nBLM system: data processing

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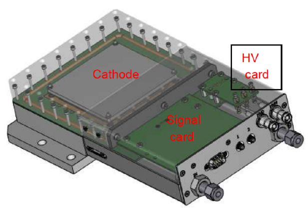
Outline

- nBLM
  - Reminder
- FW functionality – block diagram
  - Neutron detection algo
  - Protection algo
- nBLM DAQ first test (Linac4)
  - Preliminary results

nBLM: reminder

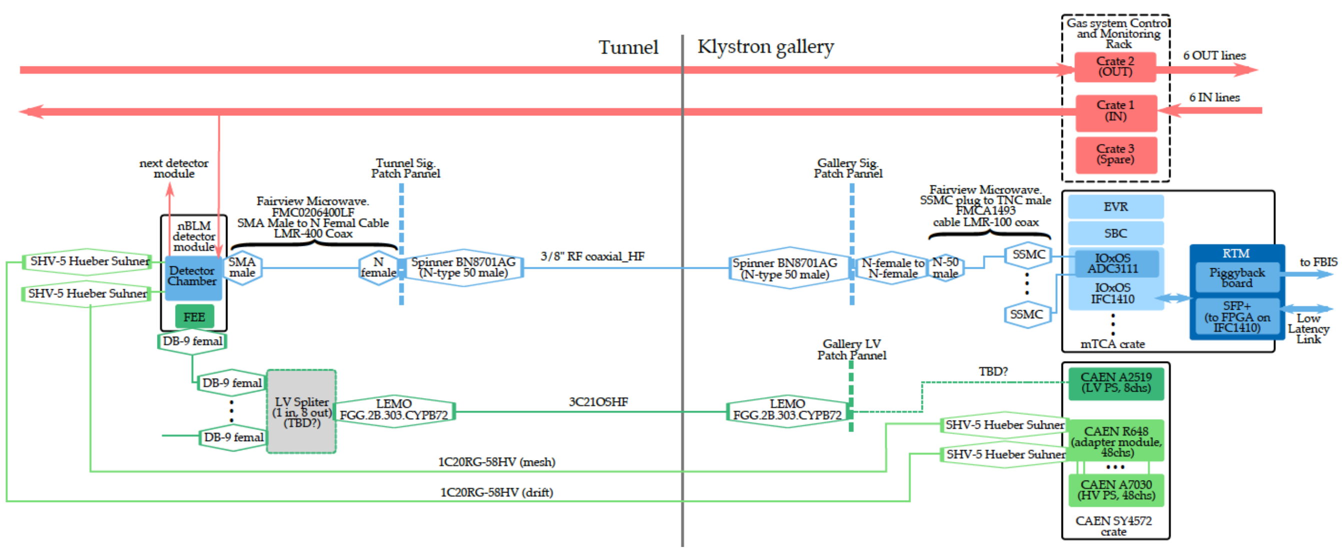
FEE & detectors

- Housed in a detector module together with the detector chamber and HV mezzanine card



BEE

- IOxOS IFC1410
- IOxOS ADC3111 FMC digitizer
  - 250MS/s, DC coupled, 16-bit, +/-0.5V
- FBIS interface:
  - RTM with piggyback card
  - IOxOS FMC, DIO3118 – temporary solution for test purposes
- Low Latency Link: SFP+ on RTM
- Alternative to IFC1410
  - Struck SIS8300-KU + SIS8900 RTM
  - 125MS/s, +/-1V, 16bit, DC coupled



nBLM: signal

nBLM mode of operation:

- Measurement: neutron counts
- The system is operating in two modes, transition is automatic on the FW level.
- **Counting mode**: individual neutron signals are counted
- **Current mode:** the rate of incoming neutrons is too high to able to distinguish between 2 individual neutron signals
  - Events pile up
  - Number of neutrons estimated through charge.

Typical neutron signal

- The characteristics depend on detector properties/settings (drift length, applied voltage/gain) - settings not finalized.
- Typical numbers:
  - 30-50ns rise time
  - 100-200ns signal length
  - Amplitude:
    - nBLM-S: ~ constant (~100mV)
    - nBLM-F: continuous (maximum value 500mV - ADC saturation)
- **Note**: the nBLM signals are negative.

Processing & monitoring requirements

- System able to run stand alone independent of linac operation.
- Each AMC able to process up to 8 detector channels simultaneously.
- Signal samples at minimum 2MS/s
- All BLM systems follow the same approach where applicable.
- Monitoring data available either:
  - On demand – DoD data
  - Periodically (@max 14Hz) – periodic data

Processing & monitoring requirements

DoD data:

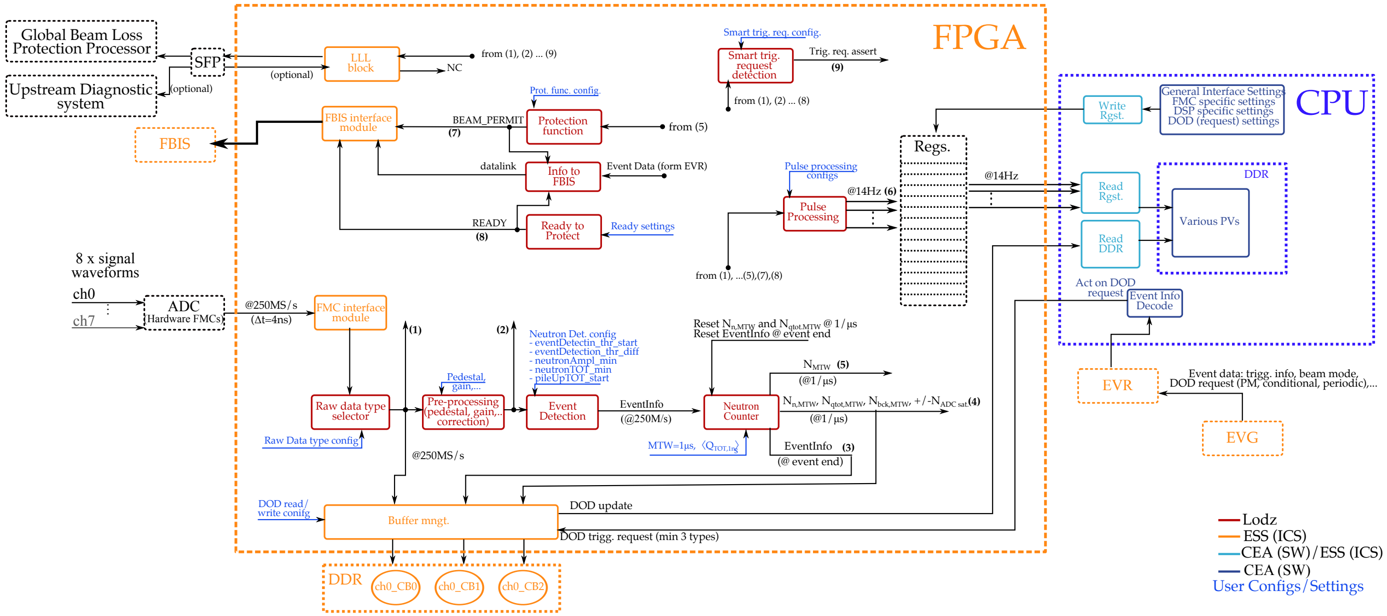
- Continuously buffered and accessible for retrieval without stopping the buffering.
- Min 3 consecutive pulse periods of raw data and 100 pulse periods of processed data available for retrieval on demand (pulse period = 1/(14 Hz)).
- Configurable post- and pre-trigger
- In case of raw data (processed data), the post and pre-trigger can be at minimum set to select from 2 (99) pulse periods before to 2 (99) pulse periods after the tagged pulse period – together minimum 3 (100) consecutive pulse periods per request.
- 3 different types of DoD trigger requests at min:
  - Post-mortem
  - Periodic (fx. 1/day)
  - Conditional (certain conditions reached in one of the systems)

Relaxed requirements on DoD data

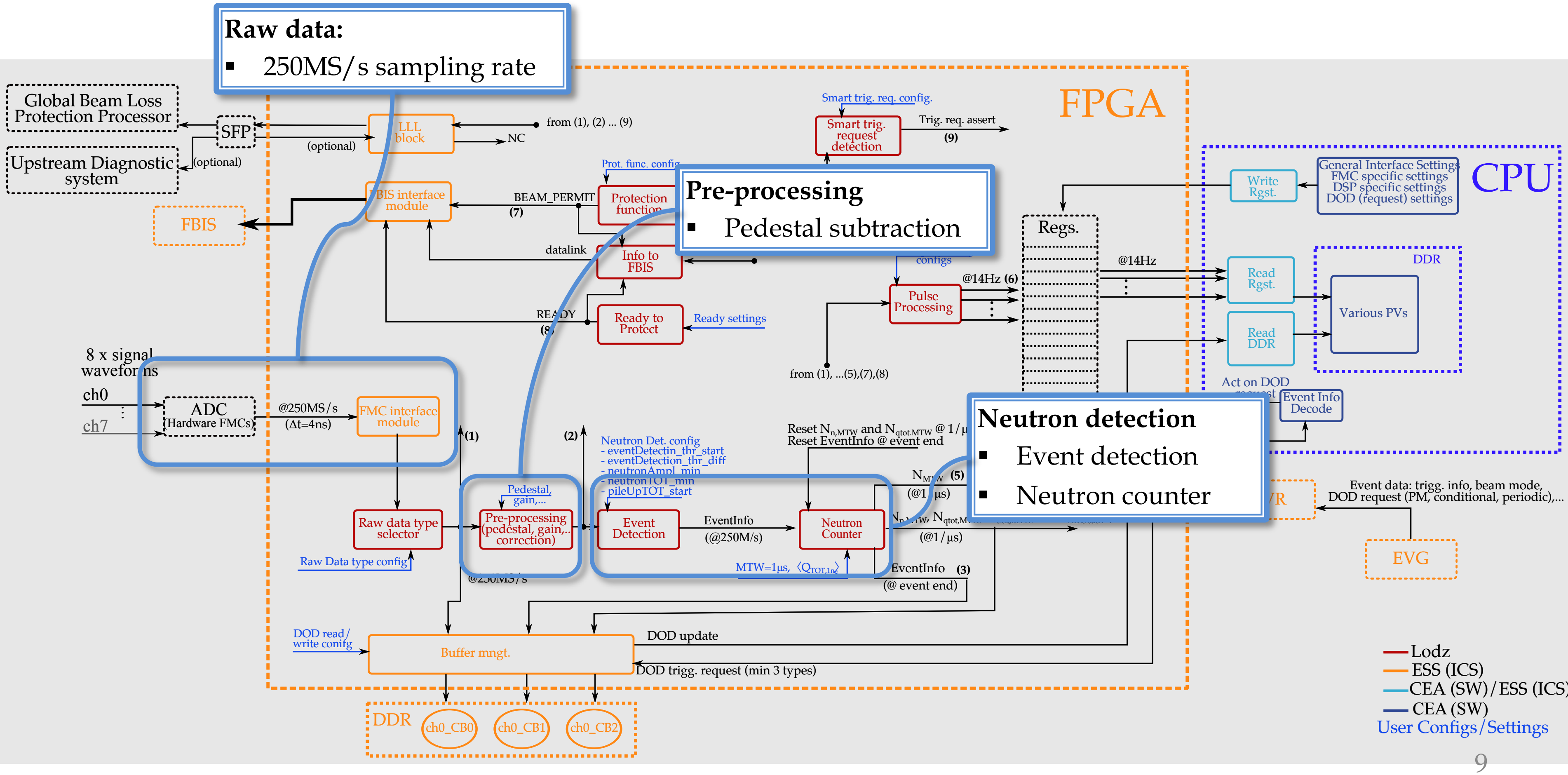
- Requirement on raw data buffering – challenge
- Requirements on nBLM DoD relaxed temporarily
- **Relaxed version**
  - Data available for retrieval on each DoD request in relaxed version:
    - Limited amount of raw data
    - Minimum 100 pulse periods of neutron counts buffer (CB2) for minimum 6 channels.
  - Limited amount of raw data, either:
    - Minimum 2 chs with continuously sampled – minimum 3 consecutive pulse periods (with per- and post-trigger option)
    - Minimum 6 chs sampled only in a certain time window inside the pulse period:
      - minimum size of sampling time window: 9ms
      - Minimum 3 consecutive sampling time windows available on demand (with pre- and post-trigger).

nBLM FW functionality

- nBLM block diagram:
  - FPGA based data processing, connection to SW
  - Here: short overview of the functionality
  - Details in nBLM CDR supporting material (I.D.Kittelmann, *"Requirements and technical specifications – ESS nBLM system"*)
- Implementation details:
  - Talk by G. Jablonski
  - More in related reports (part of the nBLM CDR supporting material)



nBLM FW functionality



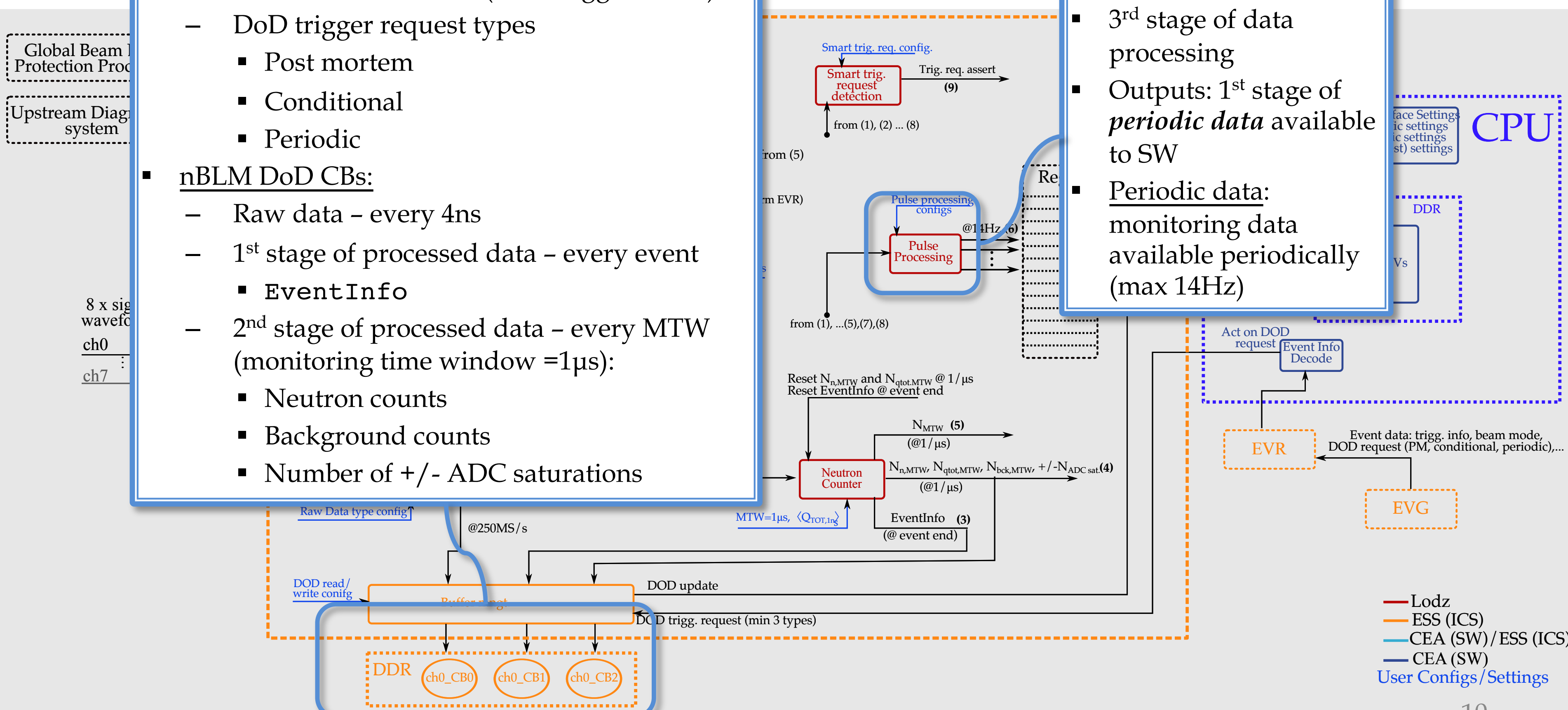
nBLM FW functionality

Buffering of *Data-On-Demand* (DoD)

- DoD data:
  - available on demand (DoD trigger assert)
  - DoD trigger request types
    - Post mortem
    - Conditional
    - Periodic
- nBLM DoD CBs:
  - Raw data – every 4ns
  - 1st stage of processed data – every event
    - `EventInfo`
  - 2nd stage of processed data – every MTW (monitoring time window =1μs):
    - Neutron counts
    - Background counts
    - Number of +/- ADC saturations

Pulse processing

- 3rd stage of data processing
- Outputs: 1st stage of ***periodic data*** available to SW
- Periodic data: monitoring data available periodically (max 14Hz)



nBLM FW functionality

Low Latency Link block

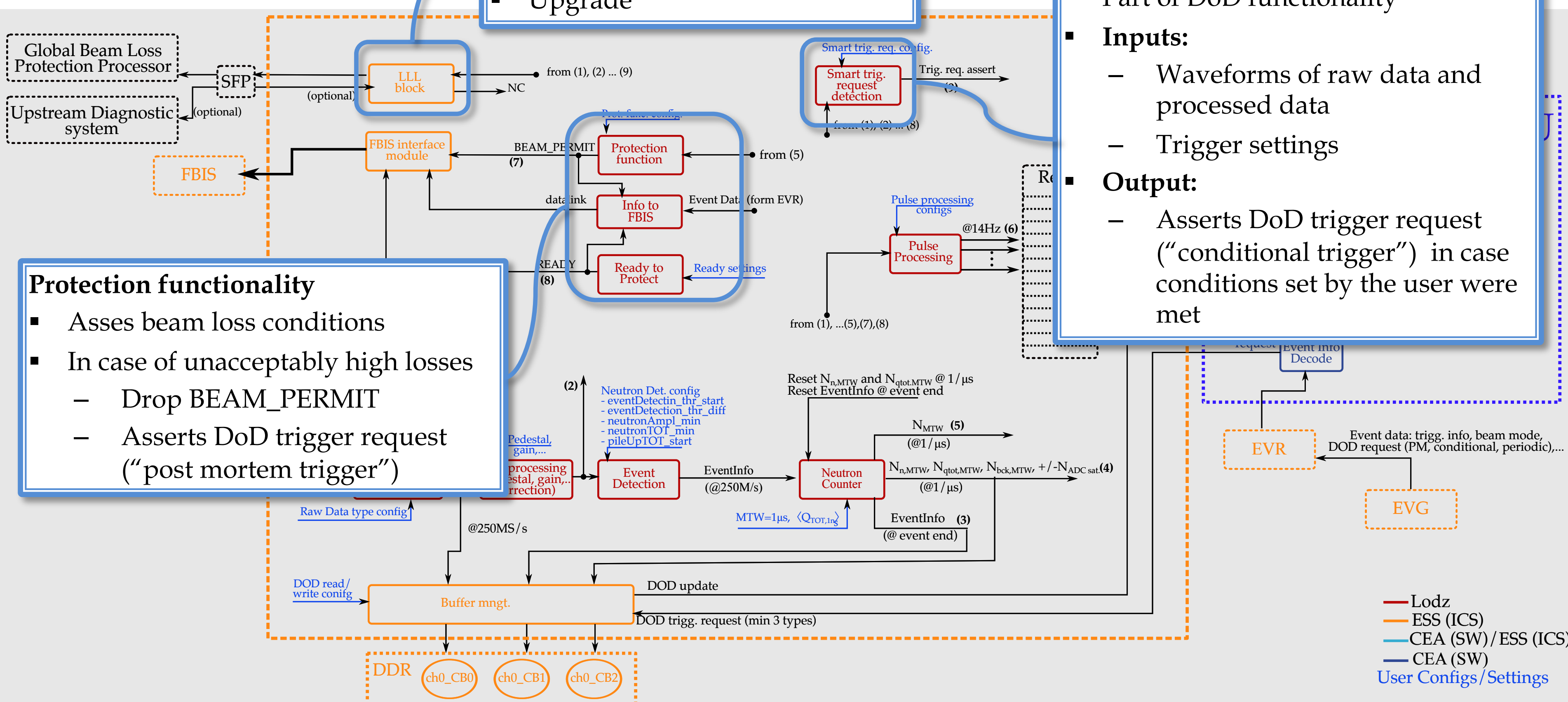
- To combine information coming from different systems of parts of a system
- Upgrade

Smart trigger

- Part of DoD functionality
- **Inputs:**
  - Waveforms of raw data and processed data
  - Trigger settings
- **Output:**
  - Asserts DoD trigger request ("conditional trigger") in case conditions set by the user were met

Protection functionality

- Asses beam loss conditions
- In case of unacceptably high losses
  - Drop BEAM_PERMIT
  - Asserts DoD trigger request ("post mortem trigger")



nBLM: neutron detection algo

What do the neutron detection related blocks provide?

- **Number of neutrons** reported after every MTW - N_{MTW}
  - Is calculated as a sum of a pair of numbers, representing the counts inside MTW calculated by the two different methods.
  - At the end of each MTW:
    - N_{MTW} is stored in the CB2 and
    - N_{MTW} is reset at the end of every MTW.
  - Additional data stored in CB2:
    - Number of pos. ADC saturations
    - Number of neg. ADC saturations
    - Background counts
- **`EventInfo`** for each "interesting event"
  - The structure contains information about the event (Q, TOT, rise time, time stamp,…)
  - The structure is stored in the circular buffer CB1 and
  - Reset at the end of each "interesting event".

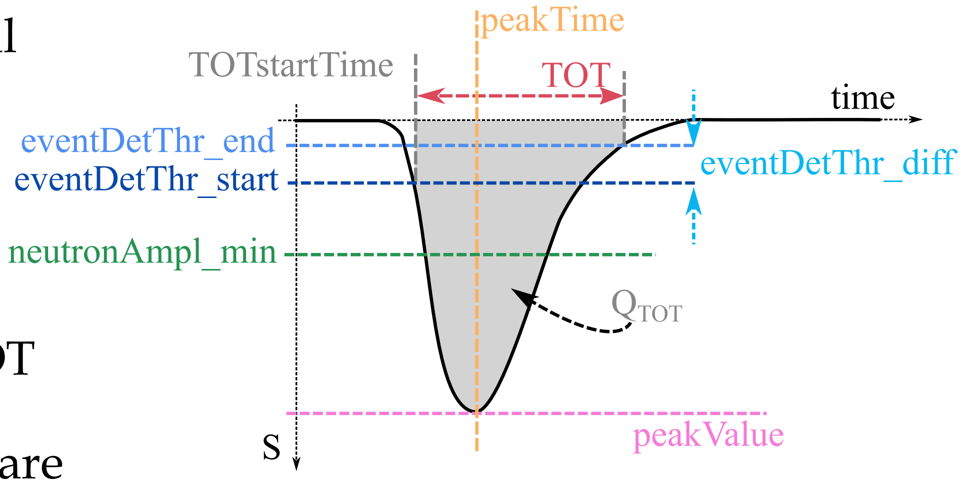
MTW (Monitoring Time Window):

- *Time window in which the neutron counts are measured/reported*
- *Currently set to 1us (250 samples).*

nBLM: neutron detection algo

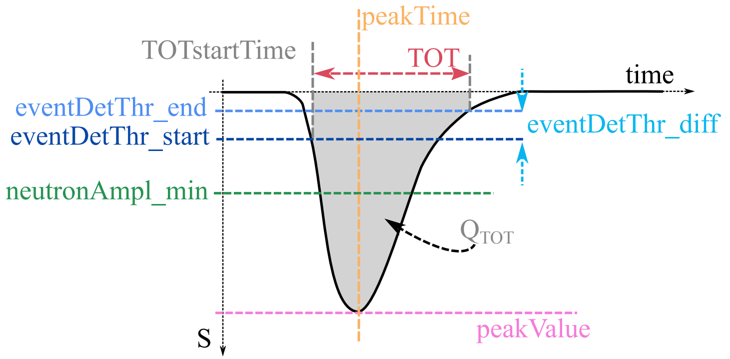
`EventInfo` structure

- `TOT` – event Time Over Threshold
- `Q_TOT` – charge inside the TOT window
- `peakValue` – amplitude (min signal inside TOT window)
- `TOTstartTime`
- `peakTime`
- `peakValid` – true if condition on amplitude for single neutron is met
- `TOTvalid` – true if condition on TOT for single neutron is met
- `pileUp` – true if pile up conditions are met
- `MTWindx` – index of the MTW where event started
- `isTruncated` – true if event 1. part of a split signal
- `isPart2` - true if event 2. part of a split signal



nBLM: neutron detection algo

Basic idea (CEA):



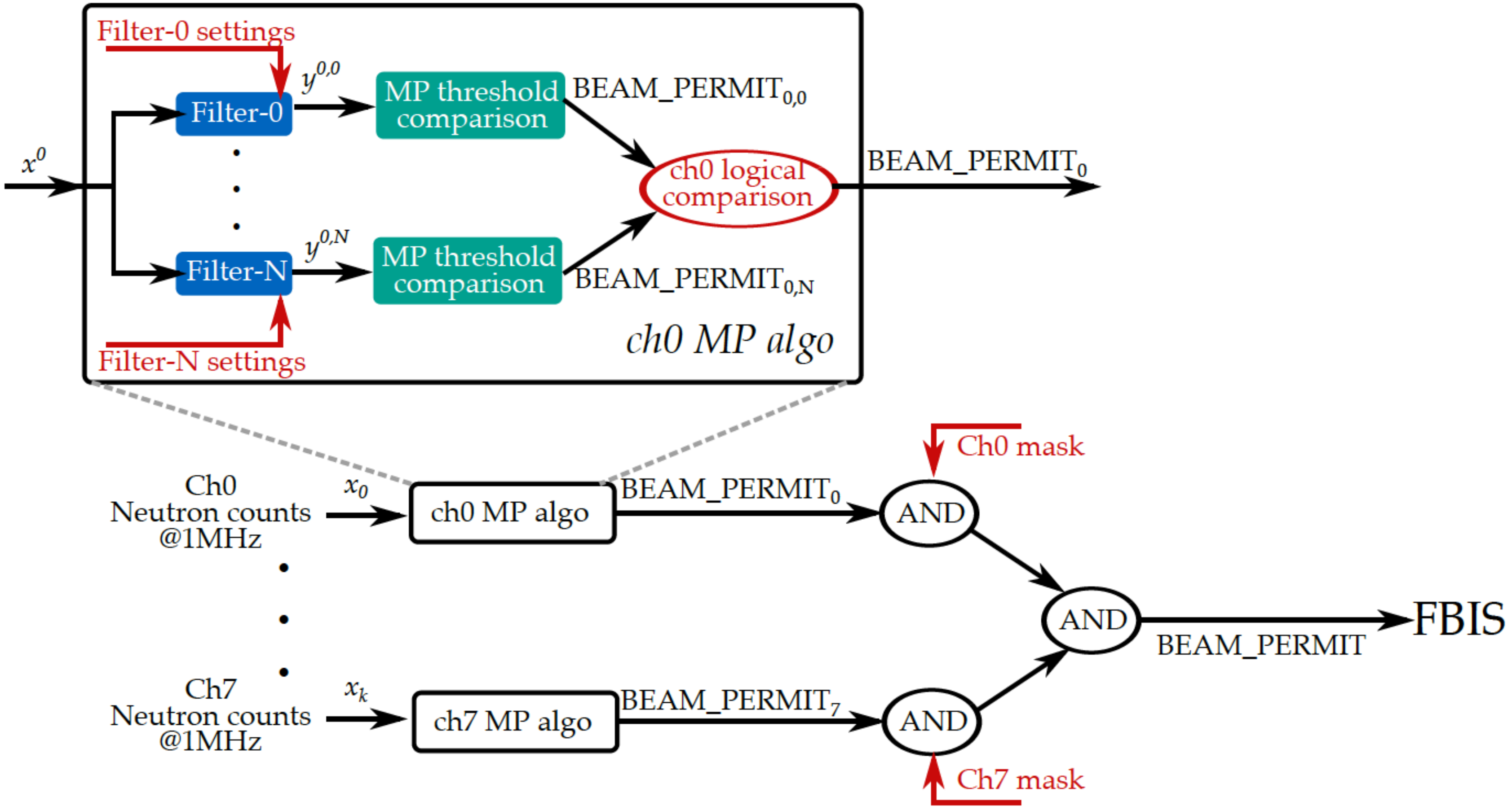
- Detect **"interesting events"**
  - Identify **single neutrons**
    - *TOT within a certain range*
    - *Amplitude below a certain limit*
  - Identify **pile-up** events
    - *Amplitude below the same limit as for single neutron*
    - *TOT above the upper limit for single neutron*
- Use either of 2 methods for neutron counting for each neutron event:
  - <u>Single neutron counting method</u>
    - for single neutron events: count events
  - <u>Charge method</u>:
    - for pile-up events: calculate counts from charge

nBLM data processing (by ESS):

- Basic idea applied to real time processing and MTW framing of counts/events.
- <u>Requirement:</u> algo must provide information (neutron counts) without unnecessary delays.
- Both nBLM-F and –S have the same neutron algo running (different settings)

Protection algorithm

1 BEAM_PERMIT per AMC propagated to FBIS



Protection algorithm

- To avoid spurious BEAM_PERMIT drops
  - Filtering measurements on each channel
  - Coincidences - upgrade (functioning LLL needed)

- Foreseen filter types
  - Relaxation filter (baseline)
  - Moving average (consistent with BCM)
  - Simple average (consistent with BCM)
  - X/Y algo

Protection algorithm

Relaxation filter

- 1^{st} order IIR filter (with feedback)
- Output = weighted sum of old output y_{k-1} and new input value x_k

$$y_k = \lambda y_{k-1} + (1 - \lambda) x_k$$

- $\lambda \to 1$:
  - Forgets little
  - Comparable to moving average with large number of points

Protection algorithm

Moving average

- Calculate local average over the last time window t_{MA} (last n input points x_k)

$$y_k = \frac{1}{n} \sum_{l=0}^{n-1} x_{k-l}$$

- Increasing n: smoothing improved, delay between output and input increased.

Protection algorithm

Simple average

- Calculation carried out with a fresh set of values on each calculation restart.

X/Y algo

- Takes Y last number of inputs x_k
- If X out of them are above the MP threshold, $BEAM\_PERMIT_{c,X/Y}=1$
- Input *x:* neutron counts @ 1MHz
- Output *y:* $BEAM\_PERMIT_{c,X/Y}$

Protection algorithm

5 filter instances to be tested during commissioning:

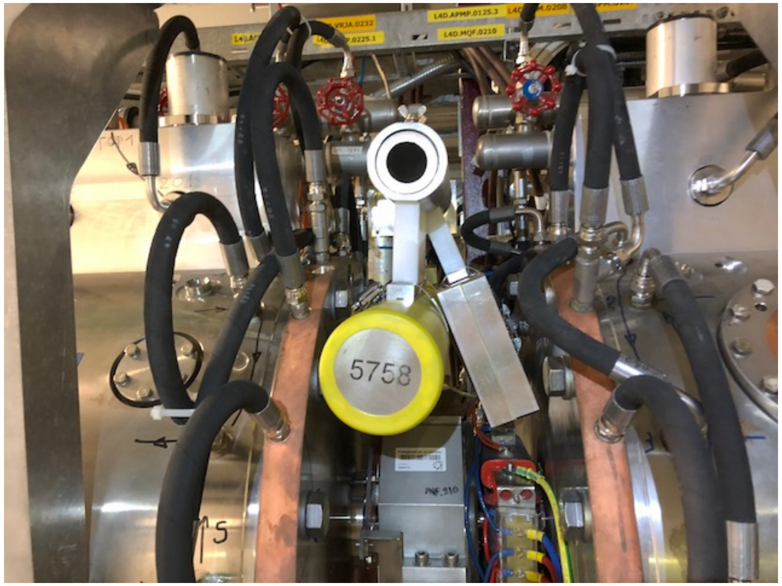
- 2 time constants for moving average ($t_{MA,1}$~1us, $t_{MA,2}$~100us)
- Simple average over beam pulse (~3ms).
- Relaxation filter.
- X/Y algo.

Further developments

- Foreseen based on beam commission experience and simulations
- Plan to co-develop protection functions across the BI systems providing loss information

1st nBLM DAQ test (LINAC4)

- Linac4 (CERN) – realistic environment (close to ESS DTL)
- nBLM-F detector installed at DTL1-DTL2 intertank region (12MeV H^-)
- 2 days available for tests with ESS DAQ in Dec. 2018
  - Controlled losses: readout split between ESS DAQ and scope (or CERN readout) – 1st day
  - Normal operation: only ESS DAQ connected – 2nd day



1st nBLM DAQ test (LINAC4)

- IFC1410 based
  - no external triggering available (working fw version, Lodz support to extract the data)
  - no useful data collected during controlled losses (2 x 10min just after DAQ installation)…
    - Need to set proper settings before meaningful processed data can be collected – no time to do that, therefore decide to collect both raw and processed data
    - Collected waveform shorter (~0.75s) than configured (2.5s) since processed data buffers were enabled.
    - A few files had zeros in collected data (reboot helped)
    - Unstable platform – frequent reboots needed
  - All useful data collected during "normal operation"
- Struck based
  - No external trigger
  - But 8s of raw data collected ~ few minutes.
  - All collected during "normal operation"

1st nBLM DAQ test (LINAC4)

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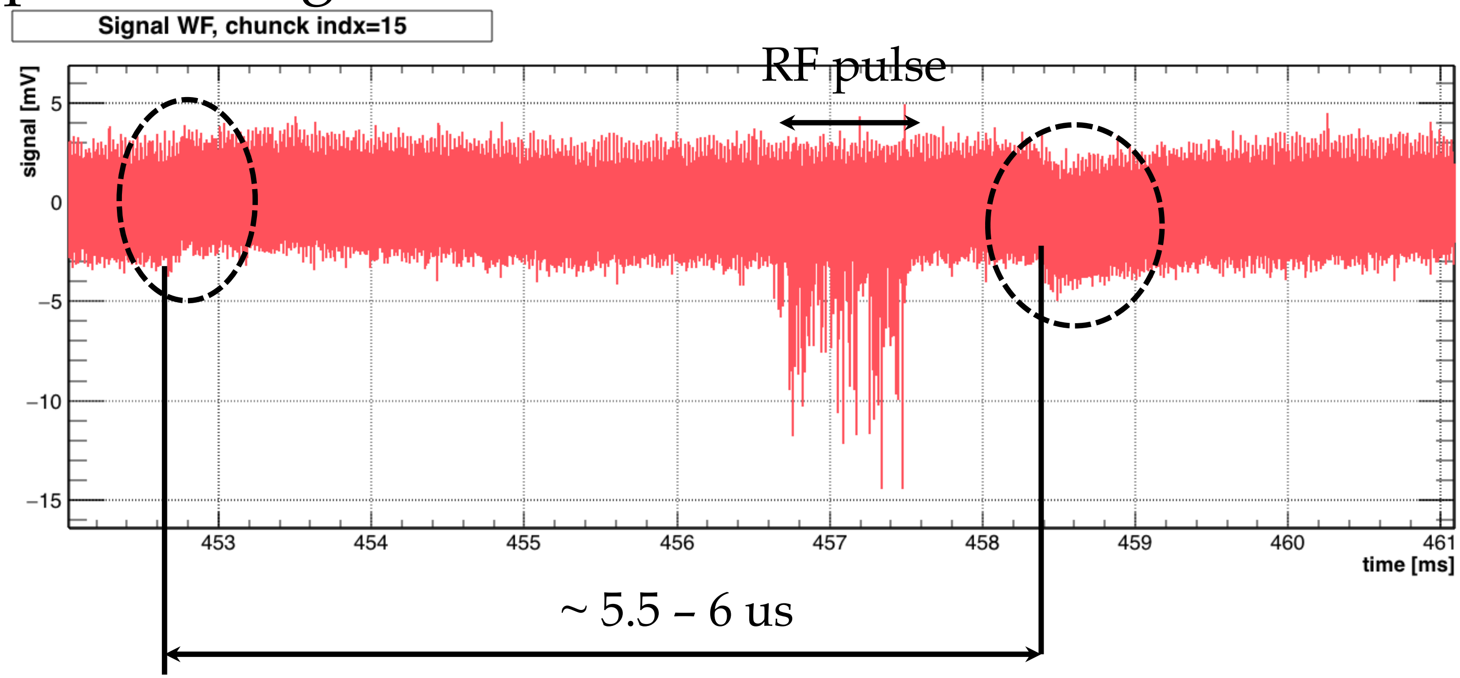
Collected data - used in analysis (last day)

- IFC1410
  - ~8 x 2s of raw data
  - ~8h of *EventInfo* data
- Stuck based
  - 5 x 8s of raw data collected.
- Detector settings: the same in all runs analysed here
- Results
  - More details in report for CDR3 (I. Dolenc Kittelmann, *"Preliminary results of the nBLM DAQ test at Linac4"*)

1st nBLM DAQ test (LINAC4)

IFC1410 raw data with subtracted pedestal

- Plot bellow: signal waveform with visible pulse (mostly gammas) during run7
- Observation: "Charging" and "discharging" structures with 5.5 -6 us distance always surrounding a pulse
- pulsed magnets?



1st nBLM DAQ test (LINAC4)

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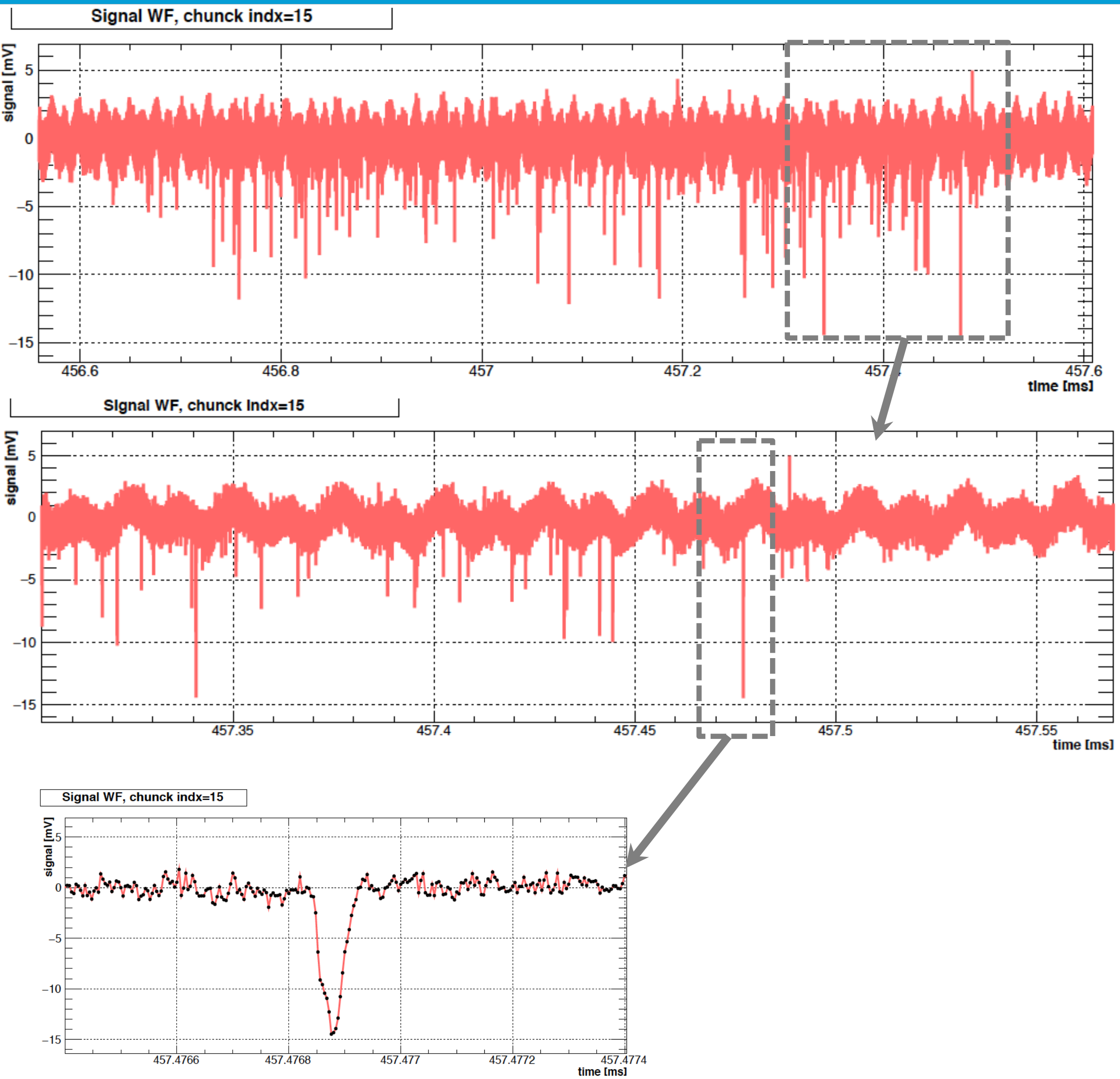


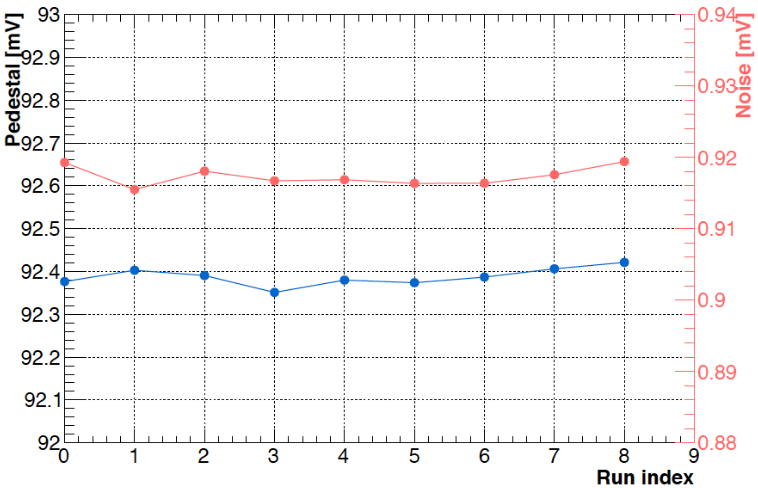
Raw data with subtracted pedestal

- Plots on the left: plot from the previous slide zoomed to
  - The RF pulse time window (top plot)
  - Last part of the RF time window (mid plot)
  - Last gamma signal in the RF time window (bottom plot)
- Observation: ~37kHz pickup

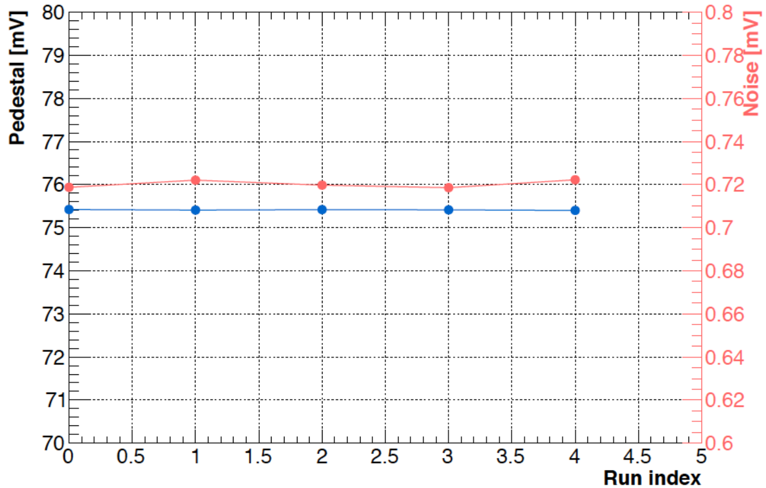
Raw data - ifc1410 vs Struck: noise & pedestal

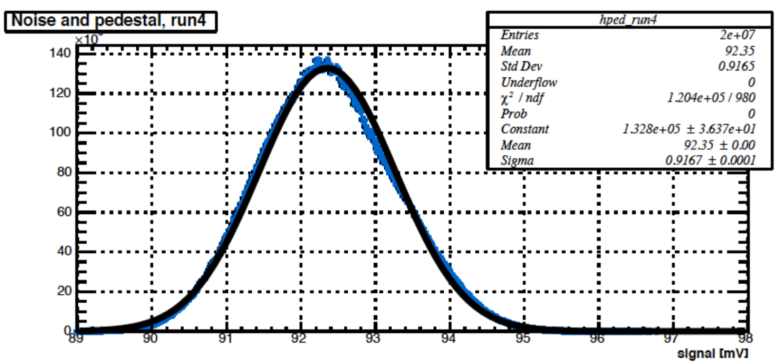
Noise & pedestal

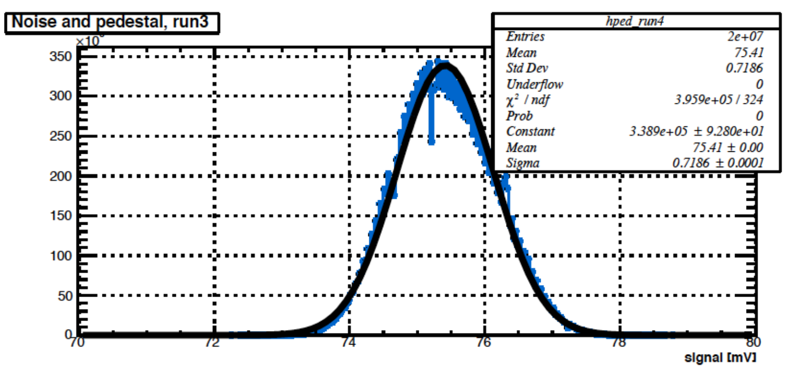
IFC1410



Struck





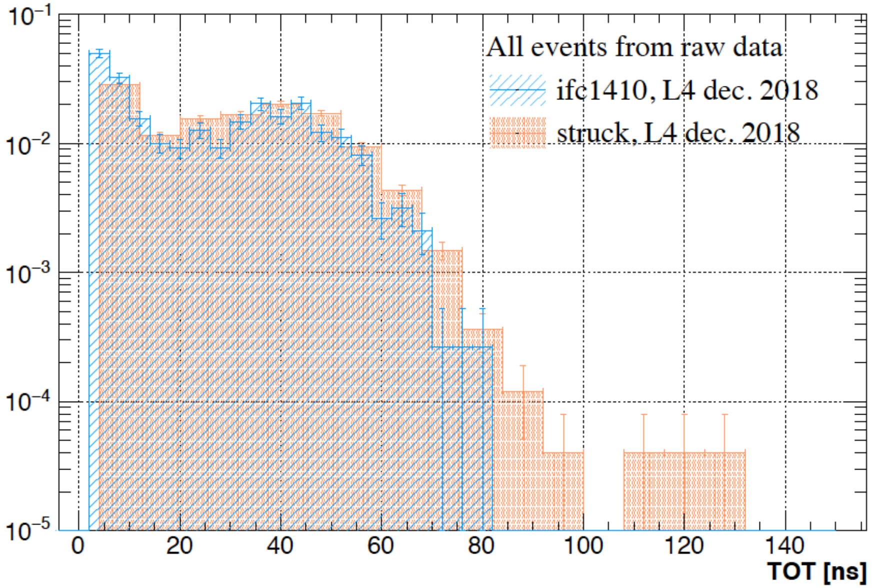


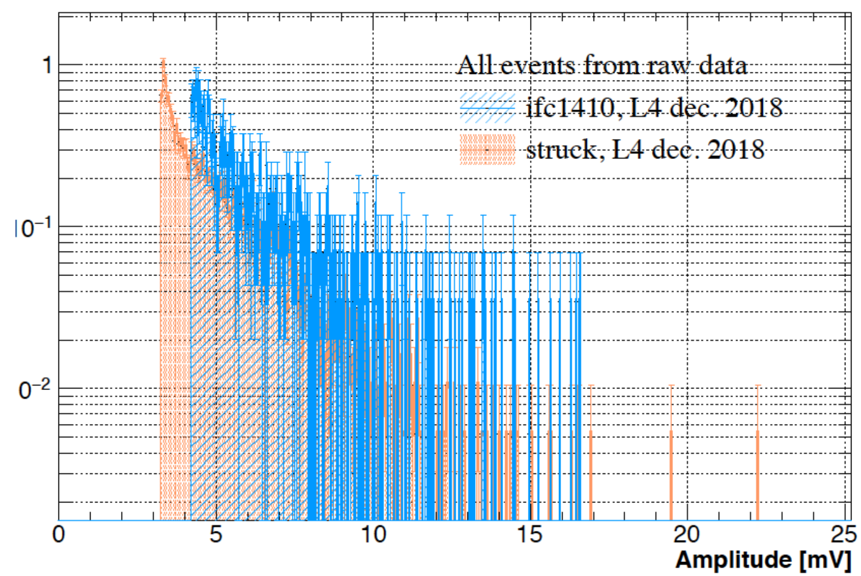
Raw data - IFC1410 vs Struck: TOT & Amplitude

Distributions from raw data - IFC1410 (blue) and Struck (orange) data

- Plots below:
  - **TOT:** time window between events start and end
  - **Amplitude**: minimum signal in the TOT window
  - **Event detection thrs:** struck settings = settings for ifc1410 scaled to give the same Threshold/noise

- Amplitude distribution:
  - 1st slop: spikes/noise, 2nd slope: gammas
  - Neutrons: after 15mV?, not enough statistics
- IFC1410 & Struck data consistent?
  - TOT - yes
  - Amplitude: yes? not enough statistics for IFC1410





IFC1410: *EventInfo* data

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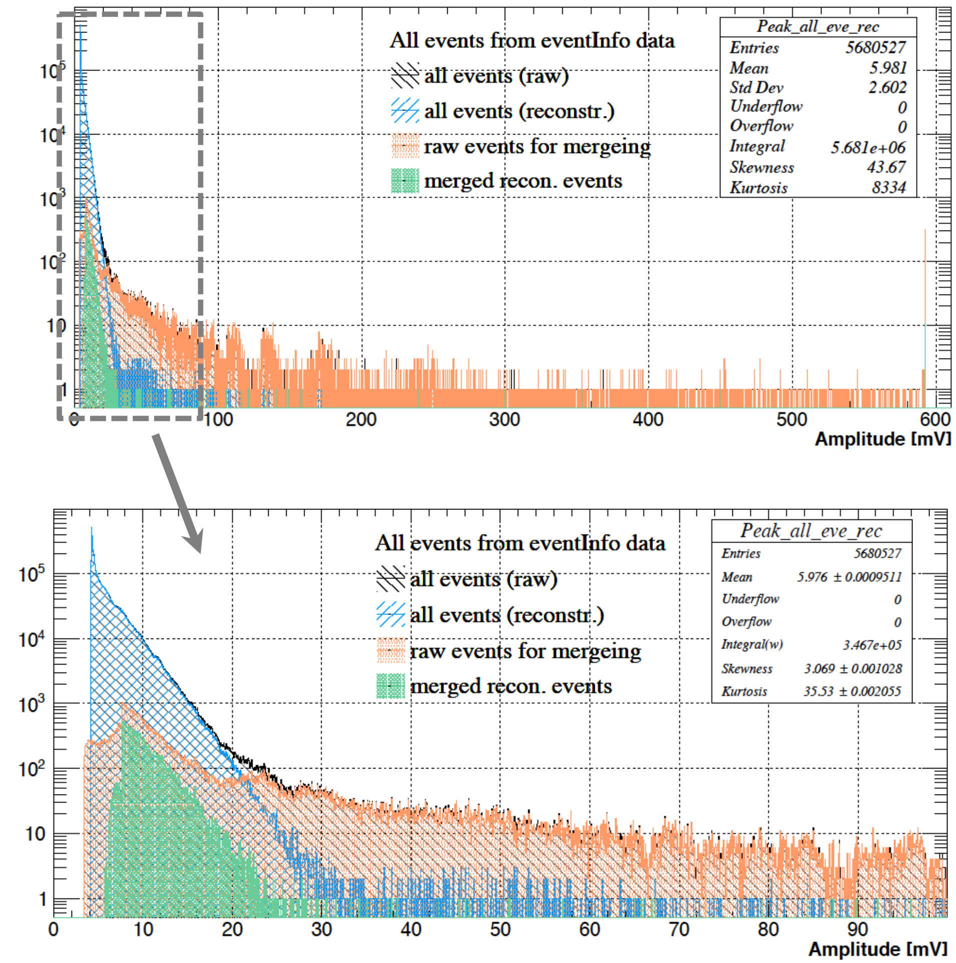
Note:

- Online event detection: framing & splitting events
- Offline analysis: event reconstruction required – blue histo
- “Raw *EventInfo* data” (as collected) – black histo

Amplitude:

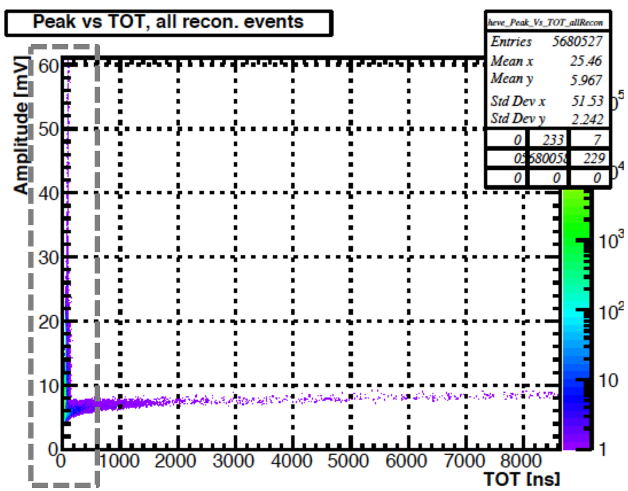
- Neutrons above ~ 30mV? – consistent with scope results (CEA)

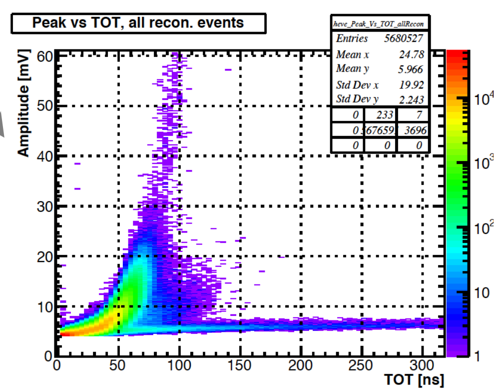


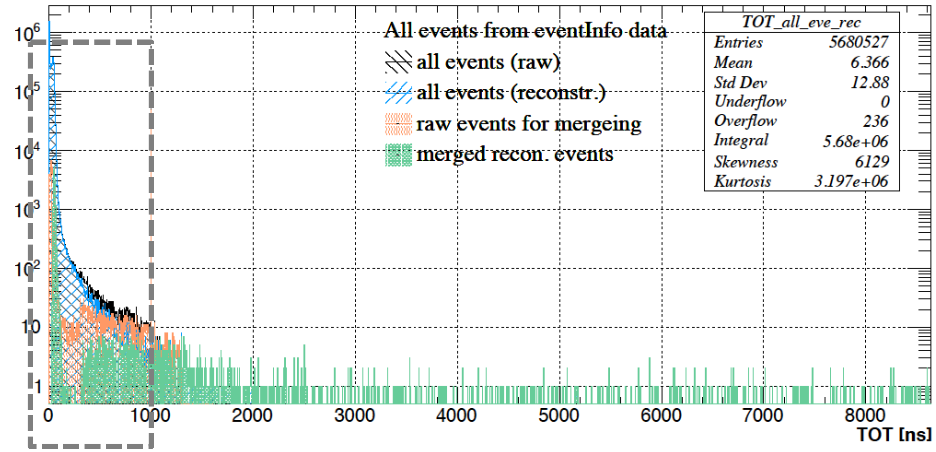
IFC1410 *EventInfo* data

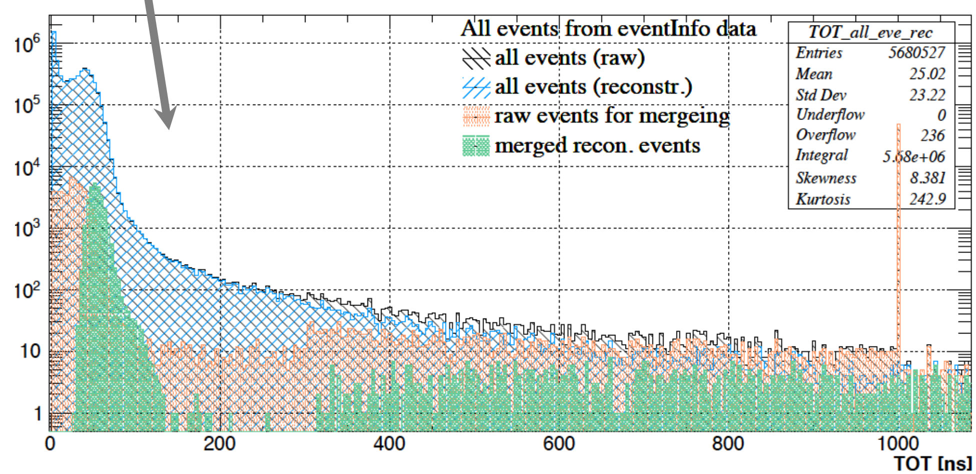
TOT:

- Events extending over several μs present – baseline/pedestal shifts
- With proper algo settings: amplitude cut enough to distinguish between gammas and single neutrons







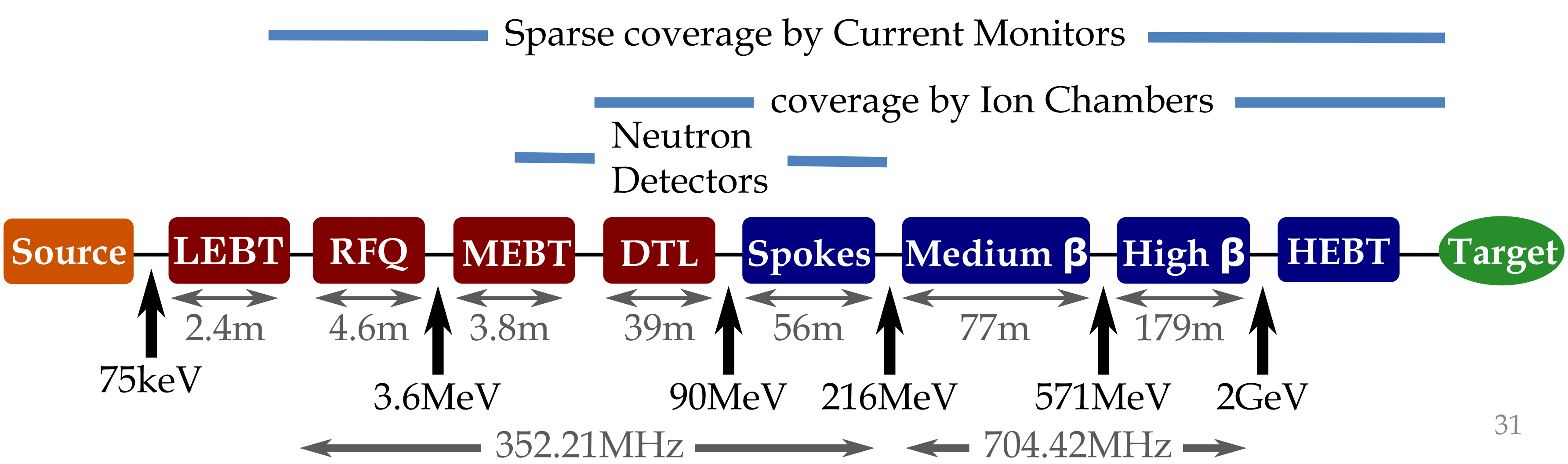


Back up material

ESS Beam Loss diagnostic tools

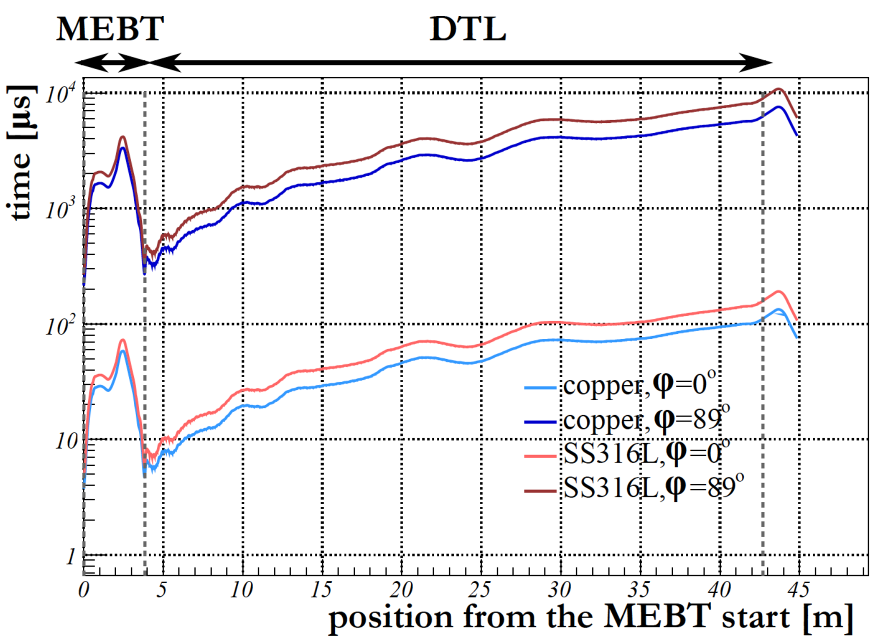
(from T. Shea)

- **Total beam loss**, microsecond measurement latency required for protection
  – BCM, icBLM (saturation, nBLM (current mode) ➔ Interlock; Threshold/derivative term for fast protection
- **> 1.6 milliamp lost for up to 200 µs**
  – BCM, icBLM, nBLM -> Interlock; Damage model for protection
- ~ **µC lost over 200 µs to many seconds** (diffusion time)
  – icBLM, nBLM -> Interlock; Damage model for protection
- ~ **"1 Watt/meter" radiation dose management**
  – icBLM, nBLM -> alarm based on dose/activation plan



ESS BLM: Response time

- Required response time set in the past:
  - NC linac (MEBT-DTL): ~5 μs.
  - SC linac: ~10 μs.
  - Numbers based on a simplified melting time calculations, where a block of material (copper or stainless steel) is hit by a beam of protons with a uniform profile under perpendicular incidence angle, no cooling considered [9].
- Numbers re-checked with a Gaussian beam and update beam parameters:
  - **NC linac:** calculated melting time values of 3-4μs imply even stronger demands on the response time (confirmed with a MC simulation as well).
  - **SC linac**: the 10μs requirement for response time fits well with the results of this calculations.
    However: other damage mechanisms ma mandate even shorter response time SCL (discussed further).



ESS BLM: detector layout (MEBT-MB)

nBLM-F vs. nBLM-S

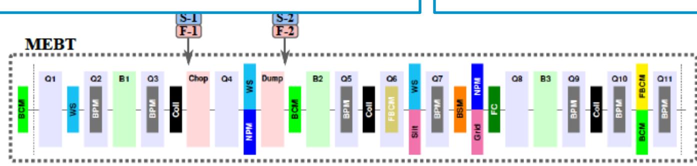
- Majority of the linac: F and S placed separately in an alternating fashion
- At certain locations: a pair of F & S device

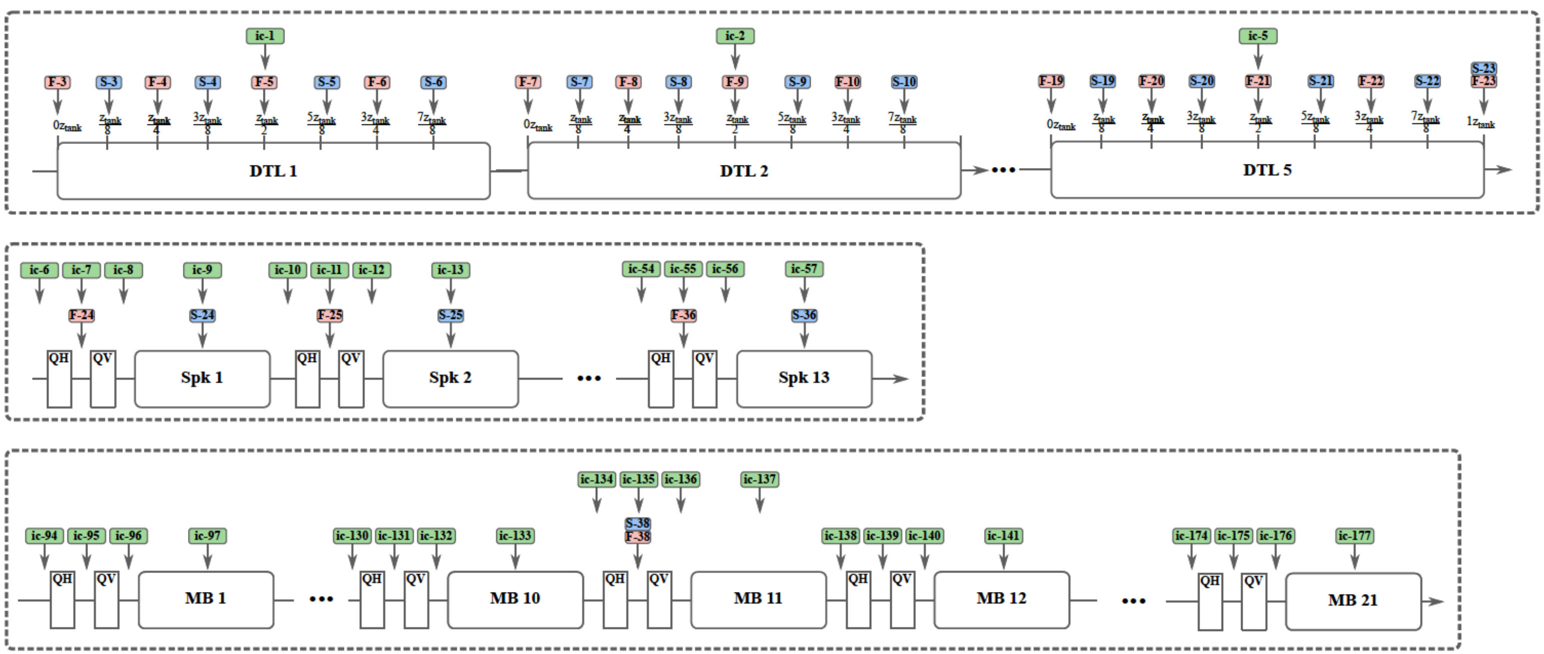
Normal conducting linac (NCL):

- **nBLM:**
  - MEBT: 4 devices (nBLM)
  - DTL: ~ 1 device / 1m
- **icBLM:**
  - DTL: 1device/tank

Superconducting linac (SCL):

- **nBLM**
  - Spoke: 1 device / 2m
  - Sparsely located in other parts of SCL
- **icBLM:**
  - 3/quad pairs
  - 1/cryo





ESS BLM: detector layout (HB – end)

nBLM-F vs. nBLM-S

- Majority of the linac: F and S placed separately in an alternating fashion
- At certain locations: a pair of F & S device

Normal conducting linac (NCL):

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  - MEBT: 4 devices (nBLM)
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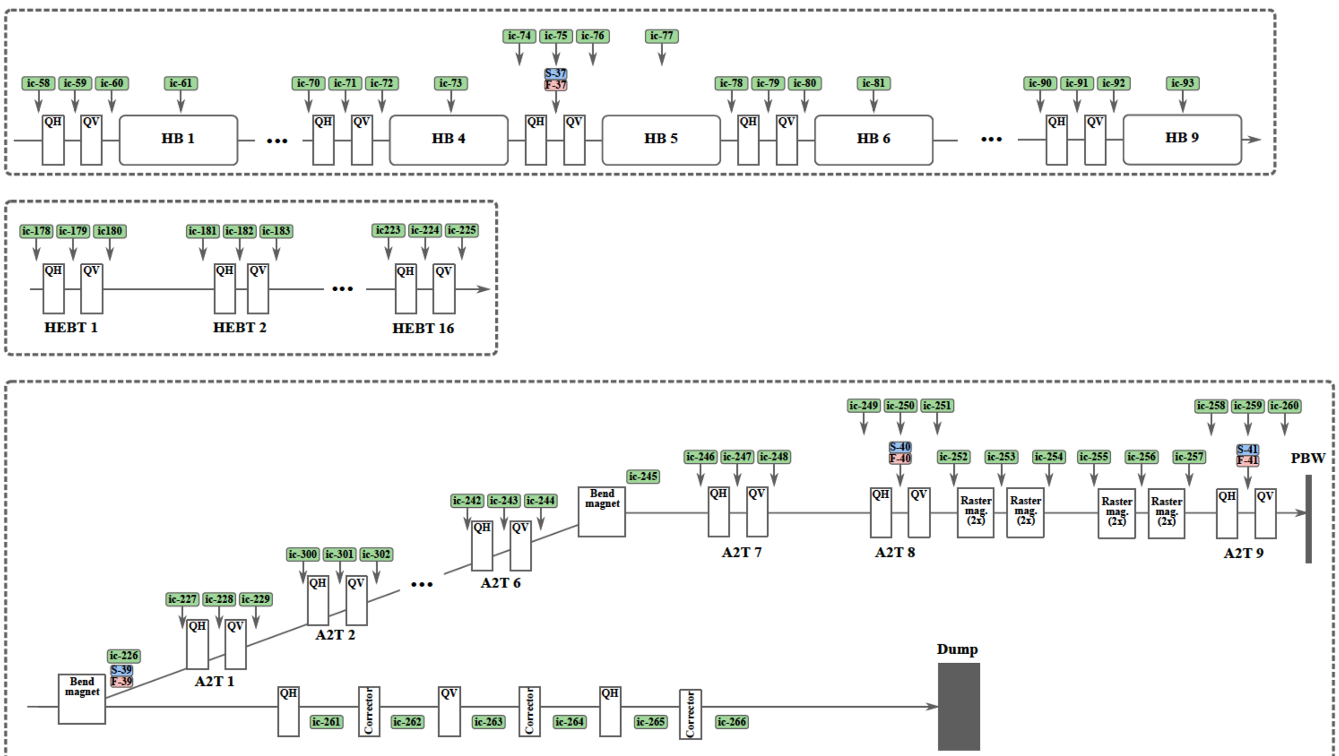
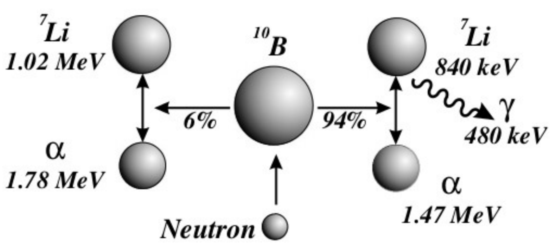


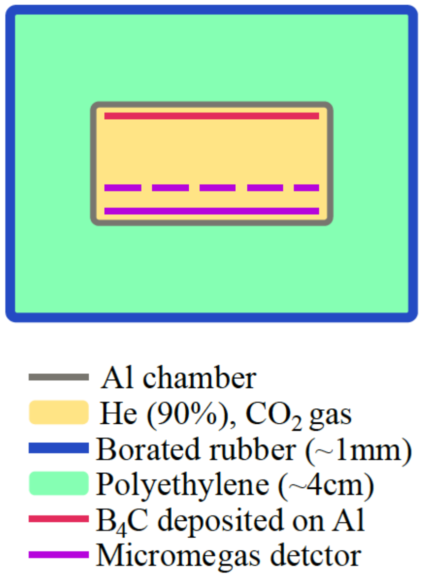
nBLM: Detectors (1)

nBLM detectors:

- 2 types,
- depending on location placed separately or back-to-back (detector unit)

- **1st module (slow losses): nBLM-S**
  - Capable of monitoring low fluxes (~few n $cm^{-2}s^{-1}$).
  - Response time: ~200µs (~10% events detected in 4µs).
  - Polyethylene (~4cm): moderator to thermalize the incoming fast n.
  - B_4C layer (deposited on the Al surrounding the gas chamber) to capture thermalized n – (n,α) ^{10}B reaction (α with fixed energy of 1.4MeV).
  - Borated rubber to eliminate background thermal *n*.
  - Efficiency: few 10^{-2} (1eV < E_n< few 10MeV)
  - Solid angle: 4π





nBLM: Detectors (2)

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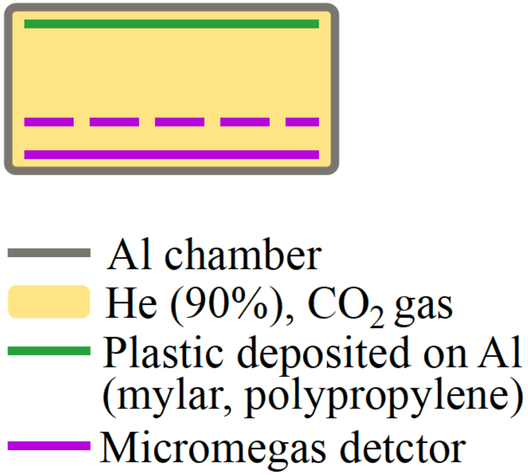
nBLM detectors:

- **2^{nd} module (fast losses): nBLM-F**
  - appropriate for high fluxes of fast *n*, coming from the front (~few 0.01 *n* $cm^{-2}s^{-1}$).
  - Polypropylene (deposited on Al foil at the entrance window) for n conversion to *p* recoils (~ few mm) through *n* elastic scattering on H atoms (continuous distribution of recoiled *p* energies).
  - Cross-section threshold: E_n~0.5MeV.
  - Efficiency: 10-100 times lower than for nBLM-S (10^{-5}–10^{-3} for *En*= ~0.5MeV – 10MeV)
  - Solid angle: 2π
  - Response time: ~10ns



nBLM: Signals

- Typical neutron signal:
  - 30-50ns rise time
  - 100-200ns signal length
  - Amplitude
    - ~Constant for S
    - Continuous distribution for F

- nBLM originally planned to operate in **counting mode**

- MC simulations: up to GHz rates expected in case of complete loss.

	Rates	
	1% 1W/m	Complete beam loss (rate in 1st μs)
Slow	0.1 – 68 kHz	10MHz – 60 GHz
Fast	1 – 400 Hz	2-700 MHz

- Minimum response time for the system to drop the BEAM_PRMIT: ~5µs
- If counts are monitored in 1µs time window: pile-up when $\gtrsim$6 counts ("neutron events") $\Longrightarrow$ transition to **current mode.**
- The FPGA neutron detection algo. is foreseen to automatically transition to current mode (monitoring both TOT and Q).

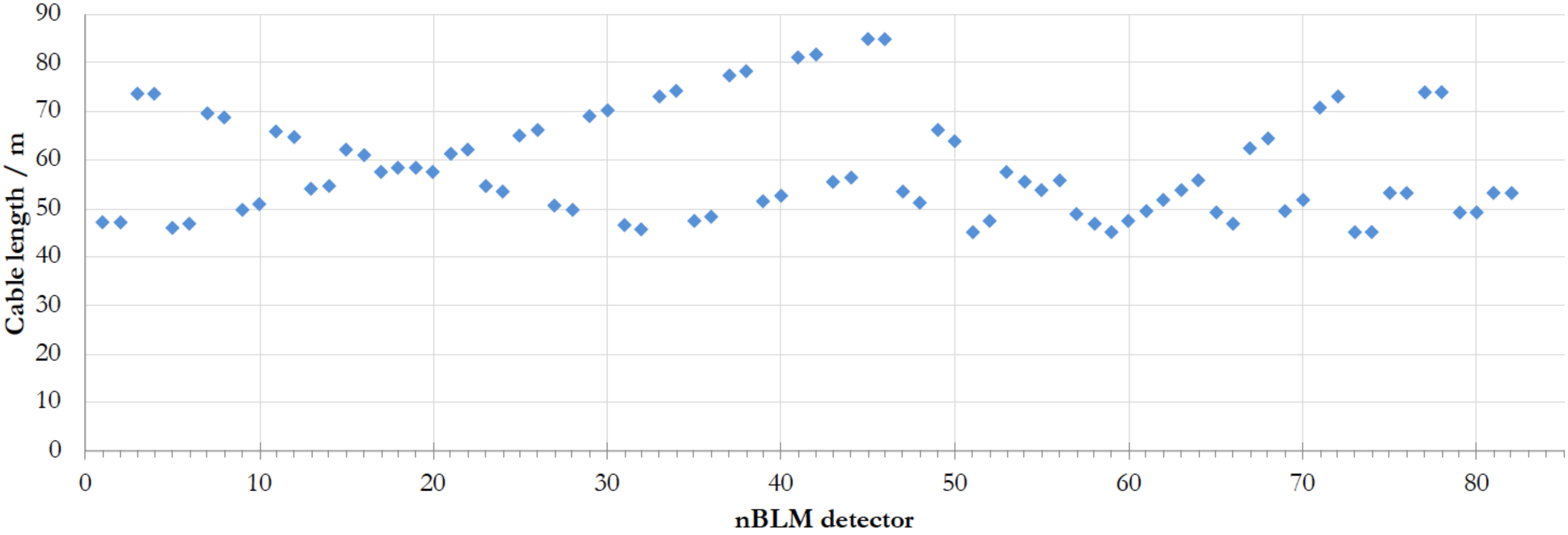
nBLM electronics layout: signal

3 groups of detectors

- To limit the situations with larger parts of the system un-operational
- MEBT - Spoke: signal electronics for each group placed in separate racks
  - Group1: Odd pairs of S & F detectors
  - Group1: Even pairs of S & F detectors
- MB - A2T: Group3

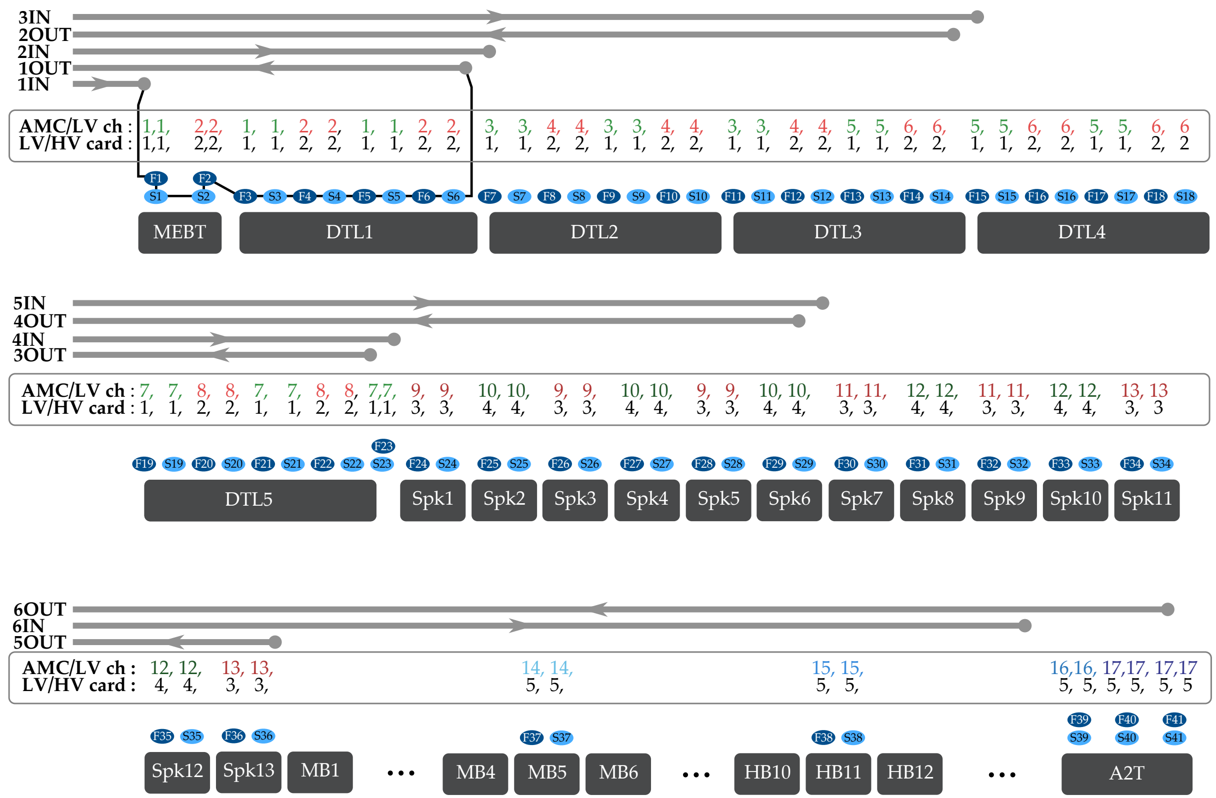
nBLM electronics layout: signal

Estimated signal cable lengths 40 – 90m



nBLM electronics layout: HV, LV

- Same crate for LV and HV PS
- 2 HV lines per detector
- Each LV channel used to power several detector modules
- 2 crates along the linac
  - Separation in HV and LV connections between group 1 and 2 not possible down to the rack level
  - A set of detector modules
    - connected to an AMC/FMC has FEE powered by the same LV channel
    - with signal connected to the same rack has all HV cables connected to the same HV module



nBLM electronics layout

Rack	Detector count	AMC count	Crate count	Detectors per AMC	AMC tag	Spare cables per rack
FEB-050ROW	24	4	2	(6+6),(6+6)	(1,3),(5,7)	2
SPK-010ROW	22	4	2	(6+6),(6+4)	(2,4),(6,8)	2
SPK-030ROW	14	3	1	(6+4+4)	(9,11,13)	2
SPK-050ROW	12	2	1	(6+6)	(10,12)	2
MBL-050ROW	2	1	1	(2)	(14)	4
HBL-090ROW	2	1	1	(2)	(15)	4
HEBT-030ROW	2	1	1	(2)	(16)	1
A2T-010ROW	4	1	1	(4)	(17)	1
Sum	**82**	**17**	**10**			**18**

Table 3: Summary of the nBLM system signal connections. The column marked with "Detectors per AMC" indicates the number of detectors connected to a crate or AMC board. The parenthesis "()" and "+" sign are used to differentiate between the crates and AMCs respectively. The colours mark different detector groups as explained in the text and shown on figure

Rack	Det. count	Det. location	LV card count	LV card tag	Det. per LV card	Spare cables per rack
FEB-050ROW	74	MEBT–MB	1	LV1	6+6+6+6	2
			1	LV2	6+6+6+4	
			1	LV3	6+4+4	
			1	LV4	6+6+2	
SPK-010ROW	0	/	0	/	0	2
SPK-030ROW	0	/	0	/	0	2
SPK-050ROW	0	/	0	/	0	2
MBL-050ROW	0	/	0	/	0	4
HBL-090ROW	0	/	0	/	0	4
HEBT-030ROW	8	>MB	1	HV5	2+2+4	1
A2T-010ROW	0		0		0	1

Table 5: Summary of the nBLM LV connections. The column marked with "Det. per LV card" indicates the number of detectors connected to each LV card. The "+" sign is used to differentiate between the channels on a certain LV card. The colours mark different detector groups as discussed in the text and shown on figure 6

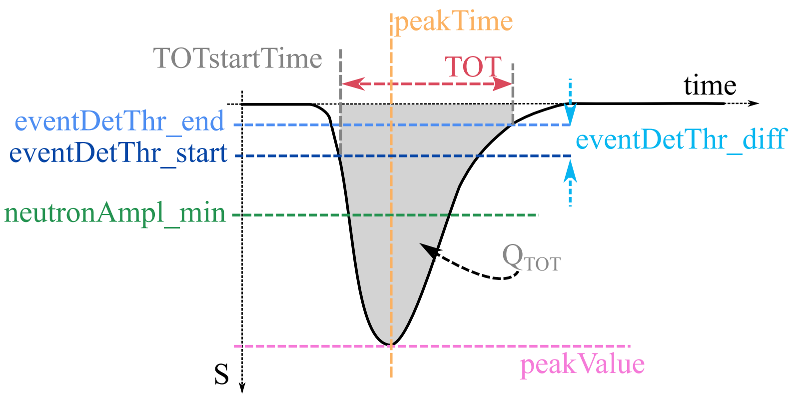
Rack	Det. count	Det. location	HV card count	HV card tag	Det. per HV card	Spare cables per rack
FEB-050ROW	74	MEBT–MB	1	HV1	24M+24D	2M+2D
			1	HV2	22M+22D	
			1	HV3	14M+14D	
			1	HV4	12M+12D+2M+2D	
SPK-010ROW	0	/	0	/	0	2M+2D
SPK-030ROW	0	/	0	/	0	2M+2D
SPK-050ROW	0	/	0	/	0	2M+2D
MBL-050ROW	0	/	0	/	0	4M+4D
HBL-090ROW	0	/	0	/	0	4M+4D
HEBT-030ROW	8	>MB	1	HV5	2M+2D+2M+2D +4M+4D	1M+1D
A2T-010ROW	0		0		0	1

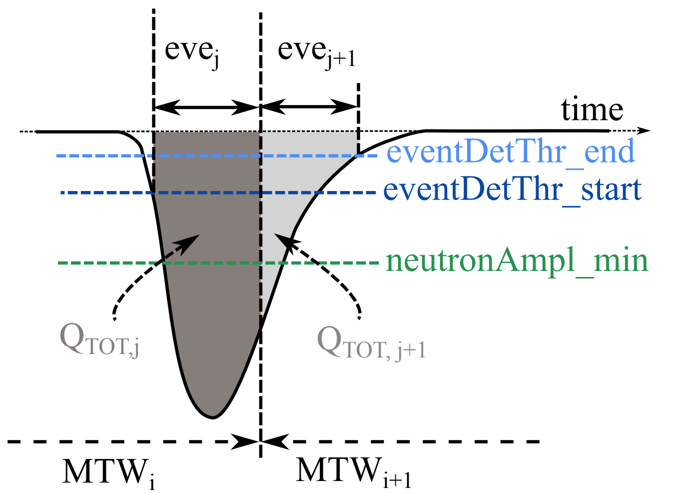
Table 4: Summary of the nBLM system HV connections. The column marked as "Det. per HV card" indicates the number of detectors powered by each HV card. Note that each a detector needs two HV connections, one for meash (M) and one for drift (D). The colours mark different detector groups as discussed in the text and shown on figure 6.

nBLM: neutron detection algo

"Interesting Event"

- Basic rule:
  - Starts when signal falls below start event threshold.
  - Ends when signal exceeds the end event threshold.
- Exceptions when signal extends over MTW edge
  - Split signal in 2 events if:
    - At the MTW edge the signal already qualifies as a single neutron.
    - Event too long (longer max TOT for a single neutron)
  - Otherwise end the event when signal exceeds end event threshold in the following MTW.

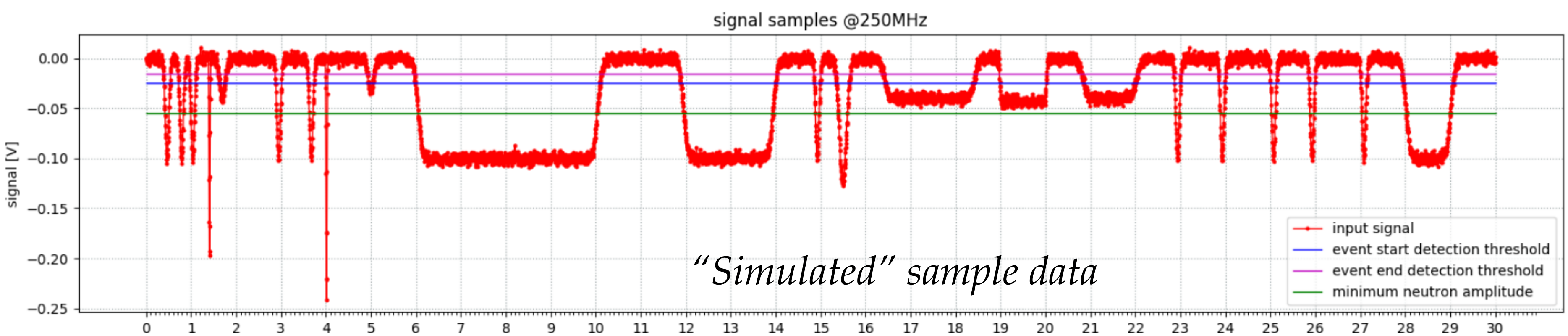




nBLM: neutron detection algo

"Interesting Event" types

- Single neutron
- Neutron pile up
- Background (gamma or other)
- Spike/noise, spark



nBLM: neutron detection algo

Neutron identification

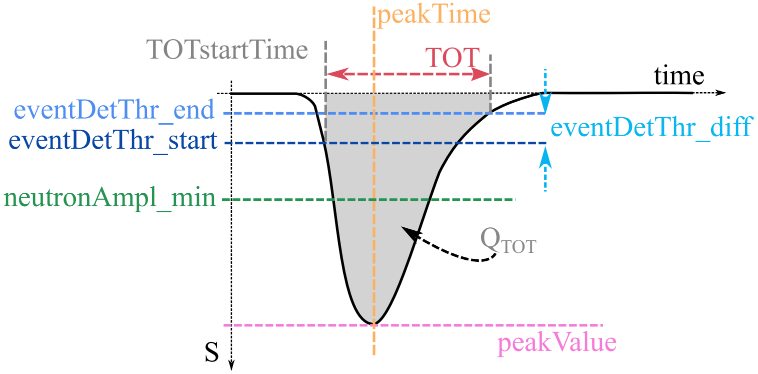
- Single neutron
  - TOT: within limits
  - Amplitude: below the threshold
- Pile up neutrons
  - TOT larger than for single neutron
  - Amplitude: below the threshold

$$\texttt{pileUpTOT\_start} > \texttt{TOT}_j \geq \texttt{neutronTOT\_min}$$

$$\texttt{peakValue}_j \leq \texttt{neutronAmpl\_min}$$

$$\texttt{TOT}_j \geq \texttt{pileUpTOT\_start}$$

$$\texttt{peakValue}_j \leq \texttt{neutronAmpl\_min}$$



Background identification

- Valuable for
  - Comparison with icBLM data and/or
  - Crosscheck that algo or detector settings are ok
- Initial version:
  - TOT above the limit for single neutron
  - Amplitude above single neutron limit

$$\texttt{TOT}_j \geq \texttt{neutronTOT\_min}$$

$$\texttt{peakValue}_j > \texttt{neutronAmpl\_min}$$

nBLM: neutron detection algo

Neutron Counts per MTW:

$$N_{MTW,i} = N_{n;MTW,i} + N_{qtot;MTW,i} = \sum_{j=1}^{n_{eve;MTW,i}} \left(N_{n,j} + N_{qtot,j}\right)$$

Number of single neutron events with i-th MTW (**Single neutron counting method**)

Number of neutrons within i-th MTW calculated through **charge method**

- For pile up (or split) events:

$$N_{qtot,j} = \frac{\text{Q\_TOT}_j}{\langle \text{Q\_TOT}_{1n} \rangle}$$

- Else:

$$N_{qtot,j} = 0$$

nBLM: neutron detection algo

Neutron detection related blocks

- "Event Detection"
  - Detects start of an "interesting event"
  - Updates `EvenInfo` every 4ns
- "Neutron counter"
  - Ends event and resets `EventInfo`
  - Sums and resets neutron counts at the end of each MTW