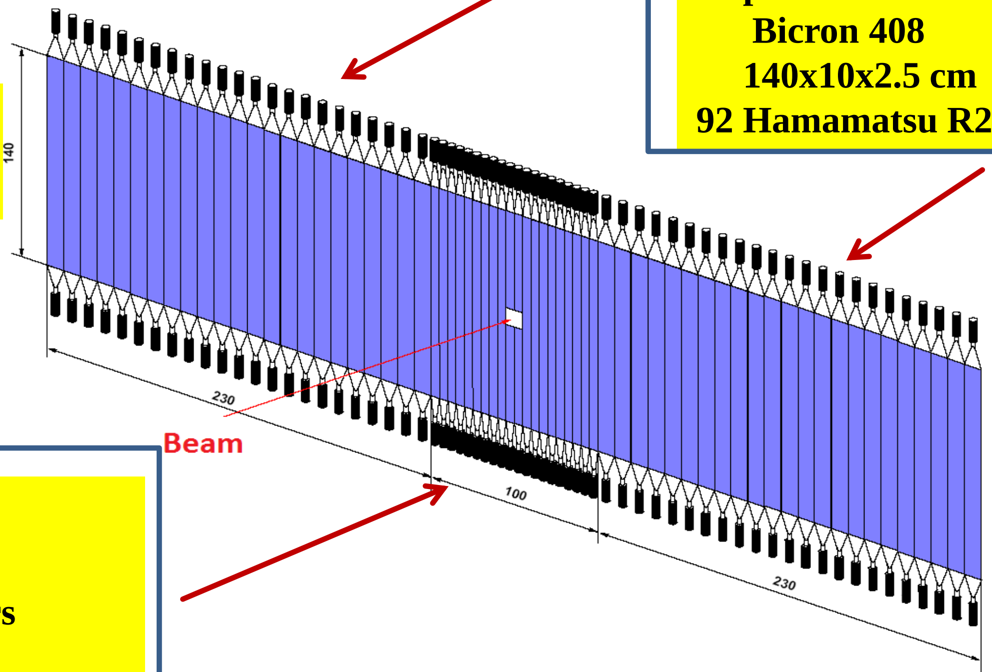
expected energy deposition range

from 5 to 50 MeV

Main technical requirements for design of FTOF scintillation wall

- **Time resolution better 100 ps**
- **FToF wall positioned at 7.5 m downstream the target**
- **Large sensitive area of the scintillation wall:**
  5.6 m width, 1.4 m height
- **Should stand counting rate 1 MHz at PANDA HL regime**
- **Dynamic range fits to energy deposition from 5 to 50 MeV**
- **Operate at dipole fringe field of $B_z \approx 20$ G, $B_{x,y} \approx 70$ G**
- **The opening in the wall for the vacuum beam pipe foreseen.**

Final Forward TOF wall configuration



Side parts
2x23 counters
46 plastic scintillators
Bicron 408
140x10x2.5 cm
92 Hamamatsu R2083 (2”)

positioned at 7.5 m from IP

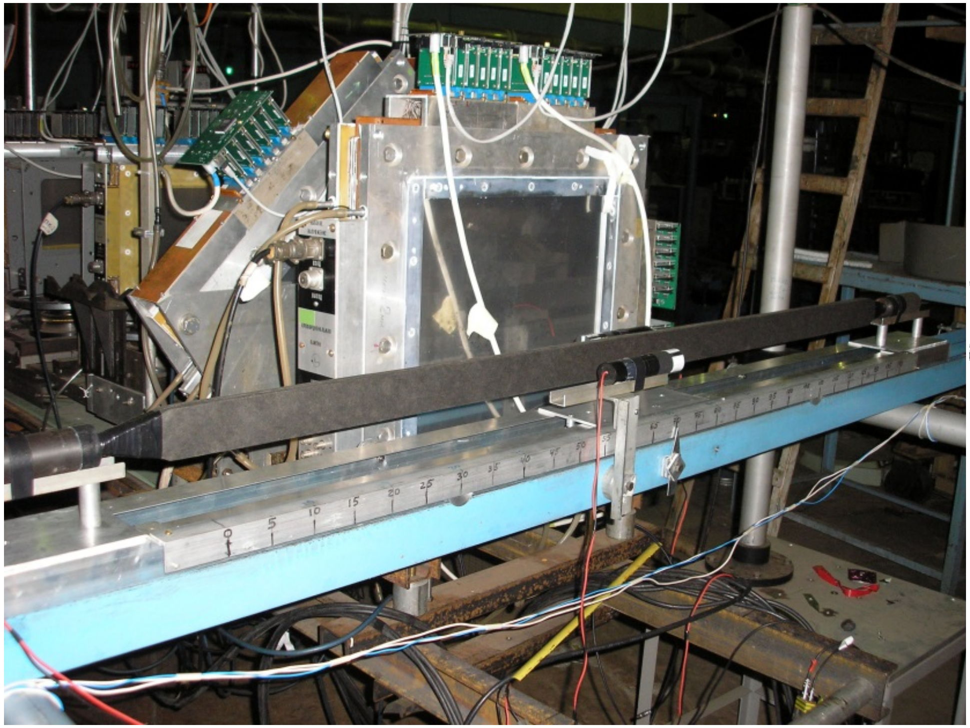
Central part
20 counters
20 plastic scintillators
Bicron 408
140x5x2.5 cm
40 Hamamatsu R4998 (1”)

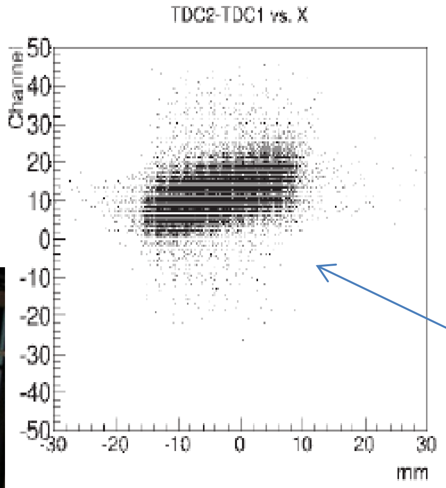
Sensitive area
width = 5600 cm
height= 1400 cm

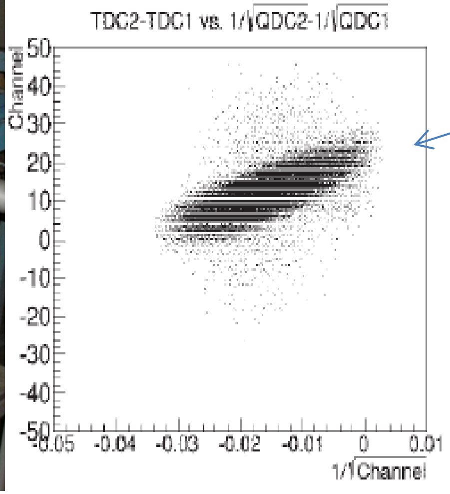
Bicron 408 (or EJ200)		***Fast PMTs** (hamamtsu)*	
(recommended for large TOF counters)		**R4998 1” (R9800) , R2083 2” (R9779)**	
Rise time	0.9 ns	Anode pulse rise time	0.7-1.8ns
Decay time	2.1 ns	TTS	160-370ps
1/e light attenuation length	210cm	Gain	$1.1\text{-}5.7 \times 10^6$

Prototyping using proton beams

PNPI 1 GeV synchrocyclotron
COSY beam in Juelich 2 GeV
740 and 920 Mev protons selected with magnetic spectrometer







After offline corrections on

hit position

and

amplitude walk

weighted mean

$$\frac{1}{\sigma^2_{TOF}} = \frac{1}{\sigma^2_{TDC1}} + \frac{1}{\sigma^2_{TDC2}}$$

in the middle of slab

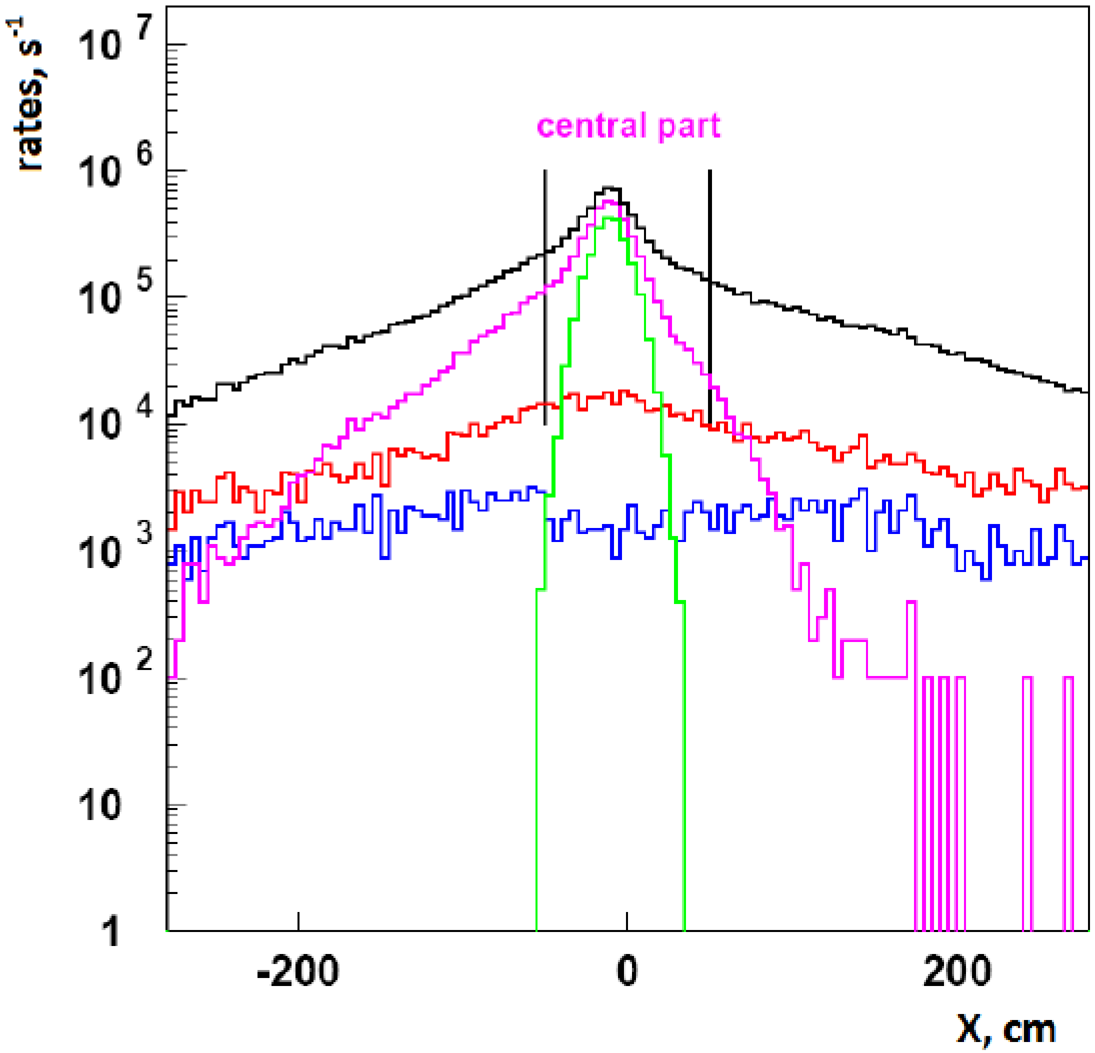
$$\sigma_{TOF} = 60 - 80 \text{ ps}$$

1 mm → 5.9 ps time uncertainty

Count rate per scintillator

Selected Monte Carlo simulation aspects

15 GeV, 10^7 int/s, Pythia6



total rate

pbar elastic scatt. peak

Pbar total

All particle produced in vacuum pipe

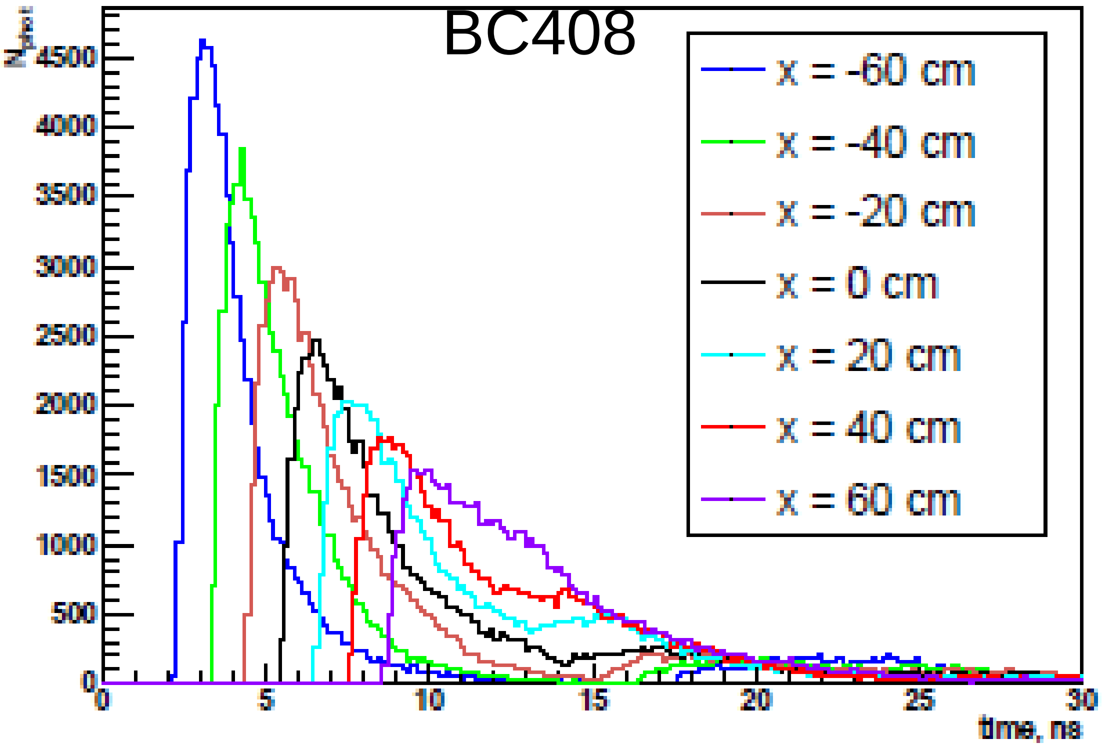
$e^+ e^-$ produced in vacuum pipe from $\Pi^0 \rightarrow 2\gamma$

Count rate per scintillator
10 cm width
always below 1 MHz
Same result in PANDAROOT

!! Binning is 10 cm (width of slabs in the wall side part), including central part !!

Light pulse attenuation BC408

Selected Monte Carlo simulation aspects



Pulse amplitude degrades by a factor of 3 while rise time is practically unchanged (about 1.3 ns)

Light pulse length (FWHM) 2 to 6 ns

Experimentally measured

Lihjt pulse speed 0.17 mm/ps
(front edge measurement)

Hit position uncertainty
1 mm corresponds to 5.9 ps

To pass full length of 1400 mm
takes 8277 ps

Geant 4 calculations
BC408
500 MeV proton hits
Light pulse detected
at one end of the
scintillator 10x140x2.5 cm^3
depending on hit position

Forward TOF wall TDR approved by FAIR in October 2018

Technical Design Report for:

$\overline{\text{P}}$ANDA

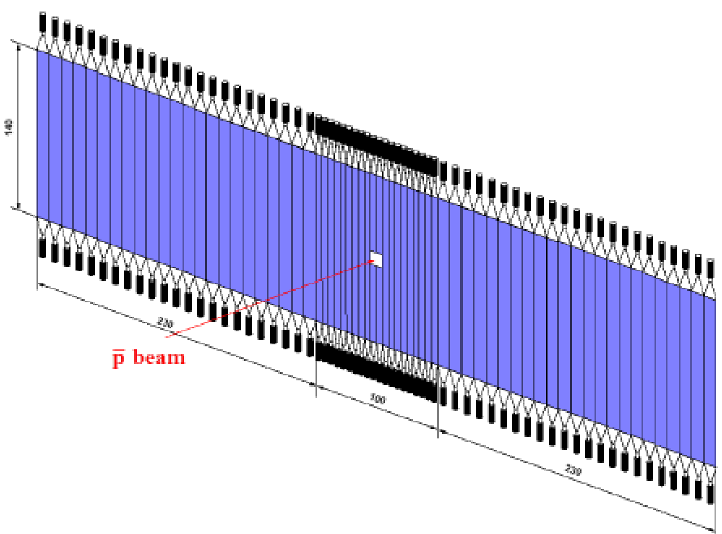
Forward Time of Flight detector (FToF wall)

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

$\overline{\text{P}}$ANDA Collaboration

January 19, 2018



Drafting committee

Stanislav Belostotski
Oleg Miklukho
Yuri Naryshkin
Denis Veretennikov
Andrei Zhdanov
Anton Izotov

Technical Coordinator

Lars Schmitt

Deputy of TC

Anastasious Belias

Spokesperson

Klaus Peters

Deputy of SP

Tord Johansson

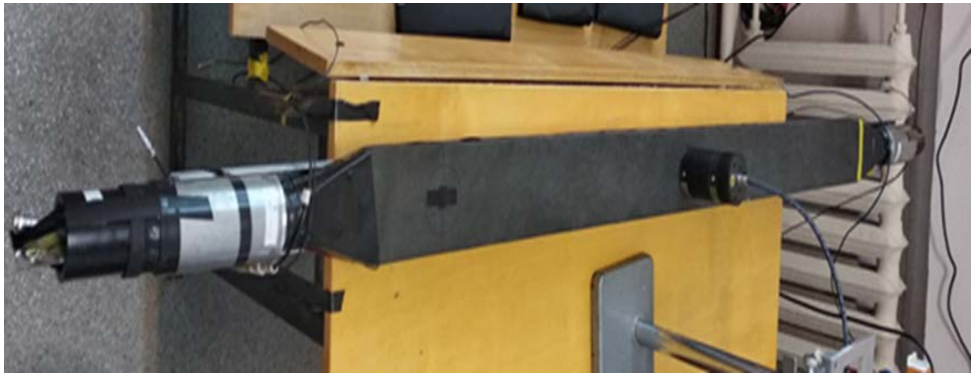
PNPI group and present activity

PNPI PANDA group

(High Energy Physics Division)

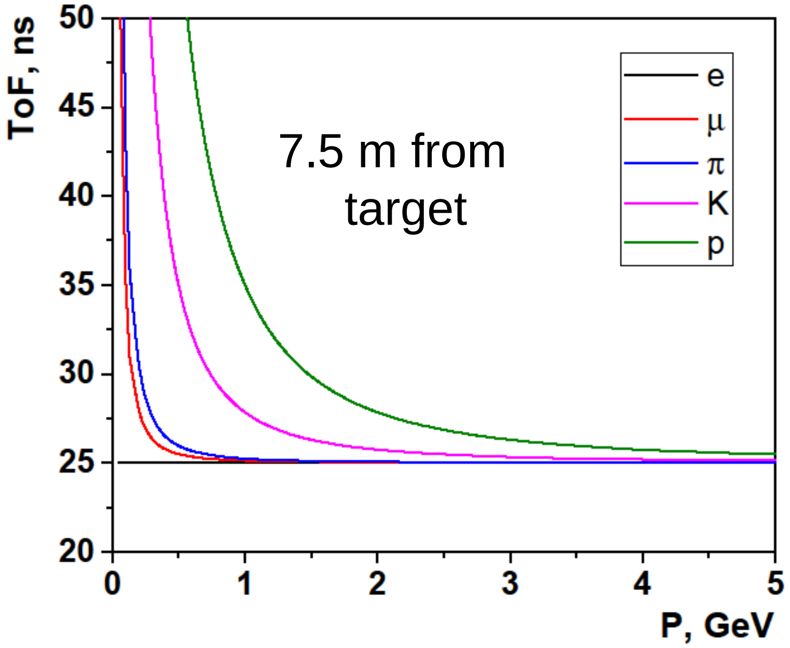
S.Belostotski prof., head of Lab
A.Izotov DAQ, frontend readout
G.Fedotov tests, scin. counters
*O.Miklukh*o tests, PNPI SC
S.Manaenkov PANDA physics
A.Zhdanov scin. counters
*D.Veretenniko*v FToF Monte Carlo
S,Volkov *FEE, active divider*
V.Fedulov technicain
L.Obrant secretary
Diploma,PhD students ??

Studies with picosecond laser



Supporting slides

FTOF wall hadron ID

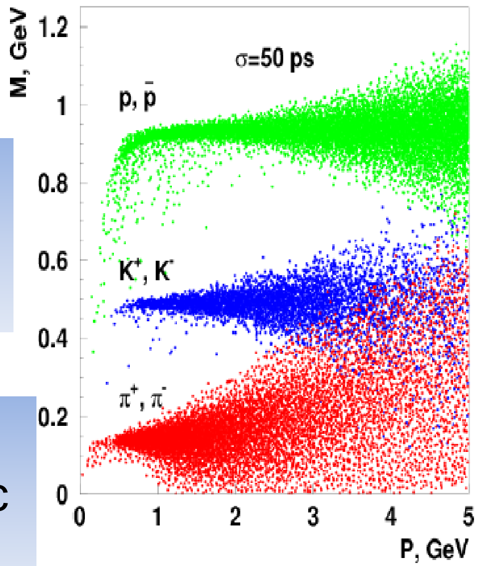


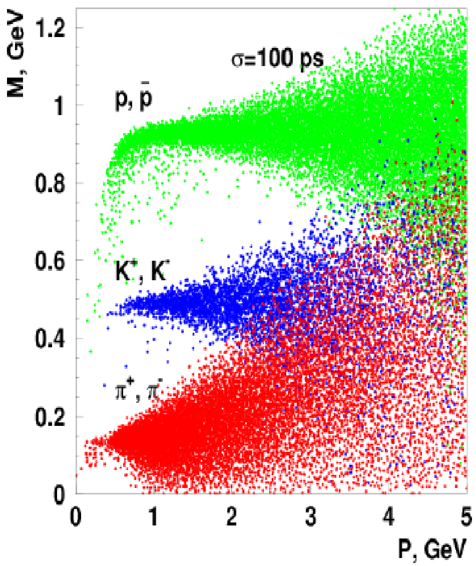
$$m = p\sqrt{\frac{t^2}{t_c^2} - 1} \qquad \frac{\delta m}{m} = \sqrt{\left(\frac{\delta p}{p}\right)^2 + \gamma^4\left(\frac{\sigma_{TOF}}{t}\right)^2}$$

$$t_c = L_{track} / c$$

At FS momentum resolution $\Delta p/p=0.01$

TOF resolution σ_{TOF} = 50 or 100 ps





σ=50 ps
Proton/ kaon separation < 4.5 GeV/c
Kaon/pion separation < 3 GeV/c

σ=100 ps
Proton/ kaon separation < 3.5. GeV/c
Kaon/pion separation < 2.5 GeV/c

Meantime variant allows for hit position measurements using TDC information only

T_3 PMT3 hit time stamp,

T_4 PMT4 hit time stamp,

T_2 PMT2 start time stamp

τ_3 delay to travel to PMT3

τ_4 delay to travel to PMT4

$\tau_3 + \tau_3 = \tau = 8276.8\, ps$

t time of flight

$T_3 = T_2 + t + \tau_3 \quad T_4 = T_2 + t + \tau_4$

$T_3 - T_2 = \tau_3 - \tau_4 \Rightarrow$ hit position

$t = (T_3 + T_4)/2 + T_2 \Rightarrow$ tof to measure

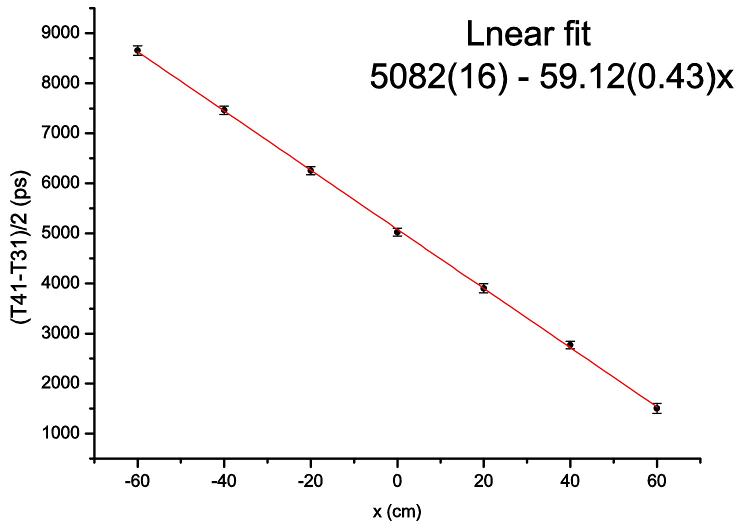
(delay omitted)

$(T_3 - T_2) + (T_3 - T_2) \approx \tau$ multihit event selection criterion

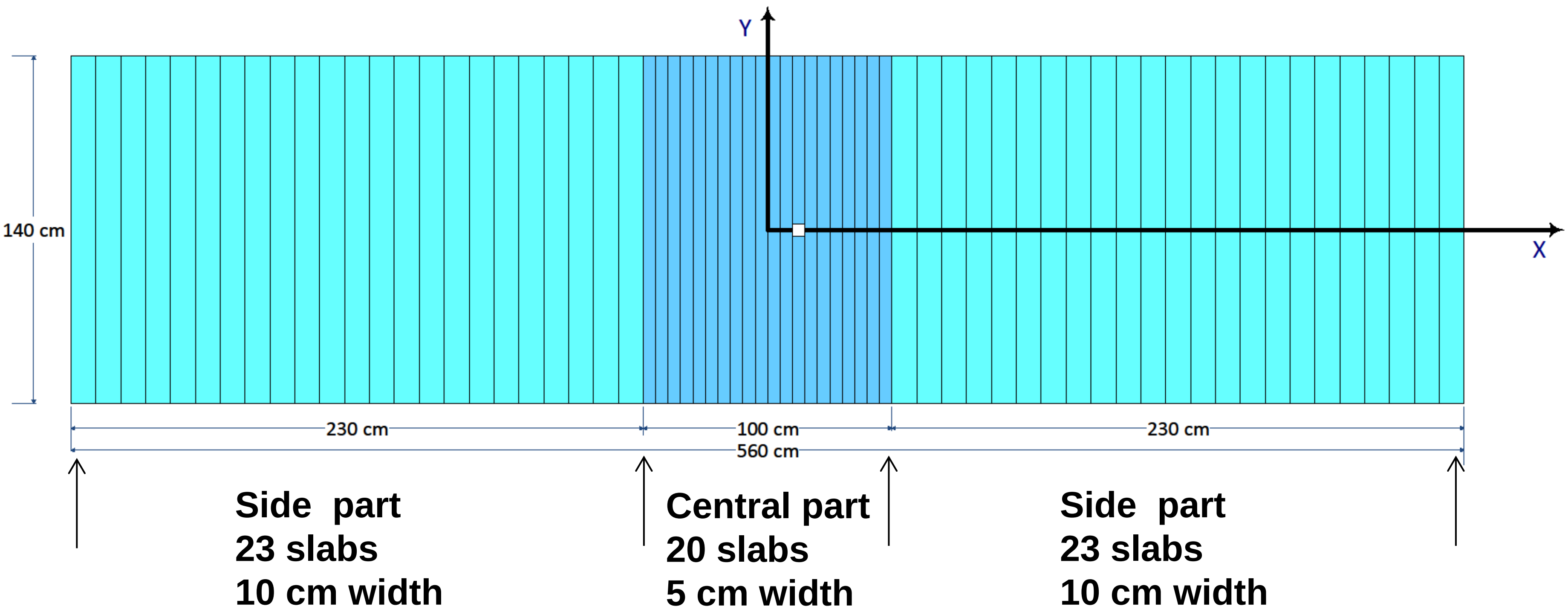
$\tau = 59.12\,\mathrm{ps/cm} \times 140\,\mathrm{cm} = 8276.8\,\mathrm{ps}$

v_{BC408} = 1/59.12 = 0.17mm/ps
speed of light in BC408 = 0.19 mm/ps

hit position resolution
80ps x 0.17mm/ps = 13.6 mm



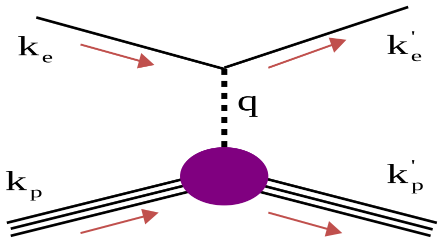
The wall can be built of commercially available plastic scintillation slabs and fast photodetectors. Sensitive area is 560 cm (width)x 140 cm (height)



Granularity : counting rate below 1 MHz at HL PANDA regime

Comment. The beam pipe diameter at this z-location is 180 mm. i.e. 4 slabs to be cut.

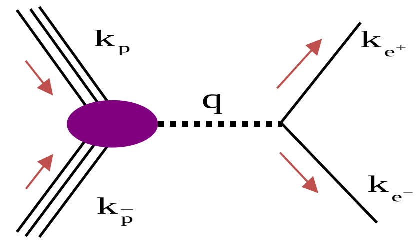
Space-Like and Time –Like (TL) FF



$$m_\gamma^2 = q^2 = \left(k_e^{'} - k_e\right)^2 = \left(k_p^{'} - k_p\right)^2$$

CM frame $q^2 = -4k^2 \sin^2 \frac{\theta_{CM}}{2}$

$t = Q^2 = -q^2 > 0$



$$m_\gamma^2 = q^2 = \left(k_{e^+} + k_{e^-}\right)^2 = \left(k_p + k_{\bar{p}}\right)^2,$$

In CM frame $q^2 = 4k^2$

$s = Q^2 = -q^2 < 0$

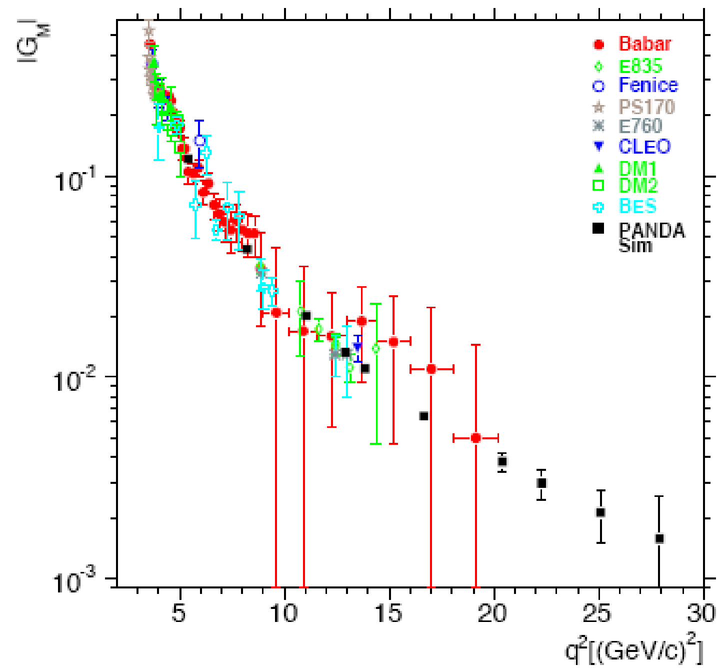
Both SLFF and TLFF problem of $\frac{\mu_p G_E^2(Q^2)}{G_M^2(Q^2)}$

(OLYMPUS, VEPP3, JLAB)

TLFF still poorly studied at $Q^2 > 10\ GeV^2$

SLFF/ TLFF->1 in the limit of pQCD

$(Q^2 \gg 1\ GeV^2)$



Supporting frame, mechanical components

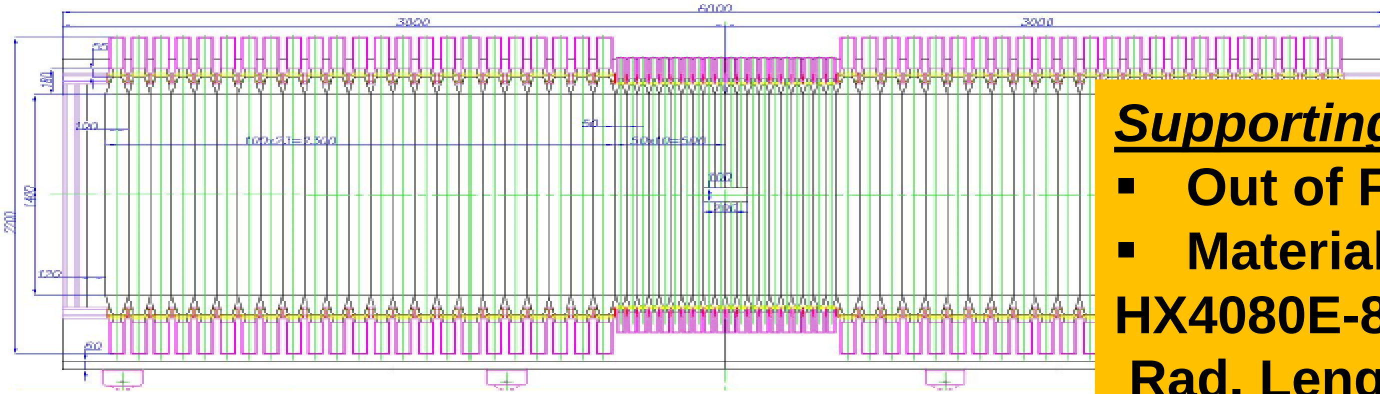


Figure 3.11: Schematic view of the FToF wall with the supporting fra

Supporting frame

- Out of FS acceptance
- Material: duralumin HX4080E-8 profile
  Rad. Length 2.8 cm
- Preliminary design

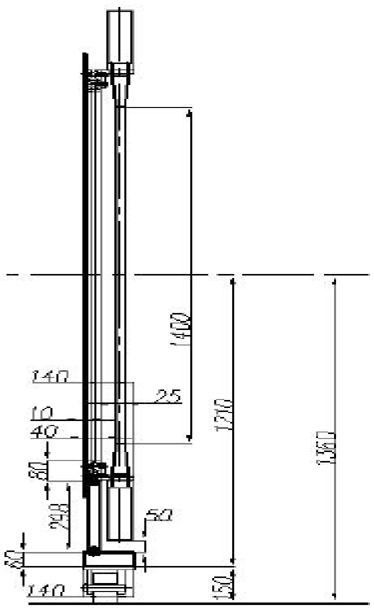


Figure 3.12: Side view of the FToF wall (cross section).

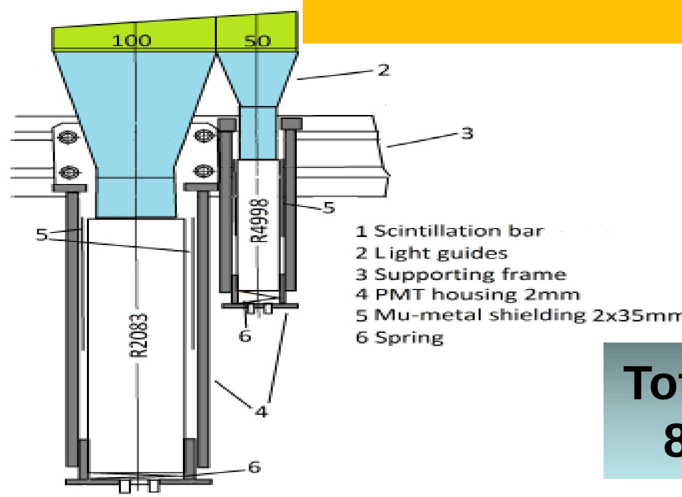


Figure 3.13: The assembly of two PMTs in the border between central and side parts of the FToF wall (see text)

Total weight 800 kg

Front End Electronics. Connectivity (produced in GSI)

compact FPGA platform based on 4 TRB3 with 18 PADIWA 2 (4) modules

PADIWA2 16 channel discriminator - fed with PMT analog signals, produces the LVDS signals both by the front and trailing part of analog signal. **Time Over Threshold TOT method of amplitude correction**

PADIWA3 AMPS contains ADC -> **direct amplitude measurement.** **to PADIWA 4**

TRB platform **Trigger and Readout Board**
with on-board DAQ functionality
fed with LVDS signal (cable ,< 200cm)

TDC channels	260	(8 ps)
Max hit rate	50 MHz	
Connectivity	95 Mbytes	

……………………………………………………

1 hit FTOF wall -> 265 bit
.multiplicity 1.5, 1 MHz -> 50 Mbytes/s
<15 Mbyte/s per one TRB

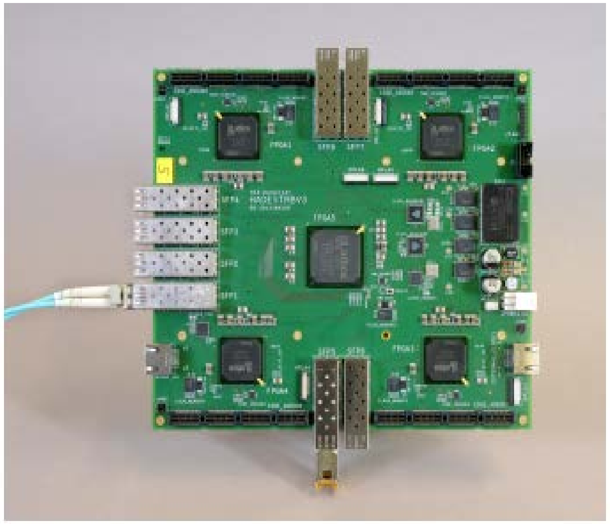


Figure 3.7: TRB-3. Functionality is described in text

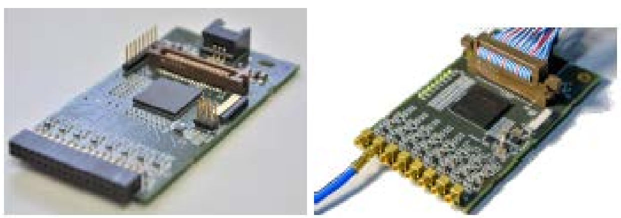
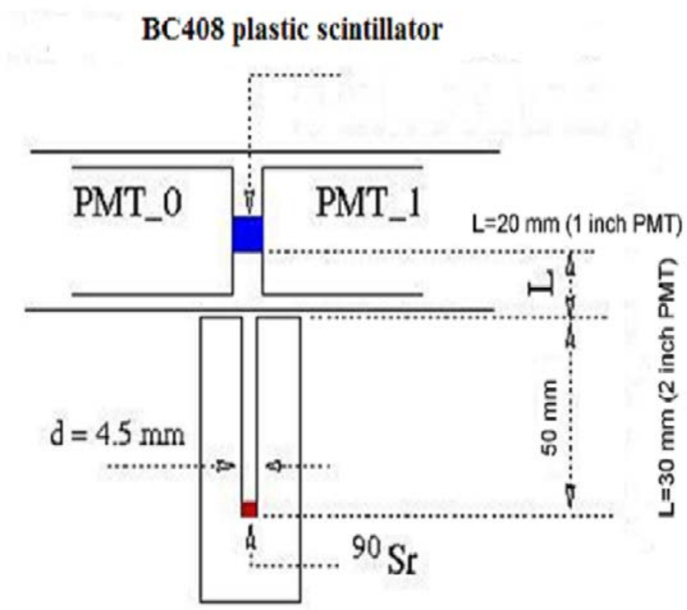
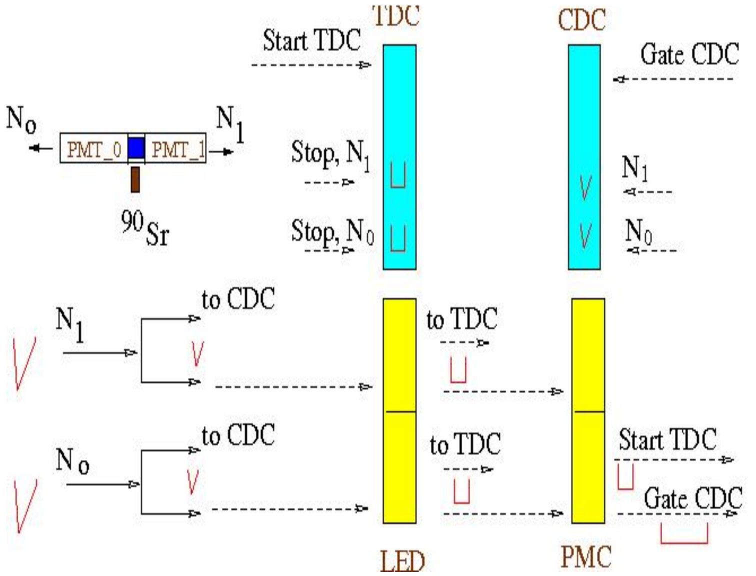


Figure 3.8: PADIWA2 (left) and PADIWA3 AMPS (right). Functionality is described in text

Tested with ketek SiPMs
σ = 79 ps
Temperature dependence studied

Prototyping. Test stand layout and electronics





CDC is charge-to-digital converter (LeCroy ADC 2249A, 250 fK/ch.), TDC is time-to-digital converter (16 Ch. CAEN V775 N, 35 ps/ch), LED is leading edge discriminator (8 Ch LeCroy 623B), PMC is programmable coincidence matrix (PNPI electronics 155/08)

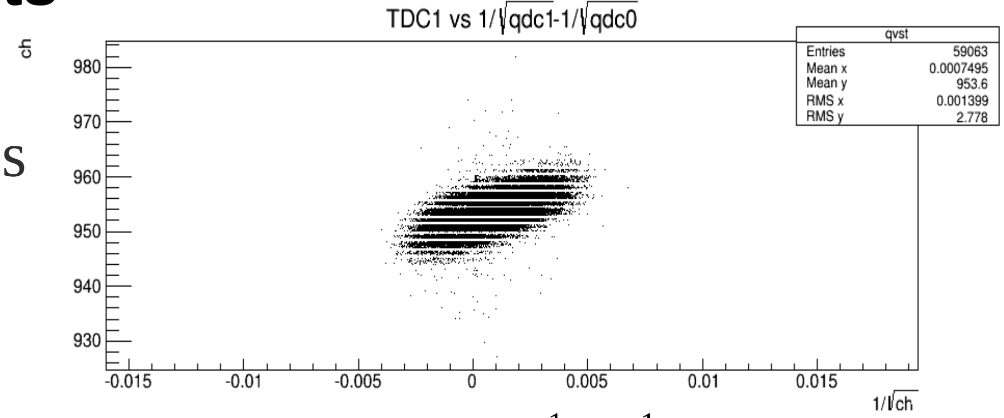
2 MeV energy deposition, $2\text{x}10^4$ photons
Track walk in scintillator $\sigma_{tr.w.}$ = 15 ps
Electronics contribution σ_{el} = 30 ps

Measured are TDC_1, TDC_0,
Common start for all TDCs
QDC_1, QDC_0

Test station main results

TDC_1 gives raw $t_1 - t_0$ distributions

Typical $\sigma_{TDC\_1\,(raw)}$ about 160 ps



$$\frac{1}{\sqrt{Q_i}} - \frac{1}{\sqrt{Q_k}}$$

After offline amplitude corrections

PMT_1	σ_{TDC_1} (ps)	σ_{PMT} (ps)
R4998 (4998/4998)	72.	44.4
R9800 (4998/9800)	86.	64.6
R2083 (2083/2083)	72.6	44.9
R9779 (2083/9779)	64	56.5
XP2020 (2.5, 2.36kV)	82	52,3

$$TDC_{corrected} = TDC_{raw} - A\left(\frac{1}{\sqrt{QDC_1}} - \frac{1}{\sqrt{QDC_2}}\right)$$

For identical PMTs

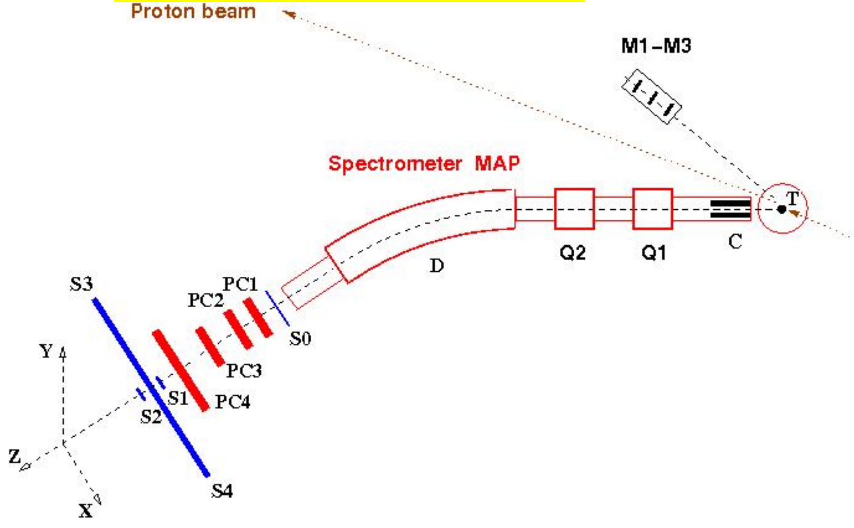
$$\sigma^2\left(TDC_{1corr}\right) = 2\sigma^2\left(R2083\right) + \sigma_s^2 + \sigma_{el}^2$$

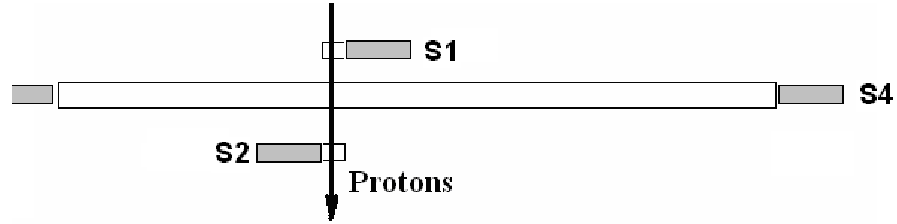
$$\sqrt{\sigma_{track}^2} = 15.8 \text{ ps} \qquad \sqrt{\sigma_{el}^2} = 31.5 \text{ ps}$$

After corrections for start uncertainty, track walk and electronics

Beam tests at 1 GeV PNPI SC

1 GeV proton beam





Typical detected protons coincidences 10 kHz

Beam intensity scan

inclusive slab count up to 2 MHz

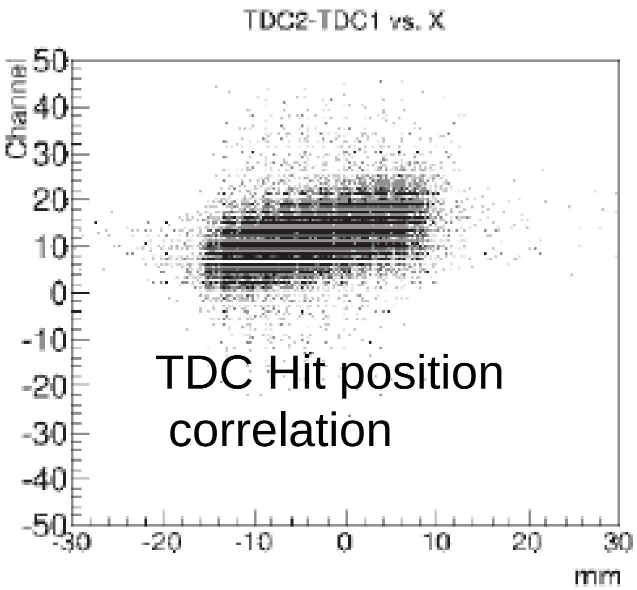
S_3S_4 scintillation slabs B408:
length 140cm
width 2.5, 5,10 cm
thickness 1.5, 2.5 cm
S_1S_2 2x2x2cm
R4998, R2083, Electron187

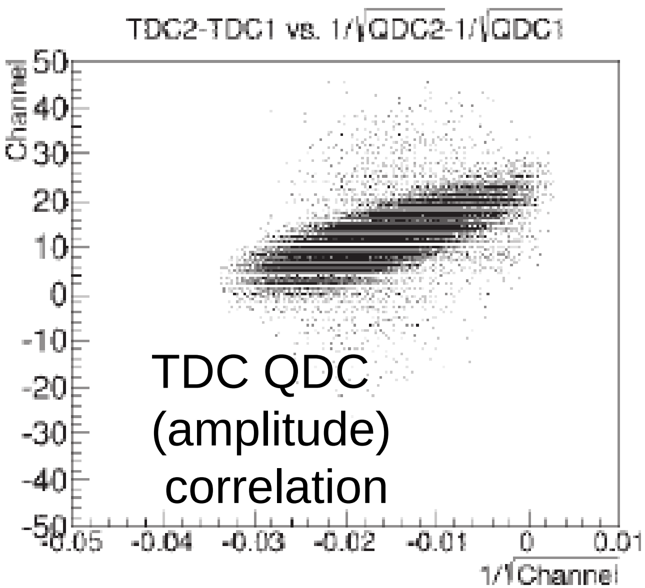
Proton energy E_p=740 or 920MeV, $\sigma(E_p)$ about 0.5%

For B408 thickness 2.5 cm Energy deposition ≈ 5 MeV

Scintillation Efficiency several 10^4 photons/MeV

Offline time resolution





"Raw" time resolution can be substantially improved due to time-hit position and time-amplitude Corrections done on event-by-event basis using correction function:

$$t_{ik} = t_{ik}^{raw} - f^{corr}$$

$$f^{corr} = t_{ik}^{raw} - Ax - B\left(\frac{1}{\sqrt{Q_i}} - \frac{1}{\sqrt{Q_k}}\right) - C,$$

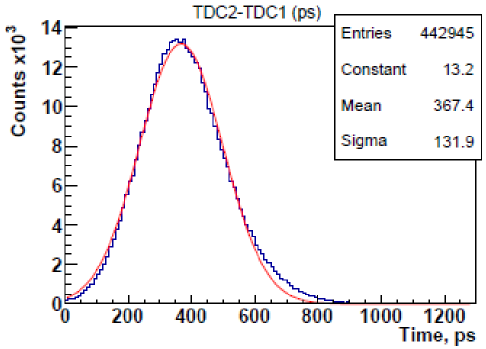
hit position correction **pulse amplitude correction**

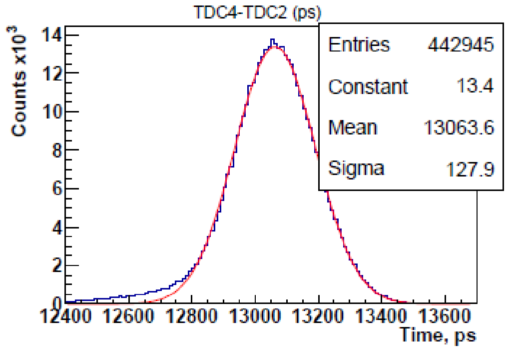
t_{ik}, t_{ik}^{raw} corrected and raw TDC_i-TDC_k distributions, X hit position, A,B,C constants to minimize functional:

$$\langle t_{ik}^2 \rangle - \langle t_{ik} \rangle^2 = \frac{1}{N}\sum_{n=1}^{N} t_{ik,n}^2 - \left(\frac{1}{N}\sum_{n=1}^{N} t_{ik,n}\right)^2.$$

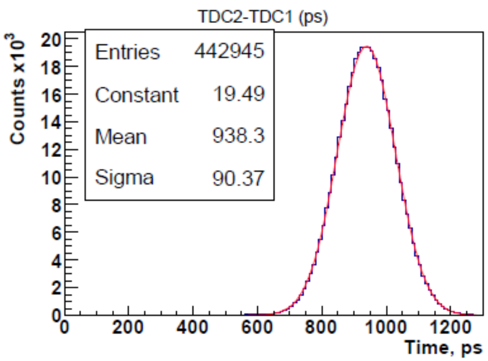
920 MeV , position x=60cm, Scintillator 2.5x5x140 cm^3 , R4998

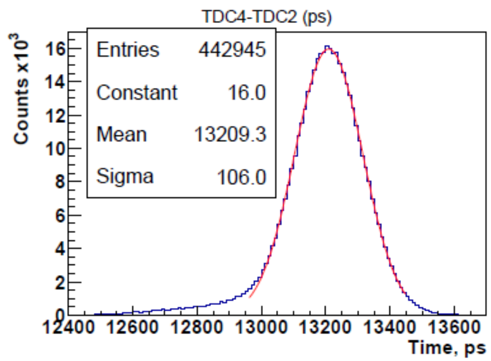
$TDC_2 – TDC_1$	TDC_4 - TDC_2



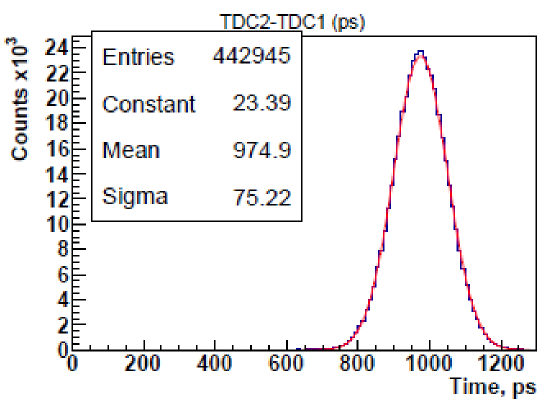


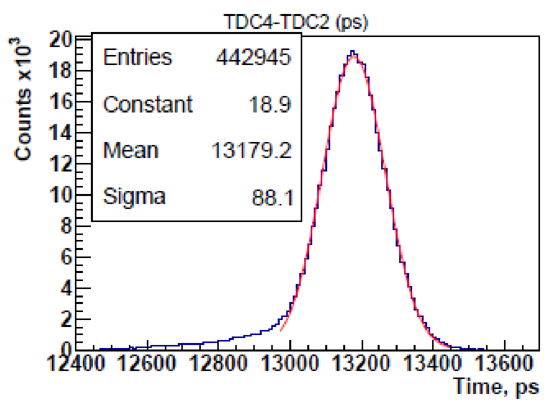
Raw spectra
σ $(TDC_2 – TDC_1)$=131 ps
σ $(TDC_4$ - $TDC_2)$=130 ps





After amplitude correction
σ $(TDC_2 – TDC_1)$=90.4 ps
σ $(TDC_4$ - $TDC_2)$=106 ps

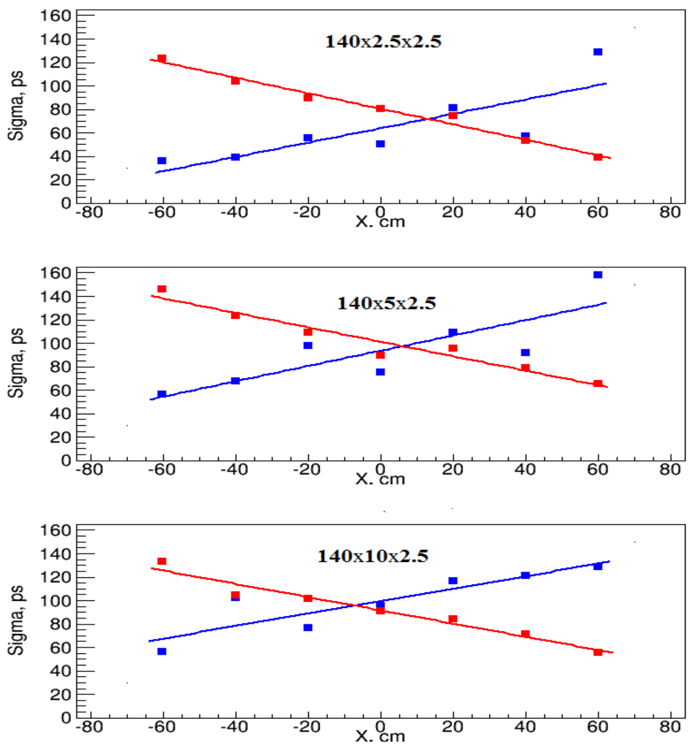




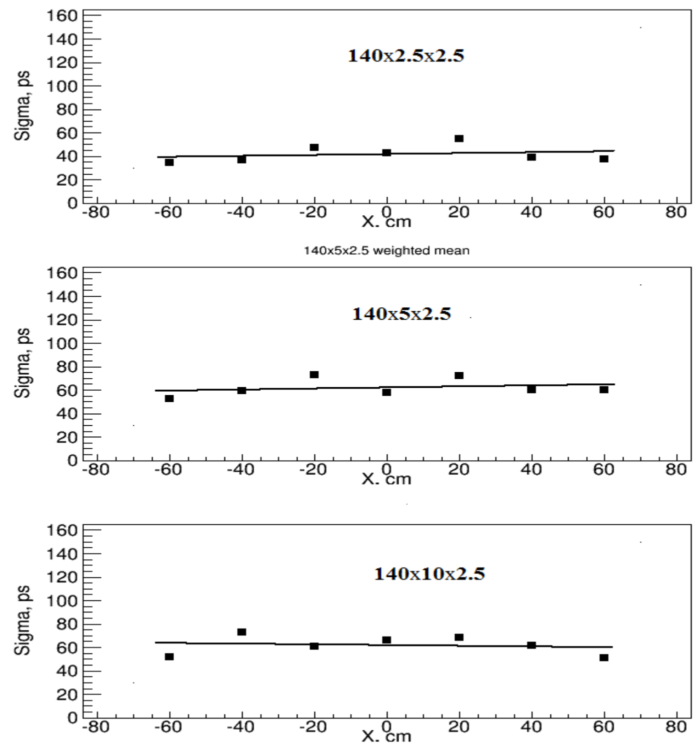
After amplitude and hit position correction

σ $(TDC_2 – TDC_1)$=72.2 ps
σ $(TDC_4$ - $TDC_2)$=88.1 ps

Timing resolution results from 1 GeV PNPI SC



σ_{TOF} vs hit position



σ_{TOF} weighted means

plastic thickness experimentally variated and chosen to be 25 mm compromising material budget, time resolution and dynamic range of detected particles

weighted mean

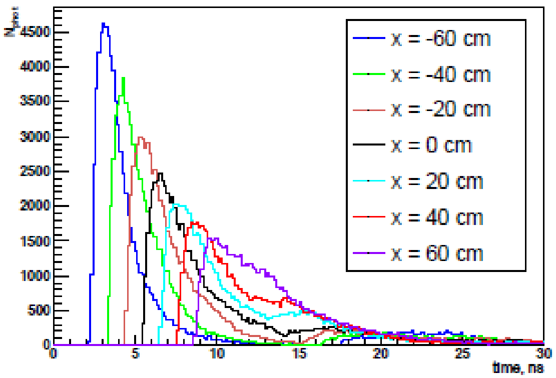
$$\frac{1}{\sigma^2_{TOF}} = \frac{1}{\sigma^2_{TDC3}} + \frac{1}{\sigma^2_{TDC4}}$$

in the middle of slab $\sigma_{TOF} \approx \frac{\sigma_{TDC3}}{\sqrt{2}} \approx \frac{\sigma_{TDC4}}{\sqrt{2}}$

Time and hit position measurements using TDC information only

x	$(T_{41}-T_{31})/2$	σ_{431}^-	$(T_{41}+T_{31})/2$	σ_{431}^+	$(T_{42}-T_{32})/2$	σ_{432}^-	$(T_{42}+T_{32})/2$	σ_{432}^+
cm	ps	**ps**	ps	**ps**	ps	**ps**	ps	**ps**
60	1504	**99**	11950	**148,5**	1503,5	**100,5**	11580	**120,5**
40	2770,5	**74**	11865	**138,5**	2770,5	**74,5**	11510	**102**
20	3904	**90,5**	11975	**145,5**	3904	**90,5**	11630	**114**
0	5025	**76**	11920	**136,5**	5025	**75,5**	11580	**103,5**
-20	6255	**81,5**	11940	**150**	6255	**82,5**	11630	**115,5**
-40	7460	**84**	11895	**143,5**	6890	**85**	11560	**112,5**
-60	8655	**93,5**	11945	**148,5**	8655	**93,5**	11600	**121**

Multihits and pileups



No worsening time
Resolution was found
At 2 MHz inclusive rate
In tests at PNPI SC

Light full pulse length at most 25 ns

PMT full pulse length at most 10-15 ns

Full time to travel through scintillator 8.3 ns

The light pulse duration ranges from 10 ns to 25 ns
PMT signal duration (foot) 10-15 ns

In PANDA spectrometer FS count below 1 MHz per a scintillation slab (PANDAROOT)

Minimum distance between adjacent hits 1000 ns (at 1MHz)

Probability to overlay less than 2 % in worst case

Summary table of beam tests

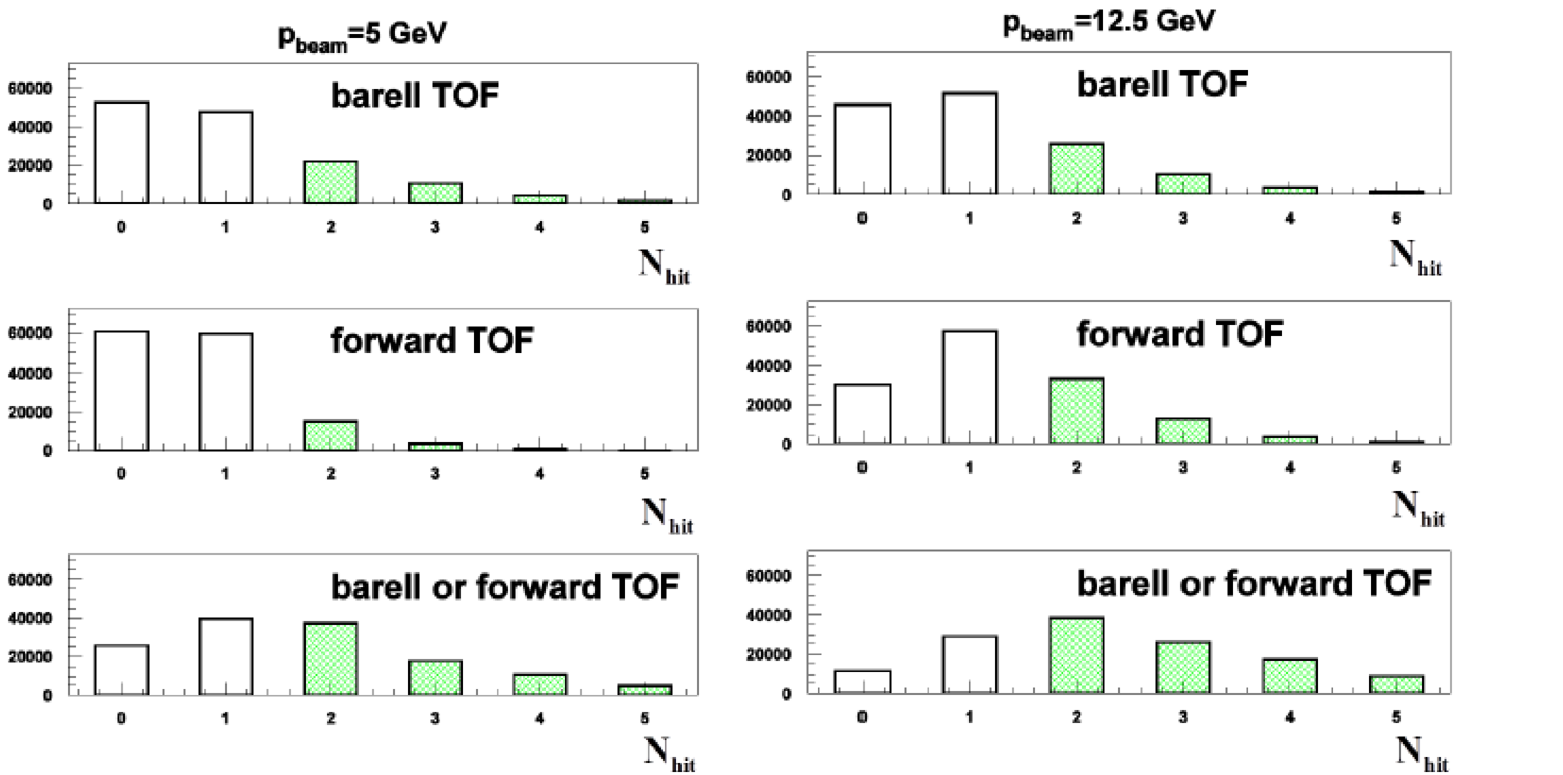
Off line time resolutions obtained as weighted means with amplitude and hit position correction using 920 MeV protons

scintillation slab dimensions (cm)	PMT	timing resolution σ (ps)	comment
140 × 10 × 2.5	**Hamamatsu R2083 (both ends)**	**63**	**Recommended for a prototype for the FTOF wall.**
140 × 5 × 2.5	**Hamamatsu R4998 (both ends)**	**60**	**Recommended for a prototype for the FTOF wall**
140 × 2.5 × 2.5	Hamamatsu R4998 (both ends)	43	a variant of a prototype with smaller stintillator width
140× 5 × 1.5	Hamamatsu R4998 (both ends)	≈ 88	projected originally for the FTOF wall
140 × 2.5 × 2.5	Electron PMT 187 (both ends)	78	magnetic field protected,
1×1×1	Electron PMT 187, Hamamatsu R4998	49	“net” timing resolution of one PMT

Selected Monte Carlo simulation aspects

No dedicated start counter.
Hit multiplicity distributions

$$\varepsilon(>1) = \frac{\sum_{i>1} N_i}{\sum_{i>0} N_i}$$



Condition for TOF analysis using one detector
at 12.5 GeV ε_{BTOF} **= 48%** ε_{FTOF} **= 38%** **for BTOF or FTOF** ε **= 80%**

Λbar detection

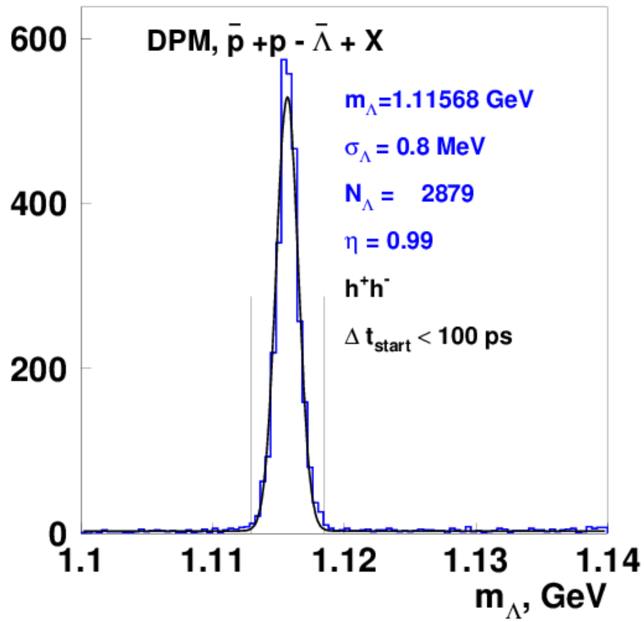
$0.72\times10^{6}\ \bar{p}p$ interactions ,10 GeV, $\frac{\sigma(p)}{p}=0.01,\ \sigma(TOF)=50\,ps$

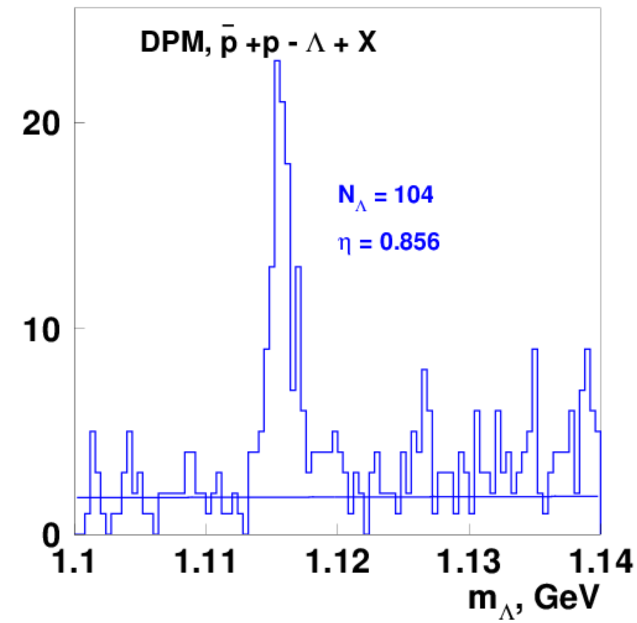
$\bar{p}+p\rightarrow\bar{\Lambda}+X$ $\qquad\qquad$ $\bar{p}+p\rightarrow\Lambda+X$

Event selection criteria

$m(h^{-})=m_{p}\quad m(h^{+})=m_{\pi}$ and $\Delta t_{start}^{\bar{p}\pi^{+}}>100ps$

$m(h^{+})=m_{p}\quad m(h^{-})=m_{\pi}$ and $\Delta t_{start}^{p\pi^{-}}>100ps$ and $z2>6mm$





$\bar{\Lambda}$ detected with high efficiency (20%) at weak selection criteria

$N_{\Lambda}/N_{\bar{\Lambda}}\simeq1/40$

Λ events also well detected

@$10^{6}s^{-1}$target interactions ($L\approx10^{31}s^{-1}cm^{-2}$)

$N_{\bar{\Lambda}}=4\times10^{3}\,s^{-1}$!!

can be used to tag exclusive

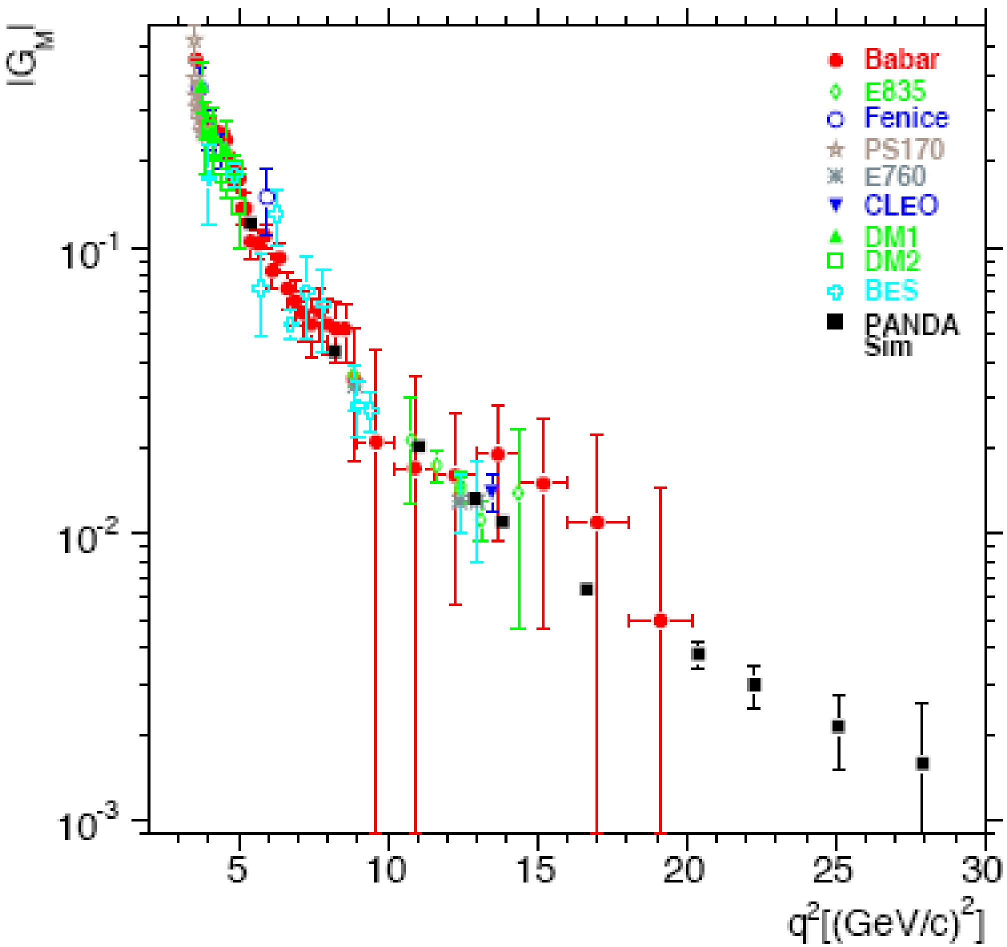
$\bar{p}p\rightarrow\bar{\Lambda}\Lambda$ production 25×10^{6} events / 7days

Milestones

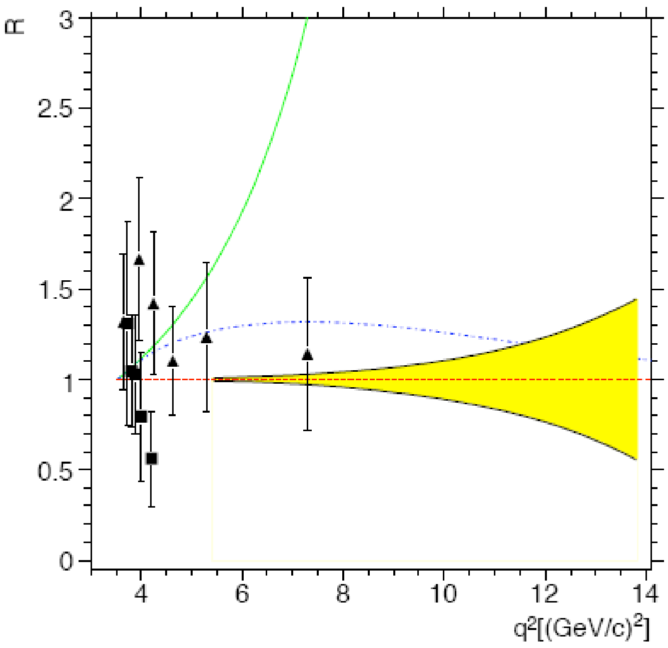
TDR approved (M3)………………………………………. … 12. 2018
Working place for assembling and tests of
scintillation counter modules organized…………………………09.2018
Funding established ……………………………………………... 03. 2019
Contract is signed…………………………………………………10.2019
Tender completed ……………………………………………......12 2019
Procurement of necessary equipment for tests and
calibrations (components not yet available) completed ………..12.2018
Procurement materials for mass production
(scintillators, PMTs, etc) completed ……………………. 12.2020
Fabrication of mechanical items completed …………….........12.2020
Assembly, tests and calibration of scintillation modules . ……...06.2020
Preassembly of the FTOF wall ………………..12.2021
Shipment to GSI …………………… 06.2022
Integration in PANDA detector (M11) …………………… .12.2022
Pre-tests, on beam tests (M12) ………… 06.2023

Expected from PANDA

assuming $\frac{\mu_p G_E^2(Q^2)}{G_M^2(Q^2)} = 1$



$\frac{\mu_p G_E^2(Q^2)}{G_M^2(Q^2)}$ ratio



Selected Monte Carlo simulation aspects

Count rate at various beam energies, PANDAROOT

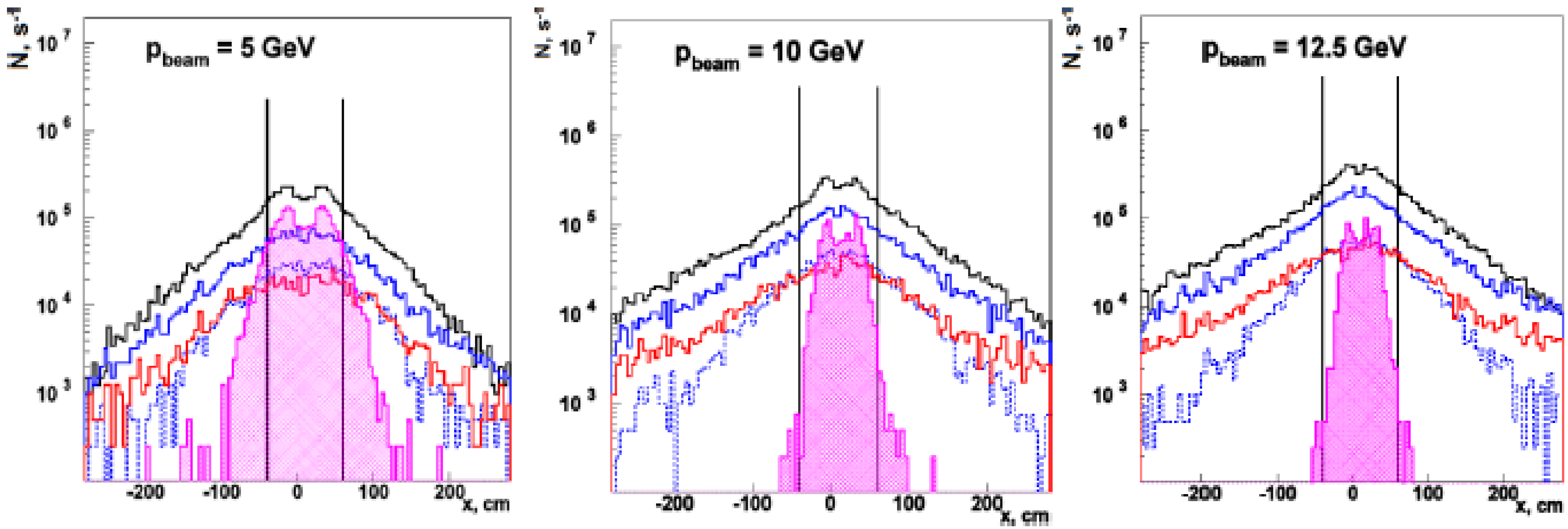
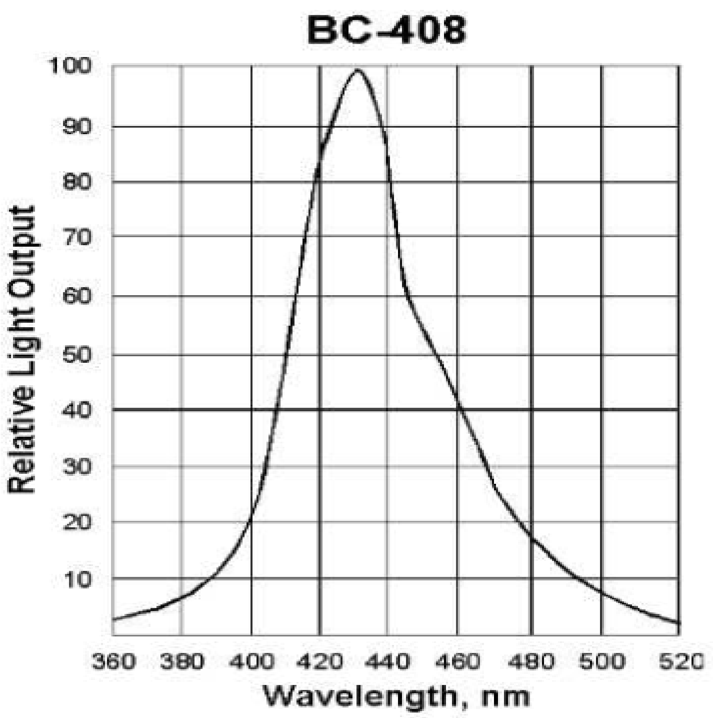


Figure 4.5: Counts of particles in the forward ToF wall for $\bar{p}$ beam energy 5 GeV, 10 GeV and 12.5 GeV versus x coordinate. Black histogram represents all charged hadrons, magenta area shows elastic $\bar{p}$ scattering, blue histogram corresponds all e^+e^-, red histogram shows contribution of e^+e^--pairs produced in the beam vacuum pipe, blue dashed histogram is contribution of e^+ or e^- resulted from backward scattering in the forward EM calorimeter

Properties of Bicron plastic scintillators

Properties	BC-400	BC-404	BC-408	BC-412	BC-416
Light Output, % anthracene.	65	68	64	60	38
Rise Time, ns	0.9	0.7	0.9	1.0	-
Decay Time, ns	2.4	1.8	2.1	3.3	4.0
Pulse Width FWHM, ns	2.7	2.2	2.5	4.2	5.3
Light Atten.Length, cm !	160	140	210	210	210
Wavelength of max. emission, nm	428	408	425	434	434
Principal uses/applications	General purpose	Fast counting	Large area tof	Large area	Large area



Peak of light output at 425 nm
well corresponds to most of fast PMTs

PMT Photon Detection Efficiency
PDE
Wavelength peak
Hamamatsu R4998 420 nm
Hamamatsu R083 420 nm

EJ-200 much better atten. Length
With very similar timing parameter,s
Lower cost

Fast PMTs selected as photodetectors

	R4998	R9800	R2083	R5505	R7761	R59 24
PMT type	linear-focused	linear-focused	linear-focused	fine-mesh	fine-mesh	fine-mesh
Tube diameter	1”	1”	2”	1”	1.5”	2”
No.stages	10	8	8	15	19	19
Q.E. at peak	0.2	0.25	0.2	0.23	0.23	0.22
Gain ($x10^6$)	5.7	1.0	2.5	0.5	10.	10.
E.Transit Time, ns	10	11	16	5.6	7.5	9.5
Rise Time, ns	0.7	1.	0.7	1.5	2.1	2.5
TTS, ns	**0.16**	**0.27**	**0.37**	**0.35**	**0.35**	**0.44**
HV_{max}, V	2500	1500	3500	2300	2300	2300

Time Transition Spread TTS: inherent PMT time uncertainty in response to a single photoelectron

Most important PMT parameter for high time resolution

R4998 and R2083 easily protected against dipole fringe field of $B_z \approx 20$ G, $B_{x,y} \approx 70$ G

Charmonium at $\bar{\text{P}}$ANDA

- At $2\times10^{32}cm^{-2}s^{-1}$ accumulate 8 pb^{-1}/day (assuming 50 % overall efficiency) $\Rightarrow$ $10^4 \div 10^7$ ($c\bar{c}$) states/day.
- Total integrated luminosity 1.5 fb^{-1}/year (at $2\times10^{32}cm^{-2}s^{-1}$, assuming 6 months/year data taking).
- Improvements with respect to Fermilab E760/E835:
  - Up to ten times higher instantaneous luminosity.
  - Better beam momentum resolution $\Delta p/p = 10^{-5}$ (GSI) vs 2×10^{-4} (FNAL)
  - Better detector (higher angular coverage, magnetic field, ability to detect hadronic decay modes).
- Fine scans to measure masses to ≈ 100 KeV, widths to ≈ 10 %.
- Explore entire region below and above open charm threshold.
- Decay channels
  - $J/\psi+X$, $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$
  - $\gamma\gamma$
  - hadrons
  - $D\bar{D}$

Main competitors: BES, Belle II, LHCb

- Precision measurement of known states
- Find missing states (e.g. D states)
- Understand newly discovered states

Get a complete picture of the dynamics of the $c\bar{c}$ system.

Cost matrix

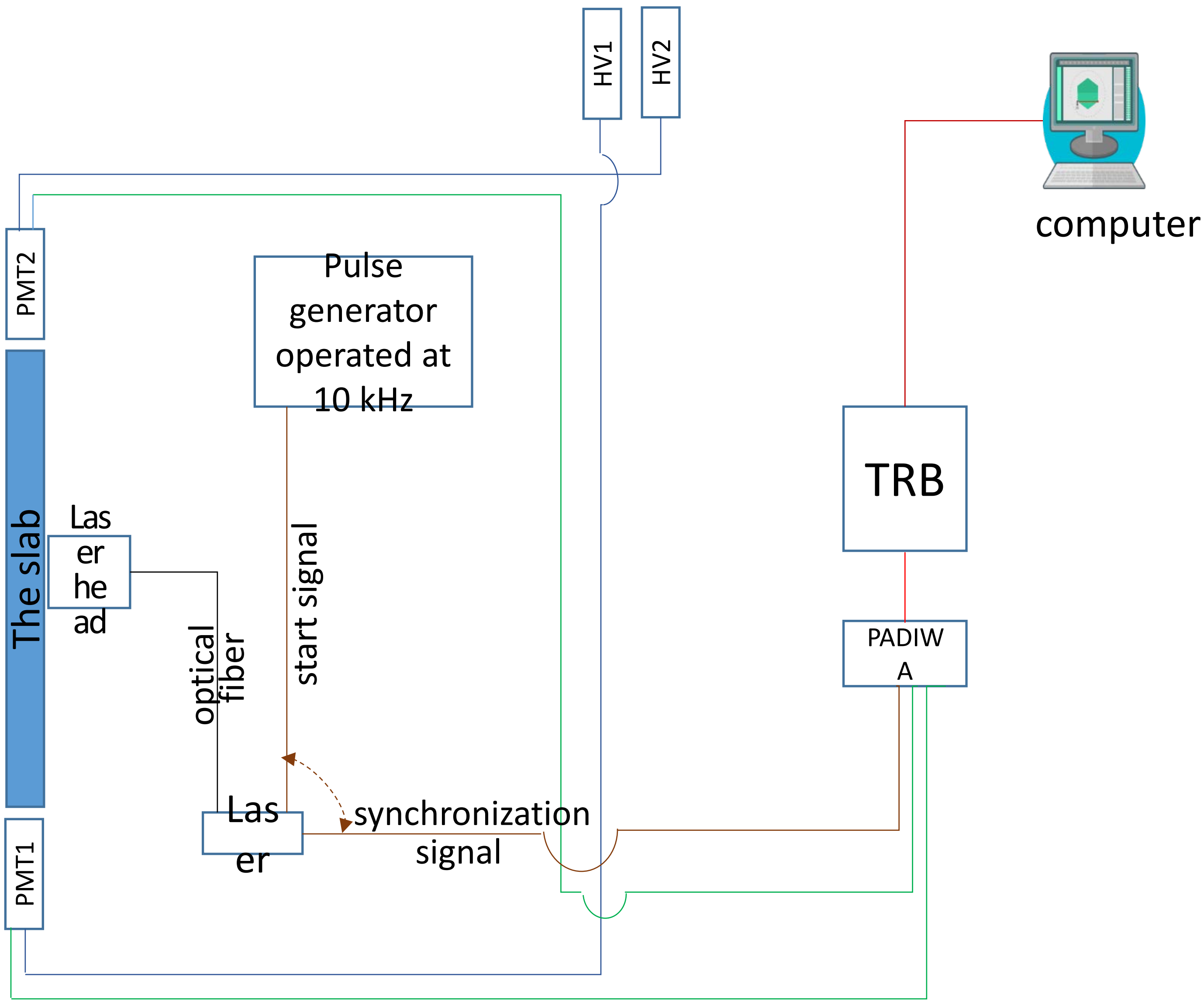
Item	cost, €
Plastic scintillator EJ200 140x10x2.5 cm^3	33 800
Plastic scintillator EJ200B 140x5x2.5 cm^3	11 500
Light guides, optical cement	16 500
PMT Hamamatsu R2083 (2”)	205 200
PMT Hamamatsu R4998 (1”)	83 600
Supporting frame	15 000

Item	cost, €
Readout electronics, TRB-3, Padiwa-3	25000
Active dividers (80€/unit)	10500
HV power supply (90€/unit)	12000
LV power supply	2900
Laser calibration system	20000
Mechanical components (PMT housing, μ-metal)	9000
Transportation, custom taxation	20000
Equipment for tests and mass Production	20000
Total	485 000

item	Number of units	Price per unit, 18% profits tax included, €	Total cost, €
Plastic scintillator EJ200 140x10x2.5 cm^3	50=46+4(spare)	647.3	33715
Plastic scintillator EJ200 140x5x2.5 cm^3	25=20+5(spare)	458.2	11455
PMT Hamamatsu R2083 (2”)	100=92+8(spare)	2051.8	205180
PMT Hamamatsu R4998 (1”)	50=40+10(spare)	1672.2	83610

471k€
In Russian List of expression interest

Flowchart of the experiment



The testing electronics

Pulse generator

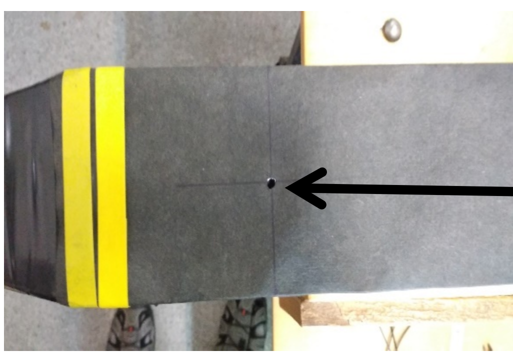
Picosecond pulsed diode laser started from the pulse generator

Two HV modules inserted in the crate

TRB

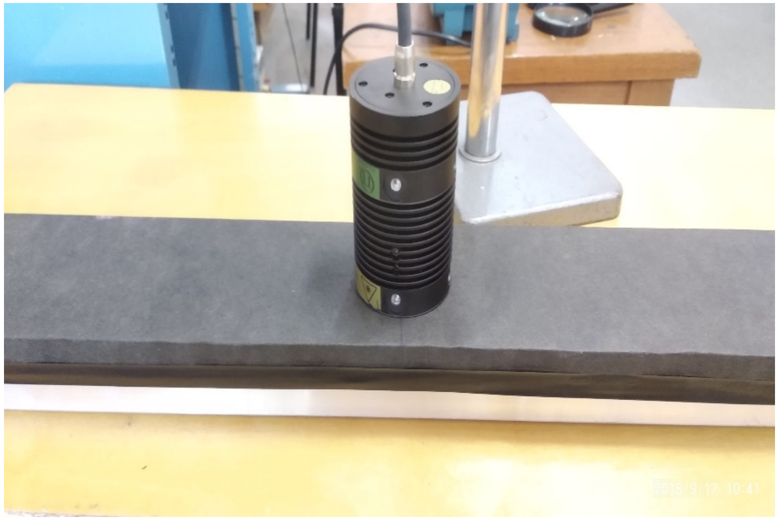
The investigated slab

140x10x2.5 cm slab with lightguides and PMTs attached from both sides.
PMT 1 (left side of the plot) – Hamamatsu R2083 (HV was set to 2.7kV)
PMT 2 (right side of the plot) – Hamamatsu R9779 (HV was set to 1.5kV)

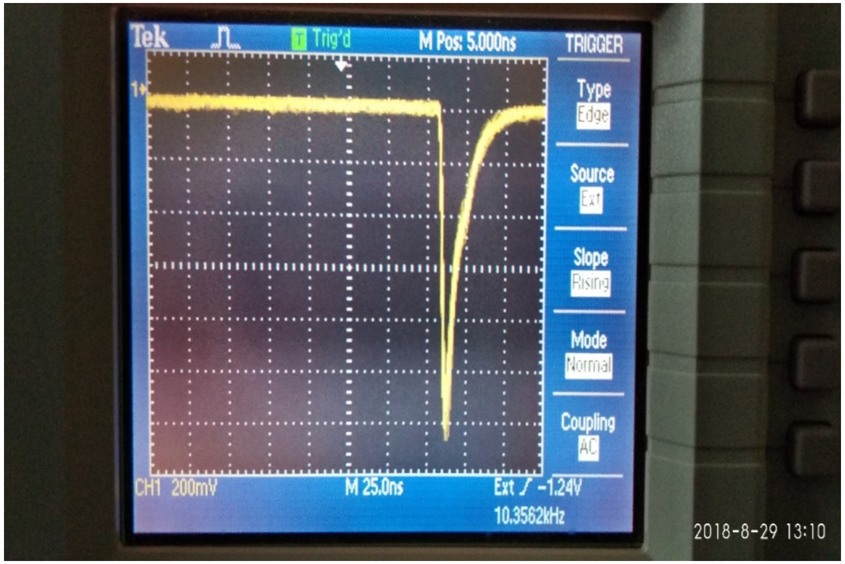


Three 5mm diameter holes in the wrapping materials were made along the slab. One in the center and one at a distance of 10 cm from each side.

Initial test with oscilloscope

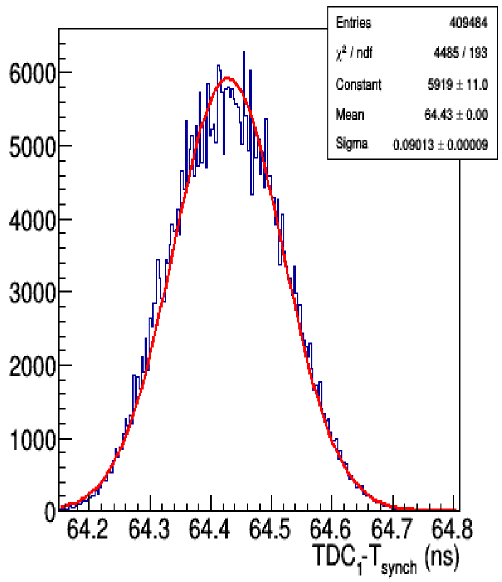


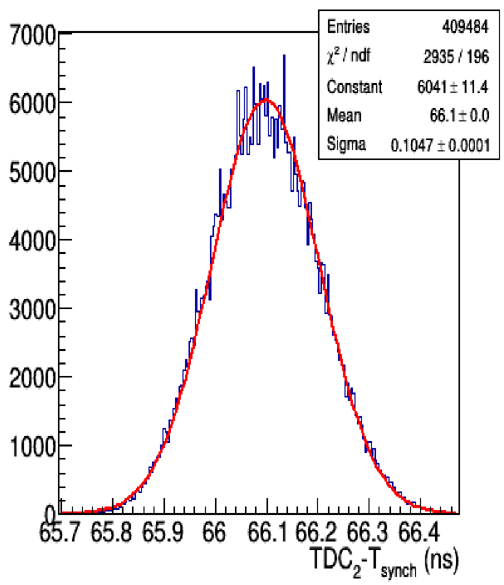
The laser head on top of the slap (central point).



A screenshot of the signal from PMT 1 (R2083) from the laser set at the center of the slab.

Preliminary results

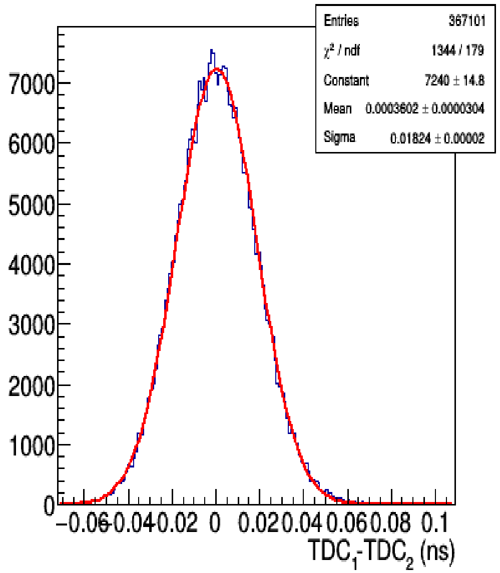




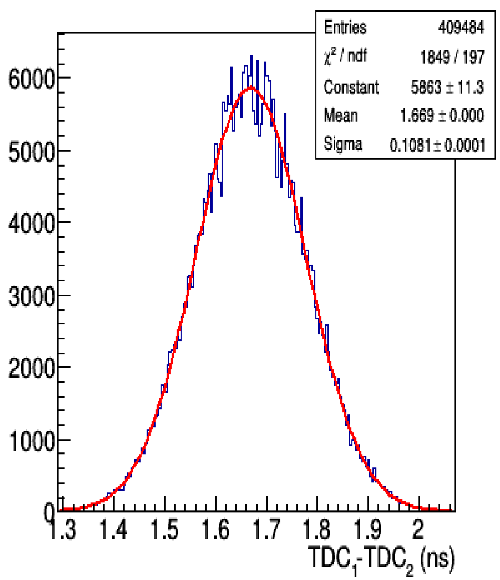
Using the differences between TDCs and synchronization signal from the laser we obtained the **90 ps** resolution for PMT 1 (R2083) and **105 ps** for PMT2 (R9779).

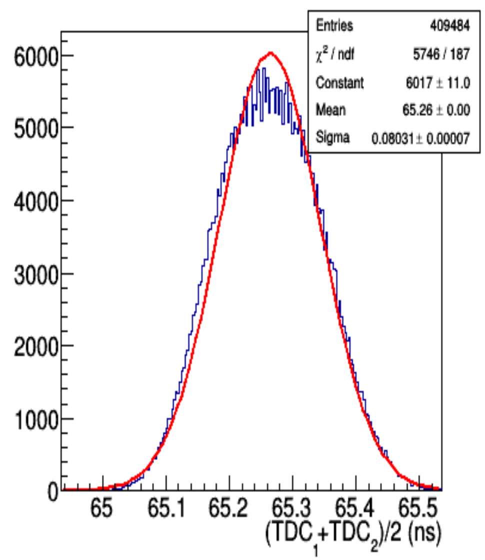
Taking into account that the synchronization signal has its own resolution one can obtained:
66.6 ps for PMT1,
85.3 ps for PMT2,
and 60.8 ps for synchronization signal itself.

Preliminary results



For the test purpose the pulse generator signal was splitted in two parts. Each of them was treated as a quasi-signal from PMT. On this way the resolution of about **18 ps** was achieved.





The measurements with the laser set to the center point give as a resolution of about **108 ps** for the TDC difference (left plot) and **80 ps** for (TDC1+TDC2)/2 (right plot).

HV power supply

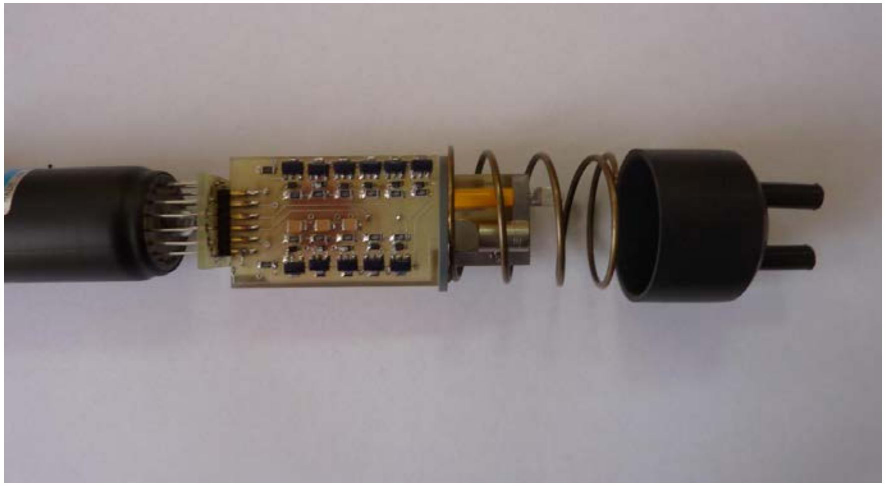
HV negative max 3500 V

worked out in PNPI for NUSTAR R3B 1000 PMT channels
/ L. Uvarov "Hvds3200 the distributed high voltage system for Neuland spectrometer."/

To power active dividers -> 200 μA current consumption (x 132 ch.)

Active divider. Produced in PNPI similar to /V. A. Kalinnikov." Low powered transistor divider for PMT. 2005. (in Russian)"/

Preliminary tested with R4998 designed for R2083

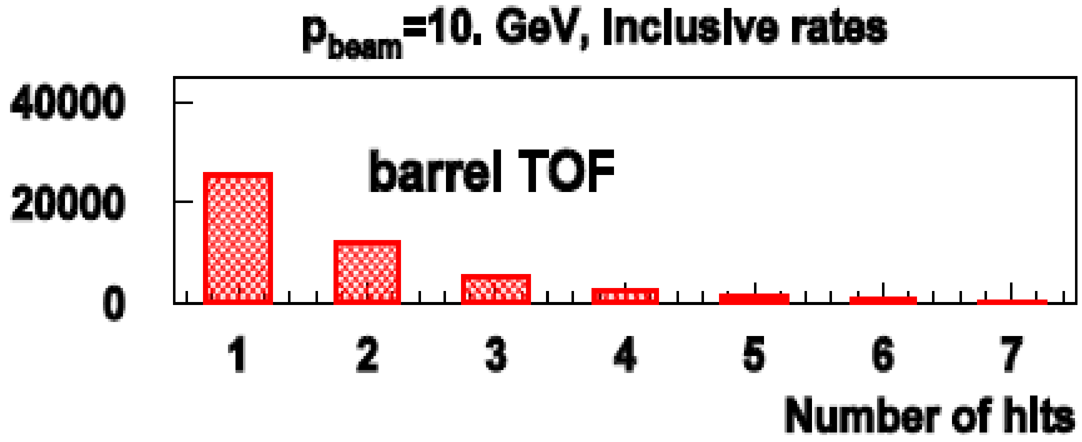


Track multiplicity/event in TOF detectors at 10 GeV

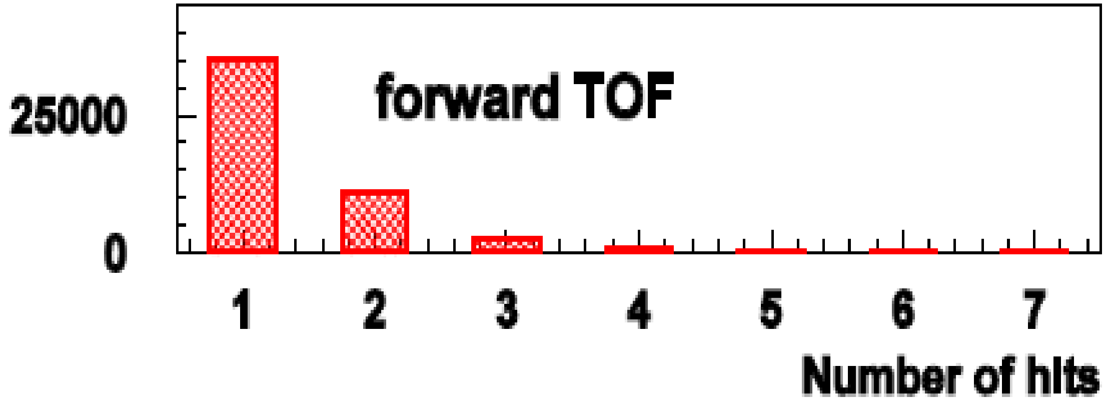
No dedicated start counter

coincidence efficiency

SciTil ≈ 50%



FTOF wall ≈ 31%



Count rates of FTOF wall and $e^+ e^-$ background at 5 GeV

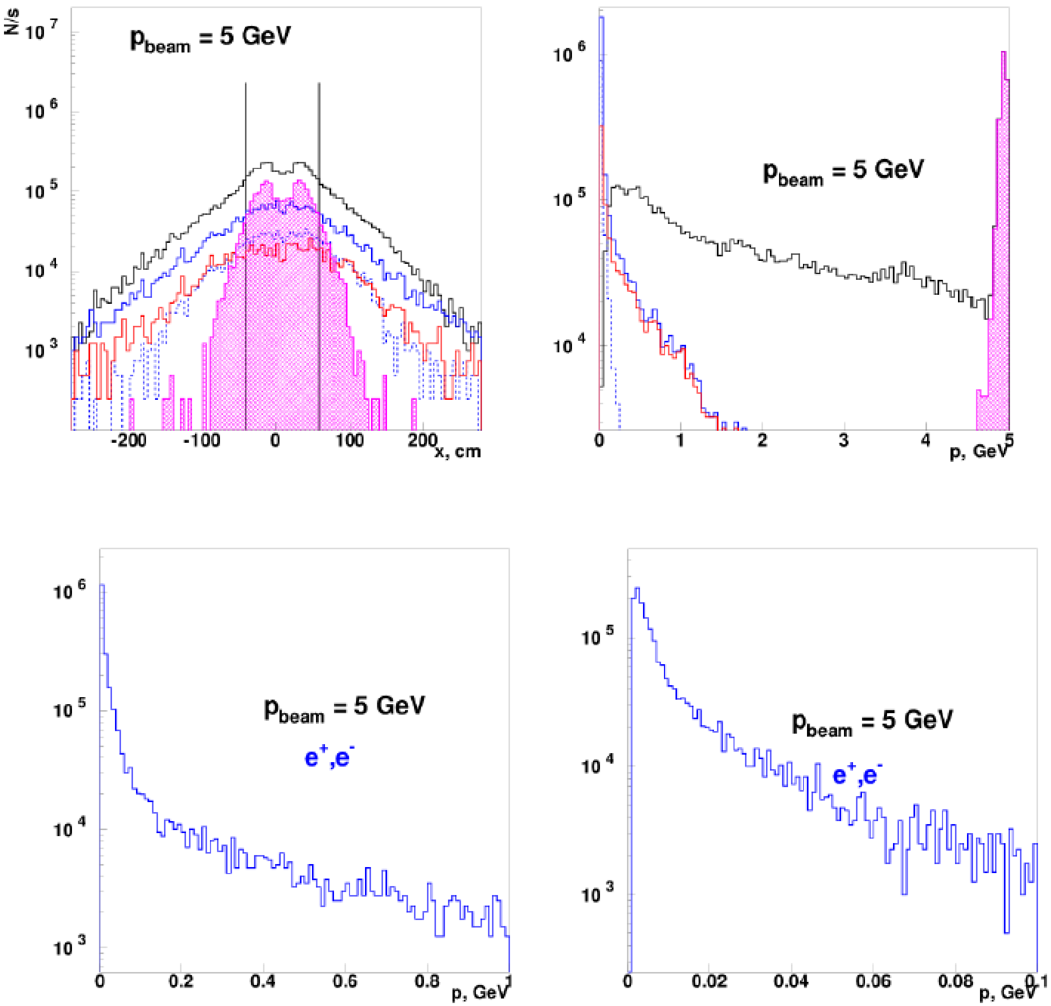
All

Pbar forward peak

$e^+ e^-$ all

$e^+ e^-$ produced in vacuum pipe

$e^+ e^-$ backward scattering from EMC (dashed)



Count rates of FTOF wall and $e^+ e^-$ background at 10 GeV (3.5 MHz)

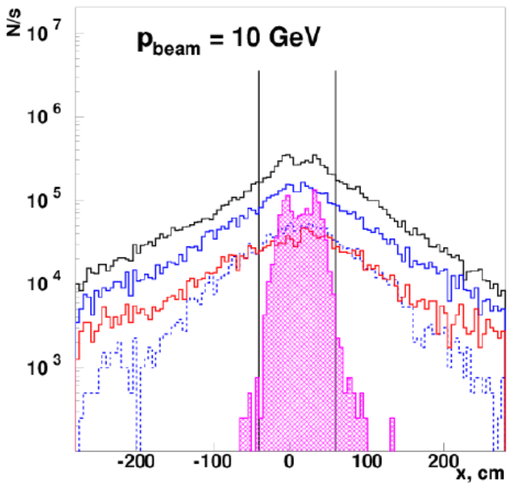
All

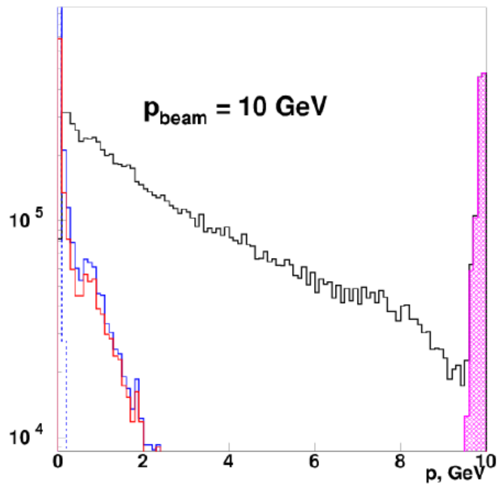
Pbar forward peak

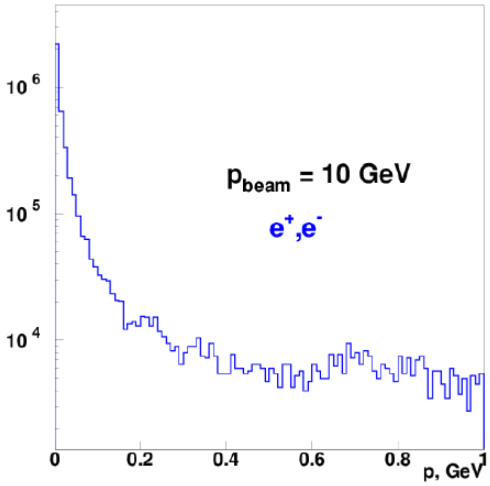
$e^+ e^-$ **all**

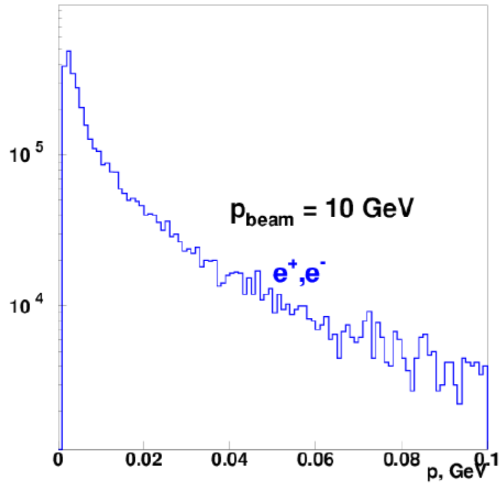
$e^+ e^-$ produced in vacuum pipe

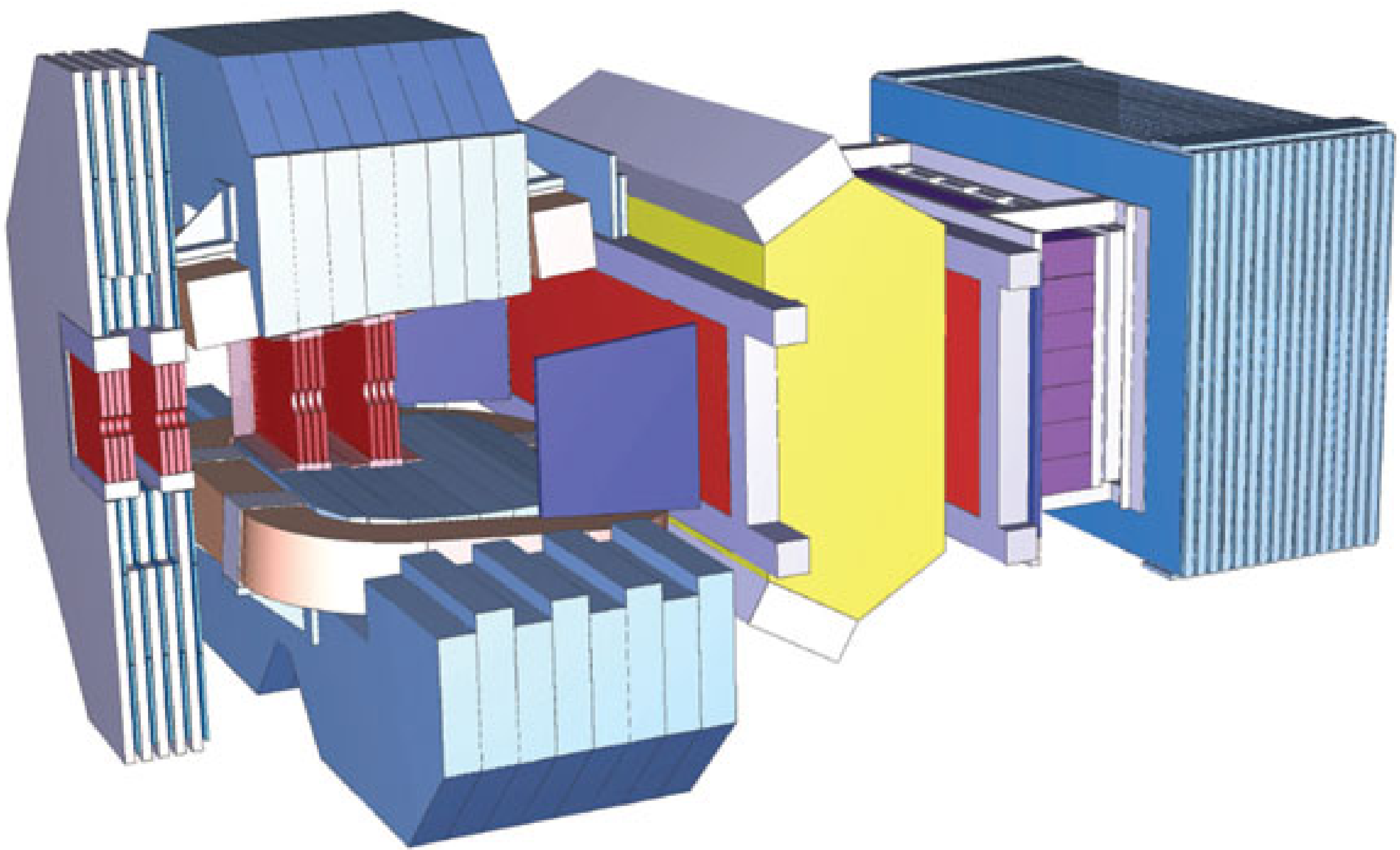
$e^+ e^-$ backward scattering from EMC (dashed)





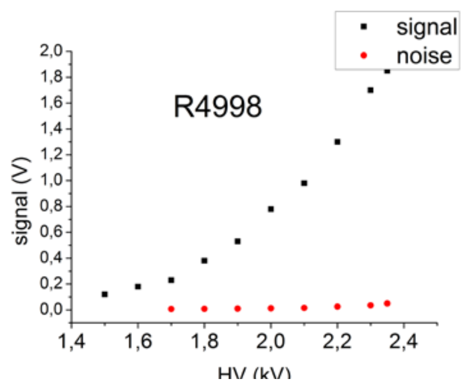


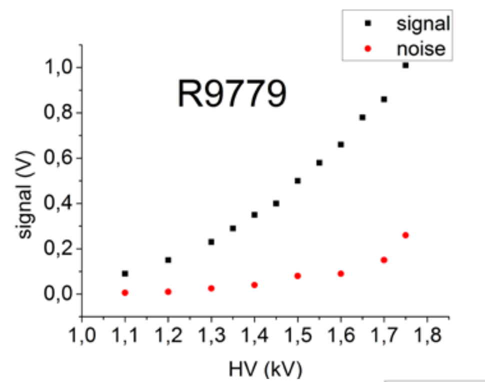


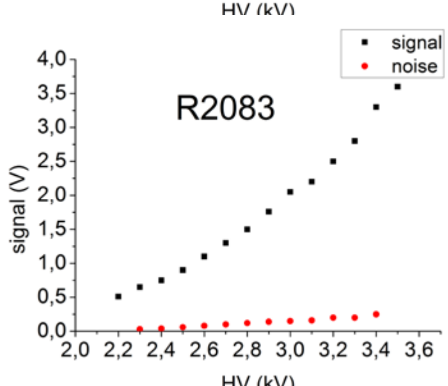


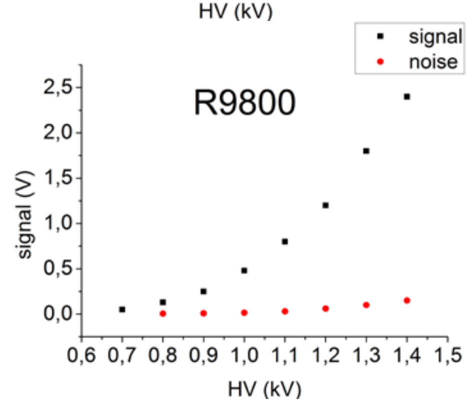
PMT characteristics

PMT	Photocathode diameter (mm)	Anode pulse rise time (ns)	Electron transition time (ns)	Transition time spread (ps)	Gain / 10^6	Typical voltage (V)
R4998	25 (1 inch)	0.7	10	160	5.7	2250
R9800	25 (1 inch)	1.	11	270	1.1	1300
R2083	51 (2 inch)	0.7	16	370	2.5	3000
R9779	51 (2 inch)	1.8	20	250	0.5	1500
XP2020	51 (2 inch)	1.6	28	??	30	2000





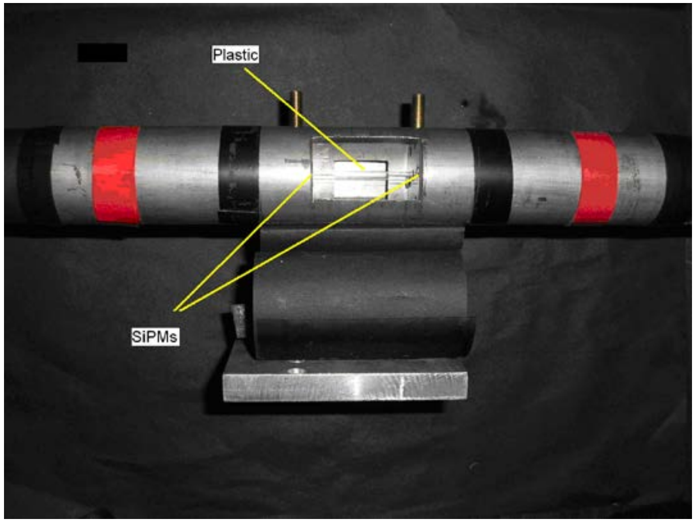




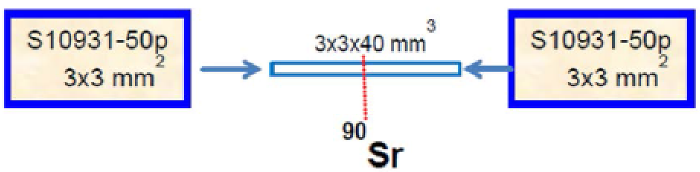
Prototyping summary

- The time resolution of 60–65 ps was obtained for the scintillation counters recommended for prototypes for the FTOF wall.
- The time resolution of 50 ps was obtained for the slabs of 2.5 cm width. Practical application of such slabs however would result in increase of number of channels which may confront the detector cost limitation.
- The time resolution of 80 ps was obtained for the scintillation counter based on the slab of 2.5 cm width viewed with the Electron PMT 187. These mesh PMTs can operate in magnetic fields up to 0.5 T without deterioration of time resolution.
- Samples with slabs of 1.5 cm thickness originally projected for the FTOF wall showed essentially worse time resolution than those of 2.5 cm thickness.
- A precise measurement of the hit position seems crucial to get the timing resolution on the level of 60 ps. Without independent information on hit position, the timing resolution of 80 ps has been measured. .
  - A satisfactory result was obtained for KETEK PM6660 samples at test station. A raw timing resoluton of σ = 71 ps (per a SiPM sample) was directly measured , and after corrections it was obtained σ_{PM6660} = 66 ps. The measurements with large scintilltors has not yet been done.
  - A very tentative test of radiation hardness of SiPMs has been made in PNPI using not powered S0931-50p SiPM (3x3 mm^2) sample exposed to 1 GeV proton beam. It was found that the radiation dose equivalent to 0.45 x 10^{11} protons having passed through the active area of the sample is crucial for its operation capabilities.

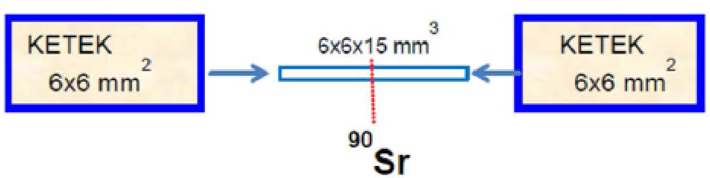
SiPM timing tests



Variant A



Variant B mm



Amplitude correction $$\Delta t = \Delta t_0 - a\left(\frac{1}{\sqrt{q_1}} - \frac{1}{\sqrt{q_2}}\right) - b$$

variant A S10931

after corrections **σ =103 ps**

variant B KETEK 6660

after corrections **σ =65 ps**

Table 4. Main parameters and time resolution of KETEK 6660.

Supply voltage (V)	Signal amplitude (mV)	Noise amplitude (mV)	Current without ^{90}Sr (mkA)	Current with ^{90}Sr (mkA)	σ_{TDC_1} (ps)	$\frac{\sigma_{TDC\_1}}{\sqrt{2}}$ (ps)	σ_{KETEK} (ps)
26.35	20÷30	~ 0.3	7.5	9	120	84.8	81.1
26.85	70÷90	~ 0.5	11	13	100	70.7	66.1

Detection Efficiency of FTOF wall

$$0.72\times10^{6}\ \bar{p}p\ \text{ interactions @10 GeV},\ \frac{\sigma(p)}{p}=0.01,\ \sigma(TOF)=50\,ps$$

$$\text{acceptance of FS}\ \ \pm10\,\text{deg. hor.}\ \pm5\,\text{deg. ver.}\ \rightarrow\ \Omega_{FS}=0.09\,sr$$

	Generated by DPM	Detected by FTOF wall	detection efficiency
π^{-}	880346	172188	0.195
π^{+}	877255	150440	0,171
K^{-}	30179	5820	0.192
K^{+}	26811	2863	0.107
$\bar{p}$	453293	202174	0.446
p	398323	51241	0.129
$\bar{\Lambda}\rightarrow\bar{p}+\pi^{+}$	19874	3840	0.193
$\Lambda\rightarrow p+\pi^{-}$	19518	≈100	$\approx5\cdot10^{-3}$

Both proton and pion detected with FTOF

Count rates in frame of DPG

Number of events selected from 100 generated $\bar{p}p$ *collisions chosen arbitrarily, at 10 GeV*

$\bar{p}p \rightarrow \bar{p}p$	24	$\bar{p}p \rightarrow \bar{p}p\pi^0$	5
$\bar{p}p \rightarrow \bar{n}n\pi^0$	3	$\bar{p}p \rightarrow \bar{p}n\pi^+$	3
$\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$	2	$\bar{p}p \rightarrow \bar{n}p\pi^0\pi^-$	2
$\bar{p}p \rightarrow \bar{p}n\pi^+\pi^0$	2	$\bar{p}p \rightarrow \bar{p}p\pi^0\pi^+\pi^-$	9
$\bar{p}p \rightarrow \bar{n}p\pi^0\pi^+\pi^-\pi^-$	4	$\bar{p}p \rightarrow \bar{p}p\pi^0\pi^+\pi^-\pi^+\pi^-$	4
$\bar{p}p \rightarrow \bar{\Lambda}n\bar{K}^0\pi^0\pi^+\pi^-$	1		

Hadron count rate by TOF wall at 0.35x10^7/s interactions in target

$\bar{p}$ beam momentum, GeV/c	Pion rate, 1/s	Kaon rate, 1/s	Proton rate, 1/s	Antiproton rate, 1/s
2	3.9×10^5	2×10^3	1.2×10^4	1.07×10^6
5	6×10^5	7.8×10^3	3.8×10^4	9.5×10^5
15	9.6×10^5	4.7×10^4	3.2×10^4	8.2×10^5

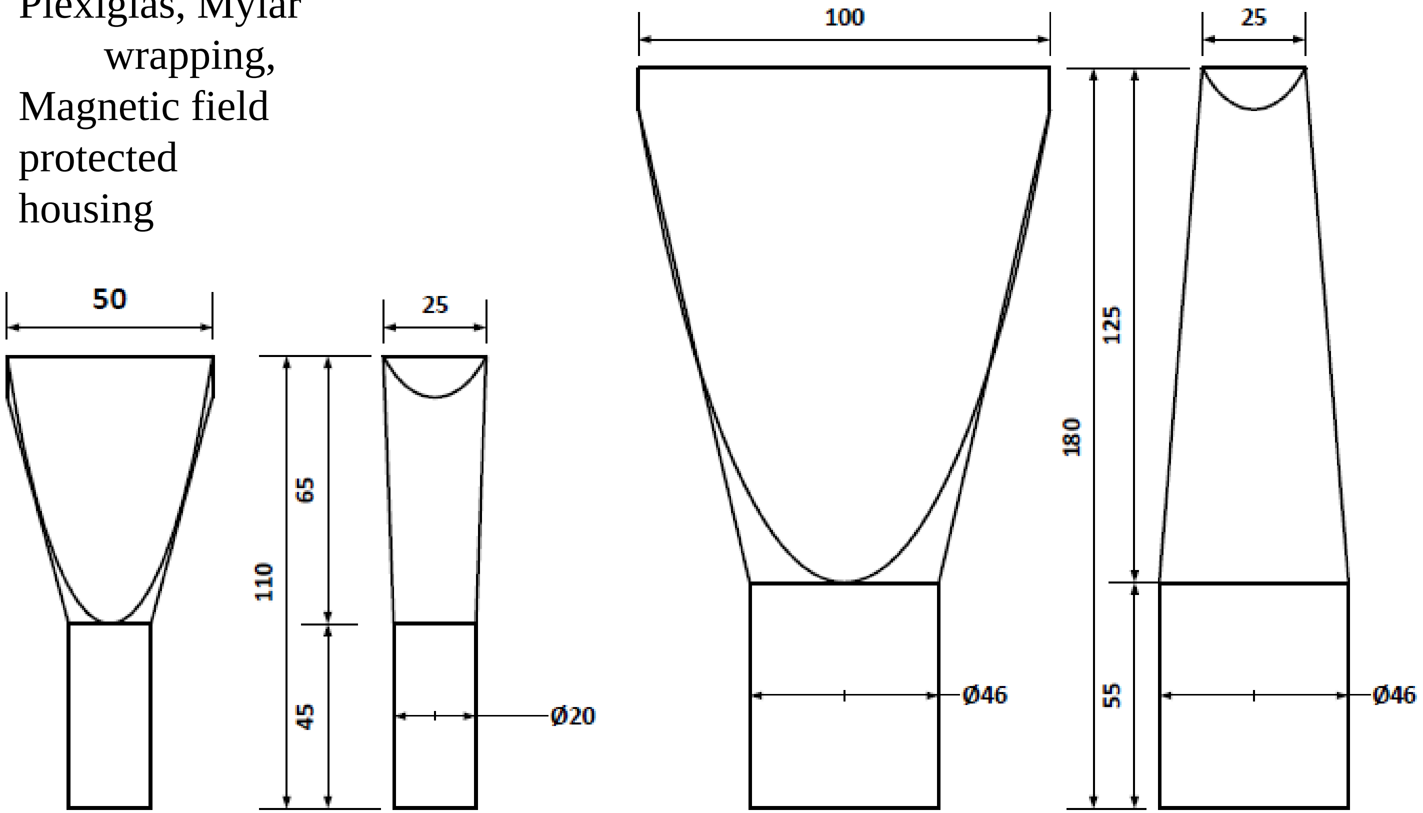
High rate of π^0

Bgr expected from

$\pi \rightarrow 2\gamma$ $\gamma \rightarrow e^+ e^-$

LIGHT GUIDES FOR 1” AND 2” PMTs

Plexiglas, Mylar wrapping,
Magnetic field protected housing

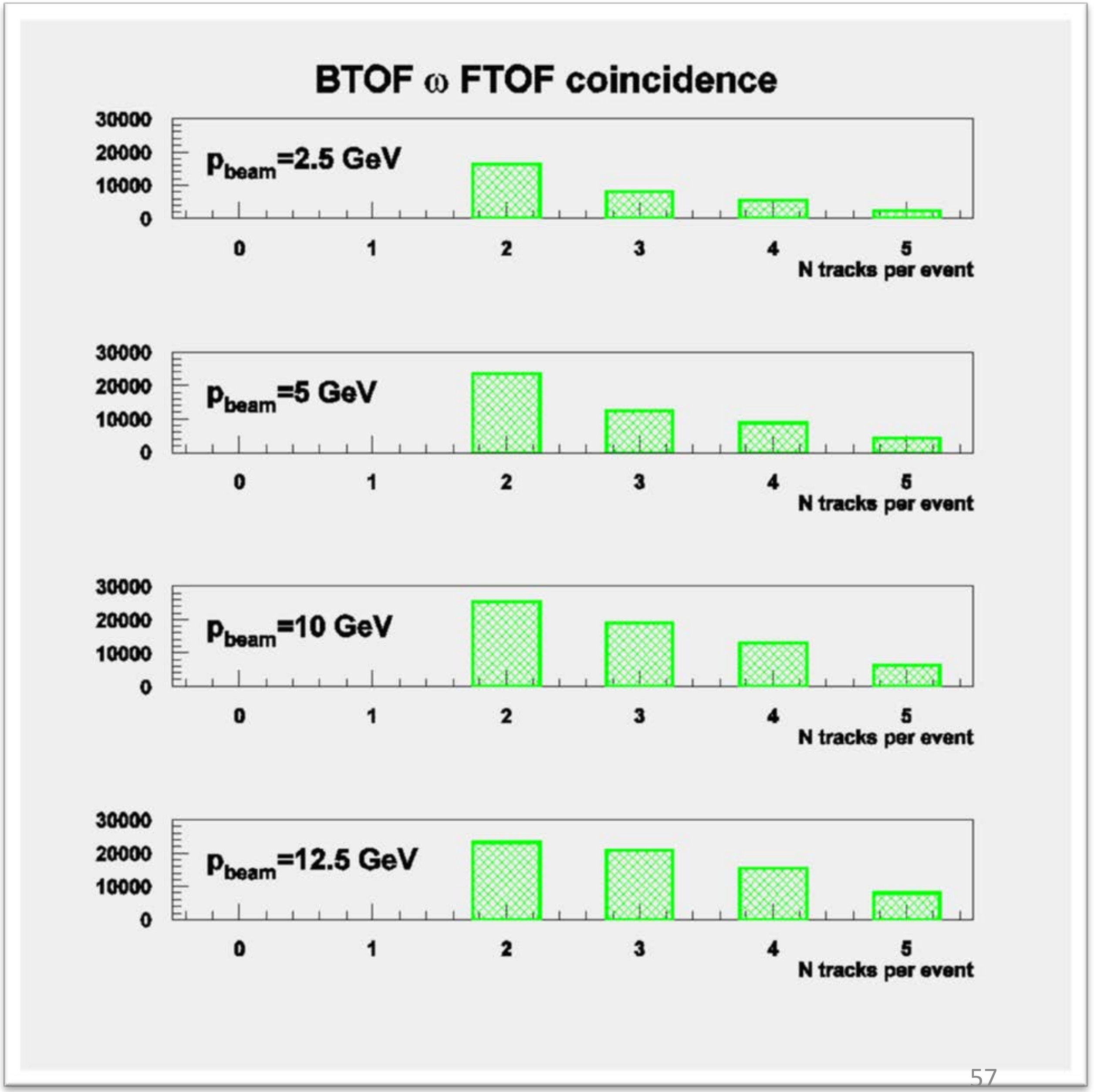


FTOF wall and barrel TOF interplay

No dedicated start counter

FTOF•BTOF coincidence probabilities

2.5 GeV	23.6%
5.GeV	35.1%
10.GeV	45.4%
12.5GeV	48.3%



FSTT impact on FTOF

Tracking station	$z_{min} - z_{max}$ [mm]	Active area w [mm]	h [mm]	Number of modules	Number of straw tubes
1	2954-3104	1338	640	4x10=40	4x288=1152
2	3274-3424	1338	640	4x10=40	4x288=1152
3	3945-4245	1782	690	4x12=48	4x384=1536
4	4385-4685	2105	767	4x14=56	4x448=1792
5	6075-6225	3923	1200	4x27=108	4x824=3296
6	6395-6545	3923	1200	4x27=108	4x824=3296

Table 1.1: Positions, width and height of active area, number of modules and number of straw tubes in the Forward Tracker stations. In the second column z-coordinate of the first and forth double layers are given. The indicated width and height of active area corresponds to dimensions of the first double layer with vertical straws in individual tracking stations.

EJ-200 PLASTIC SCINTILLATOR

This plastic scintillator combines the two important properties of long optical attenuation length and fast timing and is therefore particularly useful for time-of-flight systems using scintillators greater than one meter long. Typical measurements of 4 meter optical attenuation length are achieved in strips of cast sheet in which a representative size is 2 cm x 20 cm x 300 cm.

The combination of long attenuation length, high light output and an emission spectrum well matched to the common photomultipliers recommends EJ-200 as the detector of choice for many industrial applications such as gauging and environmental protection where high sensitivity of signal uniformity are critical operating requirements.

Physical and Scintillation Constants:

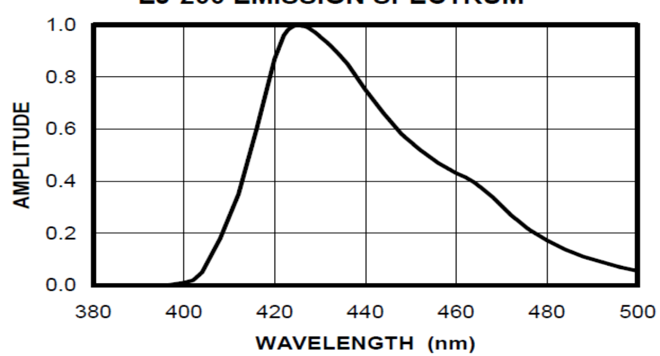
Light Output, % Anthracene	64
Scintillation Efficiency, photons/1 MeV e^-	10,000
Wavelength of Max. Emission, nm	425
Rise Time, ns	0.9
Decay Time, ns	2.1
Pulse Width, FWHM, ns	~2.5
No. of H Atoms per cm^3, x 10^{22}	5.17
No. of C Atoms per cm^3, x 10^{22}	4.69
No. of Electrons per cm^3, x 10^{23}	3.33
Density, g/cc:	1.023

Polymer Base: .... Polyvinyltoluene
Refractive Index: 1.58
Vapor Pressure: .... Is vacuum-compatible
Coefficient of Linear Expansion: .... 7.8×10^{-5} below +67°C

Light Output vs. Temperature:
At +60°C, L.O. = 95% of that at +20°C
No change from +20°C to -60°C

Chemical Compatibility: Is attacked by aromatic solvents, chlorinated solvents, ketones, solvent bonding cements, etc. It is stable in water, dilute acids and alkalis, lower alcohols and silicone greases. It is safe to use most epoxies and “super glues” with EJ-200.

EJ-200 EMISSION SPECTRUM



ELJEN TECHNOLOGY
PO Box 870, 300 Crane Street
Sweetwater TX 79556 USA
Tel: (325) 235-4276 or (888) 800-8771
Fax: (325) 235-0701
Website: www.eljentechnology.com