Beam Instrumentation performance during commissioning of the ESS Normal Conducting linac

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IBIC'23, 12th September 2023 - TU1I02

Outline

- ESS facility
- ESS linac – overview and commissioning plan
- ESS linac Beam Instrumentation
  - Deployed for the Normal Conducting Linac (NCL) commissioning phase
  - Key features and contributions for selected systems
- Summary

ESS – European Spallation source

EUROPEAN SPALLATION SOURCE

- ESS – research facility under construction
  - Provide **neutron beams** for neutron based research.
  - Neutron production based on bombardment of a tungsten **target** with a proton beam generated by a **pulsed linac**
- Location
  - ESS currently under construction in Lund, Sweden
  - DMSC (Data Management Software Centre) based in Copenhagen, Denmark
- ESS – European project
  - 13 founding countries
  - Over 40 European partner institutions
  - Over 130 collaborating institutions worldwide
  - Collaborating under in-kind model

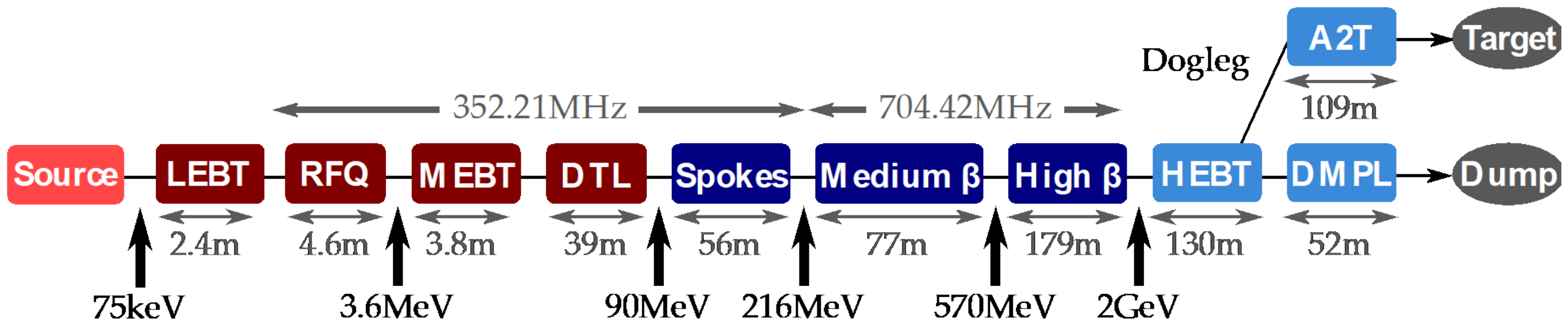
Acknowledgments

We wish to thank all current and former colleagues from ESS and external institutes for their essential contribution in making the ESS linac project possible

In particular, for help received during the design, development, manufacturing, installation and testing of the BI systems:

- Bergoz (BCM)
- CAENels (ICBLM)
- CEA (nBLM, IPM)
- CERN (ICBML, Fast WS)
- DESY-Hamburg (BCM, BPM)
- Elettra-Sincrotrone (WS)
- ESS Bilbao (EMU, WS, BPM, BCM)
- INFN-Legnaro (BCM, BPM)
- LUT (nBLM, ICBLM)
- Pantechnik (LEBT and MEBT FC)
- Radiabeam (DTL4 FC)
- STFC-UK (BCM, BPM)
- University of Oslo (Target Imaging)
- University West (Luminescent coating)
- WUT (installation, BCM)

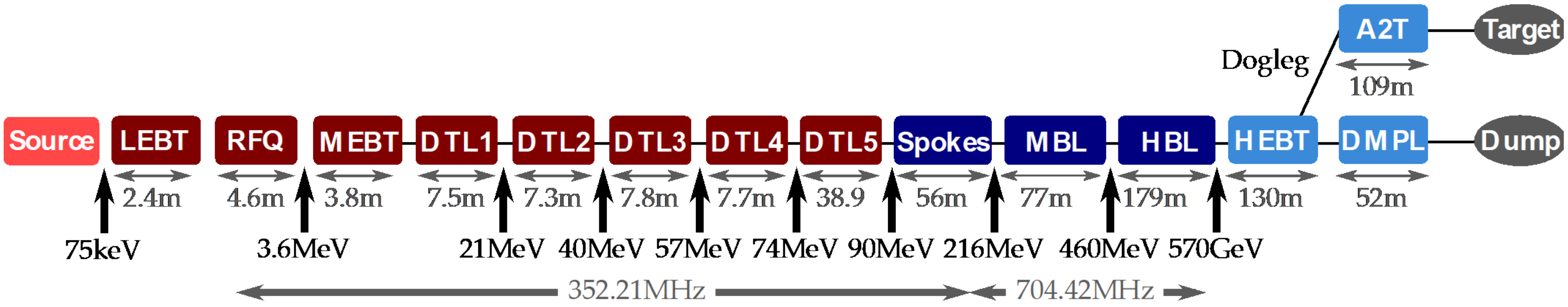
ESS linac
Overview



- **NCL - Normal Conducting Linac**
  - Ion Source, LEBT, RFQ, MEBT, DTL (5)
- **SCL – Superconducting Linac**
  - Spoke (13), MBL (9), HBL (21/5/0)
- **Beam Delivery and Transport Line**
  - HEBT (contingency, upgrade; up to 16 additional cryomodules)
  - Dump line
  - dogleg (4^o, 4.5m elevation), A2T

Parameter	Value
Average beam power – design	5 MW
Beam energy – design	2 GeV
Average beam power – initial op.	2 MW
Beam energy – initial op.	800 MeV
Average beam power – 1st beam on Target	1.4 MW
Beam energy – 1st beam on Target	570 MeV
Peak current	62.5 mA
Beam pulse length	2.86 ms
Beam pulse repetition rate	14 Hz

ESS linac
Commissioning



- ESS linac commissioning performed in phases.
- First 4 phases
  - In parallel to commissioning, installation downstream of the end destination
  - Completed
- Focus here: 4th phase, DTL4 commissioning run

Commissioning phase end destination	Start - End	Energy [MeV]
LEBT	2018/09/19 – 2019/07/03	0.075
MEBT (3 phases)	2021/11/10 – 2022/05/23	3.6
DTL1	2022/05/30 – 2022/07/22	21
DTL4	2023/04/19 – 2023/07/13	74
Dump	2024	570
Target	2025	570
Start of user program	2026	800

Beam Instrumentation for ESS linac

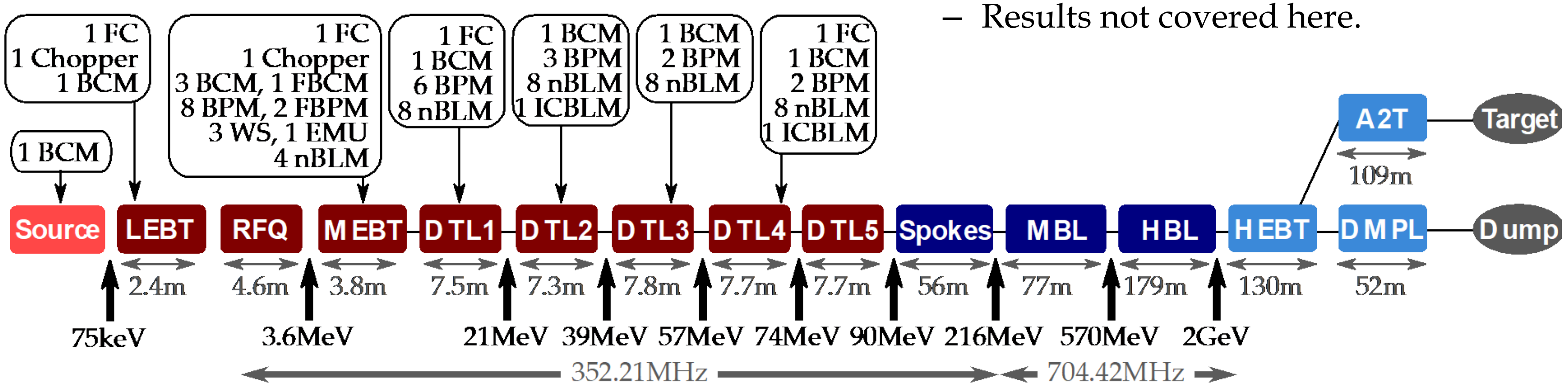
DTL4 commissioning phase

Systems critical for commissioning and agreed to be operational for certain phase

- Formal verification workflow:
  - Verified in the lab before installation.
  - Tested with other systems in the accelerator environment.
  - Verified beam → operational.
- Faraday Cups (FCs)
- Beam Current Monitors (BCMs) - **TUP038**
- Beam Position Monitor (BPMs)

Systems deployed for beam studies

- At intermediate stage of development
- To gain early experience with beam
- Collected valuable data for system development and beam characterisation
  - Neutron sensitive Beam Loss Monitors (nBLMs)
  - MEBT Emittance Measurement Unit horizontal station (EMU-H)
- Limited beam studies and offline analysis achieved.
  - Wire Scanners (WSs)
  - Ionisation Chamber based Beam Loss Monitors (ICBLMs) - **TUP004**
  - MEBT EMU vertical (EMU-V).
  - Results not covered here.



Faraday Cups

3 FCs used during DTL4 commissioning run

- Beam end-destination
- Measure transported beam current at the destination
- 6 MHz BW
- 125 MHz sampling rate, typically decimated to 10 MHz

LEBT FC

- Designed to withstand full power at the IS exit (74keV)
  - Beam current 100 mA
  - Beam pulse length up to 6 ms
  - Rep. rate 14 Hz

MEBT FC

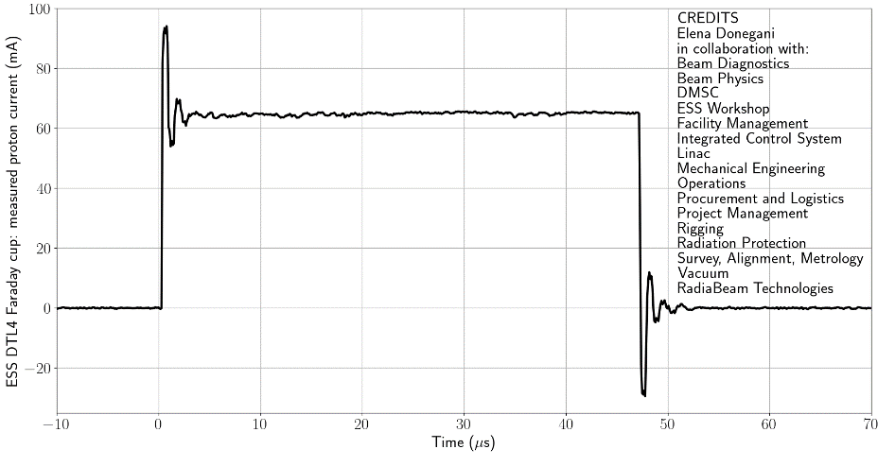
- Absorption of 3.6MeV beam with current up to 62.5mA and
  - pulse length ≤ 5 µs at rep. rate of 14 Hz
  - Pulse length ≤ 50 µs and rep rate of 1 Hz

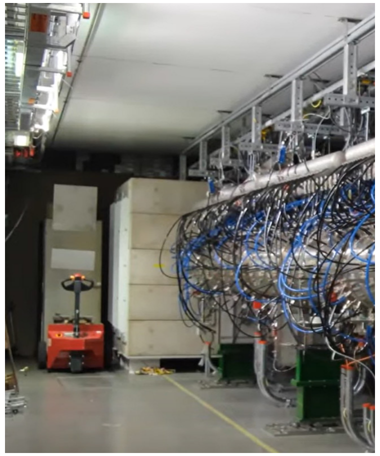
DTL4 FC

- Supported commission activities with:

Beam mode	Current [mA]	Pulse length [µs]	Rep. rate [Hz]	Restriction
Probe	6	5	1	Total pulses at 21MeV
Fast com.	6	1	14	≥39MeV
RF test	6	50	1	74MeV
Slow com.	62.5	5	1	≥39MeV
Slow tuning	62.5	50	0.2 (dose lim.)	74MeV

- In a dedicated shielding after the DTL4 tank
- The residual dose rate measured to be 1.1 mSv/h after 4 weeks of decay since the end of the DTL4 commissioning.



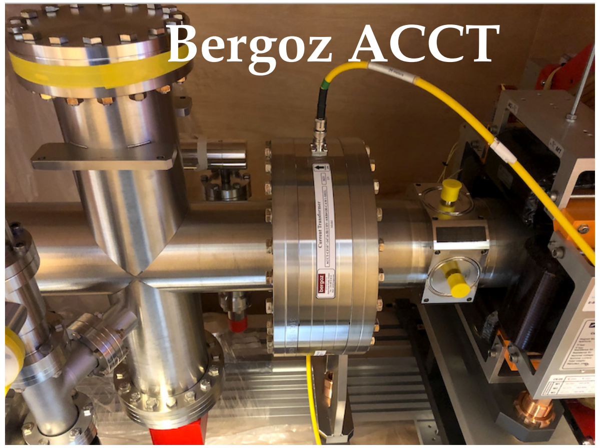


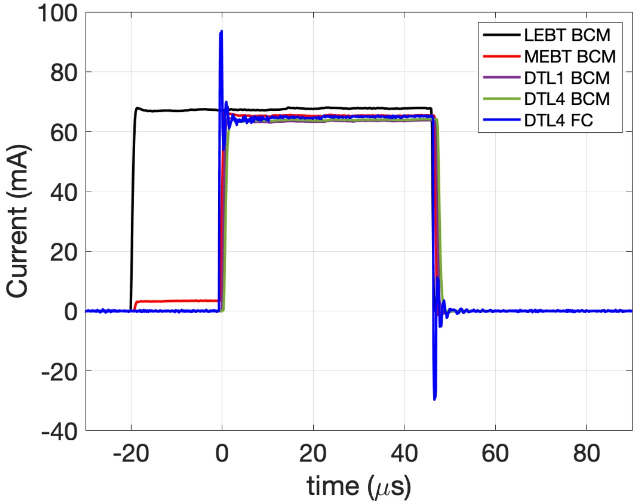
BCM
Features

- **9 BCMs** used during DTL4 commissioning phase
- **Sensors:** ACCTs mostly custom-designed by Bergoz

Measurements

- Beam current measurement
  - noise level <50µA peak-to-peak,
  - 0.1 mA accuracy,
  - 1 MHz BW
- Beam current waveform
  - 88 MHz sampling (raw), configurable for processed sampling
- Average beam current over region of interest (ROI), pulse charge
- Beam pulse width, pulse repetition rate, arrival time of beam trigger
- Beam loss – differential measurement between BCM pairs



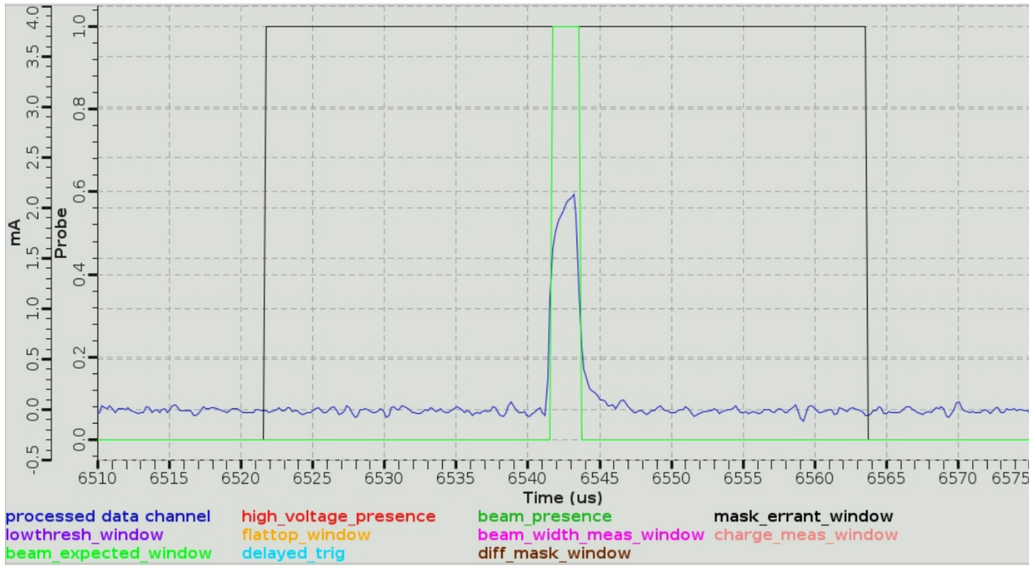


A high current beam pulse as measured by the DTL4 FC and five BCMs from the ISrc to DTL4

BCM
Features

Machine protection functions

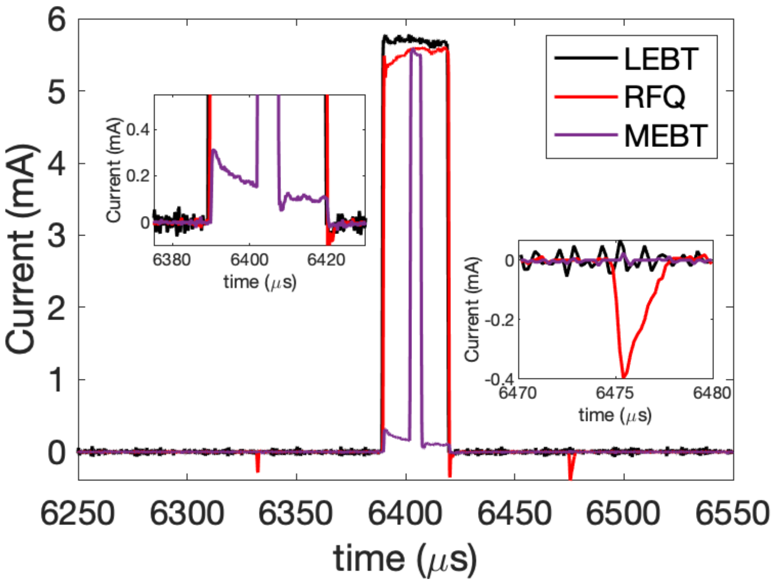
- Interlocks
  - to detect if beam current, pulse width, pulse repetition rate outside allowed limits;
  - to detect if beam pulse outside the allowed time window;
  - on differential measurement with several BCM pairs.
- Thresholds configured automatically based on selected beam destination and envelope (“beam mode”(*))
- In few cases thresholds adjusted following beam damage assessment
  - Mostly to address beam availability issues due to RF breakdowns and other disturbances **[TUP038]**
- Post-Mortem buffer implemented on FW level to capture detailed BCM data on beam trip events
- Overall reaction time of the BCM system measured to be ~1 µs

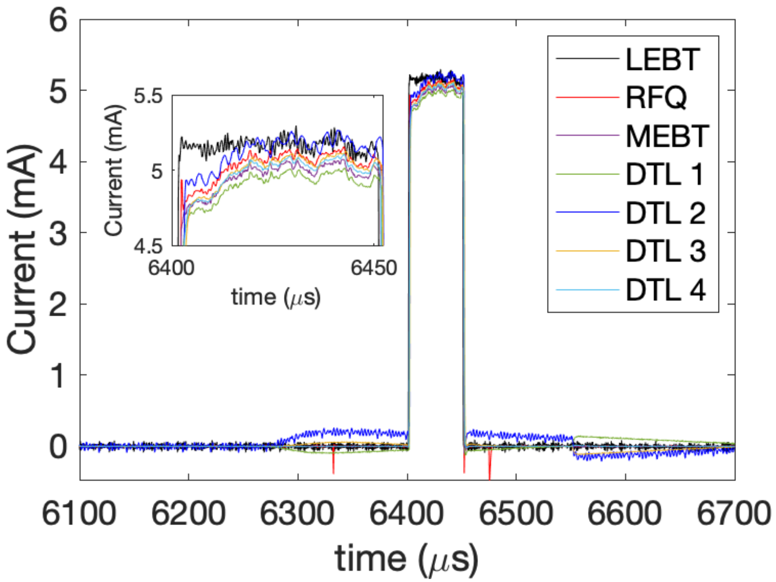


BCM processed waveform (blue) and allowed beam window (green), recorded with ~3µs, ~2mA beam

(*) Beam mode *is defined by*
- *max. beam pulse length,*
- *max current and*
- *max rep. rate.*

BCM
DTL4 commissioning run experience





MEBT chopper leakage

- Beam pulse before (RFQ BCM) and after (MEBT BCM) MEBT chopper dump.
- Non-zero floor inside the pulse on MEBT BCM
- Observed only on the BCM located just after the chopper dump (MEBT BCM).
- Leakage due to beam scattered on the chopper dump.
- Effect not observed on BPMs and FC further downstream due to geometrical constraints.

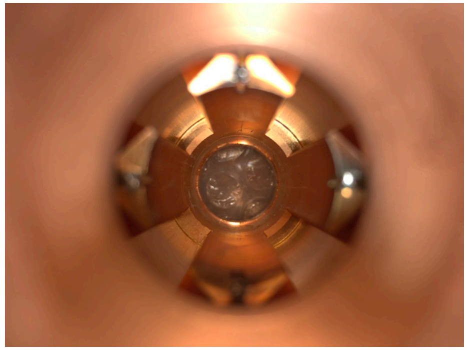
Environment

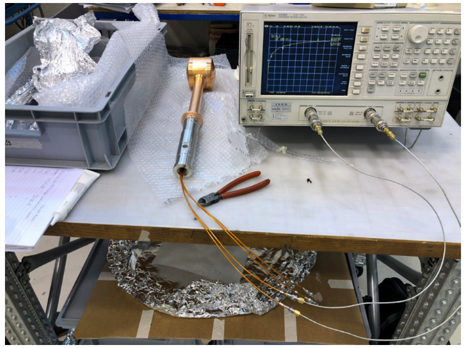
- RFQ BCM:
  - Negative spikes at the edges of RF pulse.
  - Assumed to be due to multipacting.
- DTL1 BCM, DTL2 BCM
  - Small baseline changes during the RF pulse.
  - Assumed to be due to field emission.

BPM
Features

21 BPMs operational during DTL4 commissioning phase

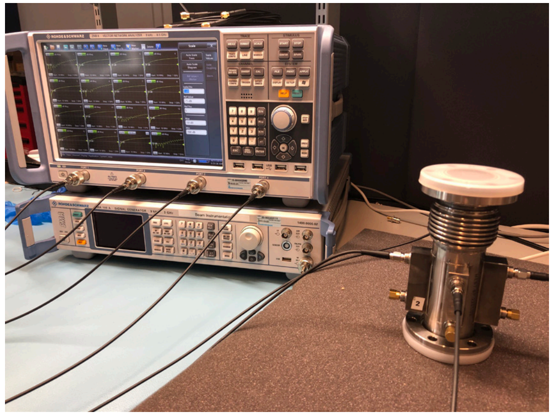
- RF systems in NCL operates at 1st harmonic (352.21 MHz)
- BPMs in NCL designed to operate at 2nd harmonic (704.4MHz) to minimize interference
- RF processing chain of the signals and data standardised for all BPMs





MEBT BPMs (8)

- Matched stripline sensors
- Placed in quads



DTL1-4 BPMs (13):

- Shorted stripline sensors
- Placed in drift tubes
- Stronger interference with RF system observed DTL1
- Strong 1st and 2nd harmonics coupling of RF system at locations in DTL where drift tubes closer to the RF ports
  - Leaking to BPM sensors nearby, interfering with the signal
  - Additional high-pass filters introduced on the BPM inputs to filter out 1st harmonic that couples into BPM sensors.
  - 2nd harmonic spectral leak from RF system is to be improved

BPM

Data and DTL4 commissioning experience

FPGA-processed data streams

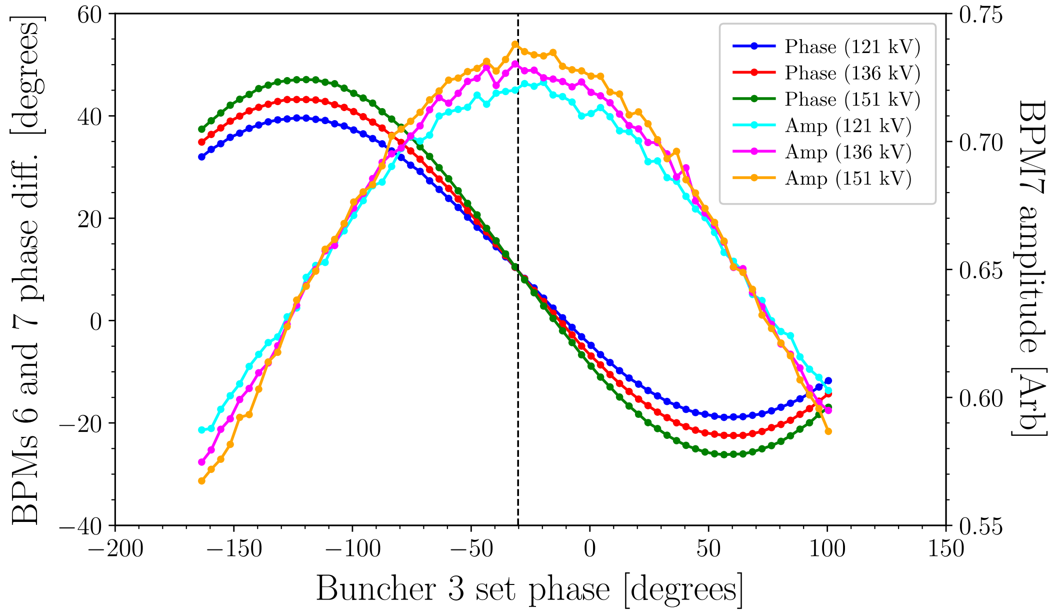
- Raw data from the 4 individual antennas
  - ~20MHz BW, 88MSa/s
- Near-IQ waveforms for positions, magnitudes and beam phases
  - ~2 MHz BW, 5.8 MHz sampling
- Averaged data for positions, magnitudes and phases
  - available at a rate of 1 per beam pulse,
  - calculated in a ROI set through timing system triggers.

DTL4 commissioning experience

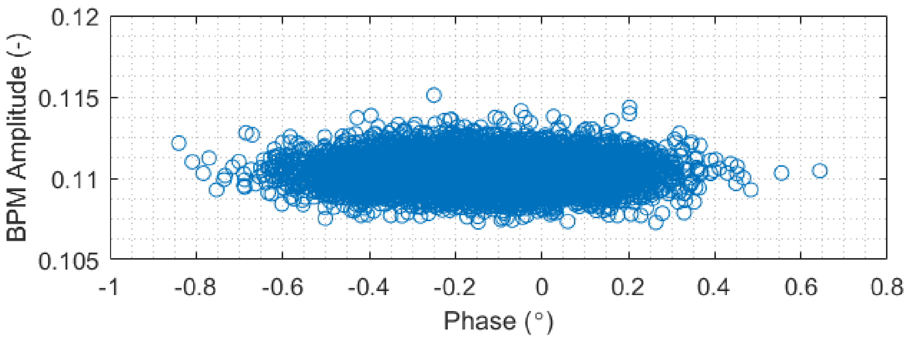
- BPMs extensively used to characterise the beam properties.
- Beam studies exploiting BPM data included
  - trajectory correction,
  - phase scans,
  - longitudinal pulse shape tuning,
  - beam timing characterisation.
- BPM waveforms crucial for
  - adjusting machine parameters to optimize uniformity in pulse characteristics within a pulse and
  - timing characterisations of the beam.

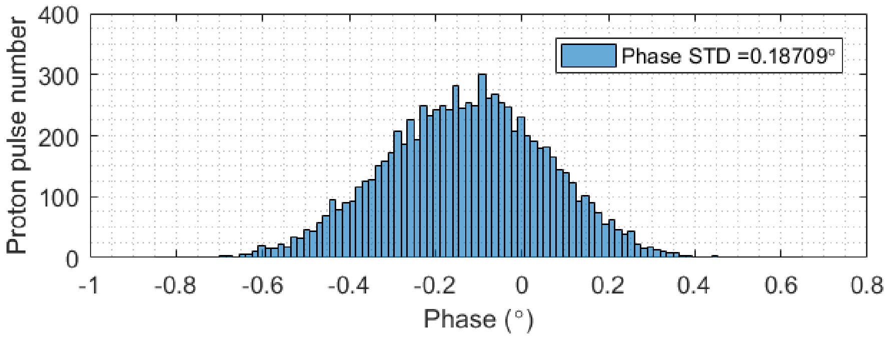
BPM
DTL4 commissioning – examples of BPM data

BPM measurements reported during a phase scan (MEBT buncher 3):
- BPM phase difference and BPM amplitude as a function of cavity set phase for different cavity set voltages
- Optimal cavity set phase
  - 90º from max. acceleration
  - BPM phase difference curves crossing
  - BPM amplitude peak



Stability run - data collected with a BPM in MEBT
- Top: 2D histogram, distribution of BPM average phase and amplitude per pulse
- Collected over 4 hours of operation with 6 mA and 5 µs beam
- Bottom: projection on x-axis
  - average phase distribution during the run
  - stability of machine and the BPM together





Bunch-by-bunch characterisations
FBCM and FBPM

Fast BPM (FBPM) and Fast BCM (FBCM)

- Provide high bandwidth and high sampling rate (20 GSa/s) measurements
- For bunch-by-bunch characterisation of the beam
  - To verify MEBT and LEBT chopper rise and fall times
  - Precise timing alignment of the two choppers.
- Both in MEBT

FBCM

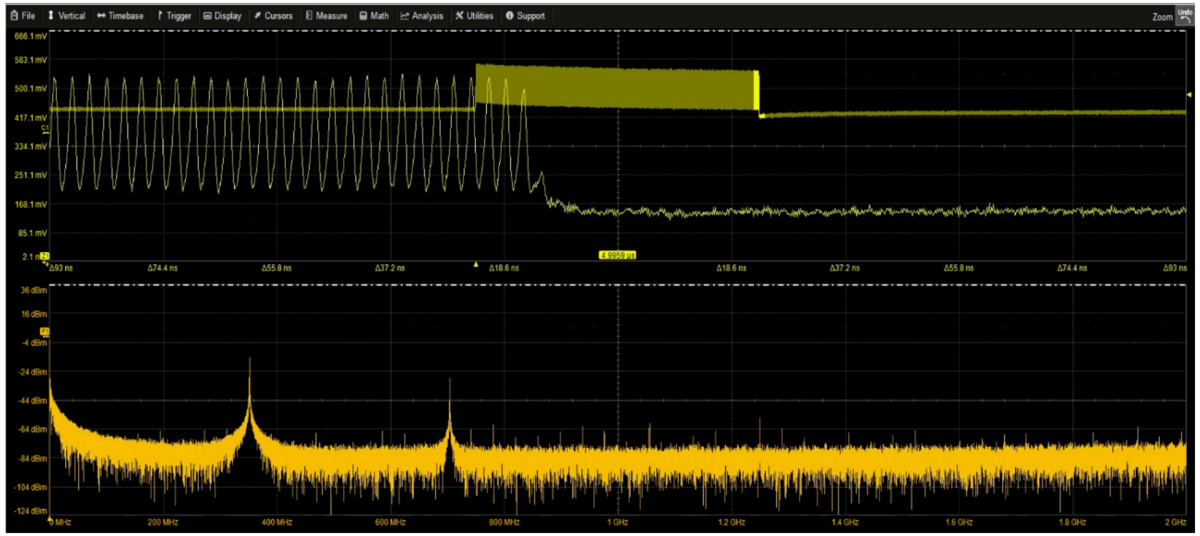
- Based on Bergoz Fast Current Transformer (FCT)
- 700 MHz BW

FBPM

- 2 regular stripline BPMs, 30.1 cm apart
- 3 GHz analogue FEE with matched propagation delay between channels (±50ps)
- Able to measure beam energy with with accuracy of ~ ±20keV and precision ~ ±100keV

FBCM:

- *Confirm Rise/fall time of the beam after MEBT chopper*
- *Measuring individual bunches*



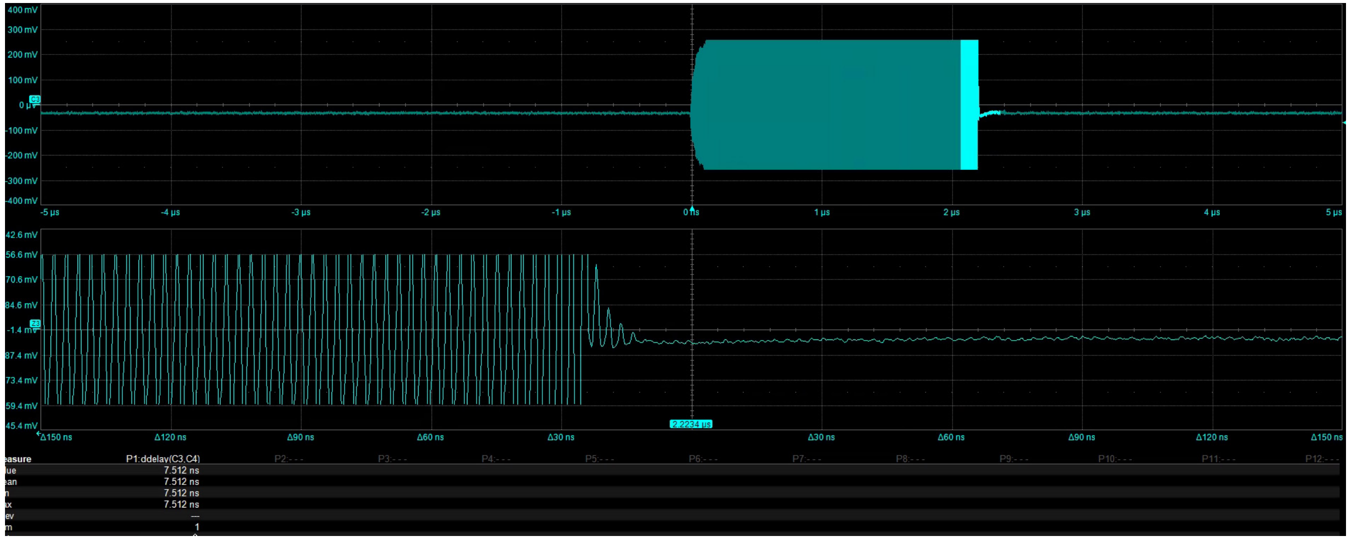
Bunch-by-bunch characterisations
Interlock reaction time

Reaction time of the complete interlock chain

- Characterised with FBPM
- Controlled interlock induced on BCM located just after MEBT chopper dump by lowering the threshold on maximum current
- Full chain reaction time consist of
  - Reaction time of BCM
  - signal transmission to FBIS, FBIS processing time,
  - signal transmission to systems acting to stop the beam production (LEBT, MEBT chopper),
  - time for systems to dump the beam
- Reaction time measured
  - With MEBT and LEBT chopper: ~2.3 μs
  - With only LEBT chopper: ~3.2 μs
  - Difference due to the beam stored in the machine between MEBT and LEBT chopper at the time of the interlock.
  - MPS requirement: 3 μs

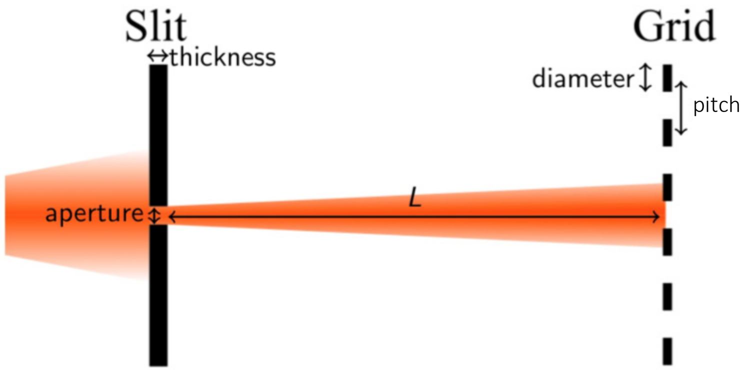
Fast Beam Interlock System (FBIS) at ESS:

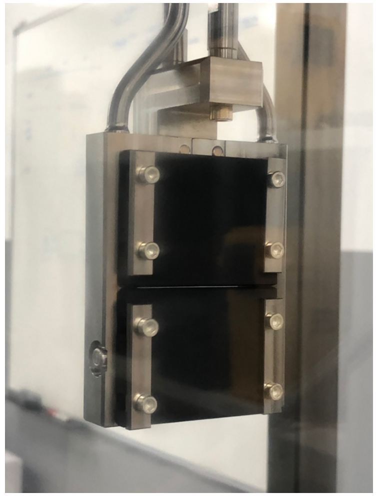
- A detection system (BCM, BLM, etc) detects unacceptable beam conditions - request to stop the beam send to FBIS
- FBIS utilises several systems to inhibit beam production – LEBT and MEBT chopper to dump the beam propagating through the front end of the linac

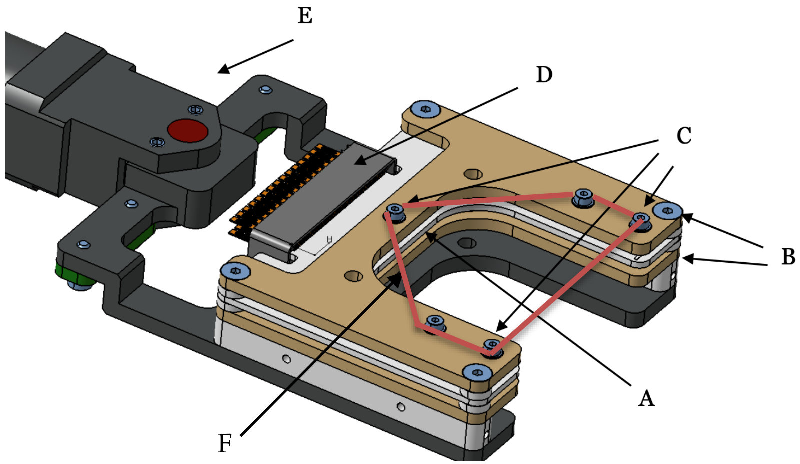


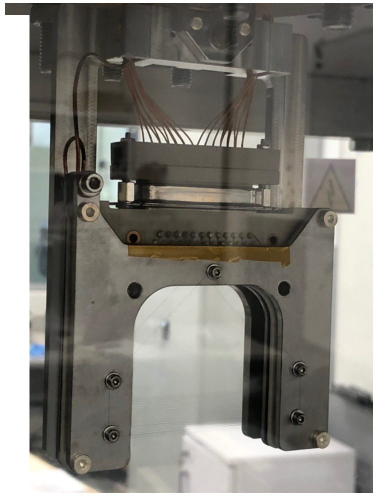
EMU
Design

- **MEBT EMU**: slit-grid type
- **Slit**
  - 368 mm upstream of grid
  - 2 graphite plates to collimate the beam reaching the grid
  - 0.1 mm aperture
  - Select a slice of beam phase space and project it on the grid.
- **Grid**
  - 24 tungsten wires, 0.5 mm pitch
  - Grid PCB (A) surrounded by bias plates (B)
    - Biased up to ±1.2kV.
    - To control the electric field experienced by the secondary electrons.
  - Additional tungsten wires (F) mounted on the bias plates to enhance the field created by the plates.
- **DAQ**
  - Signals acquired through configurable gain stages
  - Followed by 5MSa/s digitiser







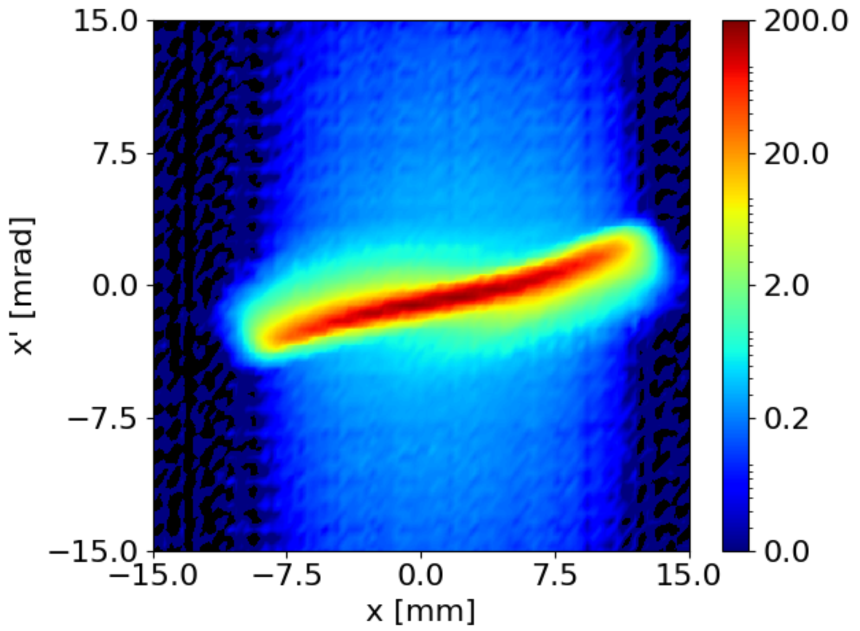


EMU
DTL4 commissioning run - results

Activities during DTL4 run:
- Signal quality investigations.
- Initial beam studies.

Scanning result for horizontal plane (at 1kV)
- Multiple slit scans
  - grid position shifted by 0/3, 1/3 and 2/3 of wire pitch
  - To improve angular resolution → 167 µm resolution
- Signal measured with 30 µs beam pulse
  - Integrated over final 15 µs
  - First 15 µs: evolution in emittance (likely from SC compensation in LEBT)
- Background over entire range of measured x′
  - Assumed to be due to beam scattering
  - Found to follow Gaussian shape
  - Preliminary analysis indicates RMS emittance close to the value expected from beam physics model

Observations:
- Bias 0V:
  - Significant contribution from SEE (neg. signal) picked up on wires adjacent to those exposed to beam
- Bias >500V:
  - Negative signals supressed
  - Positive signal enhanced by factor ~4



EUROPEAN SPALLATION SOURCE

2 types, differing in detector technology

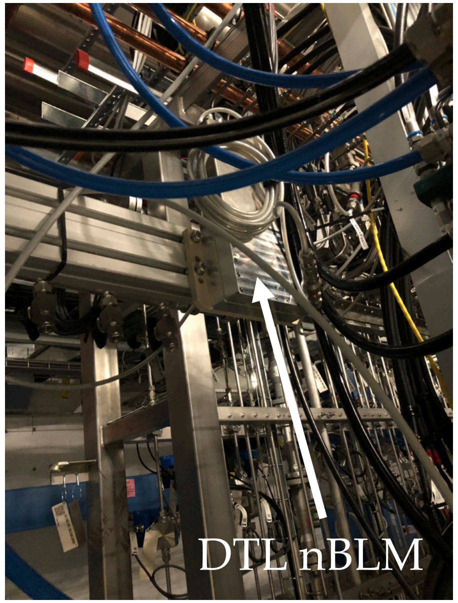
- **ICBLM – Ionisation Chamber based BLM**
  - 266 parallel plate ionisation chambers (based on LHC BLM chambers), almost exclusively in high energy parts of the linac **[TUP004]**
  - Real-time (FPGA) data processing of the raw detector signals providing induced current measurements at 1MHz rate on the FW level

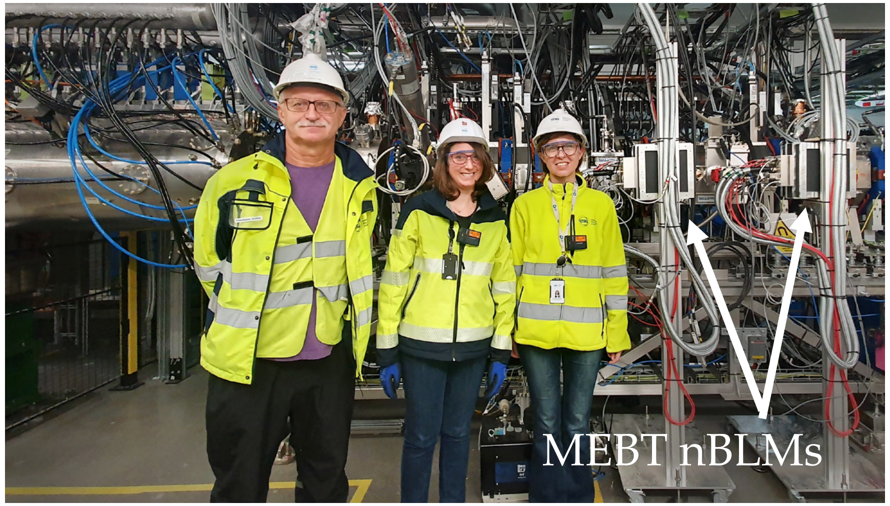
- **nBLM – neutron sensitive BLM**
  - 82 neutron detectors (Micromegas, CEA), mostly lower energy part of the linac
  - nBLM-F (fast) – for fast losses with high particle fluxes
  - nBLM-S (slow) – for losses with low particle fluxes
  - Raw signals sampled at 250 MHz (~140 MHz BW) for further processing (FPGA)
  - Discriminate fast neutrons from background (RF photons, slow neutrons) on event-by event basis – neutron rates at 1MHz on the FW level

- Available FPGA processed data:
  - For monitoring and machine protection purposes
  - Detailed data from various stages of processing (on demand)

nBLM
DTL4 commissioning run

- 36 nBLMs
  - MEBT: 2 × 2
  - DTL1 - DTL4: 4 × 8
- Collected data
  - To study system performance, background, procedure for setting system configuration.
  - Continuously collecting detailed partially processed and monitoring data during last few weeks of the DTL 4 commissioning run.
  - Dedicated experiments .
    - Different set of beam parameters constant during 30min – 1h time window.
    - Controlled loss.
  - Offline analysis ongoing.



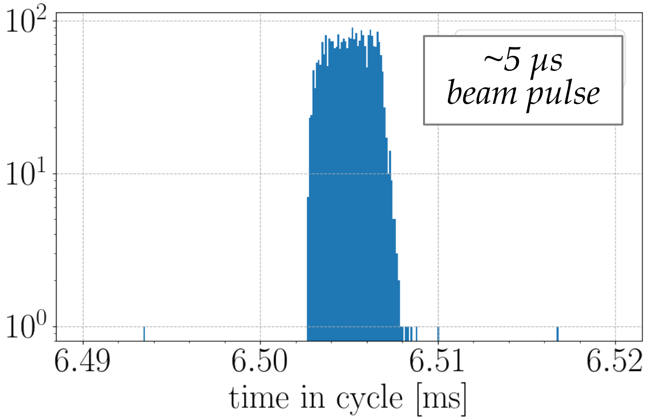


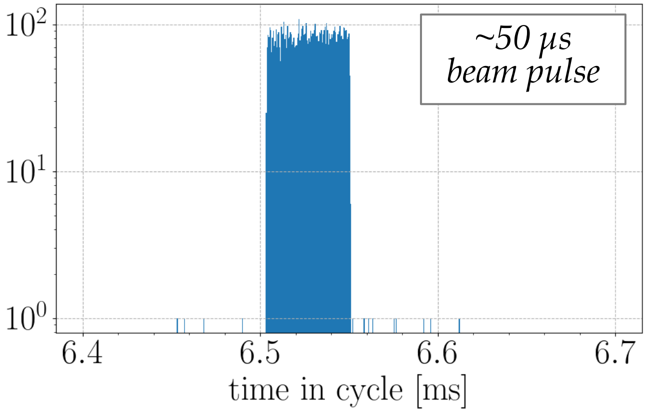
nBLM

DTL4 commissioning run - results

nBLM-F, close to end of DTL4:

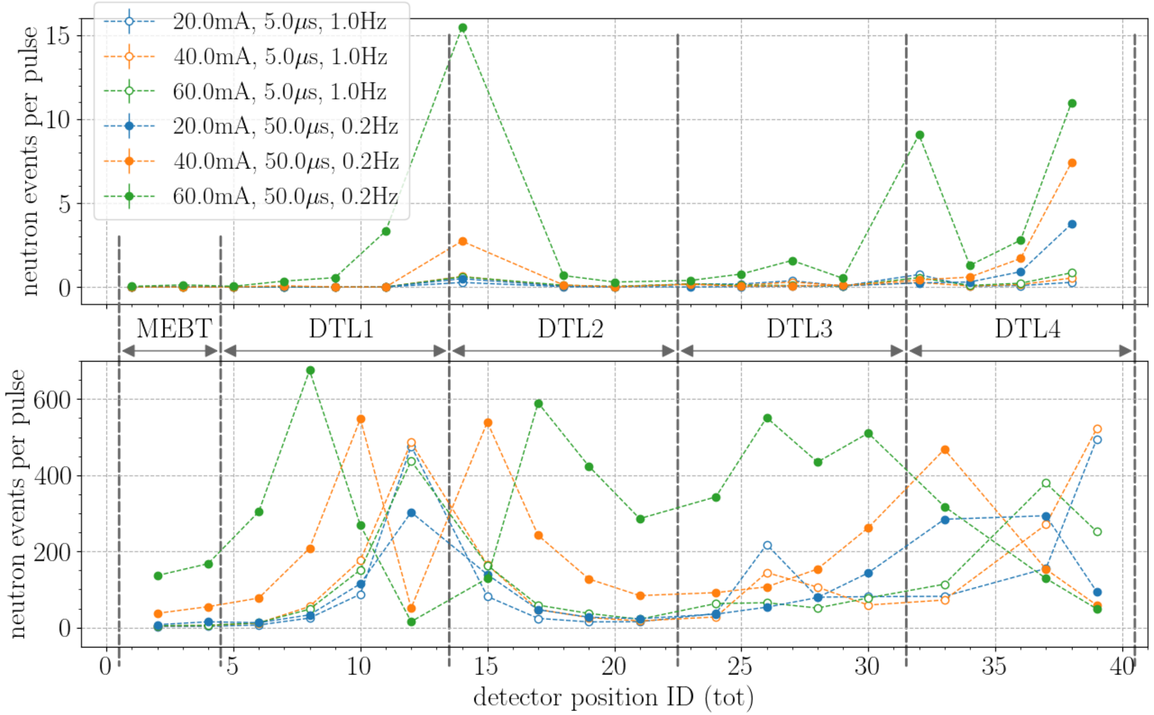
- Neutron event (single, pileup) distribution over time in machine cycle (~2-2.5h time window)
- Demonstrate pulse width and its location inside the machine cycle consistent with expected values.





Average neutron events (single, pileup) per beam pulse - preliminary:

- nBLM-F:
  - Peaks at the end of DTL3 and DTL4 consistent with observations from activation surveys
  - Peak at end of DTL1: majority of particles outside of the DTL1 acceptance are expected to be lost at the end of DTL1.
- nBLM-S:
  - Pileup: event rate defers from actual neutron rate
  - Ongoing analysis to account for that, input to neutron detection algorithm

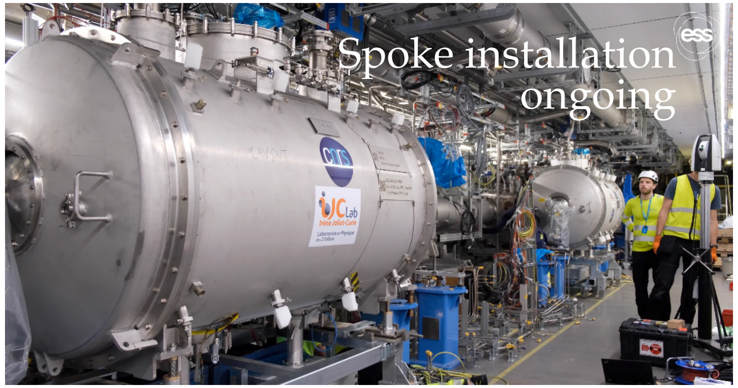


nBLM-F

nBLM-S

Summary

- NCL commissioning phase **completed**.
- Required beam instrumentation successfully supported the NCL commissioning phase.
- **Continued to install** SCL and transport line instrumentation in parallel with the NCL commissioning activities.
- Upcoming commissioning phases:
  - 2024: initial commissioning of the entire SCL and transport line to the **Dump**
  - 2025: first beam on **Target** by transporting beam through dogleg and A2T.
- **Additional instrumentation** downstream of DTL4:
  - 10 BCMs - **TUP038**
  - 77 BPMs
  - 46 nBLMs, 262 ICBLMs - **TUP004**,
  - 5 Ionisation Profile Monitors - **TUPD36** and 11 WSs
  - 4 Aperture Monitors systems,
  - 3 Target Imaging – to monitor uniformity of beam raster on the target.



Example of interesting development work at ESS on Luminescent coating (C. Thomas) of the Target wheel for the Target Imaging