Development, Testing, and Upgrade of Trigger and Neutron Detector Systems for the BM@N Experiment

Valyo Velichkov

for the BM@N trigger group

- *Hadron Physics – Scientific-Experimental Department of Baryon Matter at the Nuclotron, Joint Institute for Nuclear Research (JINR), Dubna, Moscow Region, Russian Federation.*
- *Institute of Mechanics, Bulgarian Academy of Sciences (IMech-BAS), Sofia, Bulgaria.*

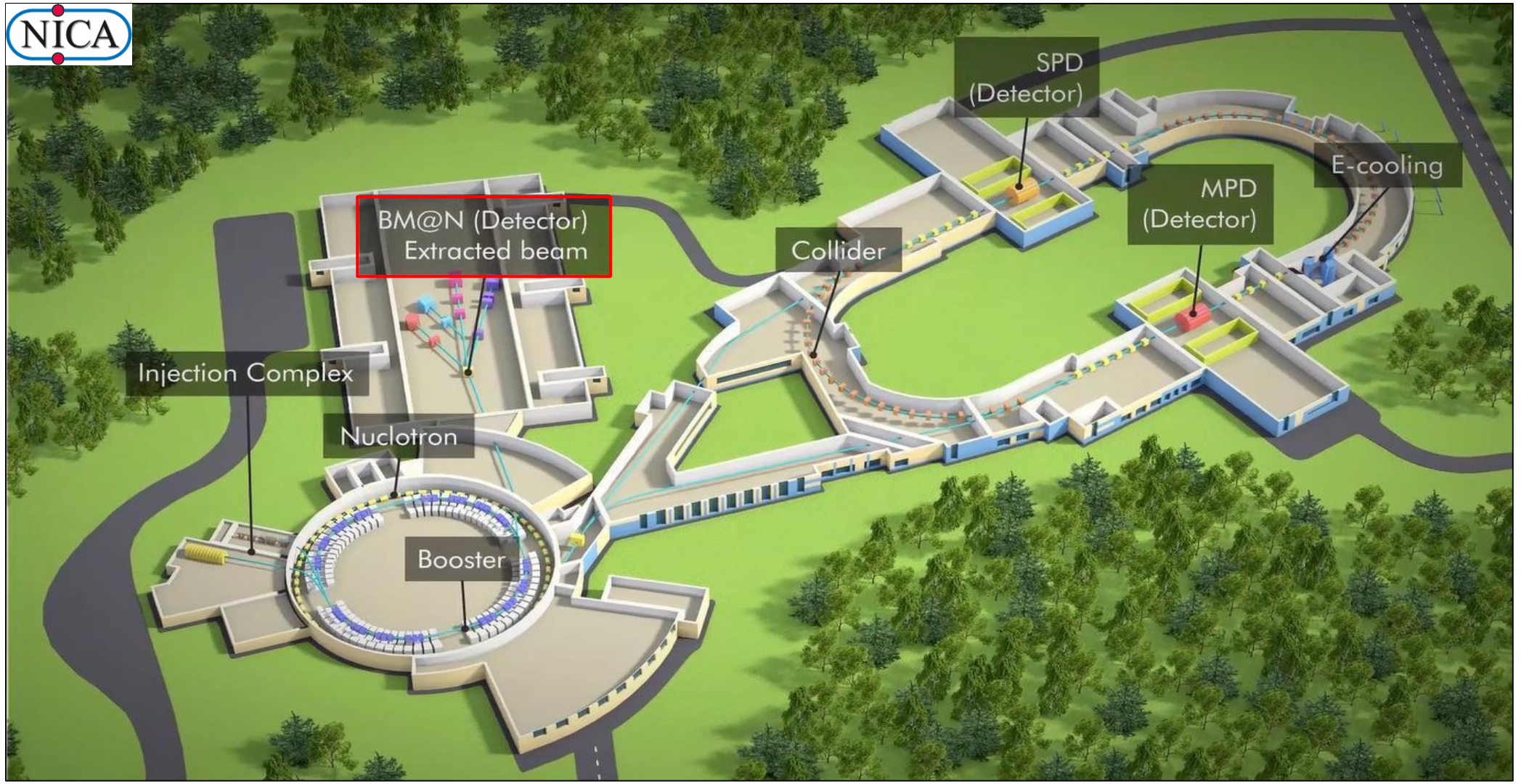








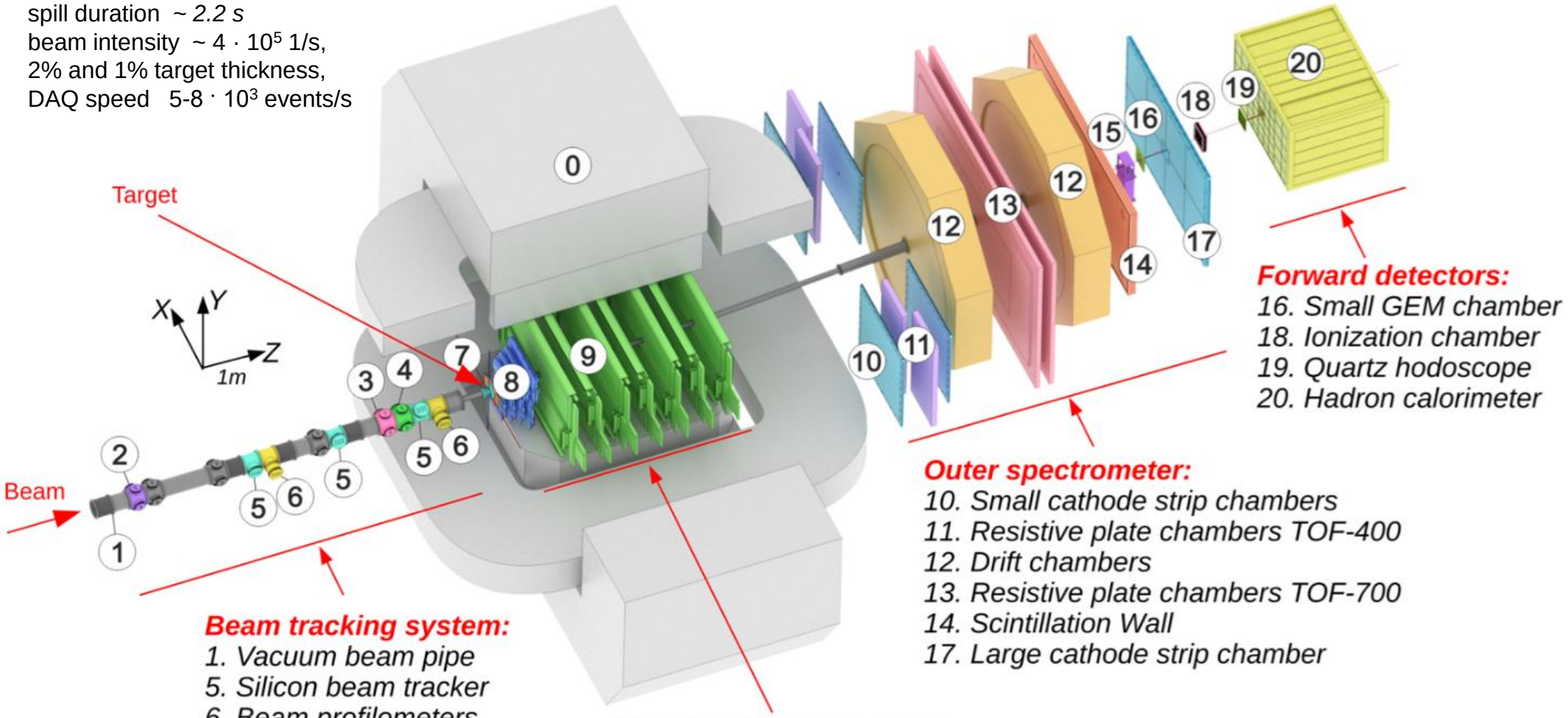
NICA accelerator complex and main experiments



Baryon Matter at Nuclotron (BM@N) is a fixed-target experiment using heavy-ion beams from the Nuclotron at energies of 2–4 A GeV, aimed at studying the properties of dense and hot nuclear matter in nucleus–nucleus collisions.

BM@N spectrometer in 2023 ^{124}Xe run

Conditions in 2023 Xe run, *3.8 A GeV*:
spill duration ~ *2.2 s*
beam intensity ~ $4 \cdot 10^5$ 1/s,
2% and 1% target thickness,
DAQ speed 5-8 $\cdot 10^3$ events/s



Beam tracking system:
1. Vacuum beam pipe
5. Silicon beam tracker
6. Beam profilometers

Central tracking system:
0. Analysing magnet
8. Silicon strip detectors
9. GEM detectors

Outer spectrometer:
10. Small cathode strip chambers
11. Resistive plate chambers TOF-400
12. Drift chambers
13. Resistive plate chambers TOF-700
14. Scintillation Wall
17. Large cathode strip chamber

Forward detectors:
16. Small GEM chamber
18. Ionization chamber
19. Quartz hodoscope
20. Hadron calorimeter

BM@N is a forward spectrometer equipped with a wide range of detectors for measuring tracks, timing, and energy deposition of charged particles from the interaction point.

Overview

The BM@N experiment requires precise start-time determination for time-of-flight measurements and efficient triggering for relativistic ion beam studies.

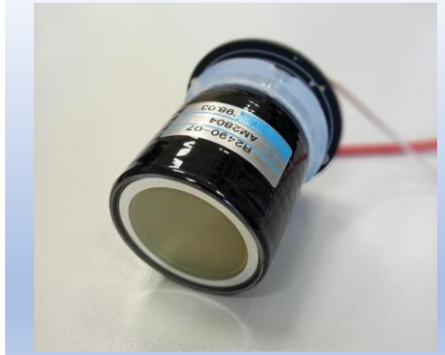
A system of trigger detectors has been developed, tested, and upgraded for the experiment.

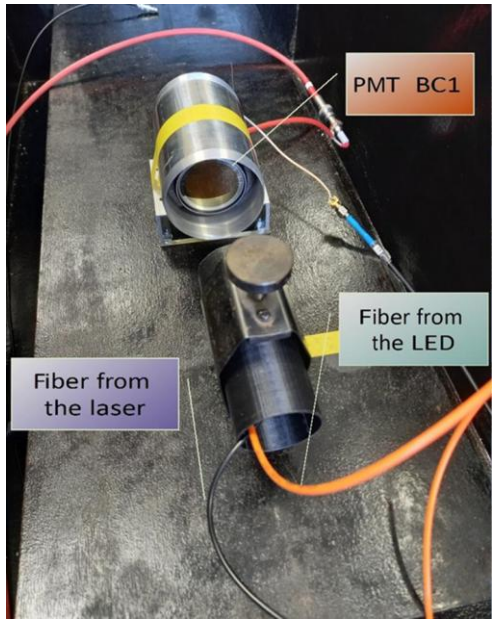
During the first phase (2021–2022), laboratory tests were conducted on the new trigger detectors BC1, BC2 (T0), and the Barrel Detector (BD), focusing on:

- Photomultiplier stability versus beam intensity
- Time resolution
- Pulse signal shape and response uniformity

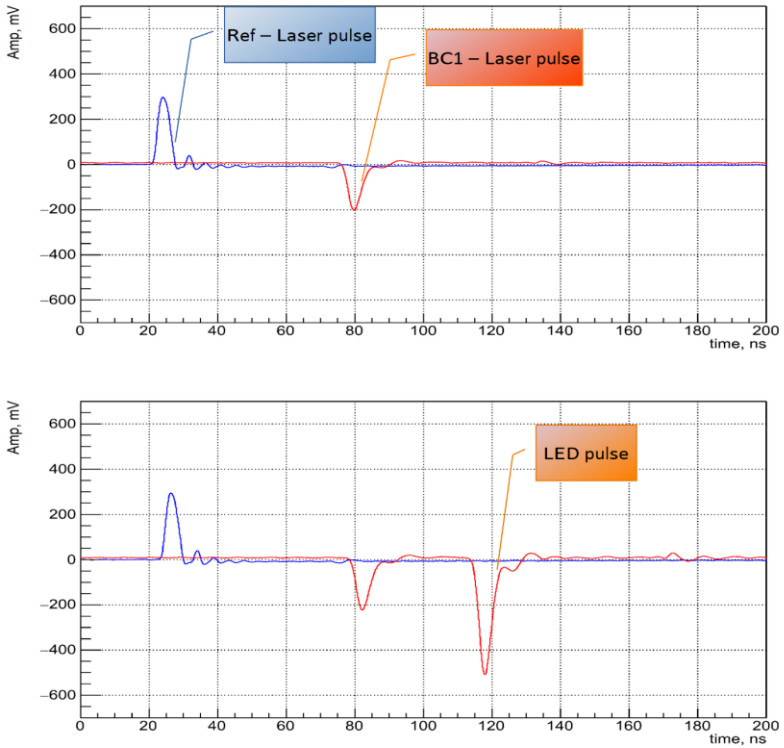
Laboratory test of the BC1 stability

Hamamatsu R2490-07



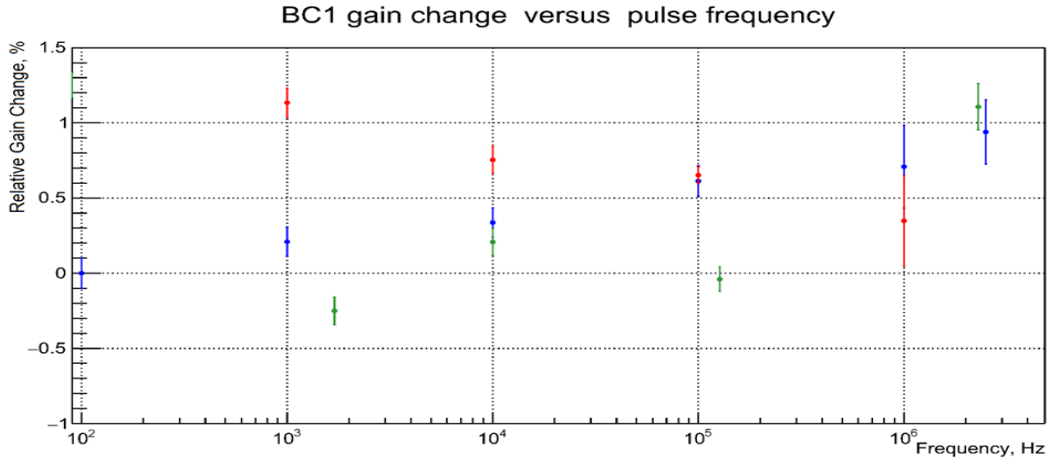


The stability of the photomultiplier in the BC1 detector was evaluated as a function of the expected beam intensity.



Blue – Reference signal;
Red – BC1 signal.
Top: laser-only event; Bottom: laser + LED event.

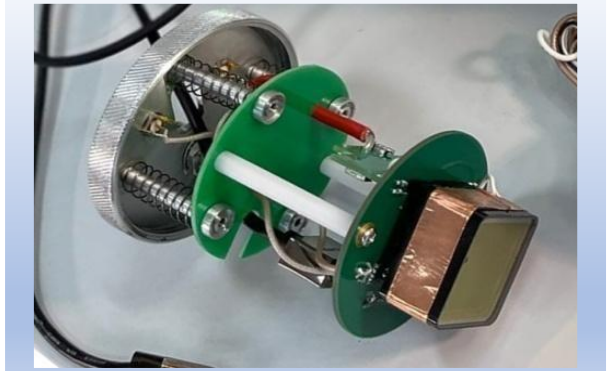
No significant changes (>3%) observed in the photomultiplier.

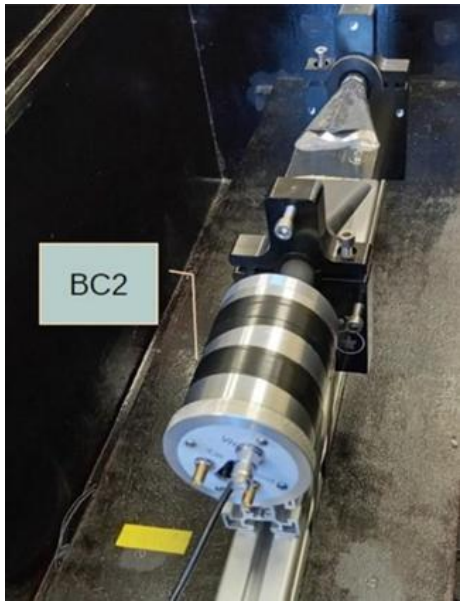


The results show that its short-term stability is sufficient for upcoming BM@N experimental runs.

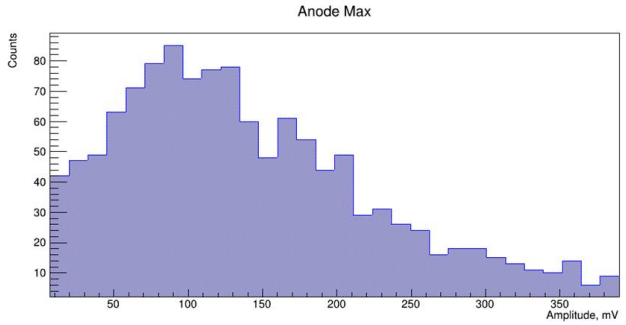
Measurement of the time resolution of BC2

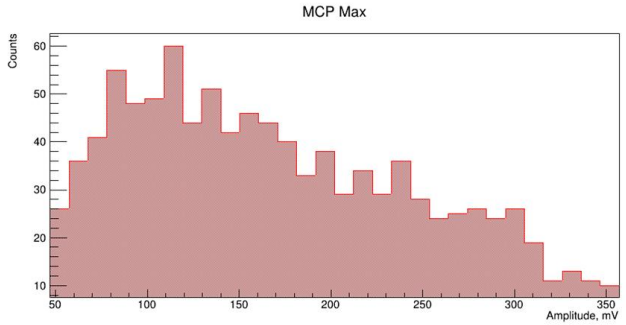
Photonis XPM85112/A1 Q400



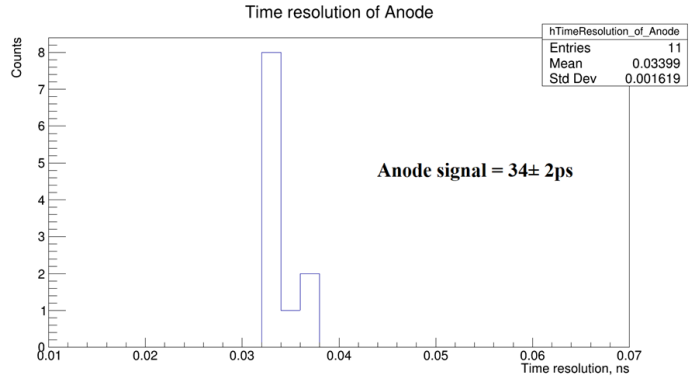


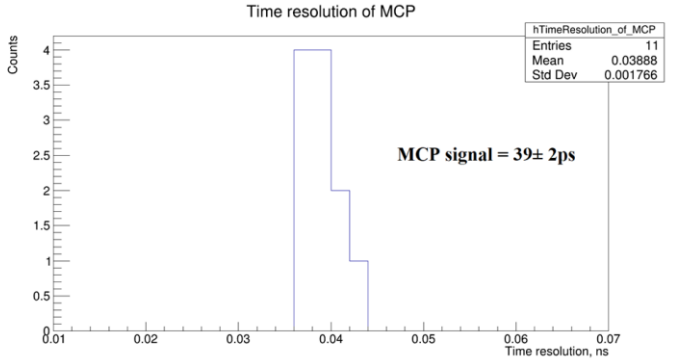
The laser setup was calibrated using scintillation light from muons, providing a reference comparable to the expected signals in the experimental setup.





Muons distribution in BC2 scintillator



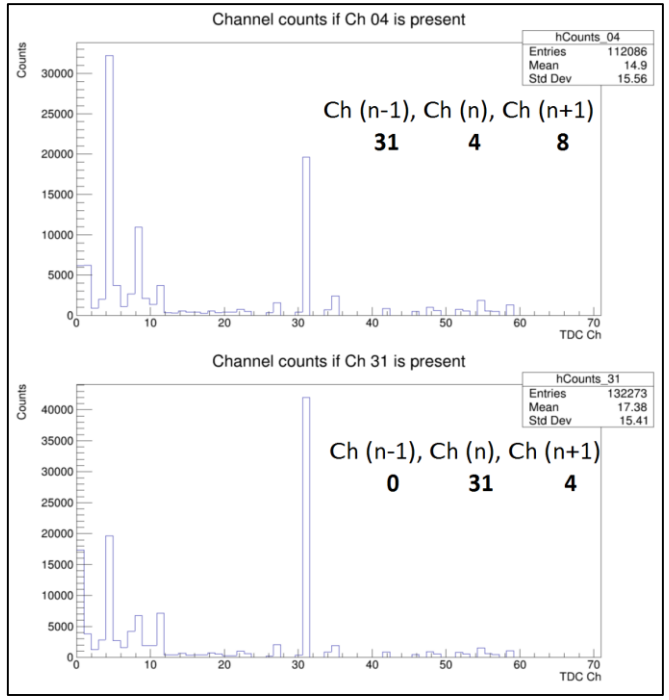


Time resolution of BC2

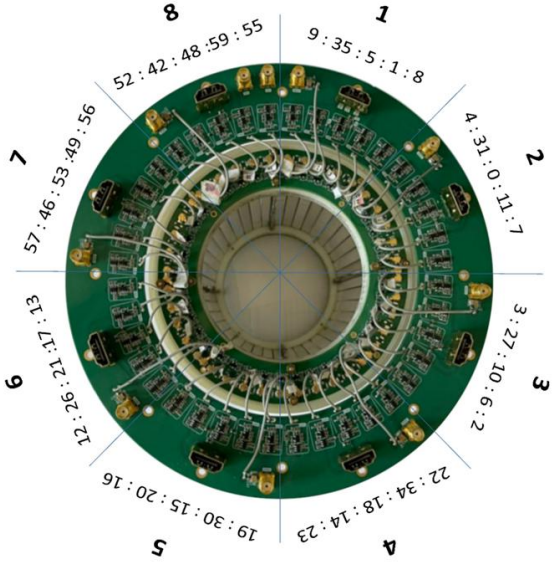
Test of the Barrel Detector

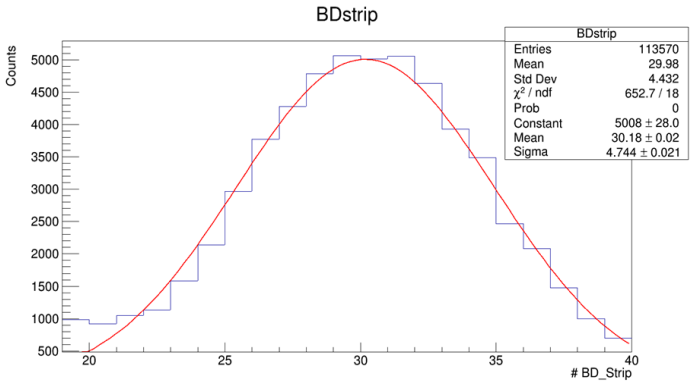
Barrel Detector (BD):
1 – 40 scintillation strips, 150 x 7 x 7 mm, BC418
2 – the board with SiPMs, Sensl C-series, 6 x 6 mm
3 – the board of front-end electronics.

Readout:
signals from every channel in BD are digitized by multihit TDC providing time and time-over-threshold width

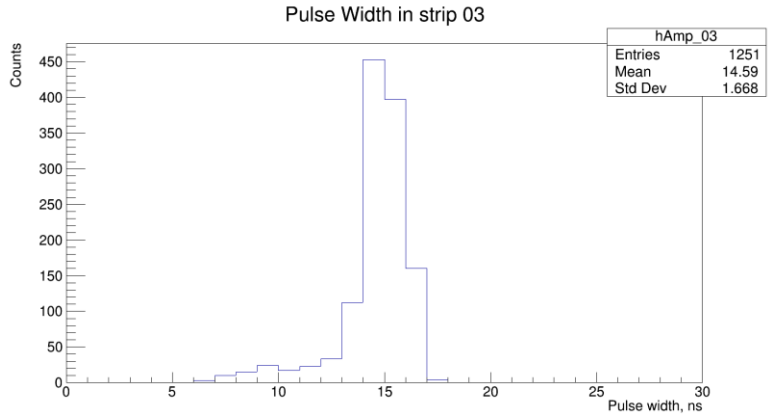


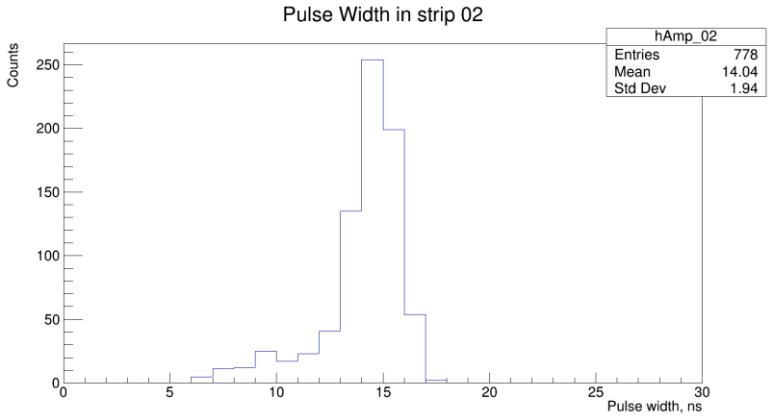
Mapping and checking channels.





Double check the channels in a horizontal position of the detector.





Checking the pulse signals for each strip.

The results confirmed the detectors' readiness for further use in the BM@N experiment.

Overview of the trigger detectors and trigger logic in 2023 ^{124}Xe run

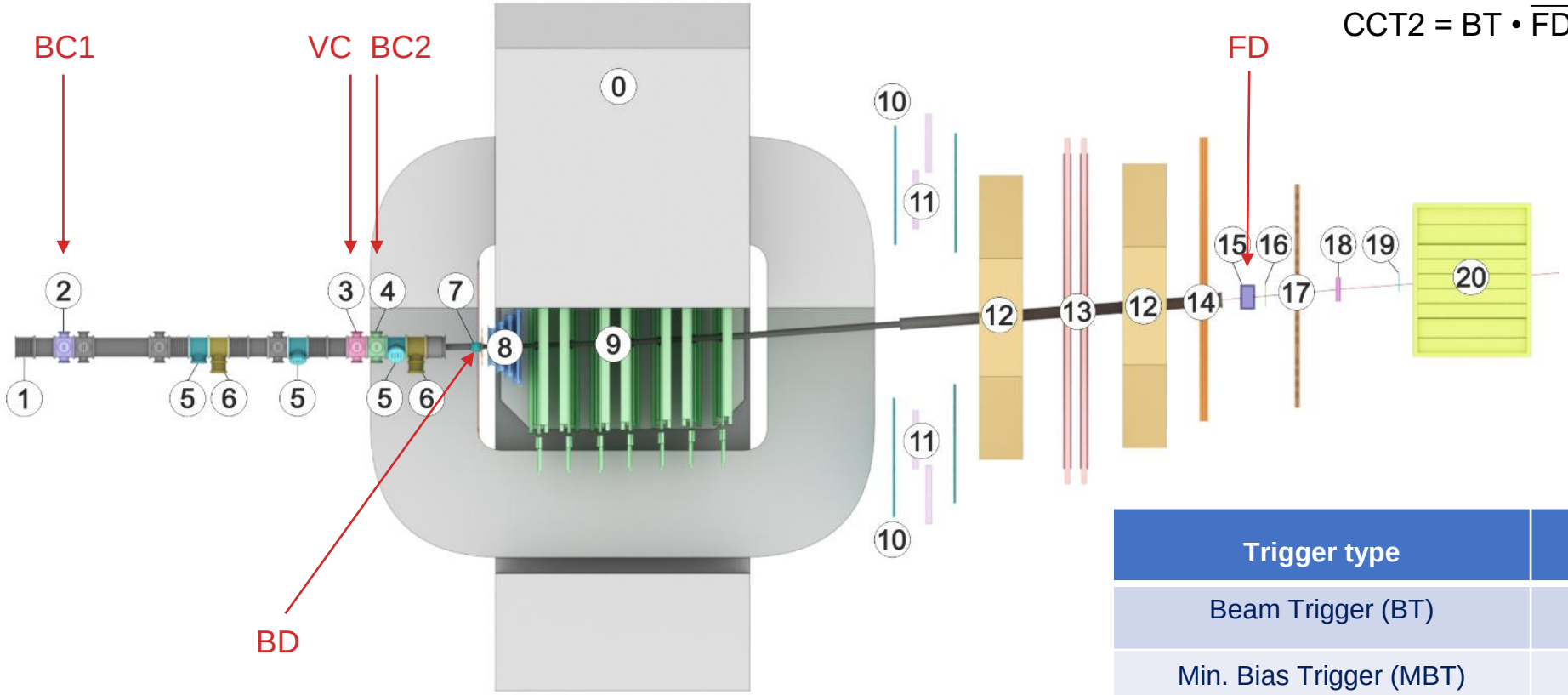
Beam trigger

BT = BC1 • $\overline{\text{VC}}$ • BC2

Minimum bias, centrality trigger 2

MBT = BT • $\overline{\text{FD}}$

CCT2 = BT • $\overline{\text{FD}}$ • BD (n ≥ 4)

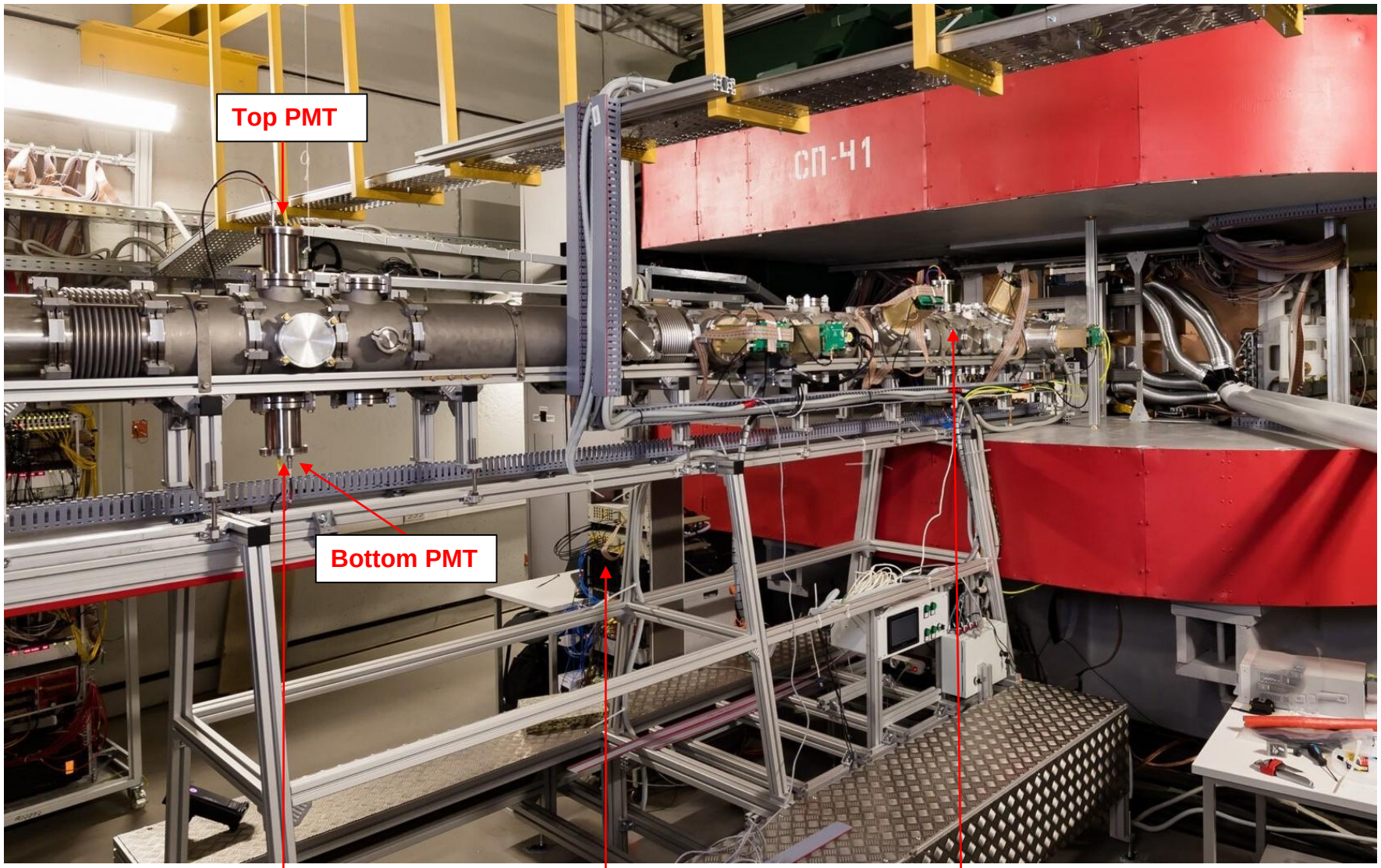


Centrality trigger 1

CCT1 = BT • BD (n ≥ 4)

Trigger type	Trigger logic
Beam Trigger (BT)	**BT = BC1 • $\overline{\text{VC}}$ • BC2**
Min. Bias Trigger (MBT)	**MBT = BT • $\overline{\text{FD}}$**
Centrality Trigger 1 (CCT1)	**CCT1 = BT • BD (n ≥ 4)**
Centrality Trigger 2 (CCT2)	**CCT2 = BT • $\overline{\text{FD}}$ • BD (n ≥ 4)**

Beam pipe and detectors upstream of the target



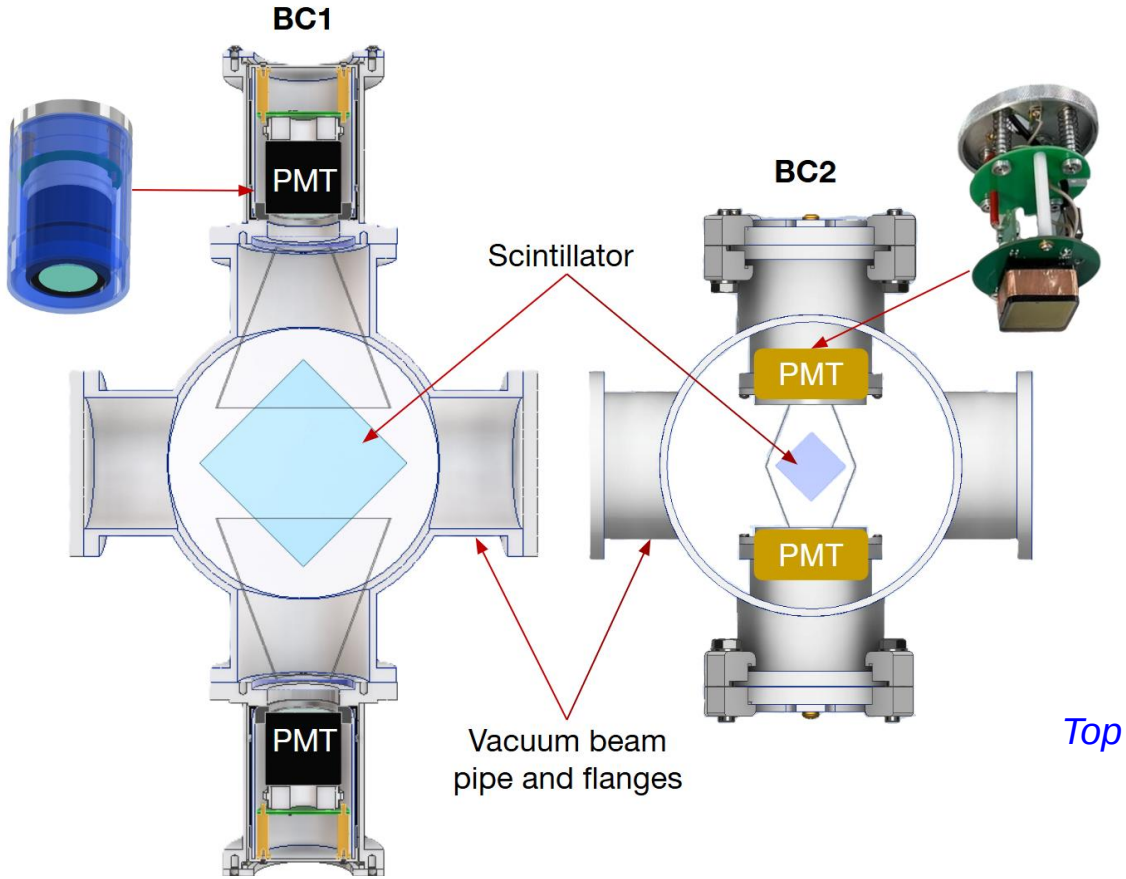
Vacuum for heavy ion runs

2020-2023: new vacuum elements in nearly entire beam transport line from Nuclotron to BM@N

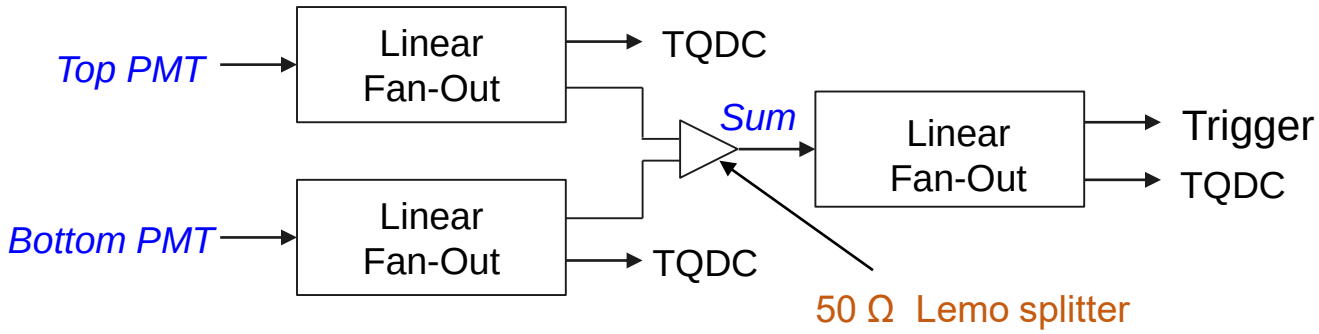
Radiators of BC1, BC2, VC are placed in the vacuum,

BC2 and VC PMTs are capable to work in the magnetic field

Beam counters in 2023 ^{124}Xe run



Detector	PMT (mesh dynodes)	Radiator
BC1	Hamamatsu R2490-07	Scint. BC400B 100 x 100 x 0.25 mm^3
VC	Hamamatsu R2490-07	Scint. 113 x 113 x 4 mm^3 Ø 25 mm
BC2	Photonis XPM85112/A1 Q400 25x25 mm^2	Scint. BC400B 34 x 34 x 0.15 mm^3



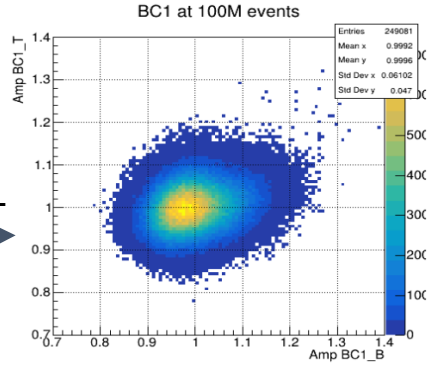
Indication of radiation damage in BC1 and BC2

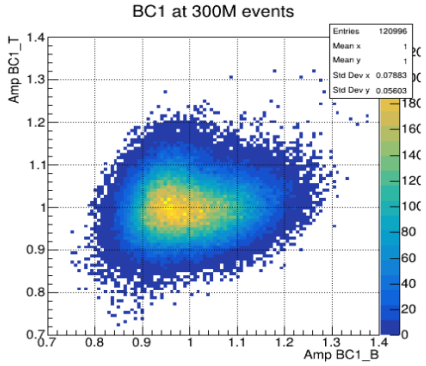
2D plot of Top versus Bottom amplitude

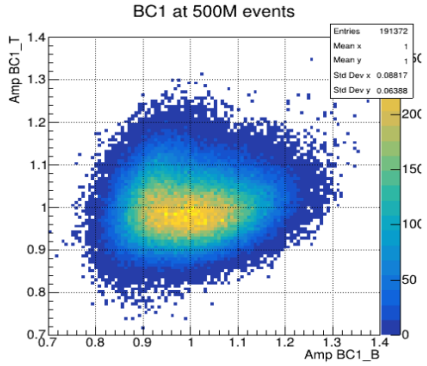
1D plot for the individual amplitudes

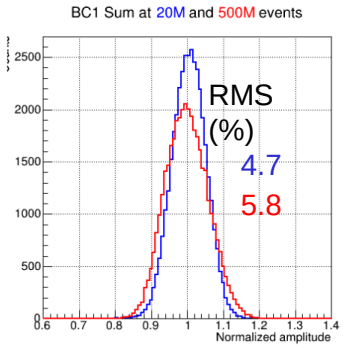
Blue - in the beginning of the run, Red - end of the run

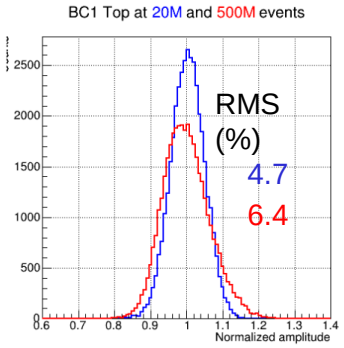
BC1 →

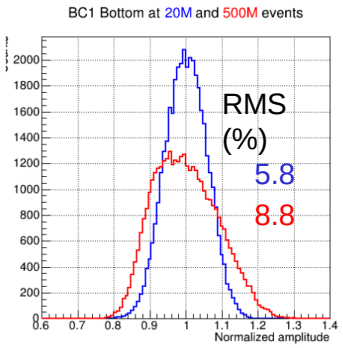




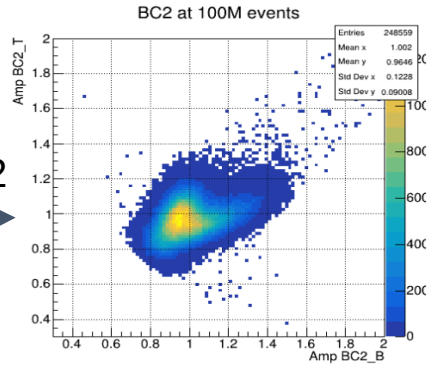


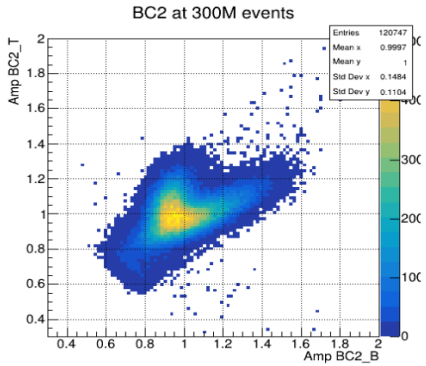


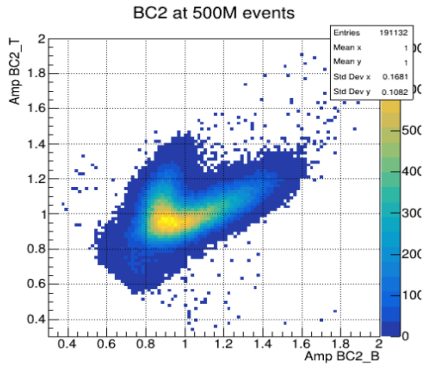


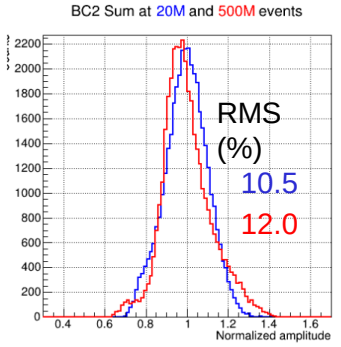


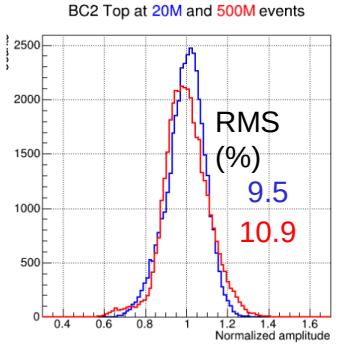
BC2 →

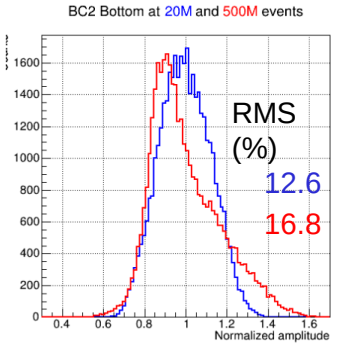












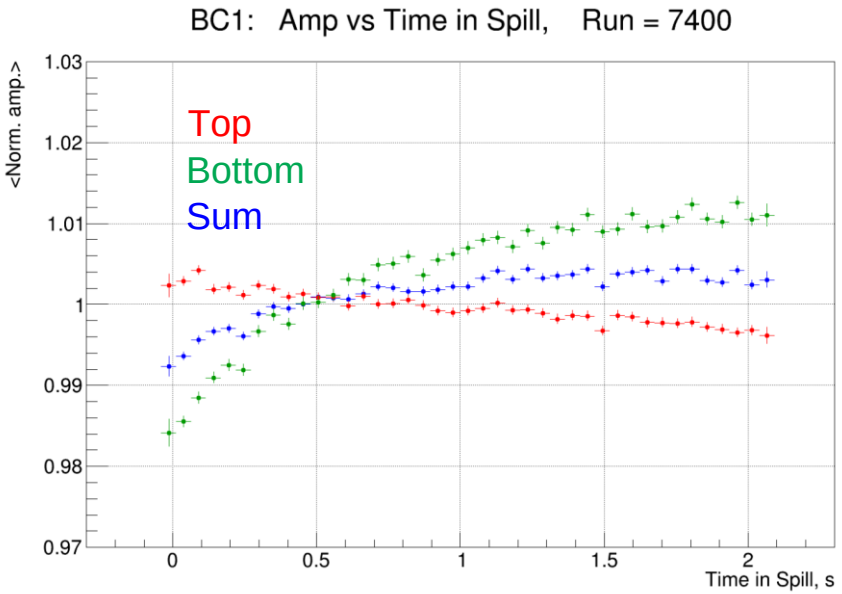
Sum →Trigger

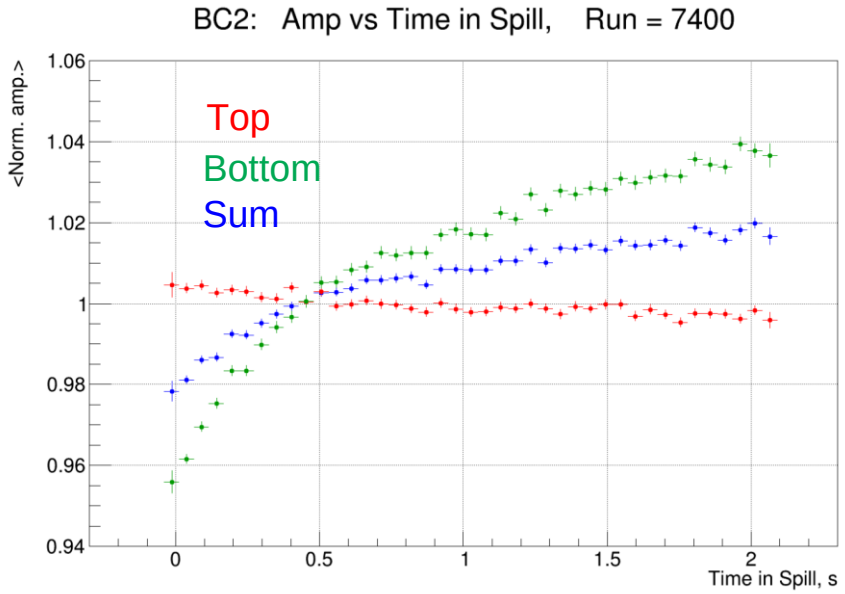
Top

Bottom

We see some degradation of the signals, which results in larger RMS at the end of the run – in BC1 Sum, BC2 Sum and individual signals.

BC1 and BC2: Amplitude and stability





BC1, BC2 response in spill

- stable at 1-2 % level for the sum signal
- stable at 2-4 % level for the individual signals
- sensitive to (X,Y) beam movement

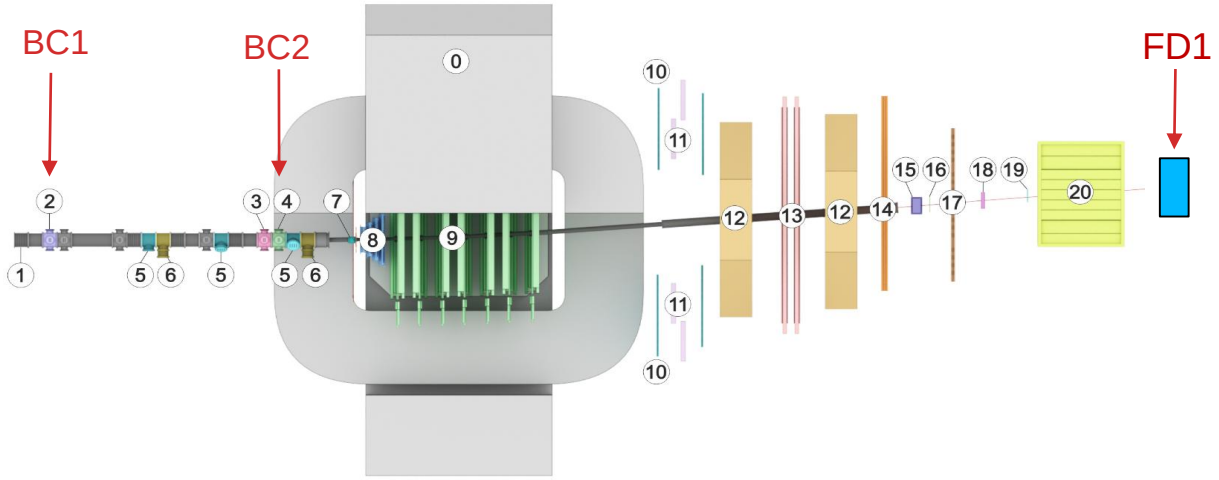
*spill duration ~ *2.2 s*

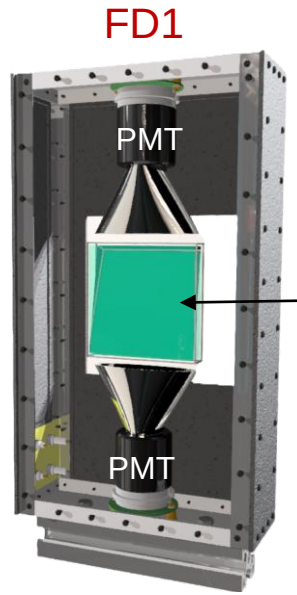
Offline amplitude resolution

Detector	Before corrections σ (%)	After corrections σ (%)
BC1	**5.4**	**4.8**
BC2	**8.0**	**7.1**

Corrections:
1. Top Amp versus Bottom Amplitude
2. TQDC 8ns binning

Time resolution of BC1, BC2





Measured with additional FD1 counter, placed behind the FHCal hole.
FD1 is similar to BC1 in design - has exactly the same PMTs and scintillator.

$$\Delta t_{ij} = t_i - t_j$$

$$\sigma_{ij}^2 = \sigma_i^2 + \sigma_j^2$$

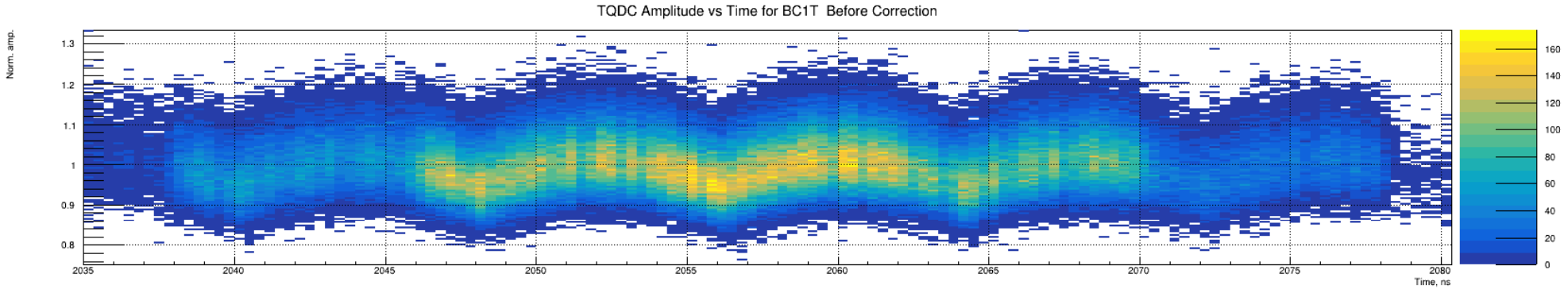
i,j: BC1, BC2, FD1

Detectors	σij, ps
BC1 - BC2	57
BC1 - FD1	61
BC2 - FD1	58
(BC1&BC2) - FD1	52

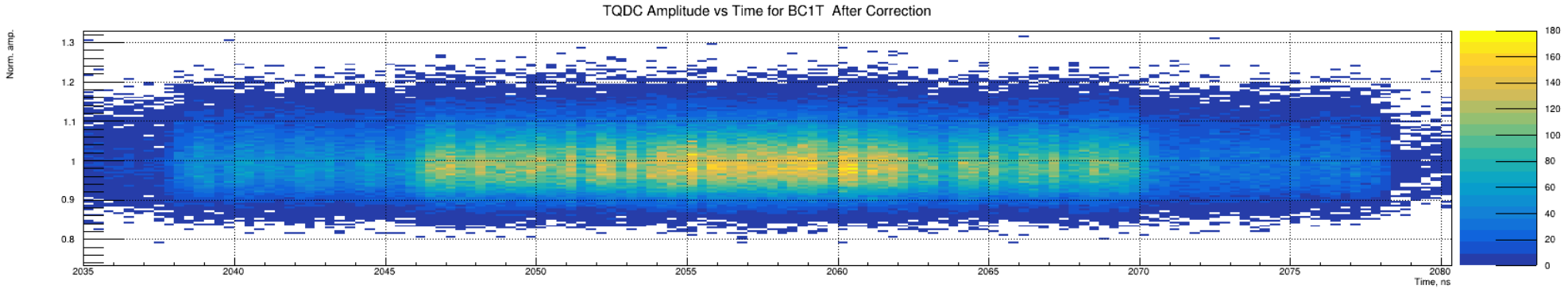
Detectors	σi, ps
BC1	**43**
BC2	**38**
FD1	**44**
(BC1&BC2)	**28.2**
	28.5

TQDC “8ns binning” correction for BC1 Top amplitude

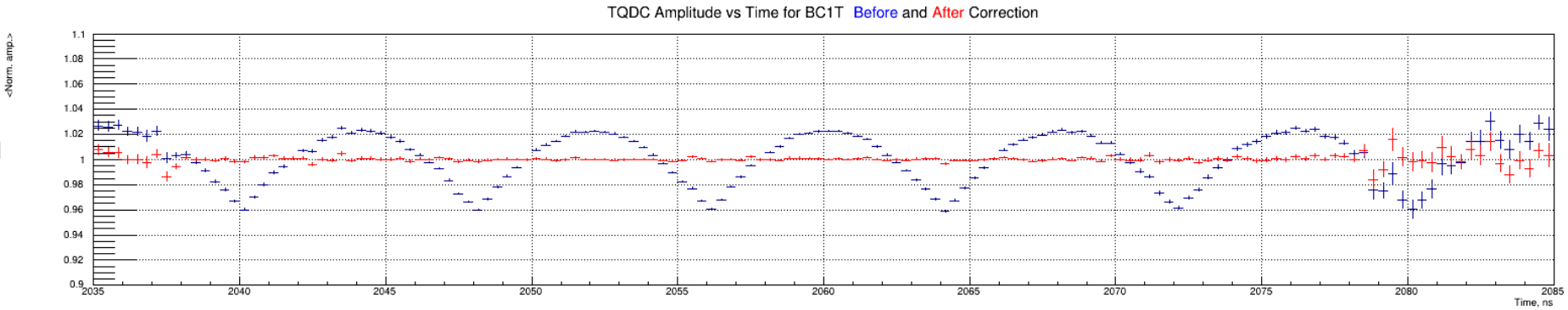
Uncorrected amplitude



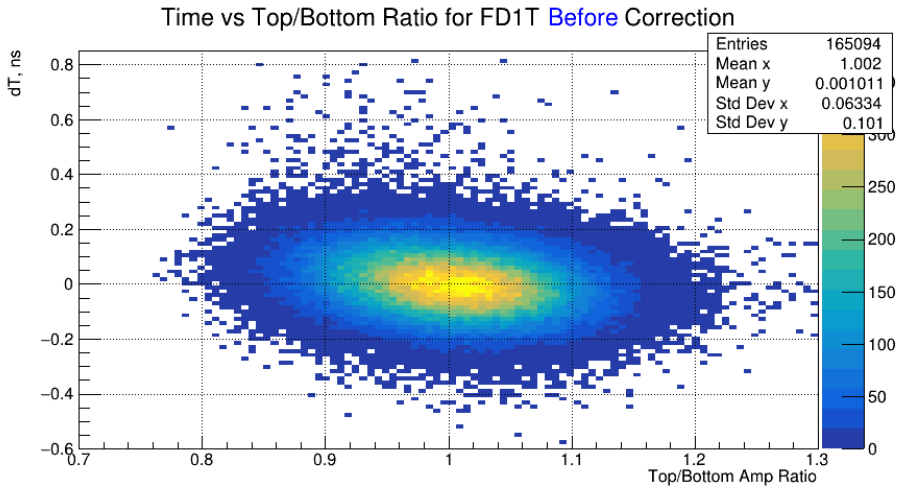
Corrected amplitude

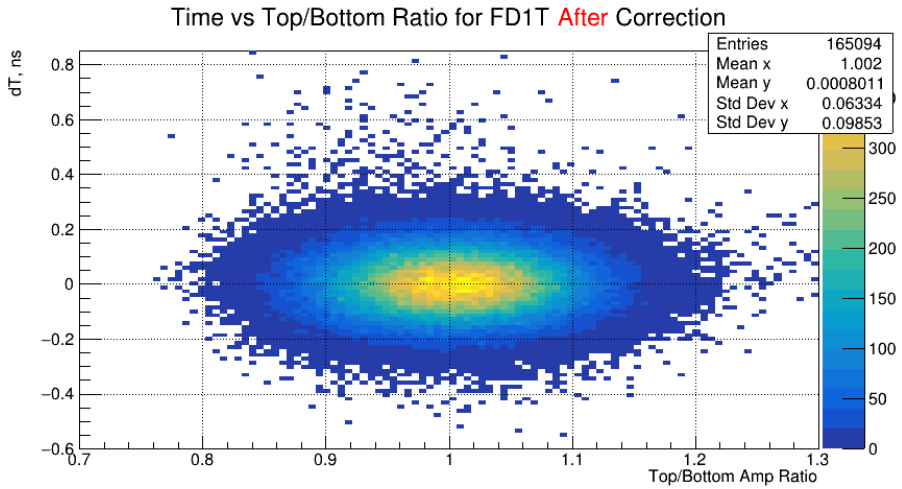


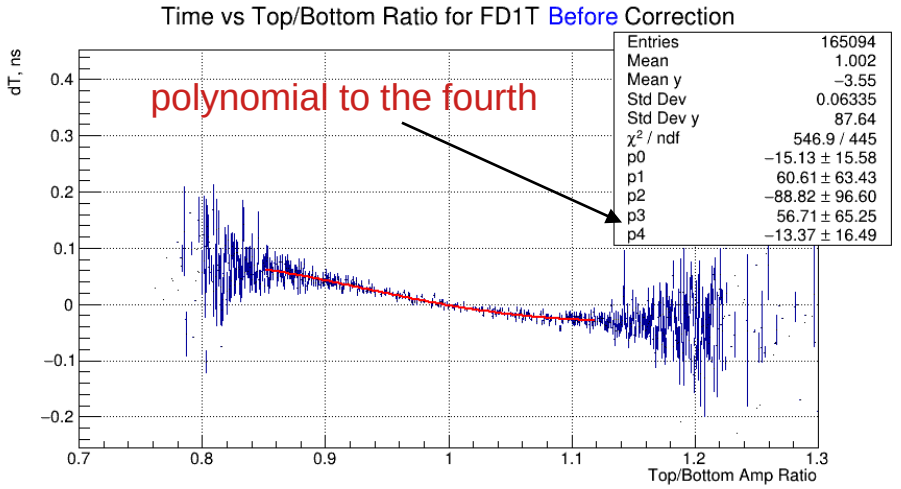
How the correction works

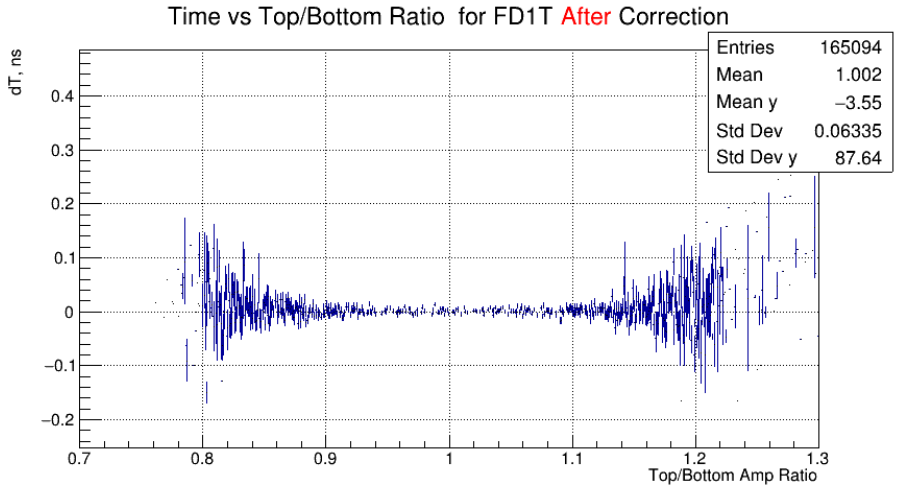


Top/Bottom correction for time resolution analysis

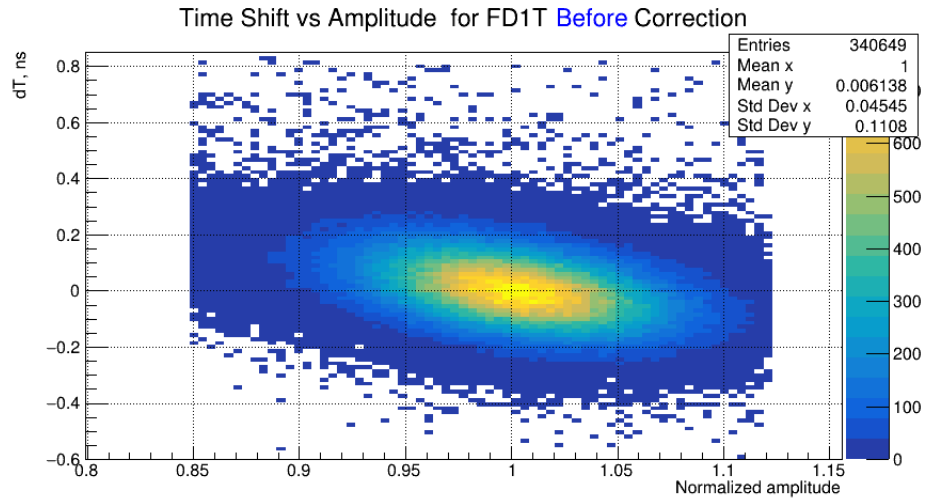


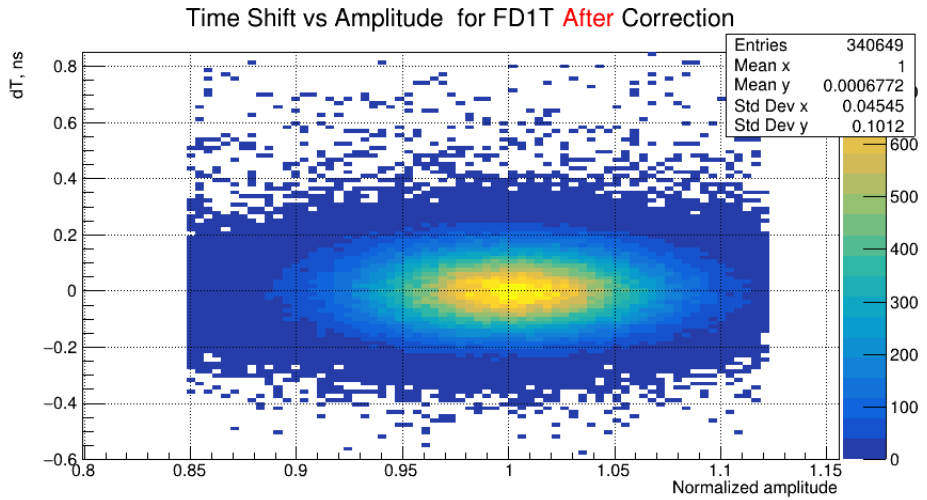


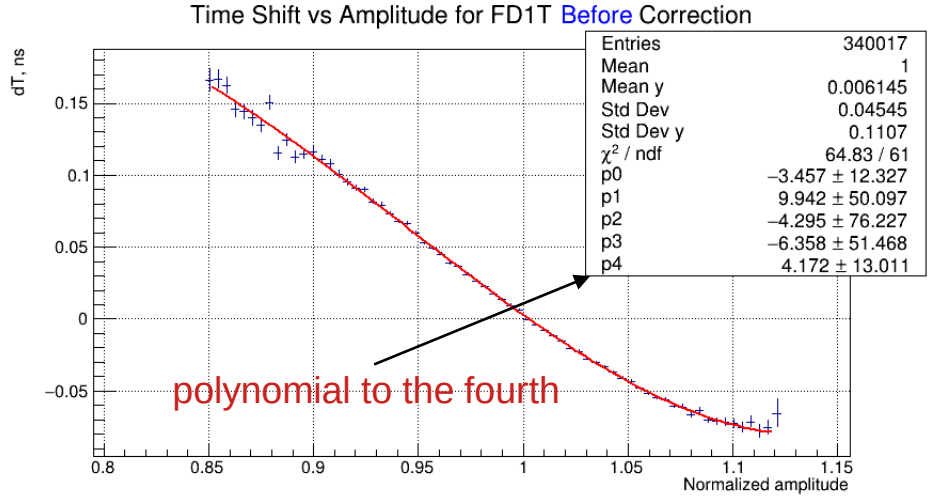


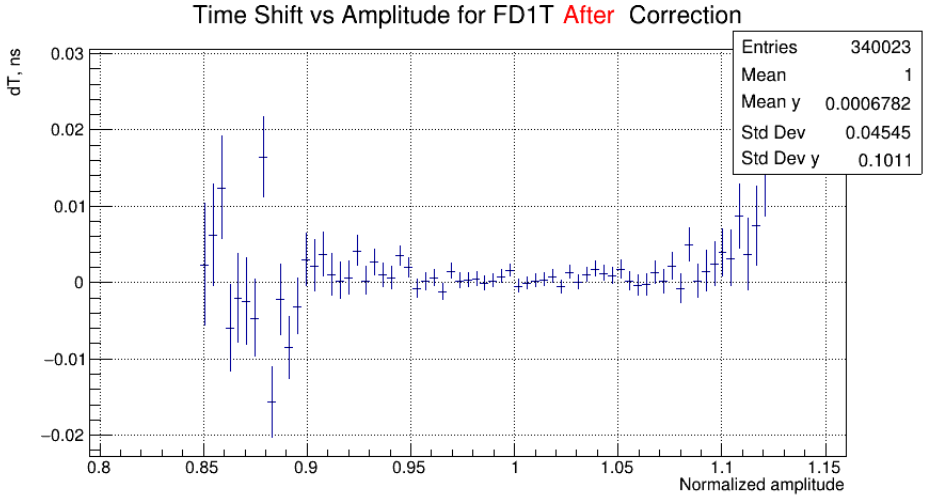


Before and after time-walk correction for FD1 Top amplitude





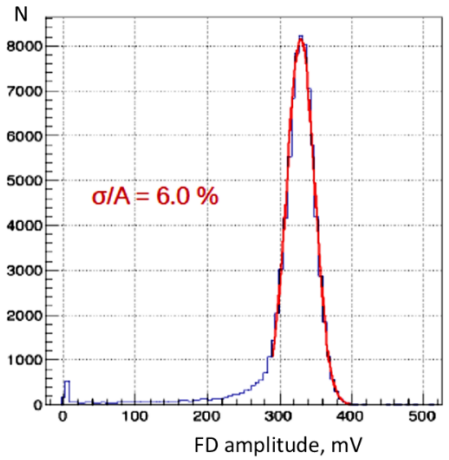




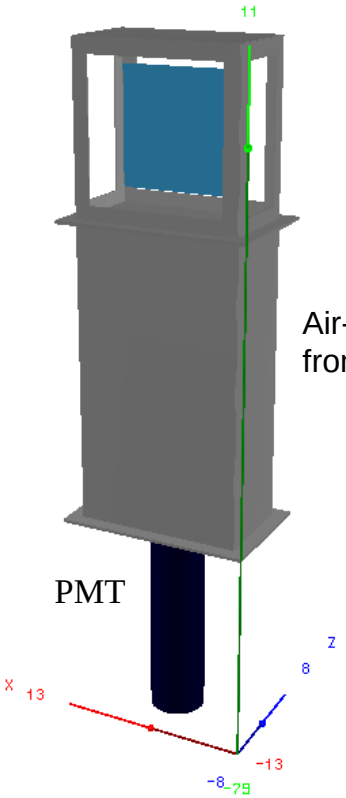
FD design and response

PMT	Radiator	σ/A (%)
XP2020	Scint. 0.5 mm	6.0
XP2020/Q	Quartz 1 mm	11.7
R2490-07	Scint. 0.5 mm	5.3

Significantly better resolution with scintillator radiator.
Less than expected photoelectron statistics with quartz radiator.

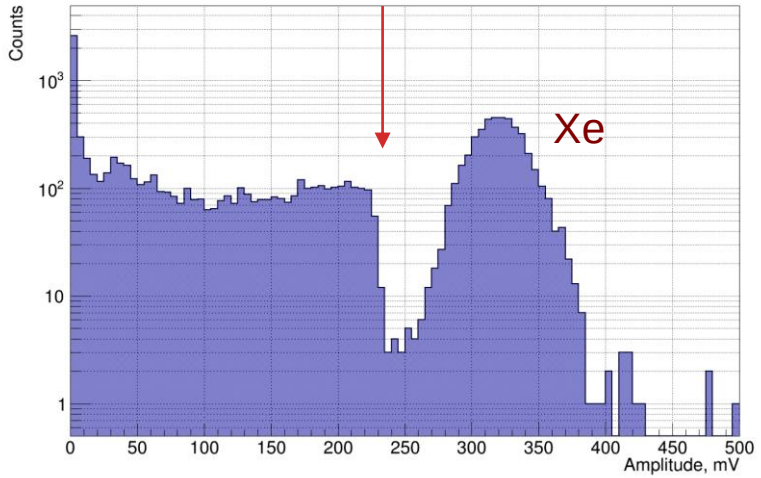


Radiator
150 x 150 mm^2

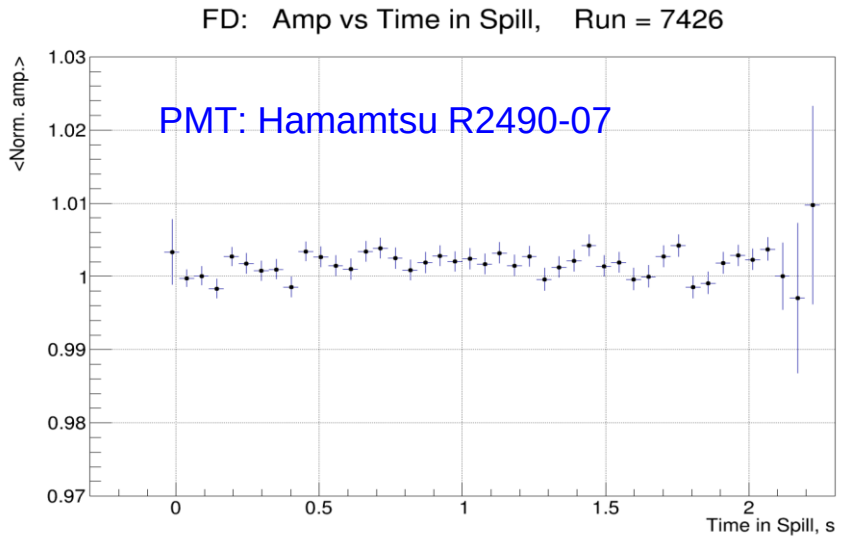


Air-lightguide
from Al-mylar

Threshold in FD

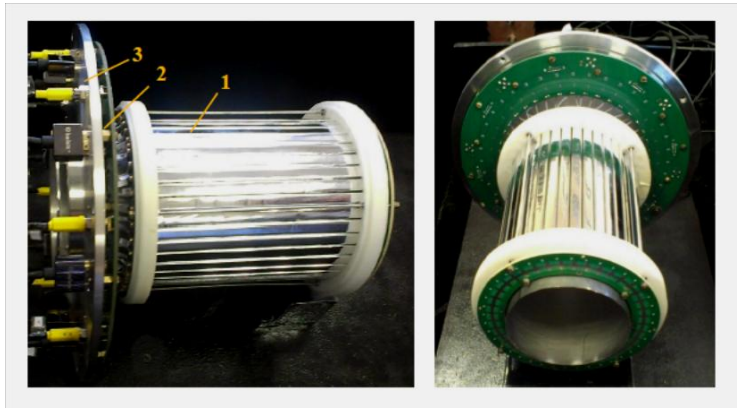


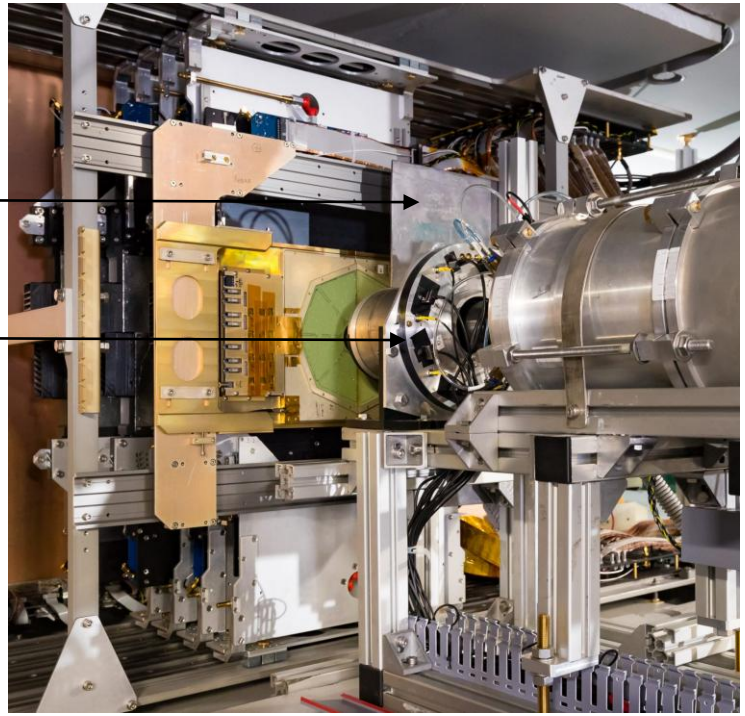
~65-70% centrality was selected by the threshold in FD



Barrel detector as multiplicity counter

Target is located inside the BD





Barrel Detector (BD):
1 – 40 scintillation strips, 150 x 7 x 7 mm, BC418
2 – the board with SiPMs, Sensl C-series, 6 x 6 mm
3 – the board of front-end electronics.

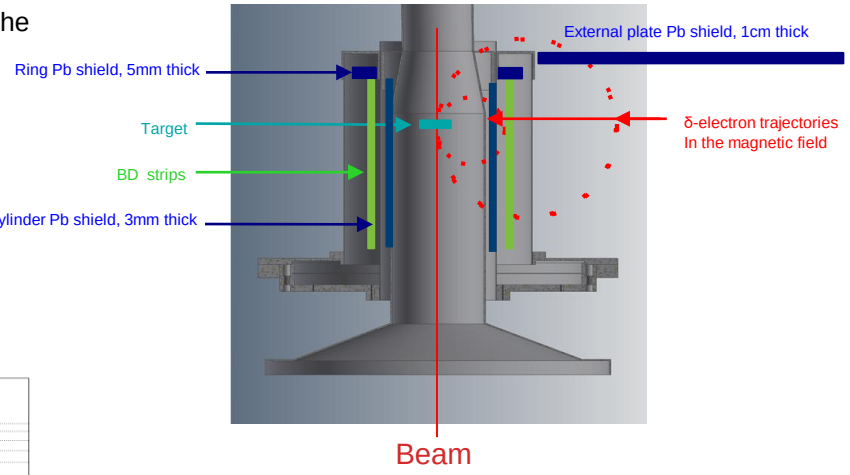
Readout:
signals from every channel in BD are digitized by multihit TDC providing time and time-over-threshold width

Settings in Xe 2023 run:

CCT1 = BT * BD(≥4)

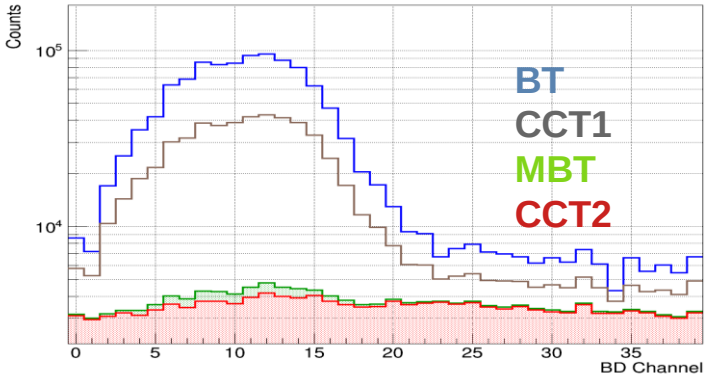
Main physics trigger - CCT2 = MBT * BD(≥4)

Strong background hits from δ – electrons, curved in the magnetic field and hitting right side of the BD.

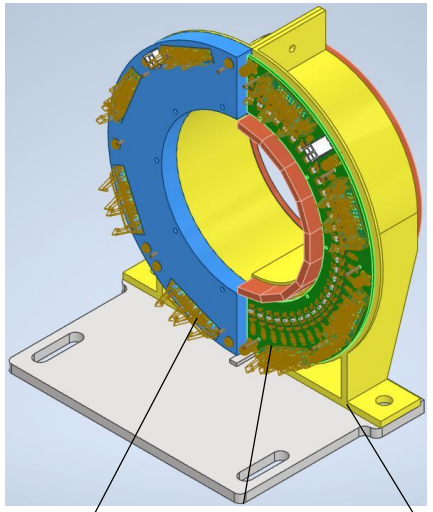


Target section of carbon vacuum pipe and BD

Distribution of hits in BD strips for different triggers



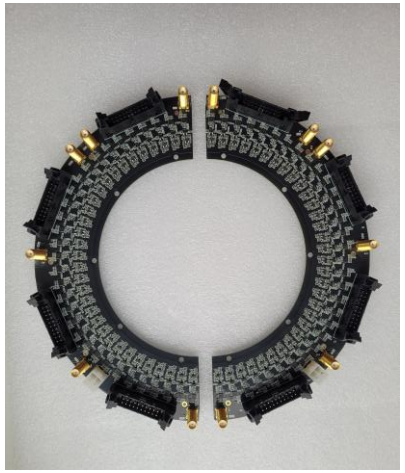
New Barrel Detector

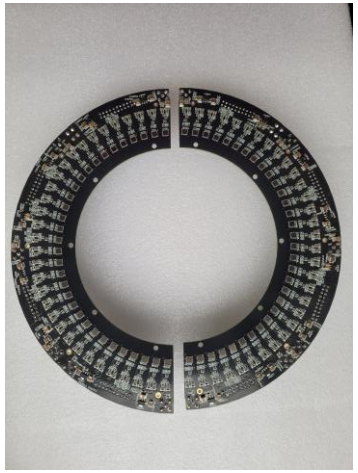




Upgrades for future runs with heavier beam ions (Bi)

- Larger number of channels - 64 scintillation strips 57×7×5 mm^3
- Readout by 3×3 mm^2 SiPMs (J-ser. SensL)
- Cu layer inside BD for delta-electron absorption
- Shorter strips, easier to protect and position
- Larger inner diameter
- Consists of two parts (left /right) for simple installation


FEE PCB connectors side


FEE PCB SiPM side

Mechanics:completed, assembled

FEE : completed, currently been tested

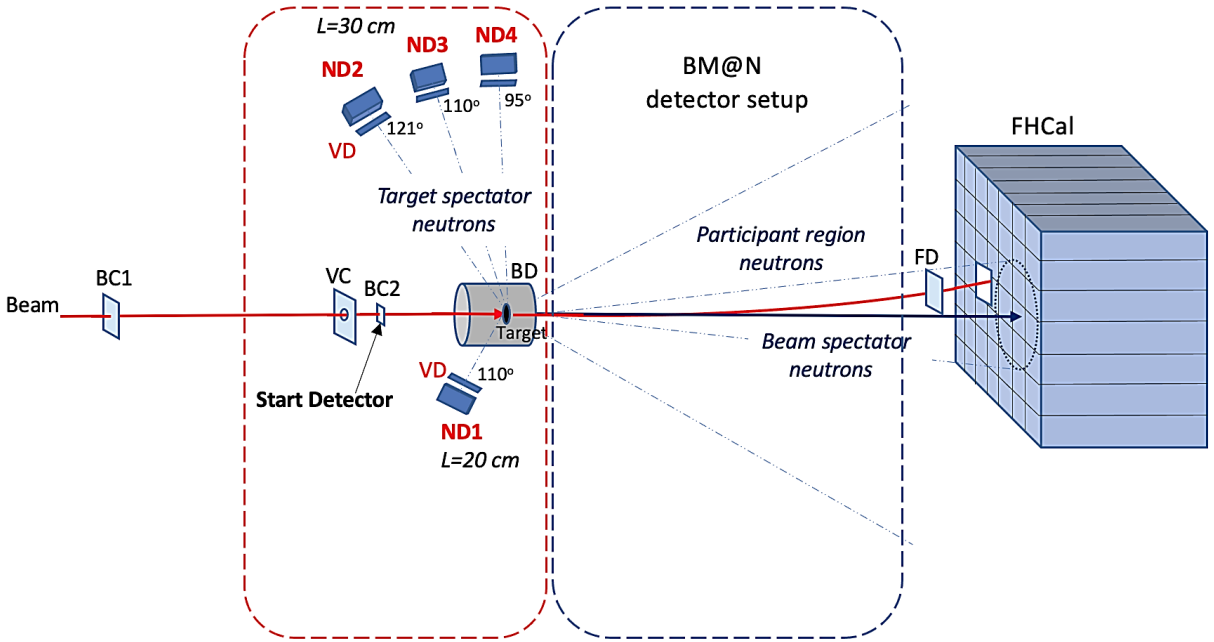
Multiplicity logic module: components available, about half a year needed for production

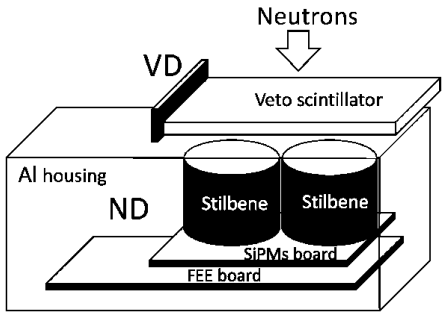
Scintillators, SiPMs : available

Simulation: done

The compact TOF Neutron Spectrometer 2023

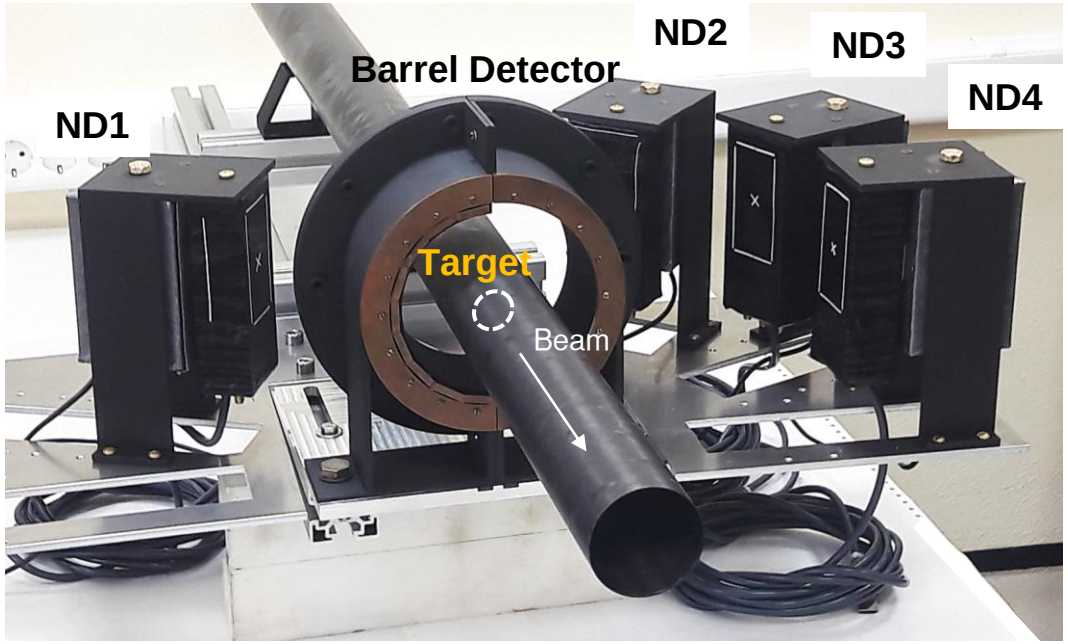
We have succeeded in creating a compact time-of-flight spectrometer (table scale) covering a wide range of neutron energies from 1 to 200 MeV.





Neutron Detectors

Detector	θ (deg.)	L (cm)	Stilbene (mm)
ND1	**110°**	**20**	**D30×10**
ND2	**121°**	**30**	**D25.4×25.4**
ND3	**110°**	**30**	**D25.4×25.4**
ND4	**95°**	**30**	**D25.4×25.4**



Mechanics: completed, assembled
(*V. Tikhomirov, V. Azorskiy, A. Timoshenko)*

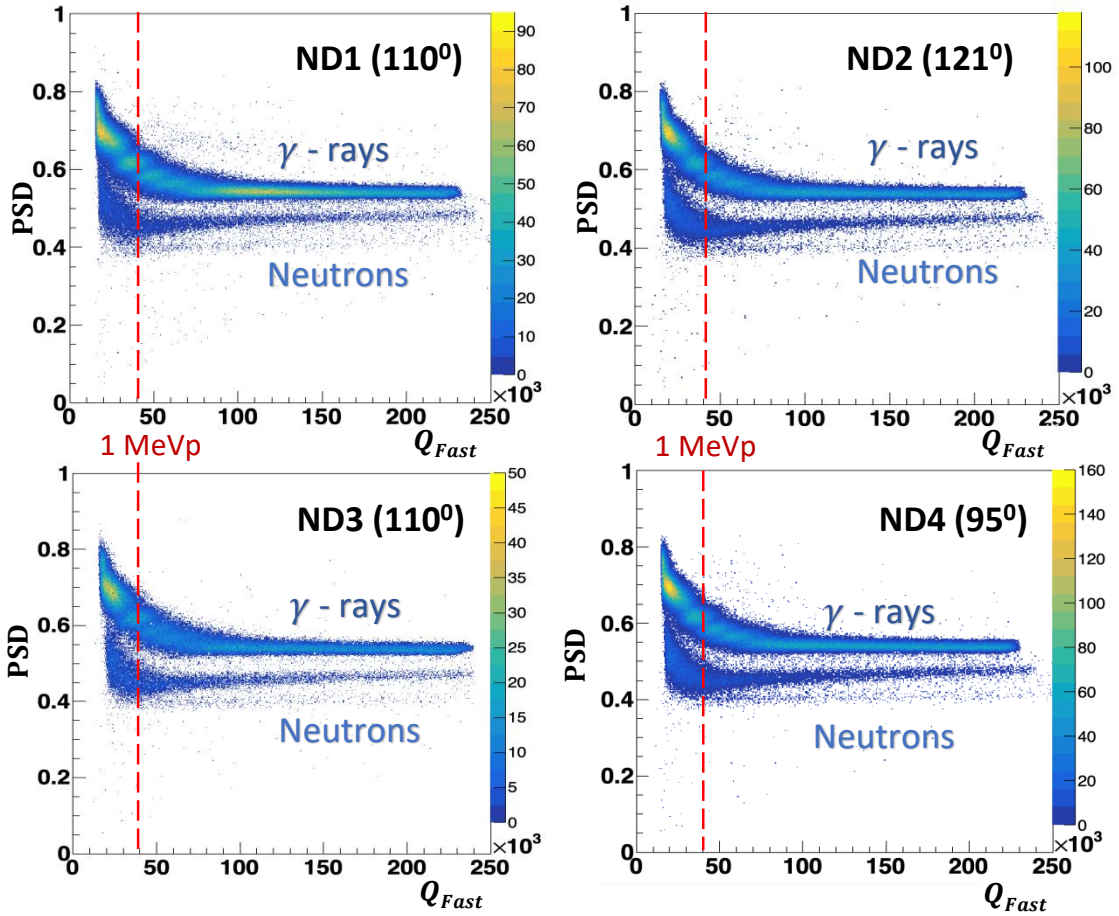
FEE : done (*V. Rogov*)

Simulation: done (*N.Lashmanov*)

Analysis of the data: (*N.Lashmanov*)

Neutron emission from target spectators in Xe + CsI collisions at 3.8 A GeV was studied via double-differential neutron production cross sections.

Pulse shape n/γ- discrimination



BC2 – Start detector (T0)
Scintillator: BC-400B, 34×34×0.15 mm^3
PMT: XPM85112/A1 (Photonis), 2 units
Time resolution: **σ_t = 40 ps**

The time resolution of ~119 ps and good gamma-ray discrimination with the PSD method are main features of the spectrometer.

	ND1	ND2	ND3	ND4
σ_t (ps)	128	114	118	110

2023 Run Summary and Outlook

During the 2023 run with ^{124}Xe beams at 3.8 A GeV and intensities up to 10^6 ions per spill the trigger system was successfully operated, demonstrating reliable performance:

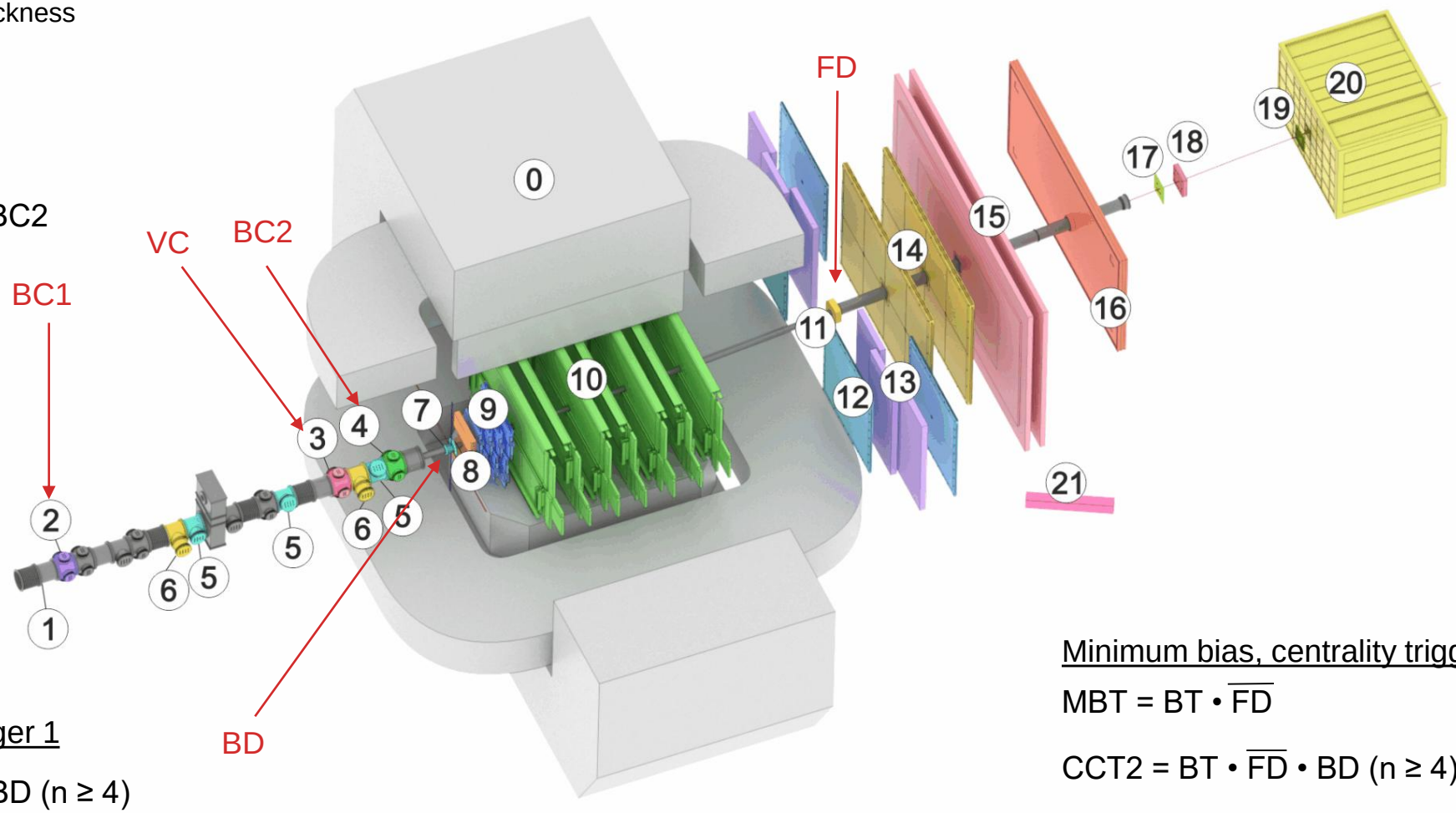
- Amplitude resolution of the BC1, BC2 and FD (~5-7 %) met the requirements for the event selection at the trigger level and at the later offline event analysis.
- Time resolution of BC1 and BC2 (~40 ps) is sufficient for a precise start time determination in the time-of-flight measurements.
- Some radiation damage of the scintillators is observed in this run.
- A compact, table-scale time-of-flight spectrometer for 1–200 MeV neutrons was successfully developed.

Based on these results, a comprehensive upgrade program was initiated and successfully realized in 2024–2025.

Overview of the trigger detectors and trigger logic in 2026 ^{124}Xe run

Conditions in 2026 Xe run, 1.8 - *3.0 A GeV* :
spill duration ~ *3 - 5 s*
beam intensity ~ $4 \cdot 10^5$ 1/s,
2% and 1% target thickness

New location of BC2 and the Fragment Detector



Beam trigger

$BT = BC1 \bullet \overline{VC} \bullet BC2$

Centrality trigger 1

$CCT1 = BT \bullet BD\ (n \geq 4)$

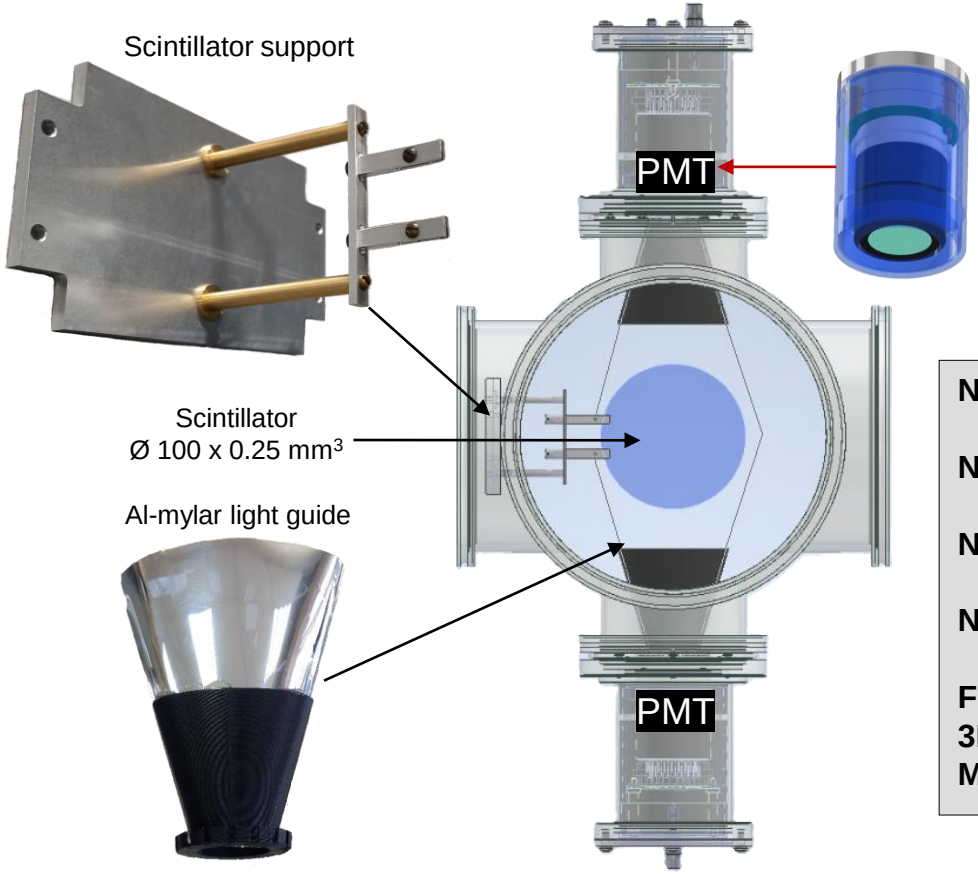
Minimum bias, centrality trigger 2

$MBT = BT \bullet \overline{FD}$

$CCT2 = BT \bullet \overline{FD} \bullet BD\ (n \geq 4)$

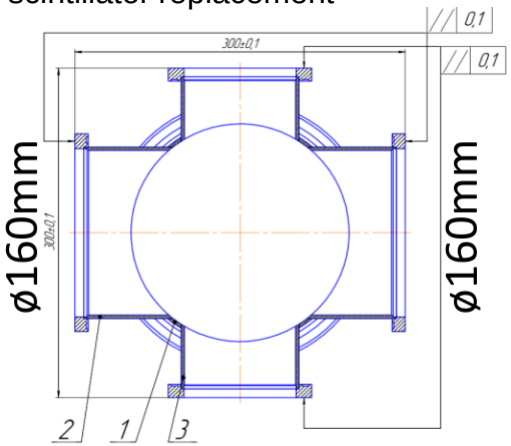
Upgrade of the beam counters

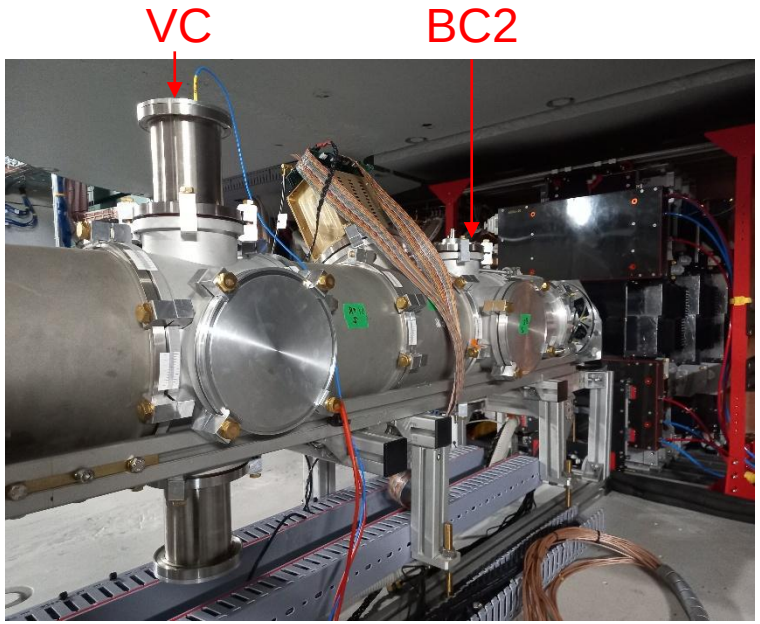
Detector	PMT (mesh dynodes)	Radiator
BC0, BC1	Hamamatsu R2490-07	Scint. BC400B Ø 100 x 0.25 mm^3
VC	Hamamatsu R2490-07	Scint. Ø 100 x 0.25 mm^3 Ø 25 mm hole



New vacuum boxes

- wider side tubes which will facilitate scintillator replacement





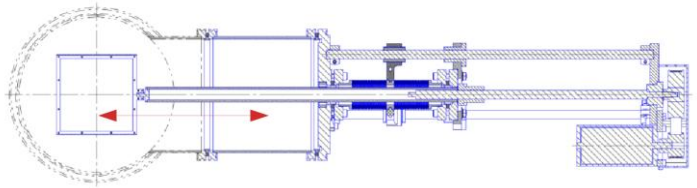
New counter BC0

New vacuum boxes for BC0, BC1, VC, BC2

New scintillator mounts for BC0, BC1, VC, BC2

New scintillators

FEE : done
3D printed parts: done
Mylar light guides: done



BC0

New detector added at the entrance of the BM@N
Scintillator can be moved in and out of the beam
Will be used for beam tuning
Not used in the physics triggers

Upgrade of BC2 (T0)

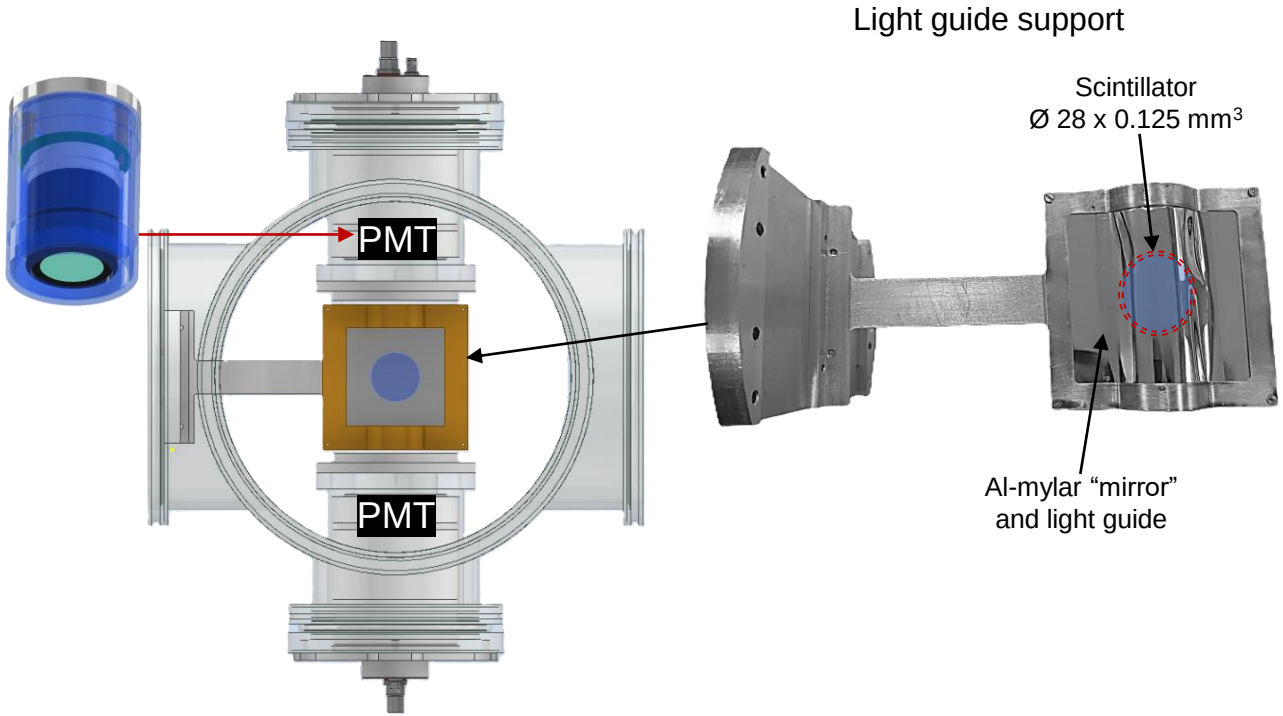
Long negative tail in BC2 pulses in 2023 run complicates analysis of pile-up events.

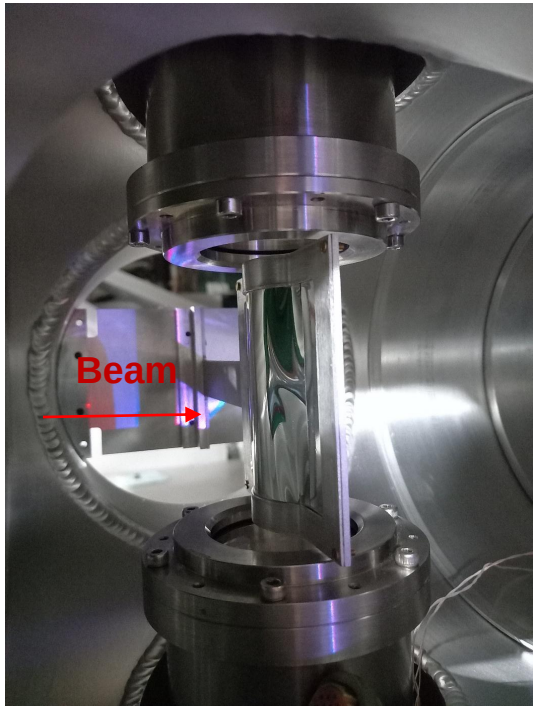
Detector	PMT (mesh dynodes)	Radiator
BC2	Hamamatsu R2490-07	Scint. BC400B Ø 28 x 0.125 mm^3

New parts for BC2

- PMTs change to R2490-07 (BC1 type)
- Support and light guide have a new design, providing less material in the beam path and easy installation







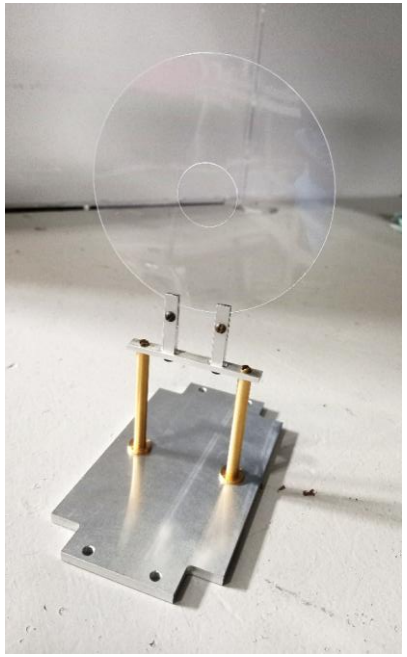
Measurements with a laser

The laser was used to measure points on the surfaces, and the data were saved in the software for comparison and evaluation.





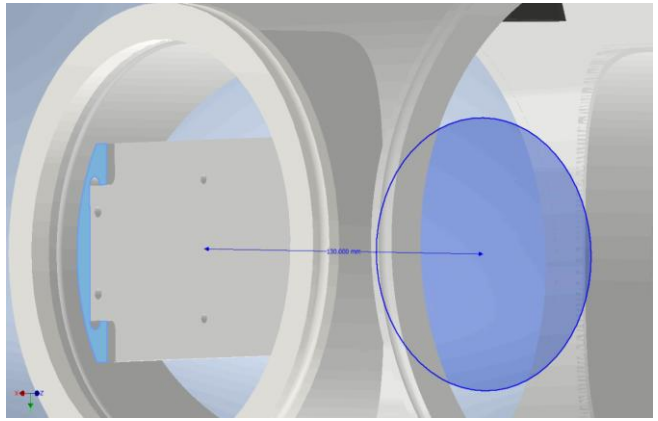
Measurements were taken on the scintillator supports to determine the positions of the scintillators relative to the beam axis and the vacuum chambers.

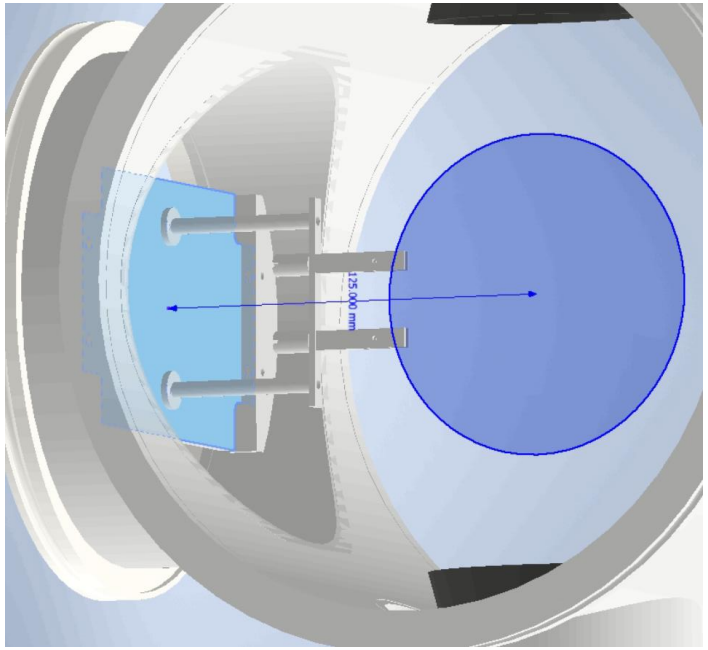


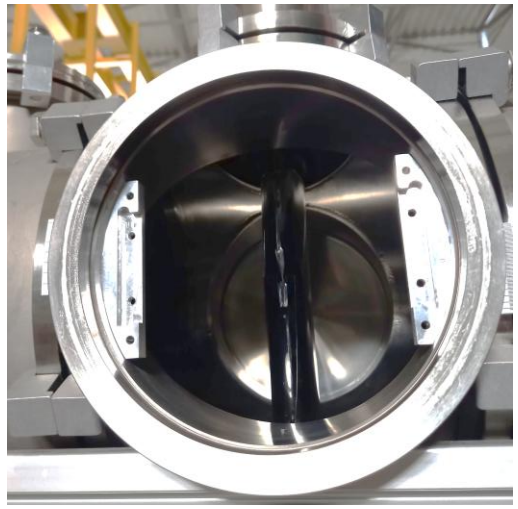
Sergey Novozhilov and Sergey Sivtsov performed the laser measurements.

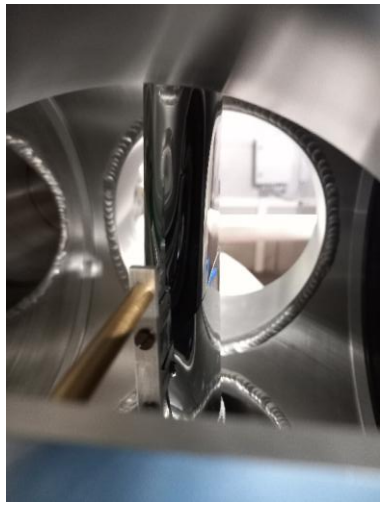
BC1 scintillator mount

In BC1, the scintillator support in the vacuum chamber (glued parts) has no inclination along the Y axis.



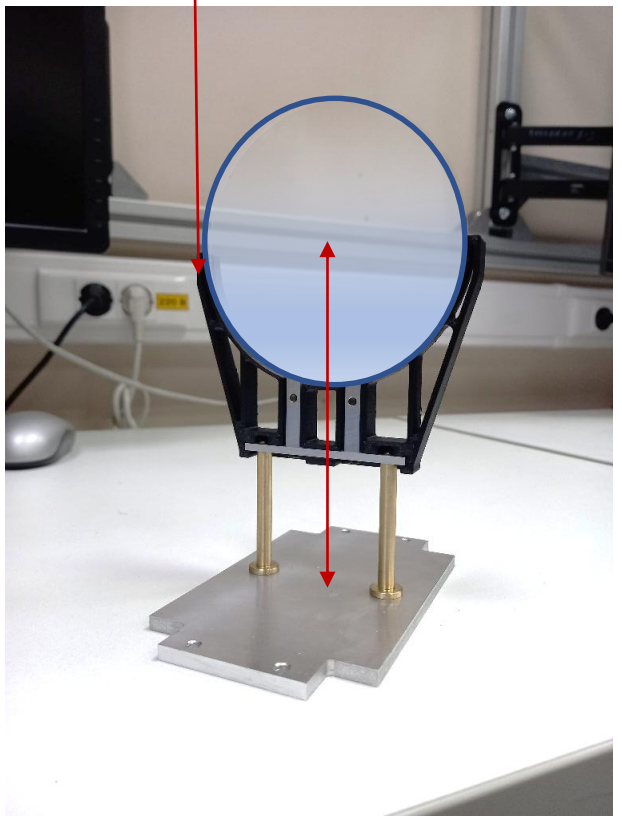








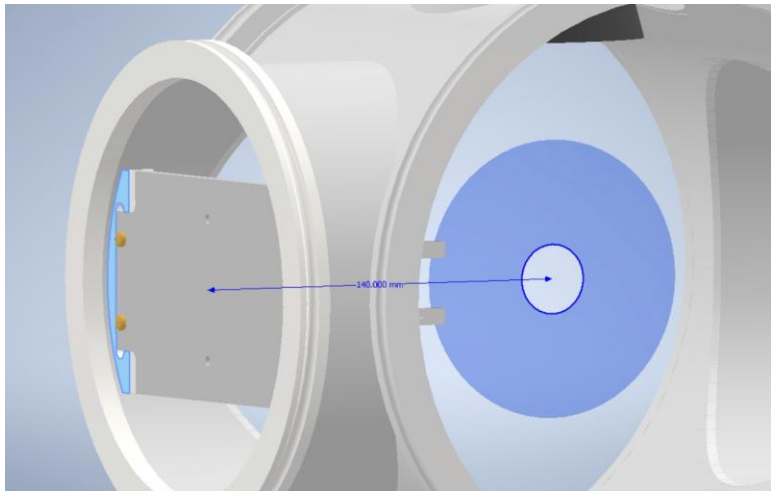
Scintillator Positioning Jig



In BC1, the displacement relative to the beam axis is 0.5 mm (+0.5 mm in X).

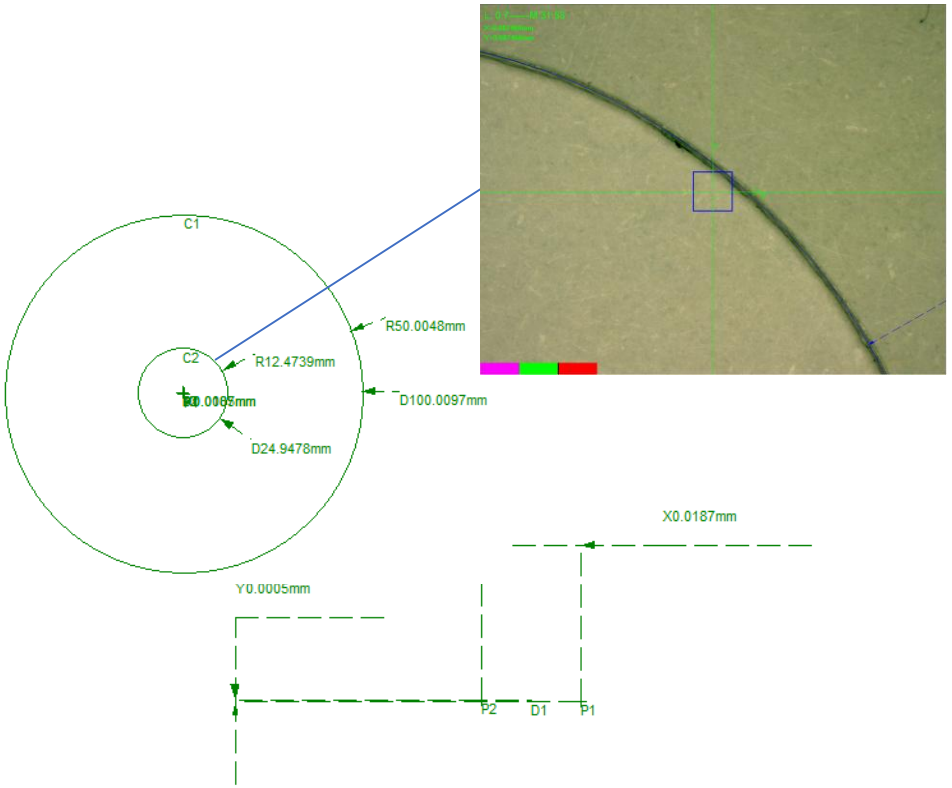
VC scintillator mount

In VC, the scintillator support in the vacuum chamber (glued parts) is inclined by 0.141° toward the Y axis.



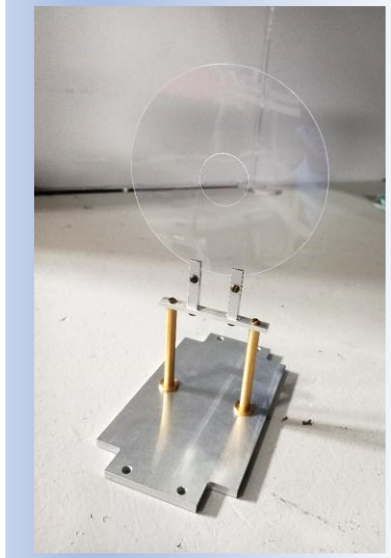
Microscope measurements were performed by Oleg Tarasov.

Microscope measurements were performed to determine the scintillator and hole dimensions.



Difference between the scintillator and hole centers

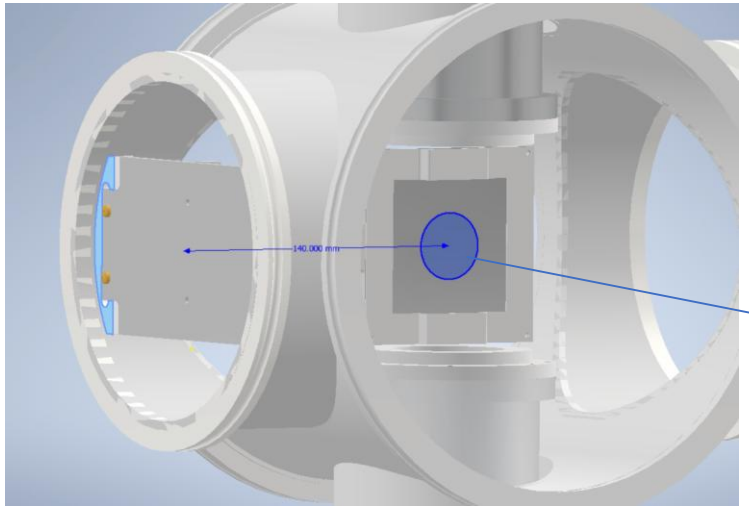
Cutting of the scintillators was performed by Vitaly Azorskiy.

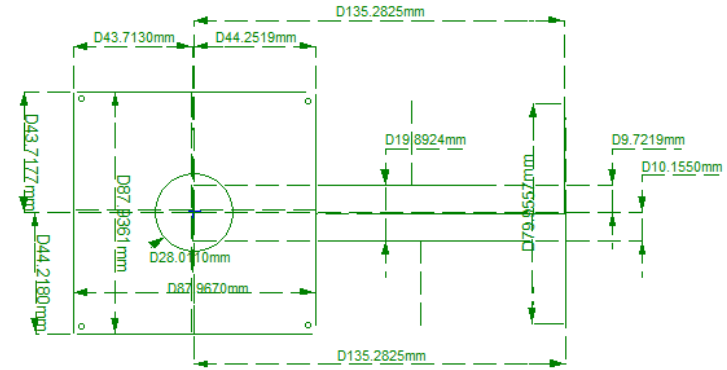


In VC, the displacement relative to the beam axis is 0.01 mm (+0.01 mm in X).

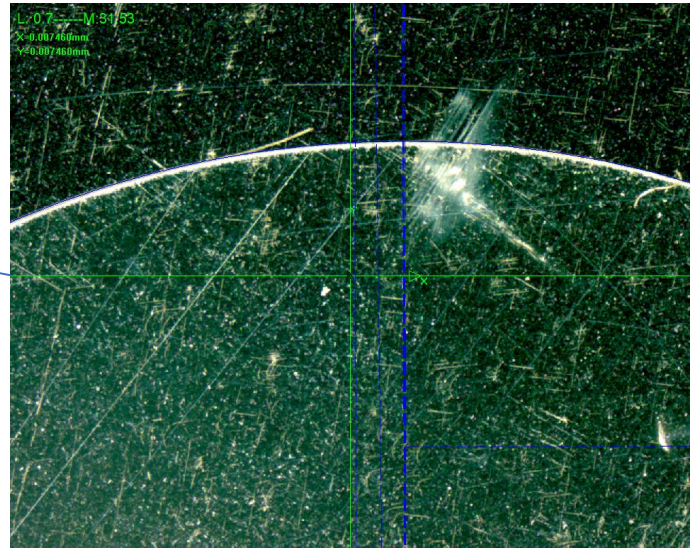
BC2 scintillator mount and light guide

In BC2, the scintillator support in the vacuum chamber (glued parts) is inclined by 0.044° toward the Y axis.

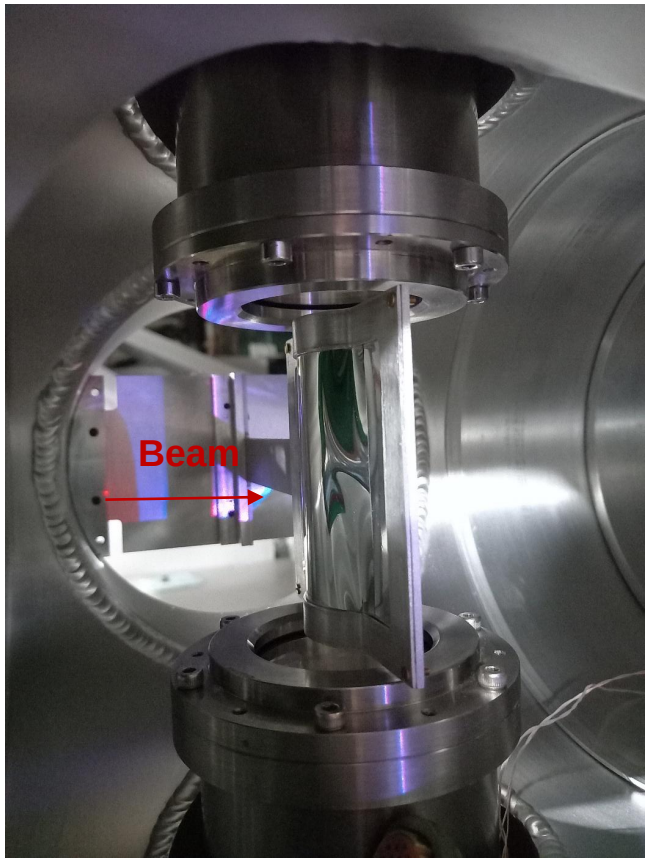




Microscope measurements were performed to determine the position of the scintillator and the dimensions of the frame.



Microscope measurements were performed by Oleg Tarasov.

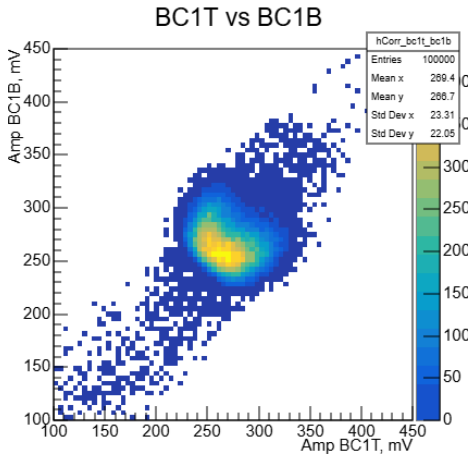


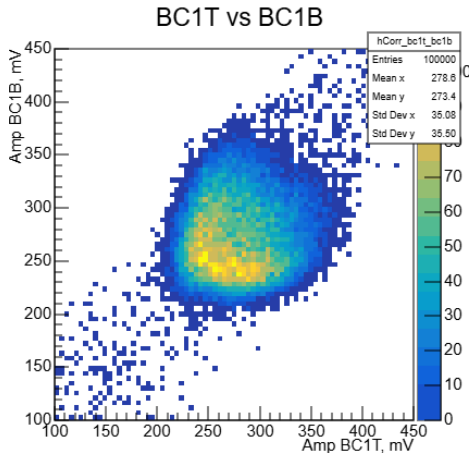
In BC2, the displacement relative to the beam axis is 0.13 mm (+0.13 mm in X).

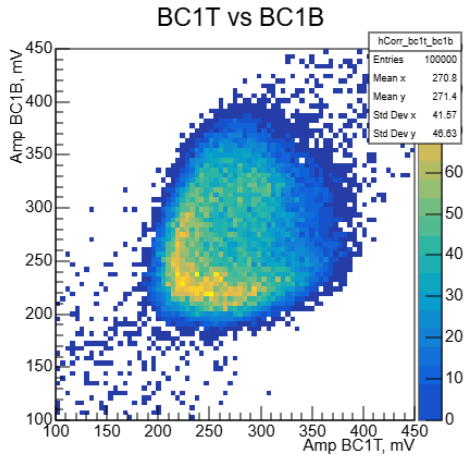
Radiation Effects and Amplitude Resolution

14.02.2026 | **16.02.2026** | **19.02.2026**

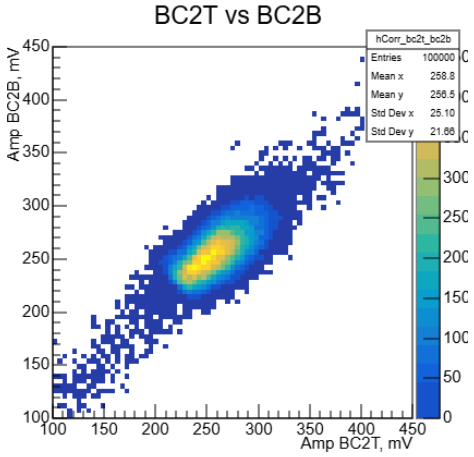
BC1 →

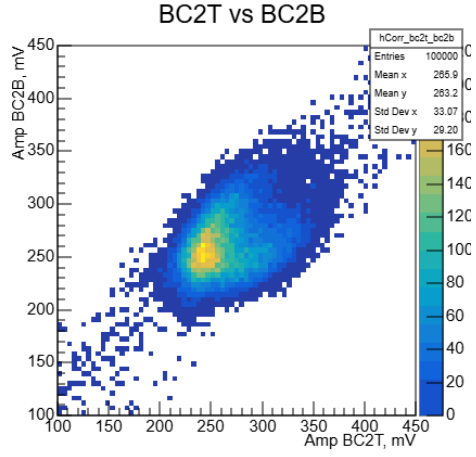


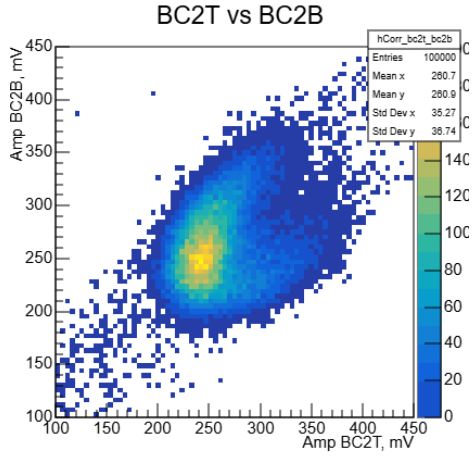




BC2 →







RMS Difference from 14.02.26 to 19.02.26

Detector	RMS(%) 14.02.26	RMS(%) 19.02.26
BC1 Top	**8.6**	**15.3**
BC1 Bottom	**8.3**	**17.2**
BC2 Top	**9.7**	**13.5**
BC2 Bottom	**8.4**	**14.1**

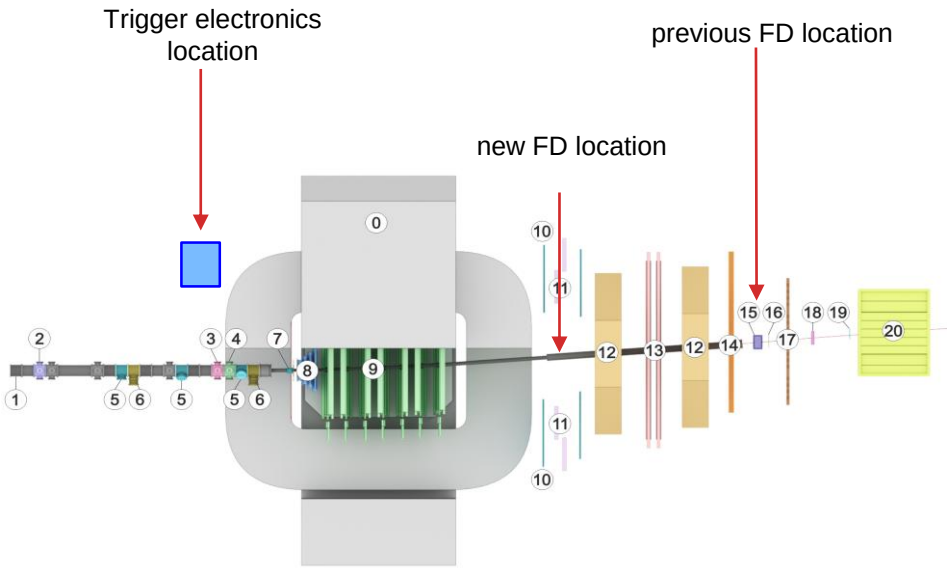
Offline amplitude resolution

Detector	σ (%)
BC0	5.1
BC1	3.9
BC2	5.8

Some signal degradation is observed, resulting in increased RMS values for BC1 Sum, BC2 Sum, and individual signals.

New Fragment Detector

Detector	PMT (mesh dynodes)	Radiator
FD	Hamamatsu R2490-07	Scint. BC400B Ø 70 x 0.25 mm^3



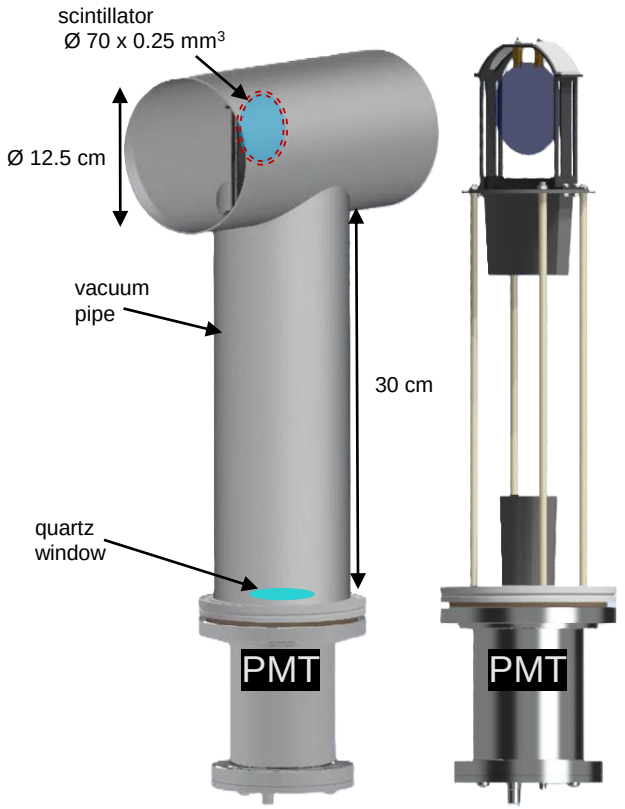


Photo of FD installed in the beamline



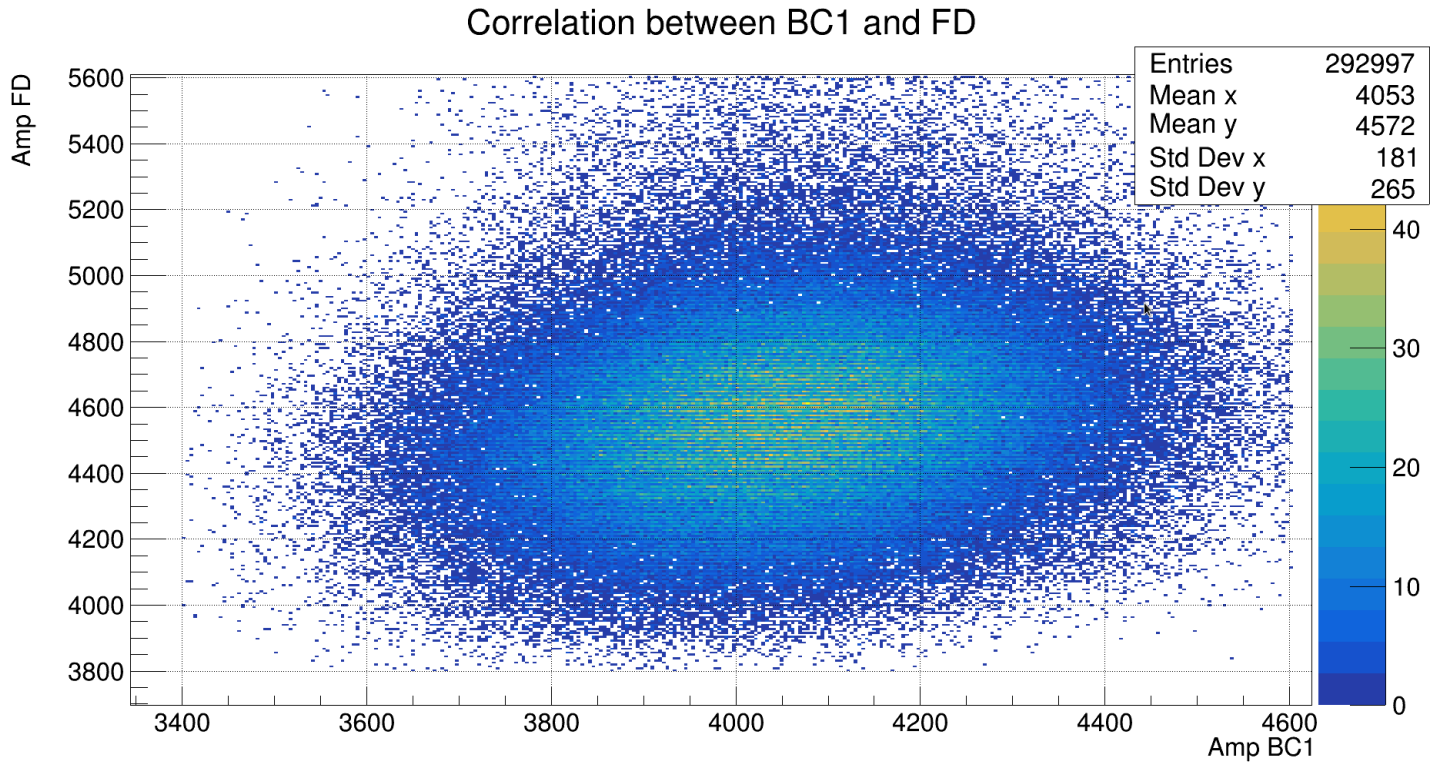
1. FD radiator in vacuum, i.e. min. material between target and FD
2. Shorter distance between target and FD, shorter cable between FD and trigger electronics
3. Rejection of close pile-up in the T0U

The 2026 data show a non-linear correlation between BC1 and FD due to the FD threshold settings.

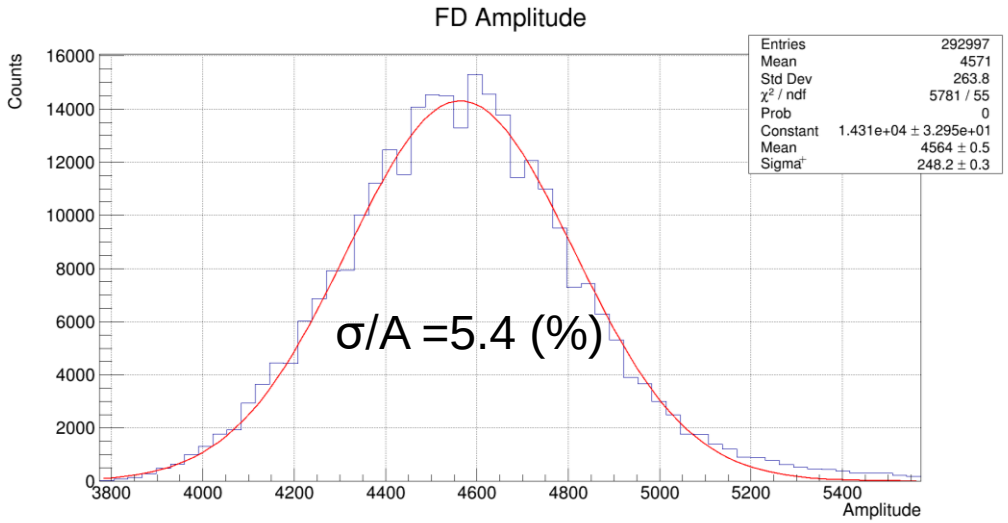
- FD/BC1 ratio: 0.93 (low threshold), 0.89 (high threshold)

FD_Low/BC1	0.93904
FD_High/BC1	0.89459

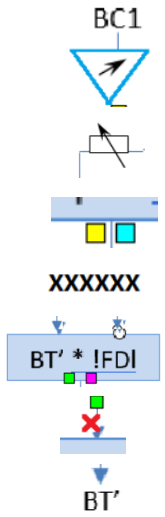
BC1 – FD Amplitude Correlation (NIT Events, AR Trigger Mask)



Offline amplitude resolution



BM@N trigger manager



Input signal

Discriminator threshold settings

Programmable delay lines

Test points (oscilloscope)

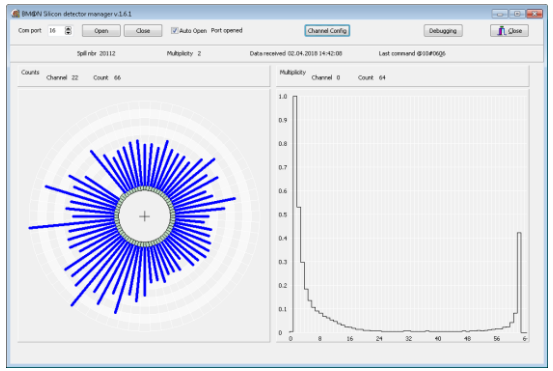
Counters

Logic function

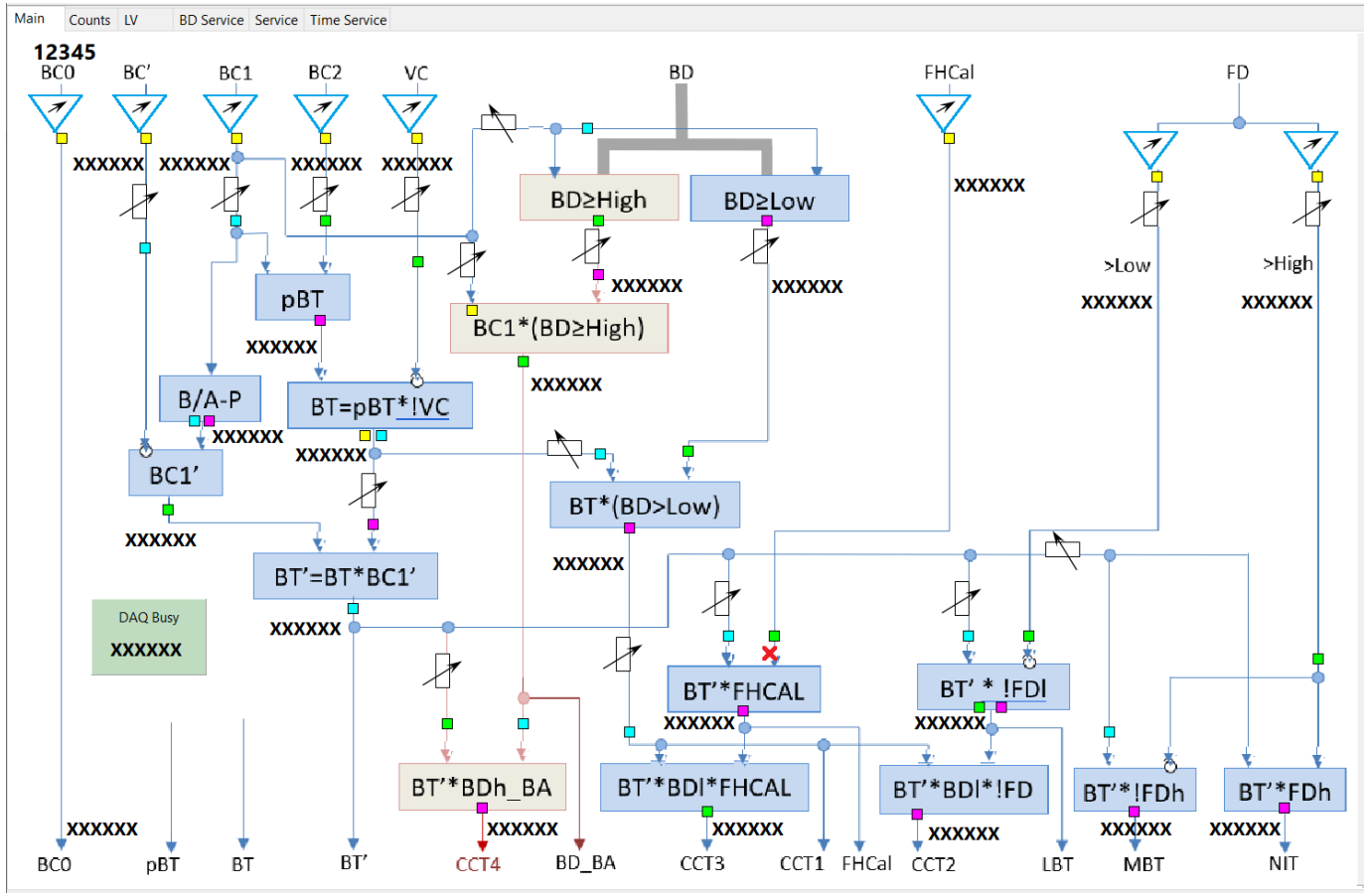
Signal excluded from the logic function

Output signals – triggers

Threshold setting and BD monitoring



Interactive Trigger Logic Scheme



The software was developed by S. Sergeev.

BM@N TRG MGR

Beam
Feb.2026

♥ Spill nbr. 0000125334 23.02.2026 00:15:08

Detectors

BC1	1673542
BC2	1624052
VC	39977
BC' (BC1 high)	79933
NBD≥Low	159406
NBD≥High	165800
FD Low	1571515
FD High	1497137
FHCAL	289362
BC0	0

Internal signals

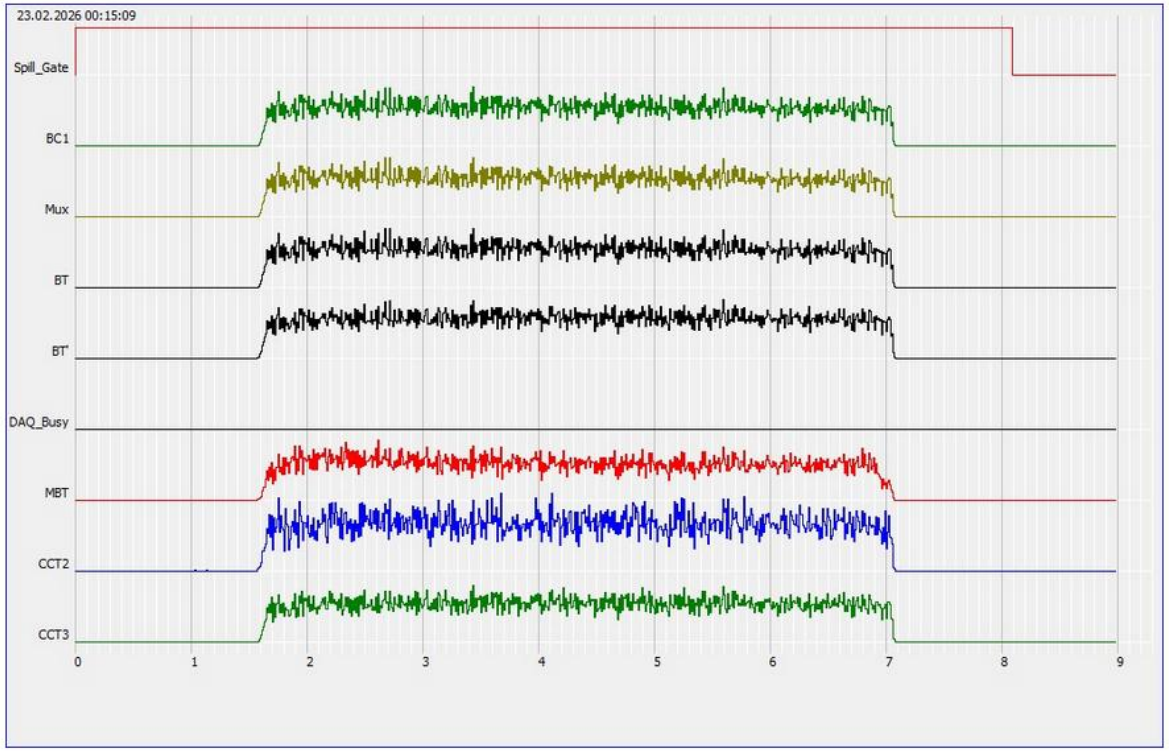
CCT1	137972
BD_BA	1501013
DAQ_Busy	0
PBT	1627859

Triggers

BT	1618102
BT'	1395001
MBT	100527
NIT	1294740
LBT	33224
CCT2	21904
CCT3	186416
CCT4	118865

Ratios

BC2/BC1	0.97043
VC/BC1	0.02389
BC'/BC1	0.04776
NBD≥Low/BC1	0.09525
NBD≥High/BC1	0.09907
FD_Low/BC1	0.93904
FD_High/BC1	0.89459
FHCAL/BC1	0.17290
BT/BC1	0.96687
BT'/BT	0.86212
MBT/BT'	0.07206
NIT/BT'	0.92813
LBT/BT'	0.02382
CCT1/BT	0.08527
CCT2/BT'	0.01570
CCT3/BT'	0.13363
CCT4/BT'	0.08521

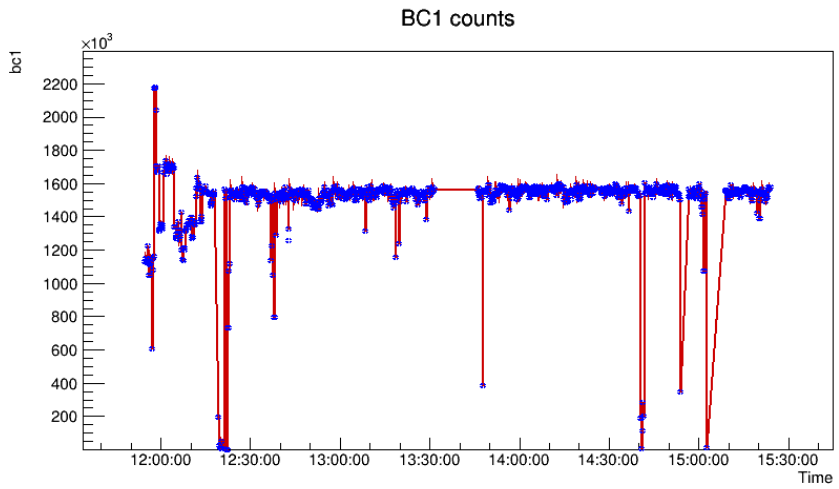


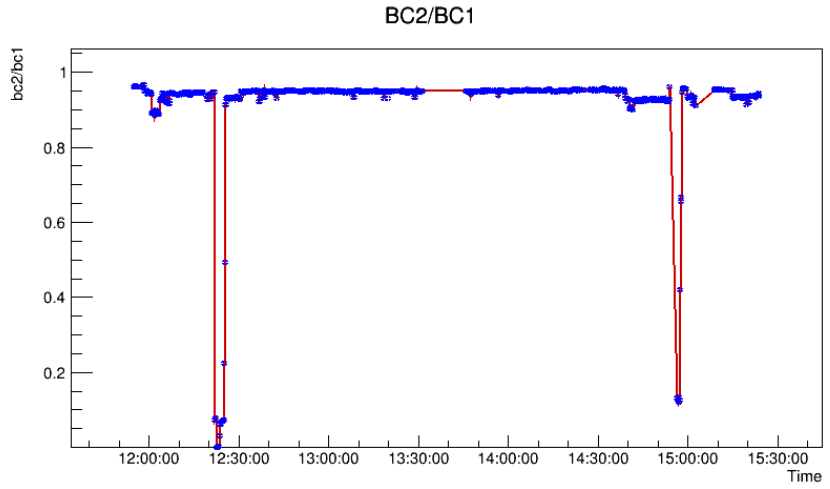
The software was developed by S. Sergeev.

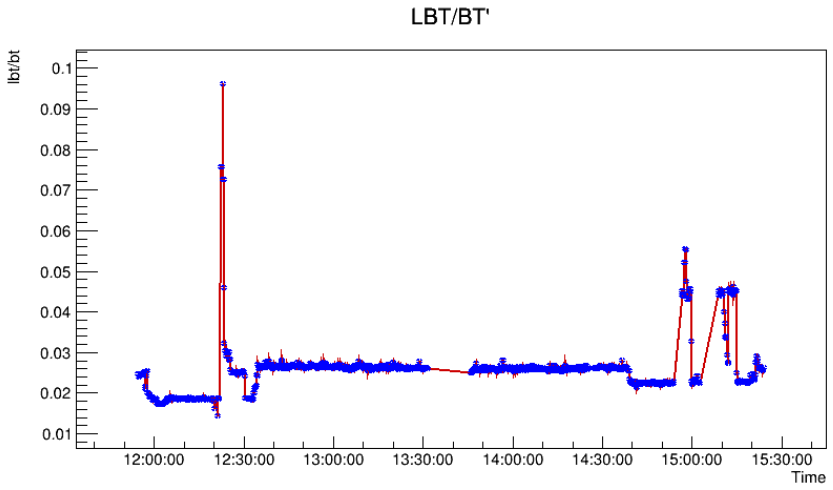
Monitoring of the BM@N trigger manager

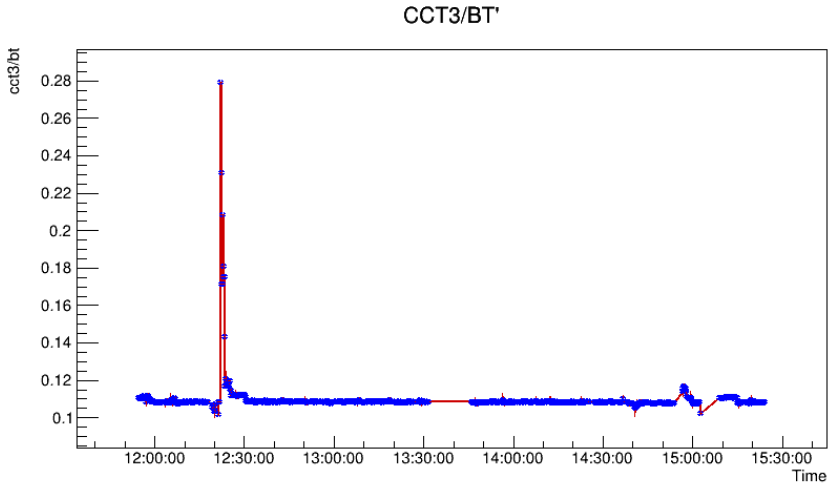
Ratios

BC2/BC1	0.97043
VC/BC1	0.02389
BC'/BC1	0.04776
NBD≥Low/BC1	0.09525
NBD≥High/BC1	0.09907
FD_Low/BC1	0.93904
FD_High/BC1	0.89459
FHCAL/BC1	0.17290
BT/BC1	0.96687
BT'/BT	0.86212
MBT/BT'	0.07206
NIT/BT'	0.92813
LBT/BT'	0.02382
CCT1/BT	0.08527
CCT2/BT'	0.01570
CCT3/BT'	0.13363
CCT4/BT'	0.08521









Macros made by N. Lashmanov

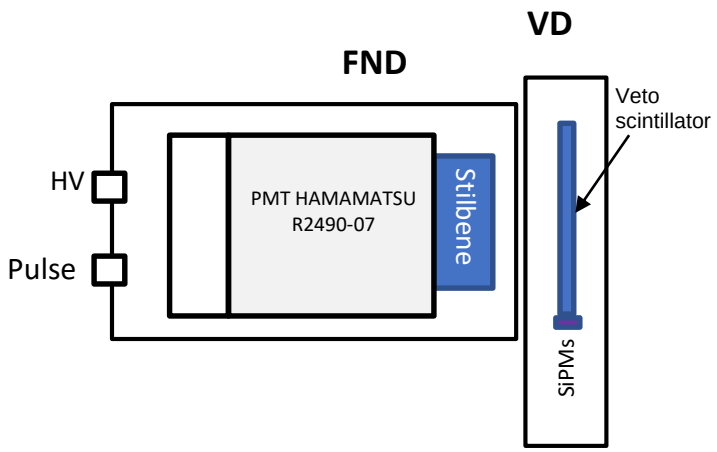
New neutron detectors for measurements at small angles

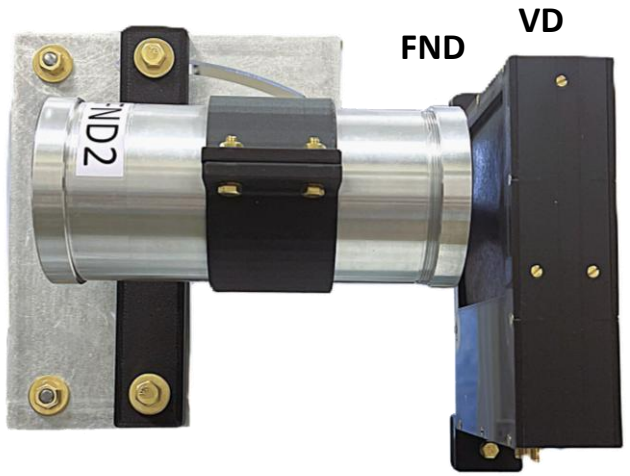
Another aim was developing detectors with stilbene crystals to study neutron energy spectra at small angles via TOF measurements (50–5000 MeV).

Forward Neutron Detectors

Detector	Stilbene
FND1	D31 × 31 mm
FND2	D31 × 31 mm
FND3	D40 × 20 mm
FND4	D40 × 20 mm

Energy range: 50 – 5000 MeV

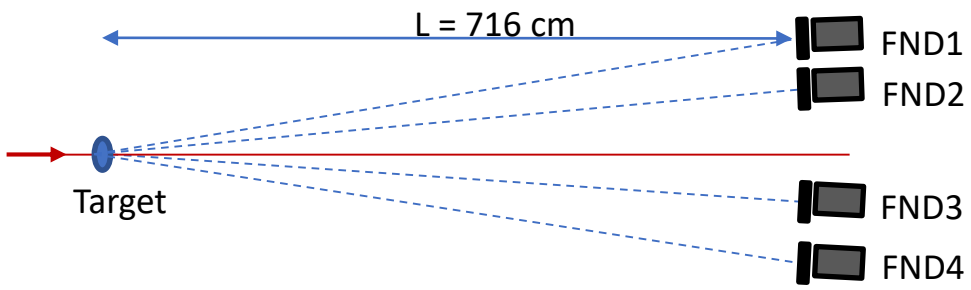




Aim of the measurements

- ✓ Study of neutron emission from beam spectators and comparison with theoretical models and results from the compact TOF spectrometer at large angles
- ✓ To obtain reference data for the HGND project
- ✓ Study of energy and angular distribution of neutrons coming to nZDC

New neutron detectors for measurements at small angles



Detector	Stilbene	XZ Angle Position	YZ Angle Position
FND1	D31 × 31 mm	-1.86°	1.84°
FND2	D31 × 31 mm	-1.85°	-1.94°
FND3	D40 × 20 mm	-1.87°	3.53°
FND4	D40 × 20 mm	-1.85°	-3.54°

XZ tilt: −1.85°; YZ tilt: −3.54° to +3.53°

Photo of FND installed in the BM@N



Design of the detector: completed
(V. Velichkov, *V.Yurevich,* V. Azorskiy)

Radiators mounts and assembly: design completed,
preparation done (V. Velichkov)

Mechanics: done (V. Azorskiy)

FEE : done (V. Rogov)

3D printed parts: done (A. Timoshenko)

Analysis of the data: (*N.Lashmanov*)

Summary and outlook

2021–2022: Laboratory studies

- BC1, BC2 (T0), and Barrel Detector (BD) tested and confirmed ready for BM@N runs

BM@N 2023 Run:

- Amplitude resolution BC1, BC2, FD: ~5–7%
- Time resolution BC1, BC2: ~40 ps
- Some radiation damage observed
- Compact table-scale TOF spectrometer developed (1–200 MeV neutrons)

2024–2025: Upgrade program

- New counter BC0
- New vacuum boxes for the beam counters
- New scintillator supports for the beam counters
- New PMTs for BC2
- New FD with scintillator placed in vacuum
- New neutron detectors for small-angle measurements (50–5000 MeV)

BM@N 2026 Run: Trigger system operated reliably, consistent with 2023 run

Planned activities for 2026

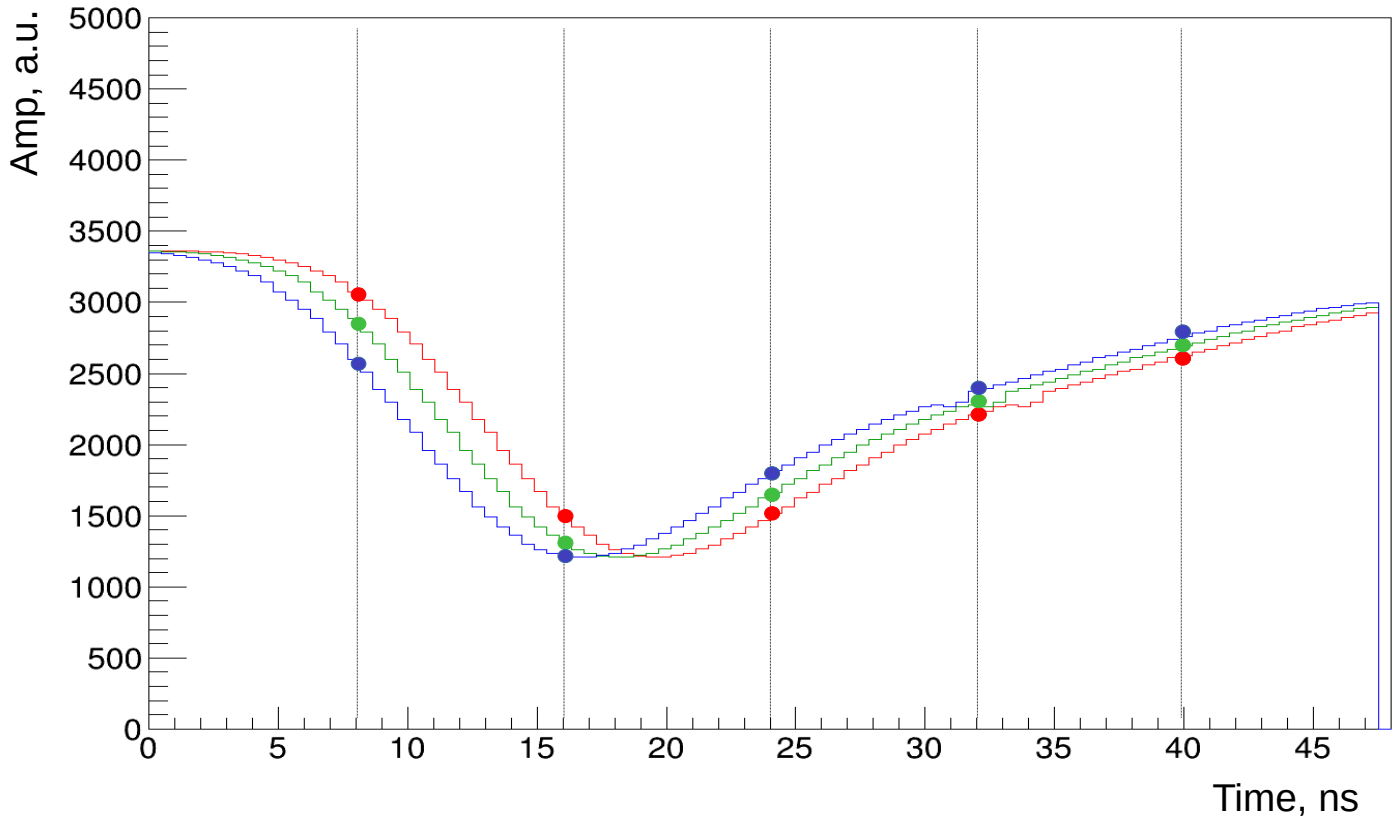
- New Barrel detector
- Data analysis of the latest run
- Tests of quartz radiators for BC1, BC2, FD

Thank you for your attention!

Backup slides

Dependence on the position of the pulse

Red, green and blue – the same pulse, shifted by a few nanoseconds.
- The dots show the values of 8ns samples.



TQDC_Digit → GetPeak() will return different values, depending on the pulse phase with respect to the 8ns binning grid.

Pulse shape n/γ- discrimination

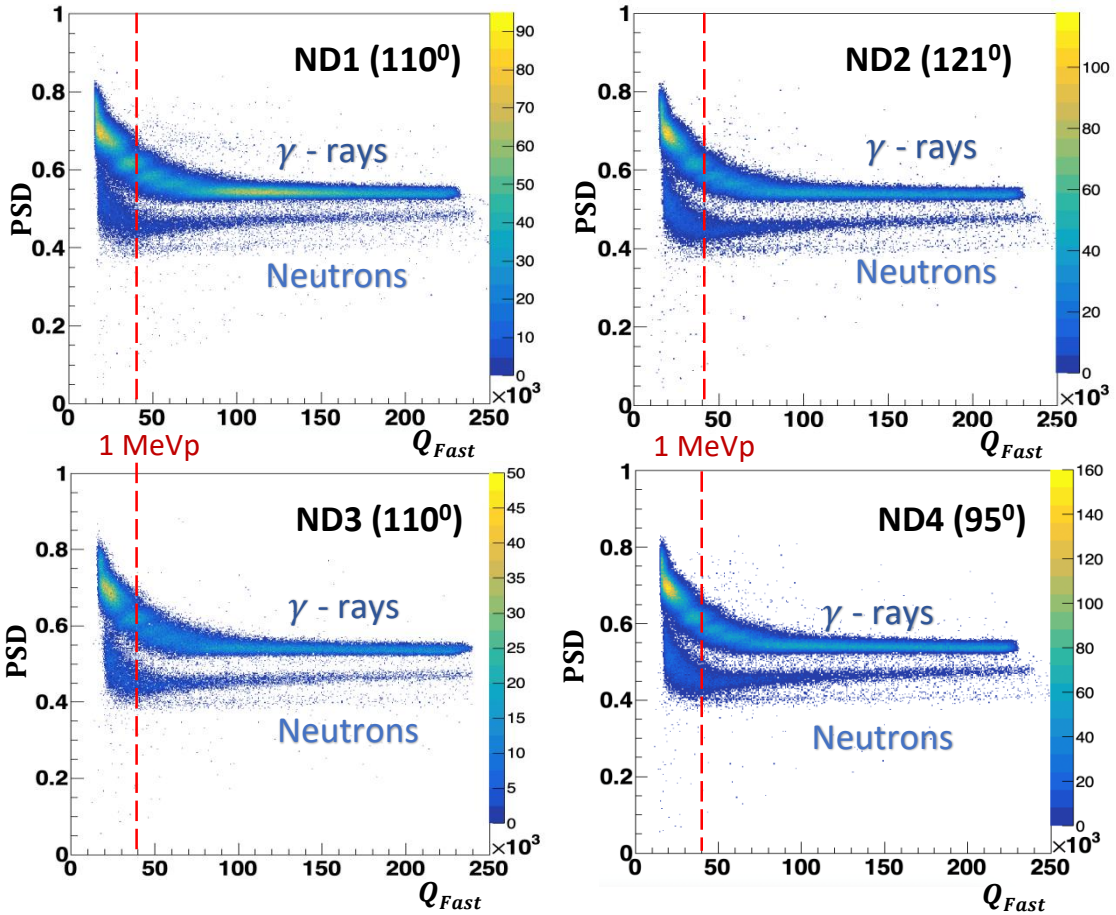
Quality of pulse shape discrimination:

$$PSD = \frac{Q_{fast}}{Q_{total}}$$

T_{fast} = 0.12 μs : time window for charge integration Q_{fast}

T_{total} = 1.5 μs. : time window for charge integration Q_{total}

The integration time intervals are determined by pulse processing in TQDC module



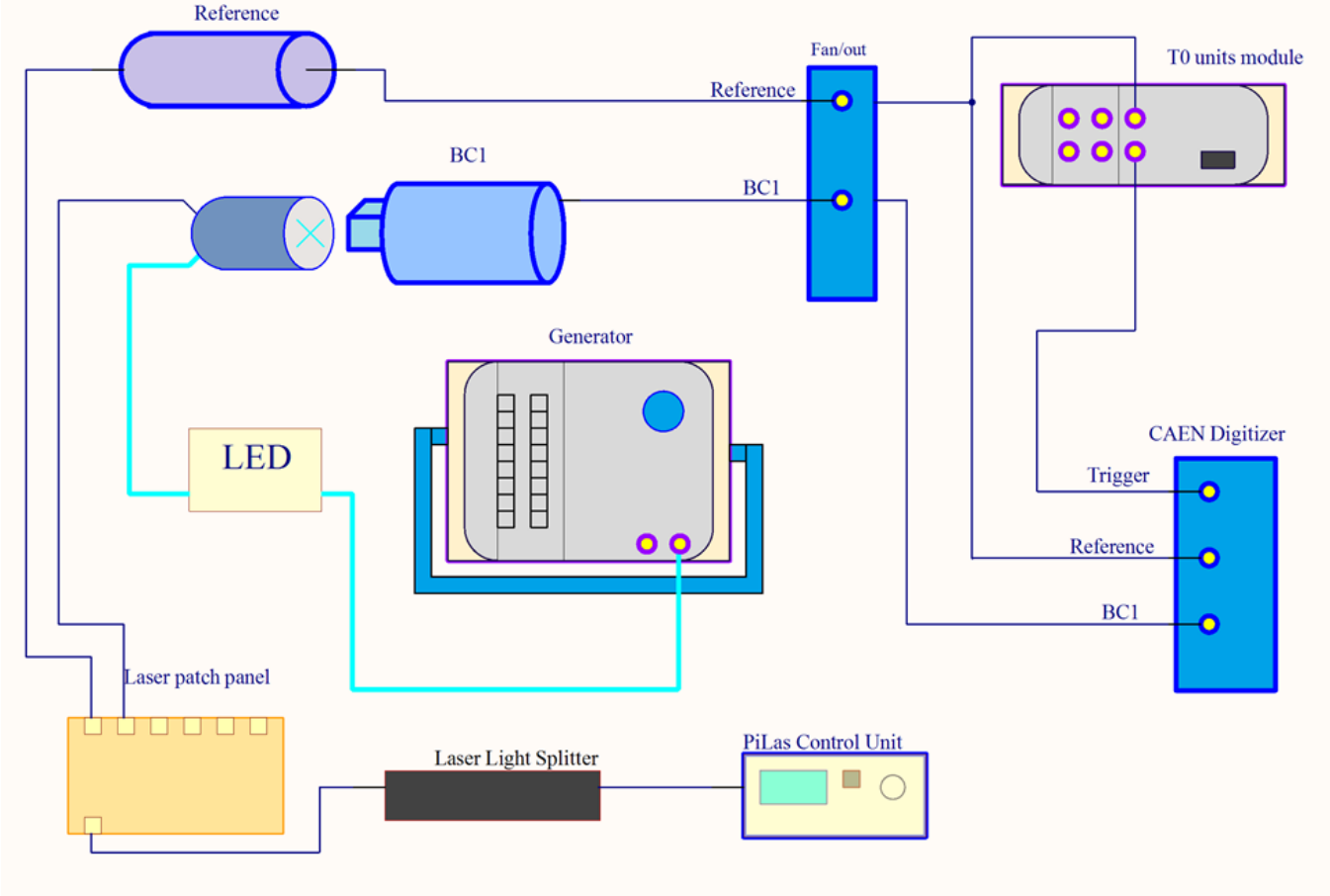
PSD represents the fraction of the fast component in the total signal, used to distinguish between neutrons and gamma rays based on pulse shape.

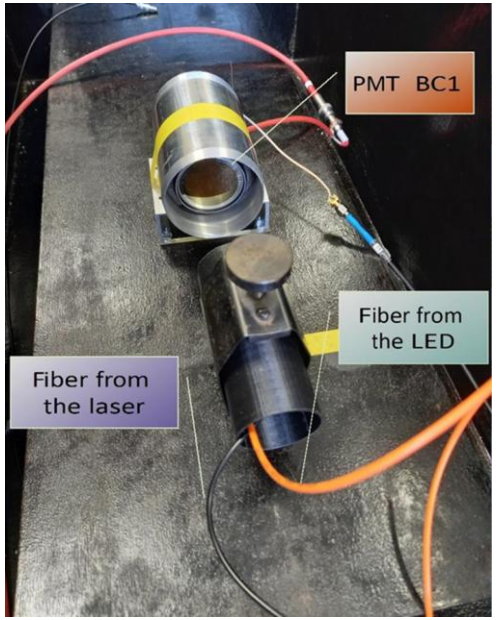
	ND1	ND2	ND3	ND4
σ_t (ps)	128	114	118	110

Time resolution of Neutron Detectors is estimated by a half of maximum of gamma-peak and time resolution of the T0 - detector

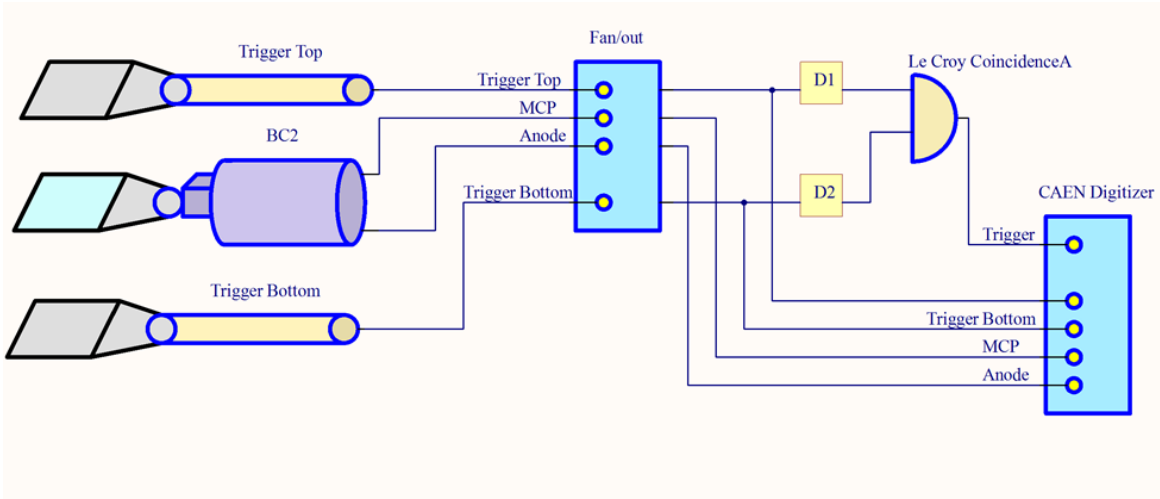
Laboratory test of the BC1 stability

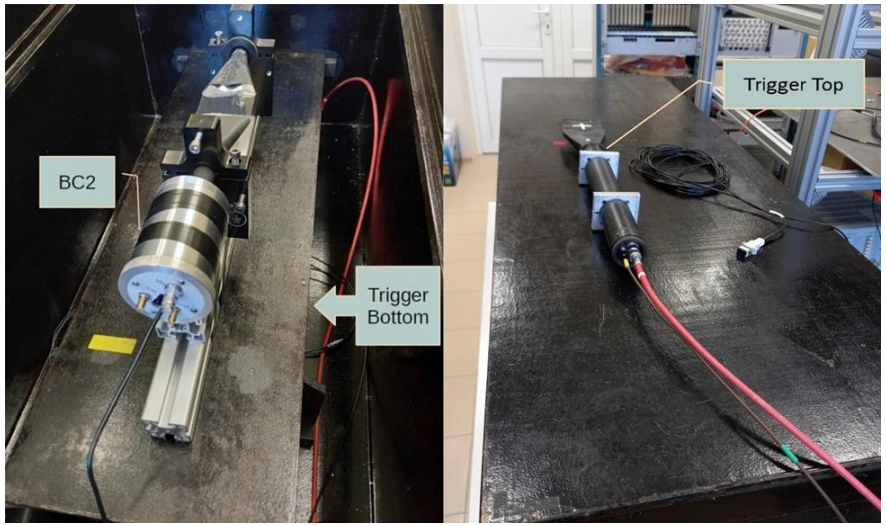
The stability of the photomultiplier in the BC1 detector was evaluated as a function of the expected beam intensity.





Measurement of the time resolution of BC2



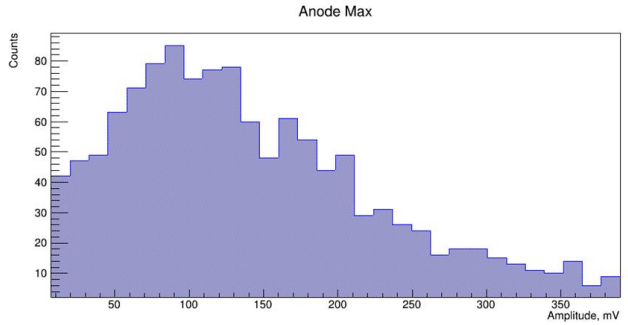


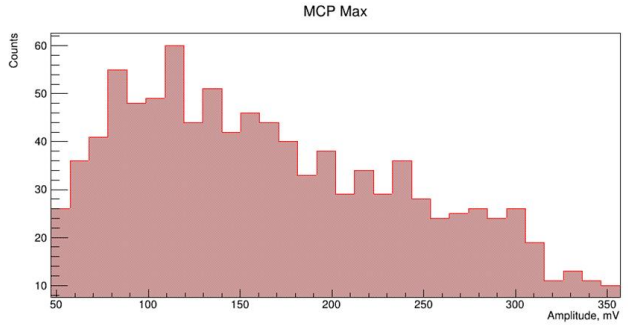
Amplitude considerations:

- Peak amplitude ~100 mV
- Without amplifier: ~10 mV signal for muons
- For the laser setup, expected signal ~300 mV at the same HV (SRC)

Beam and Signal Considerations:

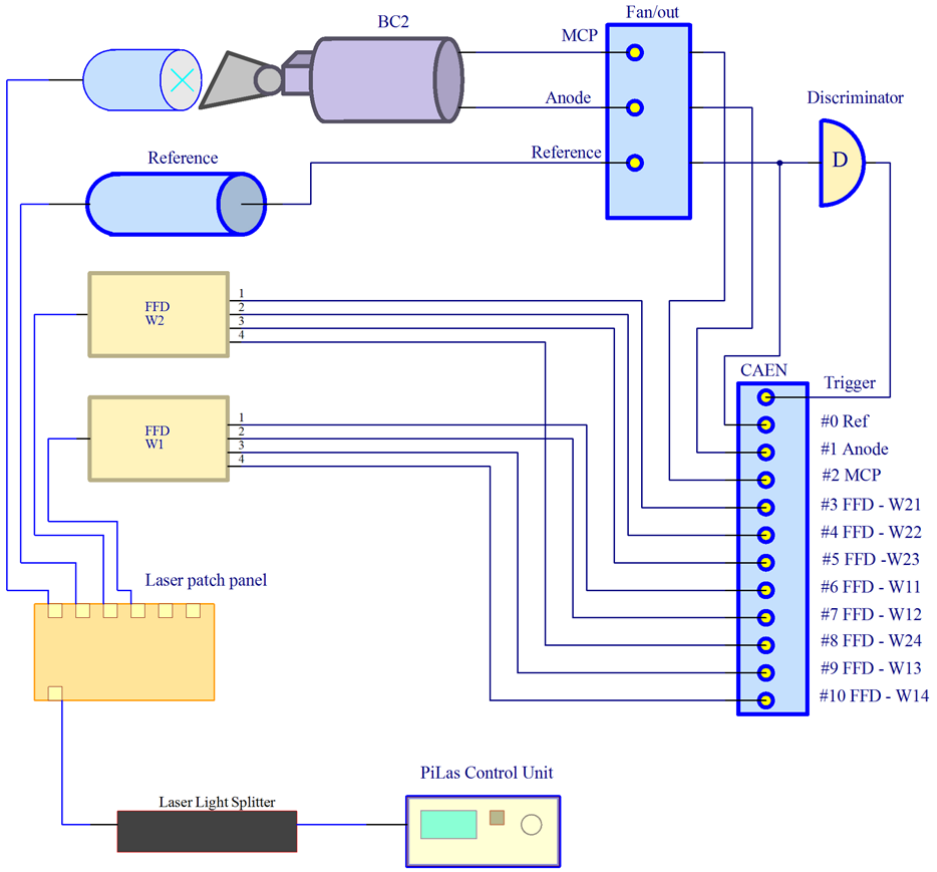
- Expected beam in SRC: **^{12}C (Z = 6)**
- BM@N experiment: **^{131}Xe (Z = 54)**
- Ionization scales as **Z^2**:

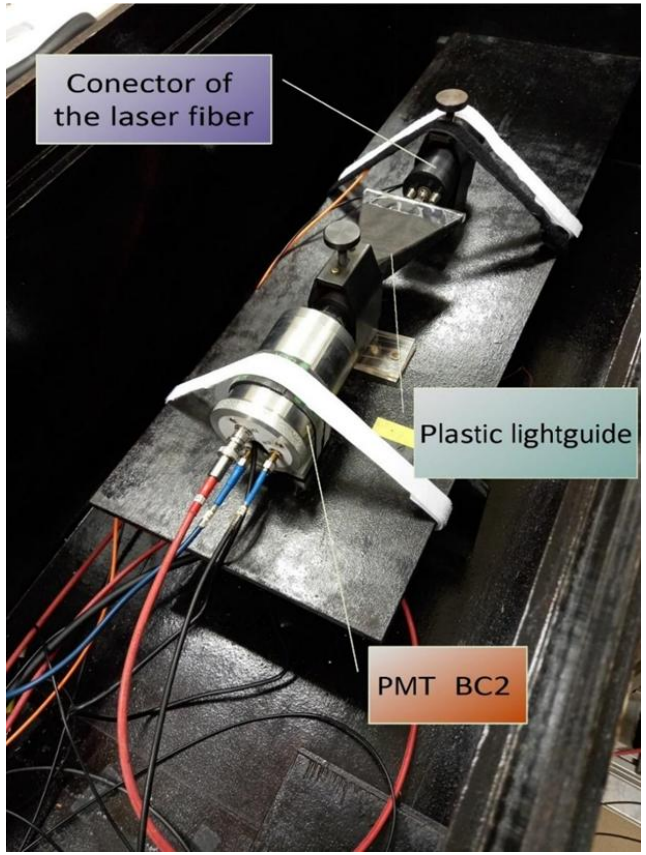




Muons distribution in BC2 scintillator

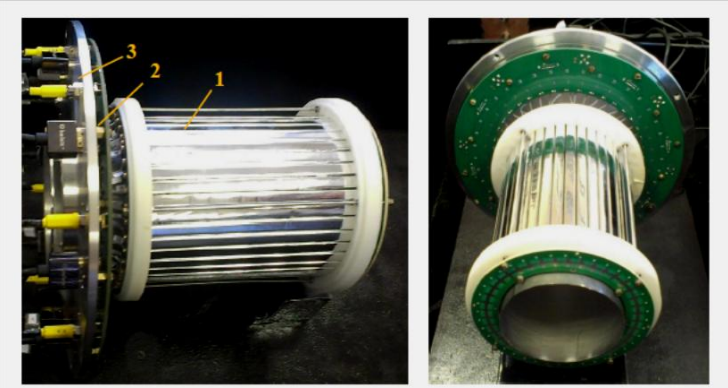
Measurement of the time resolution of BC2

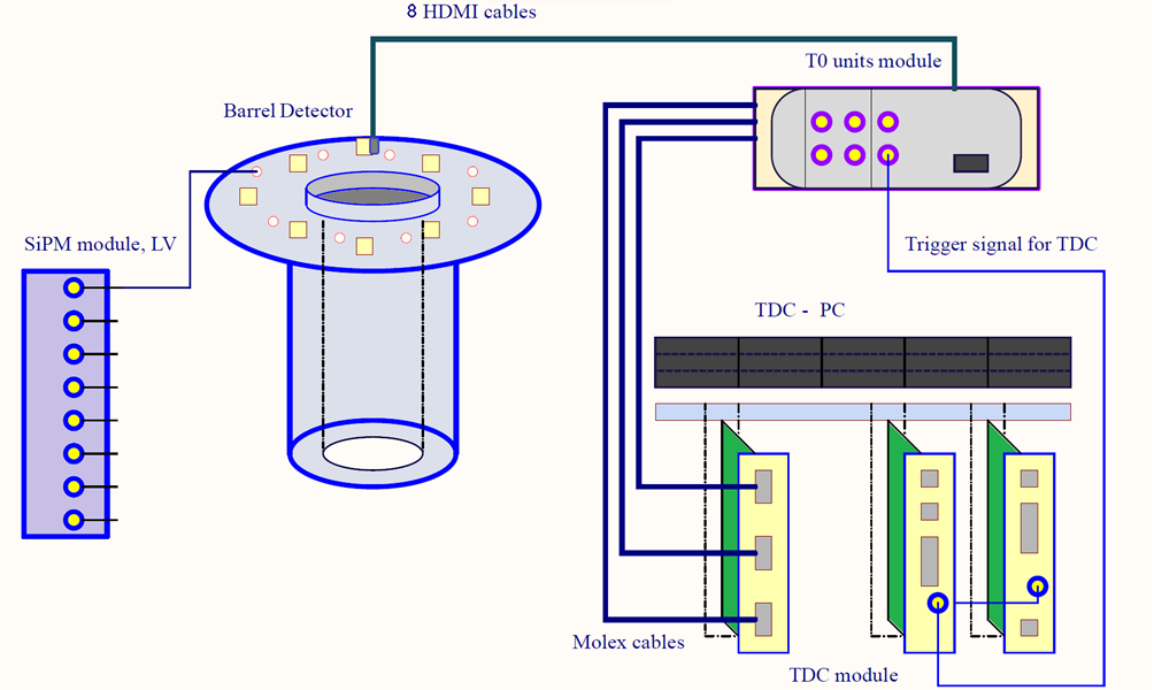




Detector signal	Time resolution, ps
Anode	34 ± 2
MCP	39 ± 2
Reference	28 ± 2
W11	35 ± 2
W12	51 ± 2
W21	44 ± 2
W22	40 ± 2
W23	53 ± 2

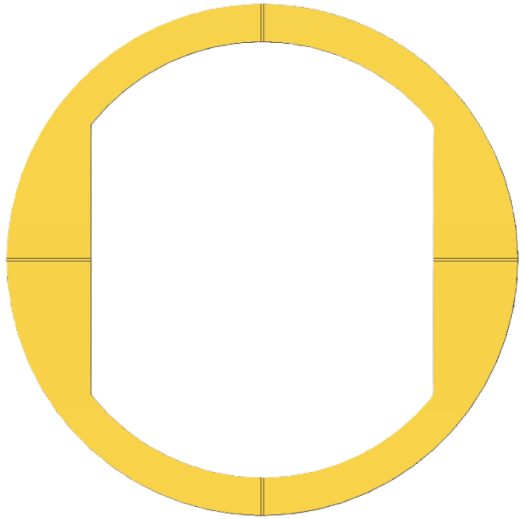
Test of the Barrel Detector

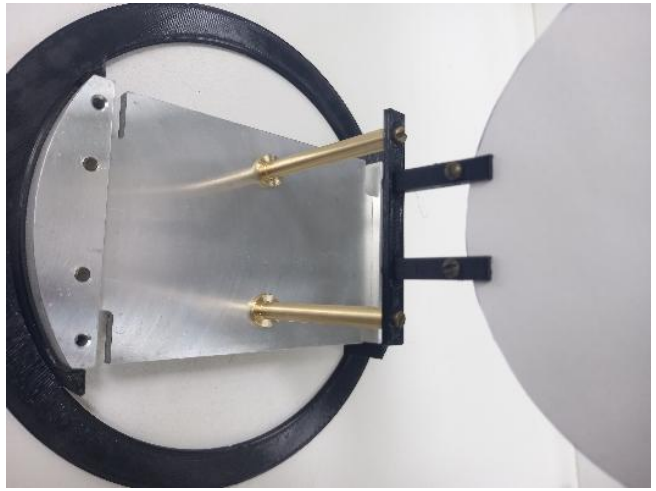


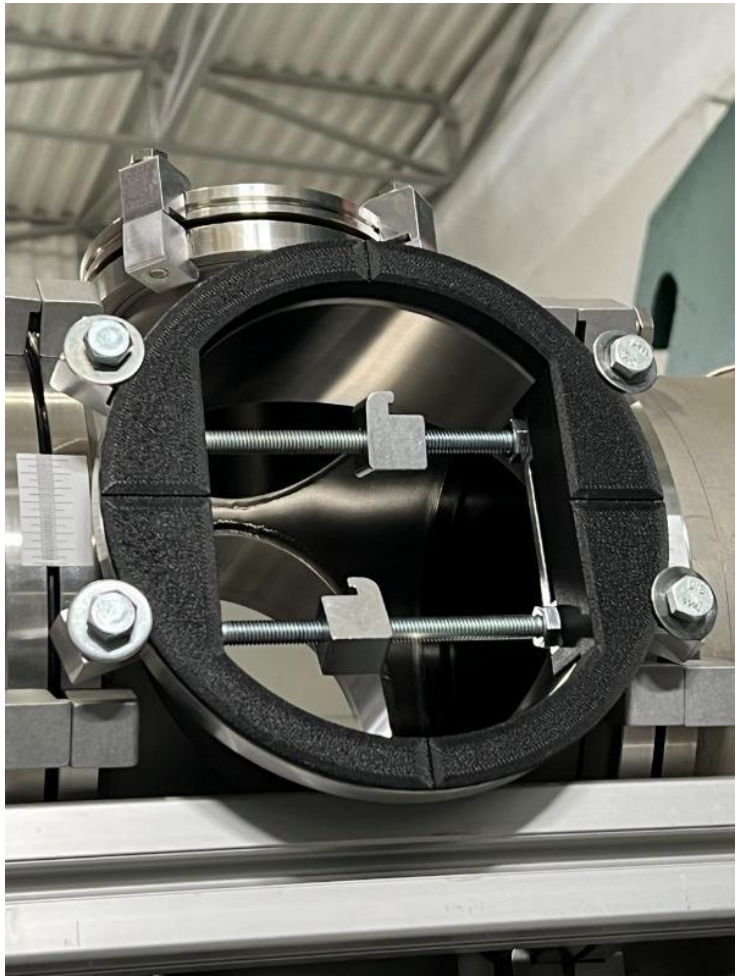


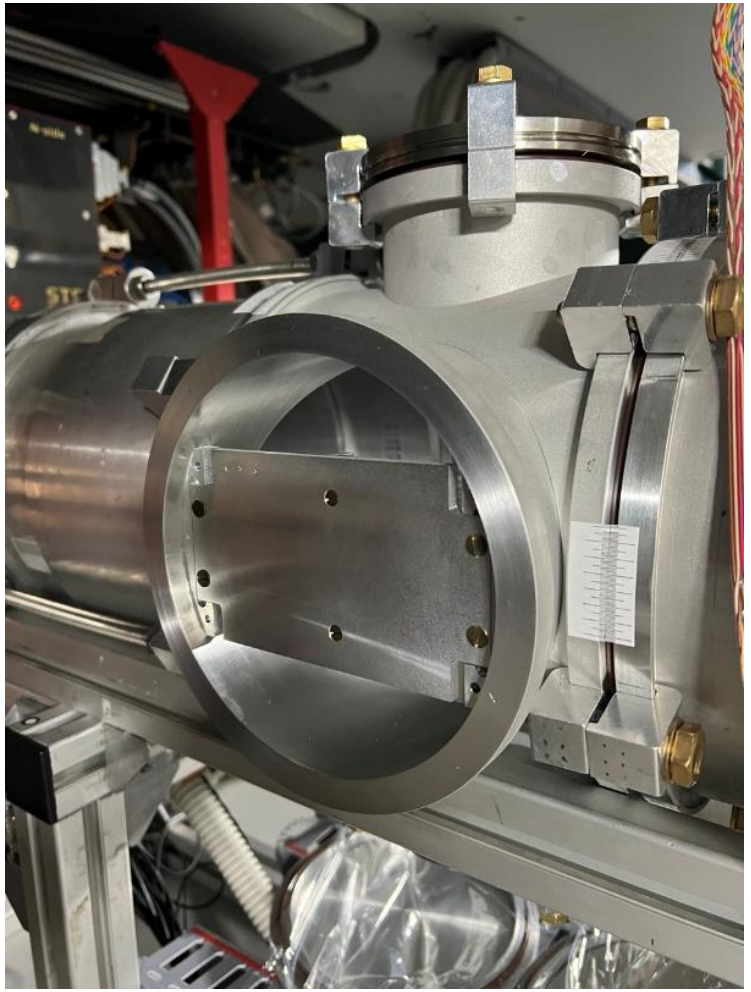
BD group	TDC channel
# 1	9 : 35 : 5 : 1 : 8
# 2	4 : 31 : 0 : 11 : 7
# 3	3 : 27 : 10 : 6 : 2
# 4	22 : 34 : 18 : 14 : 23
# 5	19 : 30 : 15 : 20 : 16
# 6	12 : 26 : 21 : 17 : 13
# 7	57 : 46 : 53 : 49 : 56
# 8	52 : 42 : 48 : 59 : 55

Beam counters scintillator mount

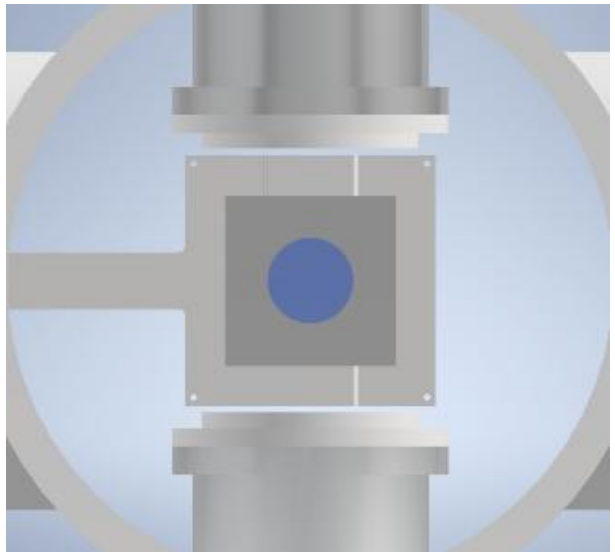




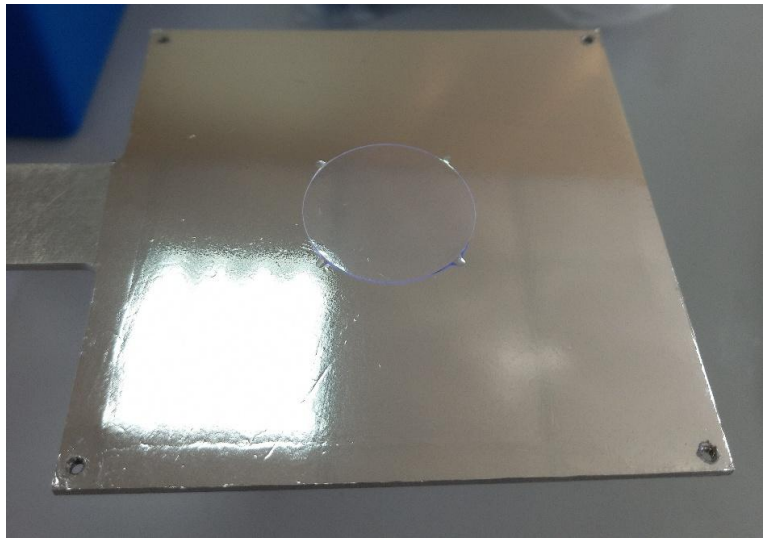


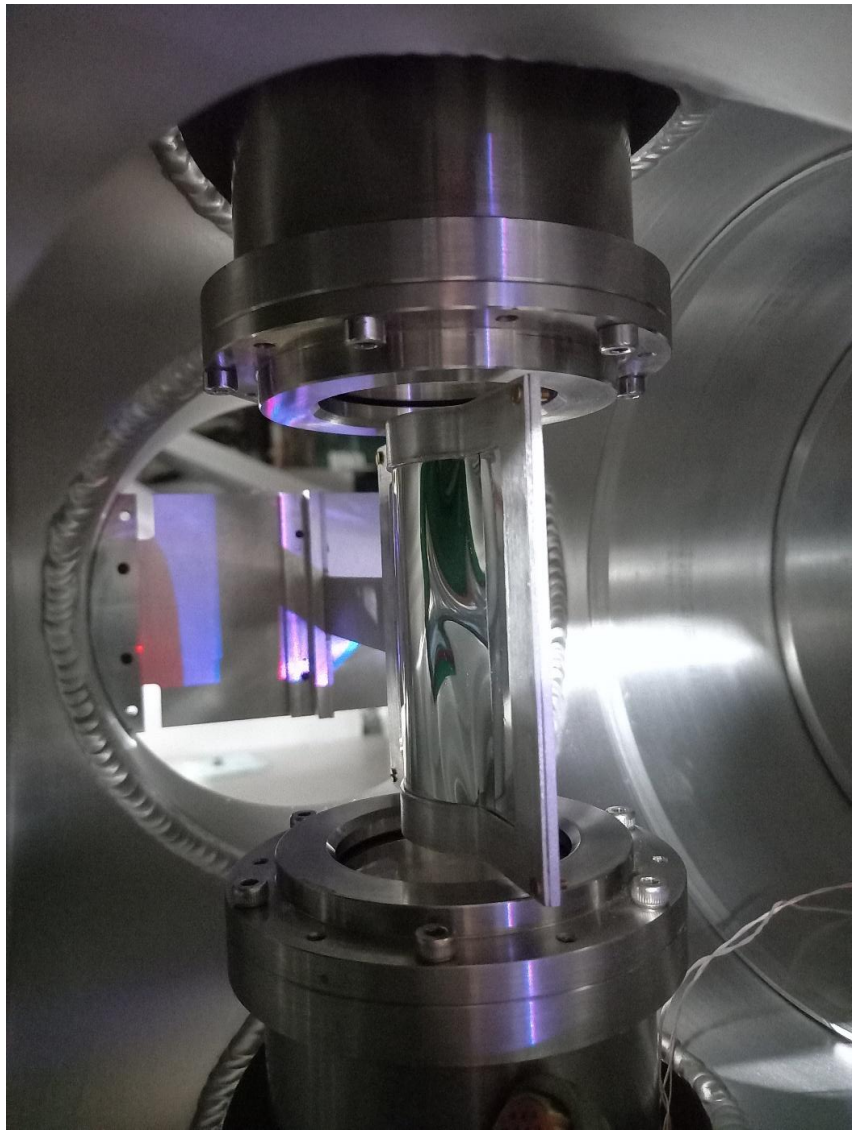


BC2 scintillator mount









BC0 scintillator mount

