Slow-Spill-Fast-Monitor at the CERN SPS

Operational Experience, Status & Plans

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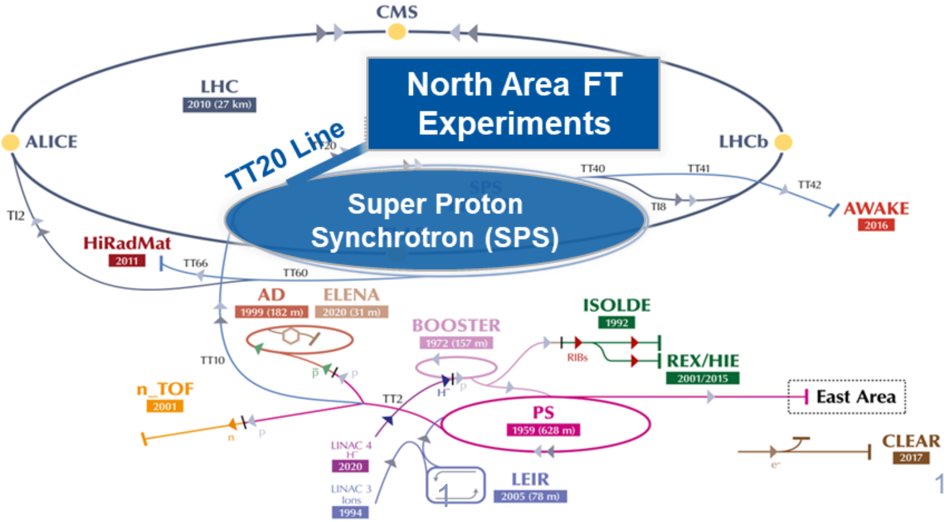


Content

- Recap of the system concept, architecture, implementations and expected performance
- 2024-2025 Experience with beam
- Outlook of next steps

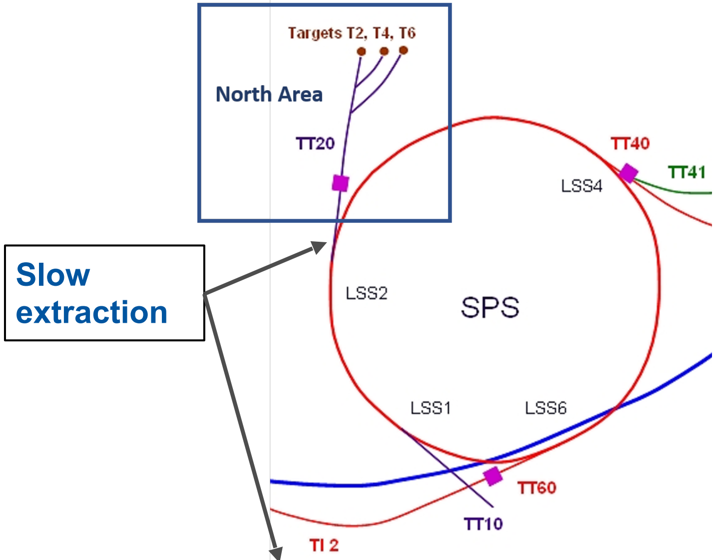
CERN SPS for Fixed Target Experiments

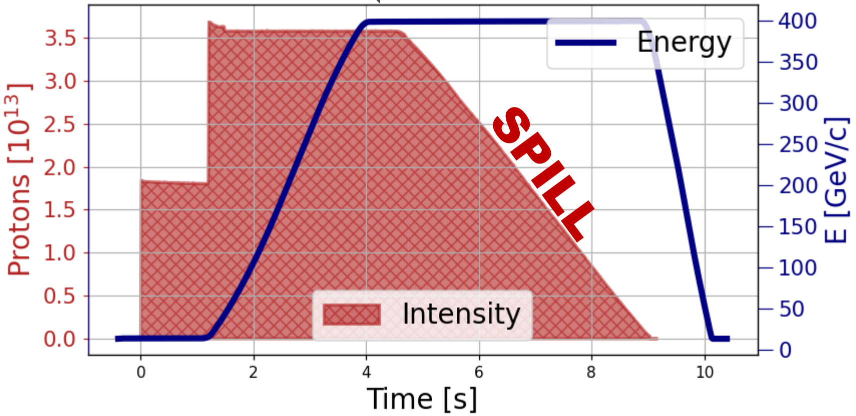
Protons @ 400 GeV sent towards NA experiments via **Slow Extraction** process

– RF disabled at flat top, ideally **fully de-bunched** beam is sent to transfer line

Spill '**quality**' affected at macro and micro-structure level by:

– **hysteresis**, non-reproducibility of **momentum distribution**, regulation and **ripples** of power supplies, **spikes** at RF switch-off





V.Kein @ : ICFA Mini-Workshop on Slow Extraction, 2022

24 Jan 2022, 06:00 → 28 Jan 2022, 08:40 Asia/Tokyo

SPS_SX_status_plans_Jan2022 (kek.jp)

Spill Monitoring Requirements - General

Table 1: Key parameters of interest for the SPS spill monitors requirements.

Parameter	Value or Range	Comment
Spill Duration	4.8 [s] 1 [s]	present operation future, e.g. PBC
Beam Intensity	1-400 [1e11p]	
Spectrum Harmonics of interest	50 Hz,100 Hz 43.86 kHz 476 kHz 200 MHz 800 MHz 10 GHz	e.g. Noise, PC ripples SPS 1^{st} and 2^{nd} Harmonics* PS $1st$ Harmonic** RF capture RF long. blow-up Future, e.g. PBC

* the SPS circulating beam structure includes 2×10 µs injections, the *abort gap* for the dump kickers rise

** the slow extracted beam can still contain a time structure from the PS (the SPS injector)

From **few nA** to **few uA**

From **few Hz** to

- **800 MHz** (SPS NA CONS, short term)
- **several GHz** (PBC, long term)

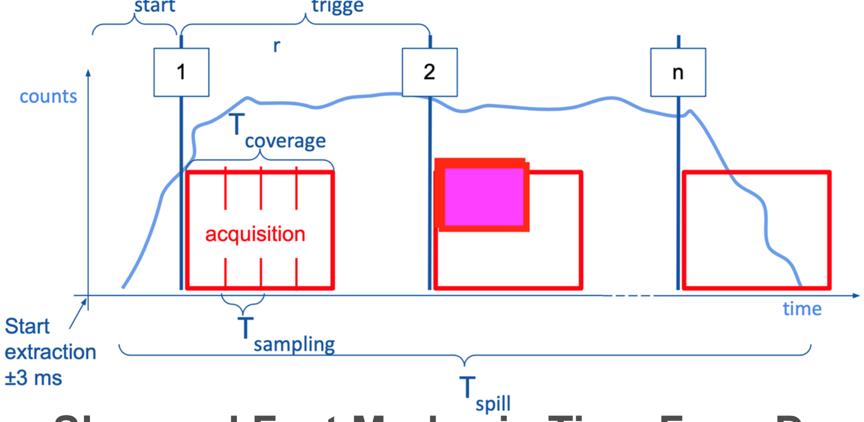
Spill Monitoring Requirements – DAQ

For NA CONS monitors == current developments

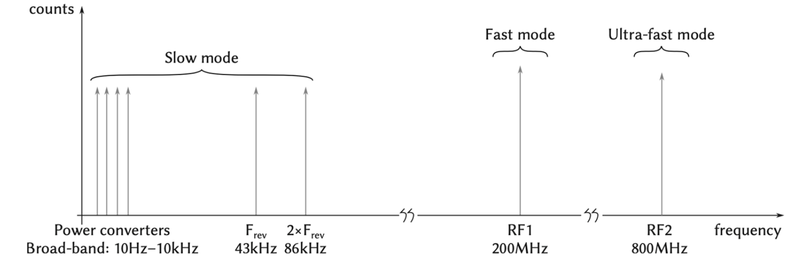
	Acquisition Mode		
	Slow	**Fast**	**Ultra-fast**
Application	Autospill, power-converter ripple	RF debunching	Empty-bucket channelling
$f_{bw} = \frac{1}{2\Delta t}$ (MHz)	≥ 0.1	≥ 10	
f_{centre} (MHz)	$f_{bw}/2$	≈ 200	≈ 800
n triggers	1	≥ 10	
$T_{coverage}$ (ms)	Whole spill	≥ 10 (per trigger)	
$T_{offload}$ (ms)	200 (example, see text)		
Phase information	Yes	No	

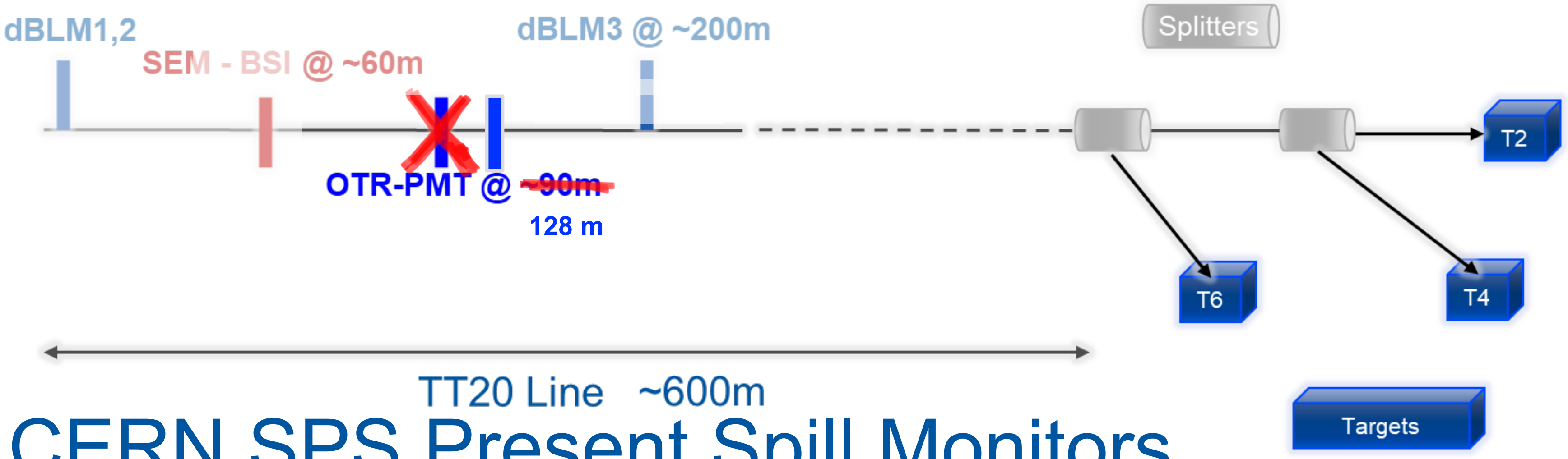
Table 3.1: List of requirements for North-Area spill monitors data processing.

Fast Mode in Time Domain



Slow and Fast Modes in Time Freq. Domain

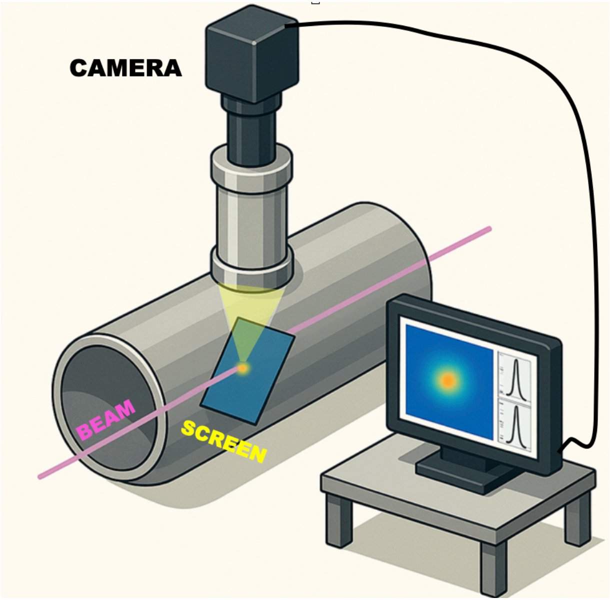




CERN SPS Present Spill Monitors

1. Secondary Emission Monitor (SEM)
2. 2 x Diamond Beam Loss Monitors (dBLM)
3. **Optical Transition Radiation – Photomultiplier Monitor (OTR-PMT)**

Optical Transition Radiation Screens



Optical Transition Radiation (OTR):
When a charged particle crosses the boundary between two media with different dielectric constants (e.g., vacuum to titanium), it emits OTR photons due to the sudden change in electromagnetic field configuration.

Key Formula:

- **OTR Photon Yield per Unit Frequency and Solid Angle (Normal Incidence):**

  $$\frac{d^2N}{d\omega d\Omega} = \frac{\alpha}{\pi^2} \cdot \frac{\beta^2 \sin^2\theta}{(1-\beta^2\cos^2\theta)^2}$$

  Where:

  - α = fine structure constant (~1/137)
  - β = v/c (relativistic factor, ~1 for high-energy beams)
  - θ = observation angle
  - ω = angular frequency of emitted light

- For ultra-relativistic beams, emission is sharply peaked at small angles ($\theta \approx 1\ /\ \gamma$).

OTR –> Photo Multiplier Tube (PMT)

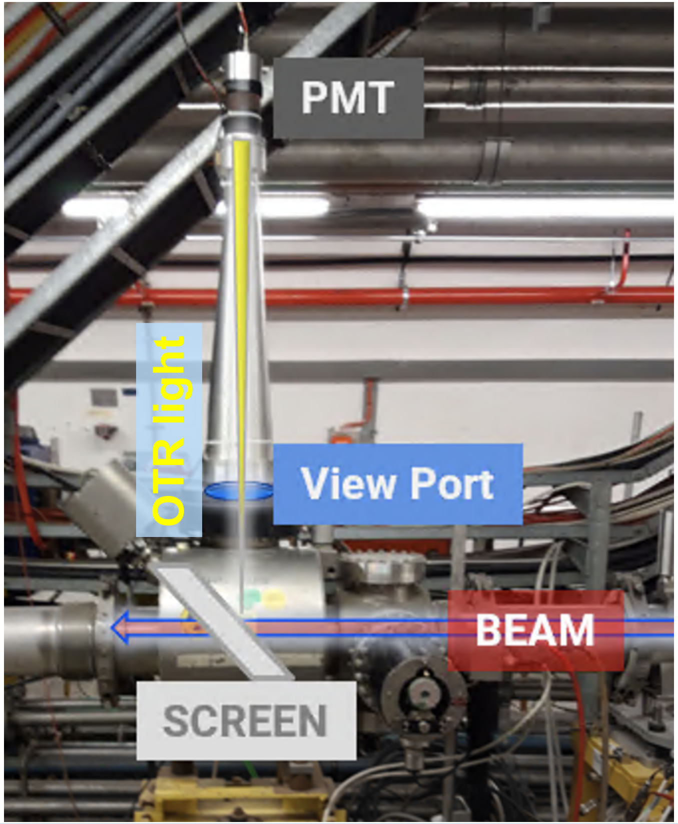
Concept: ~~imaging~~ integrate photons from OTR

2021-2022:

Existing imaging system refurbished with new Ti screen (12um thick), PMT and amplifier

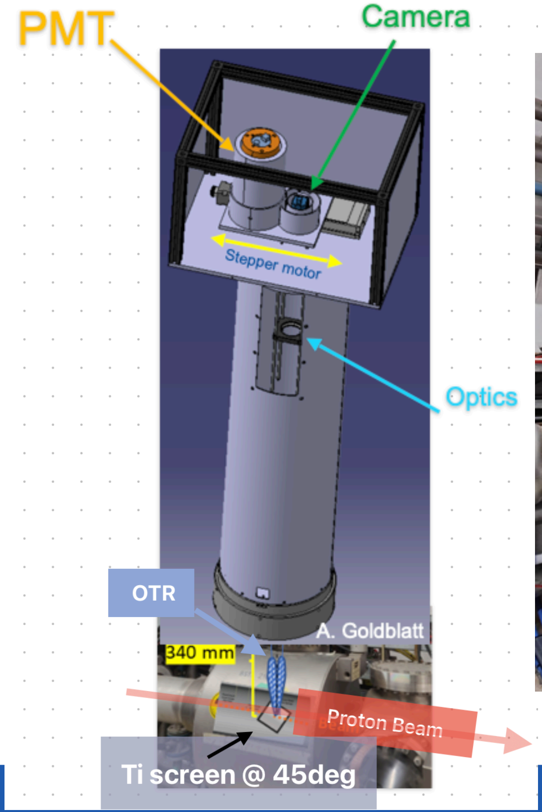
2022-2023

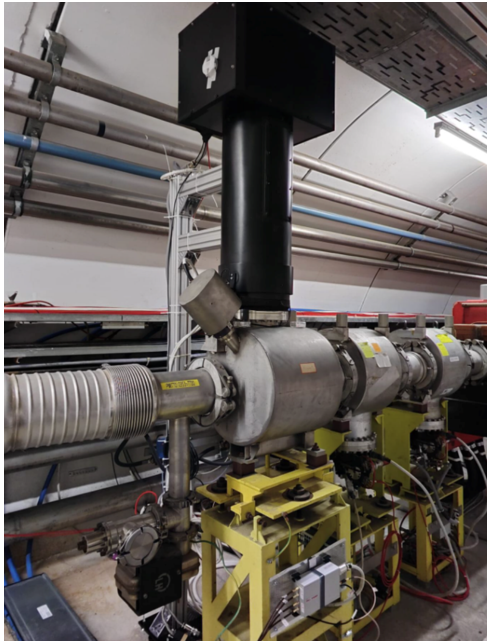
- Test measurements via non-operational DAQ (PicoScope)
- Recorder signals from DC to 300 MHz
- High signal even with OTR screen OUT → **System sensitive to beam losses**
- Small (~== no) signal increase with screen IN → **captured OTR radiation < than expected**



OTR-PMT – New Location, New Layout

- **2023-24 Shutdown**: moved to new location
- More robust optical design
- Added translation stage hosting PMT and Imaging camera, to check OTR photons are focused on sensor.





Imaging check at PMT location

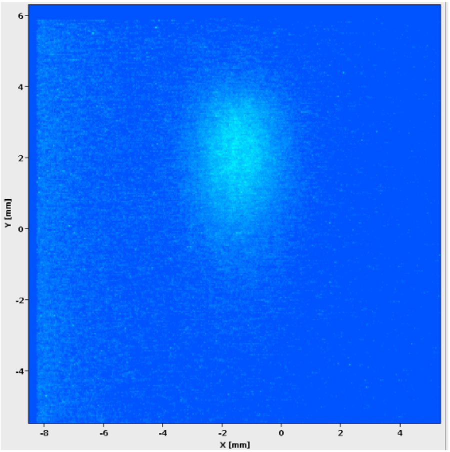
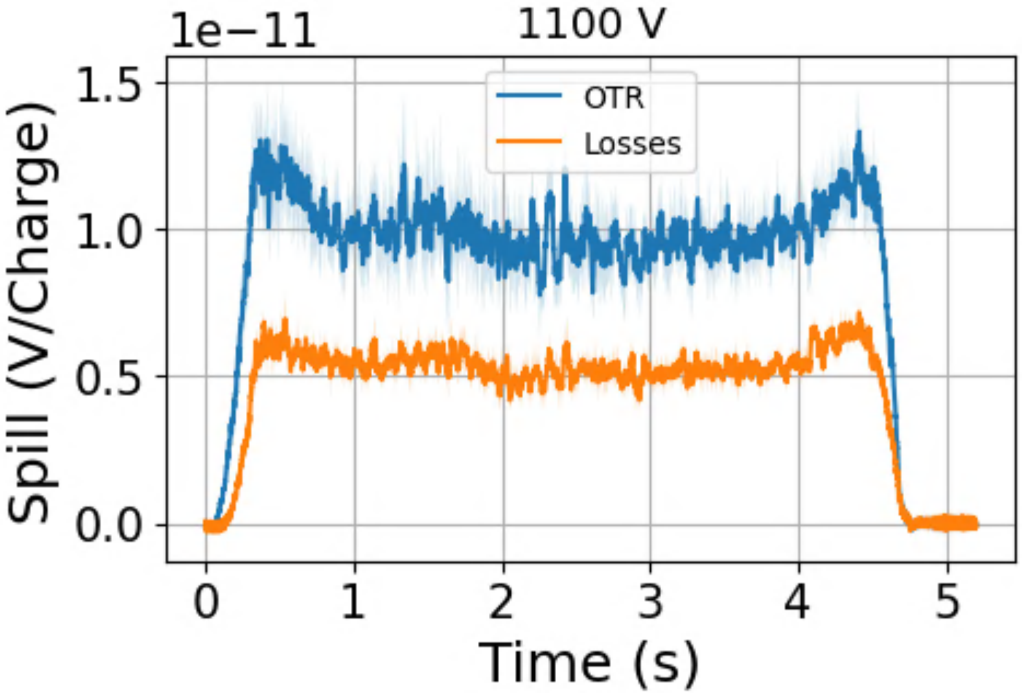


Figure 3: Image of the OTR light captured by the analogue camera, installed as a component of the OTR-PMT monitor. From this image, the beam horizontal and vertical size results to be approximately $\sigma_x = 1\,\text{mm}, \sigma_y = 2\,\text{mm}$.

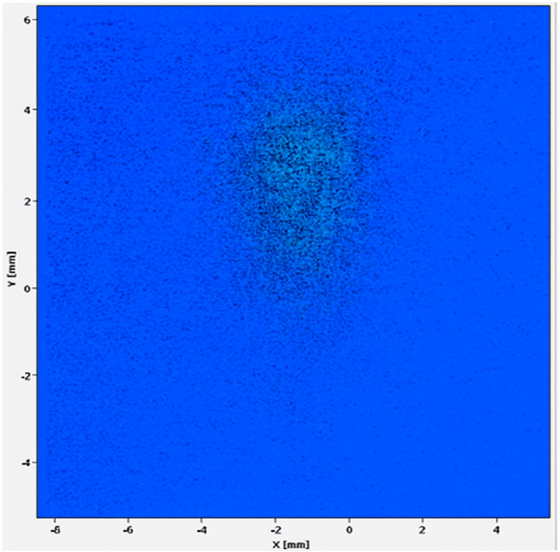
Operational experience:
OTR exists ;-) and we send it at the right place

PMT signal w. and w.o. screen



Operational experience:
Losses impact our detector
Losses well reproduce spill structure (up to xxx MHz)

Imaging check at PMT location after few months



Operational experience:

DAQ synoptics and implementation as of today

The PMT signal is amplified in the tunnel and split to the two path

High quality cables to the surface Heliflex HCA78-50, low attenuation (2 dB/100 m at 300MHz) , air-filled coaxial cable with exceptional inter-modulation performance.

FMC ADC (4CH, 500MS/s) inputs require 50Ω DC —> buffering amplifiers have to condition the signals

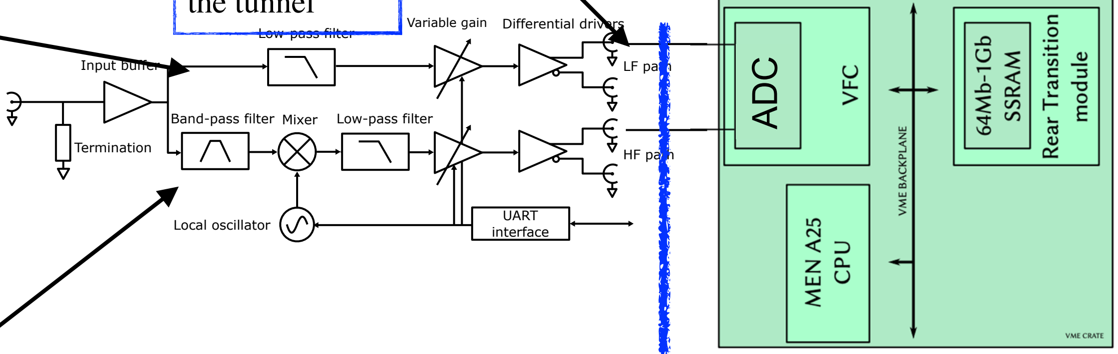
On CERN VFC

1 ‘Low - high frequency path’ designed for up to 250MHz :

- operational up to 4 MHz sampling, all spill digitised
- For up 250 MHz : Work in progress

2 ‘Ultra High frequency’ : to probe 800 MHz, down-mixed to 125 MHz. Work in progress

FE amplifier and mixer in the tunnel

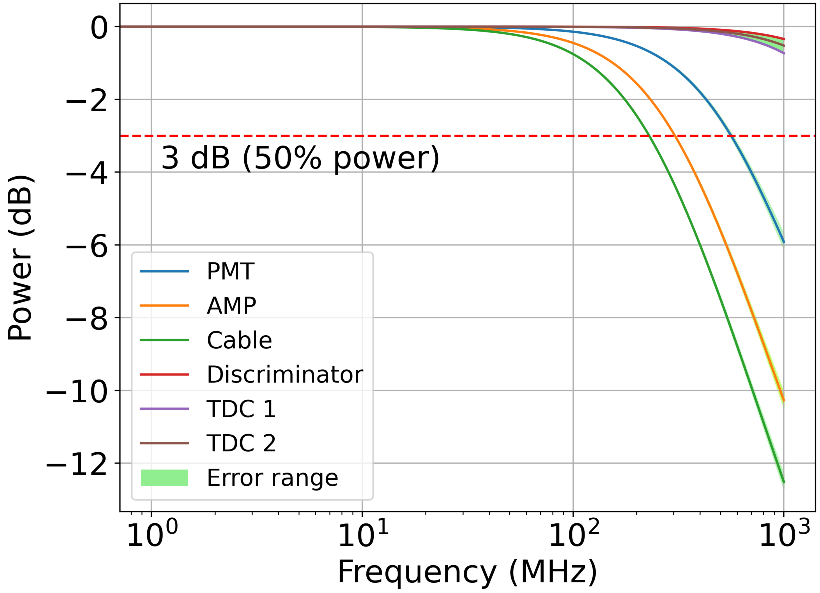


Tunnel

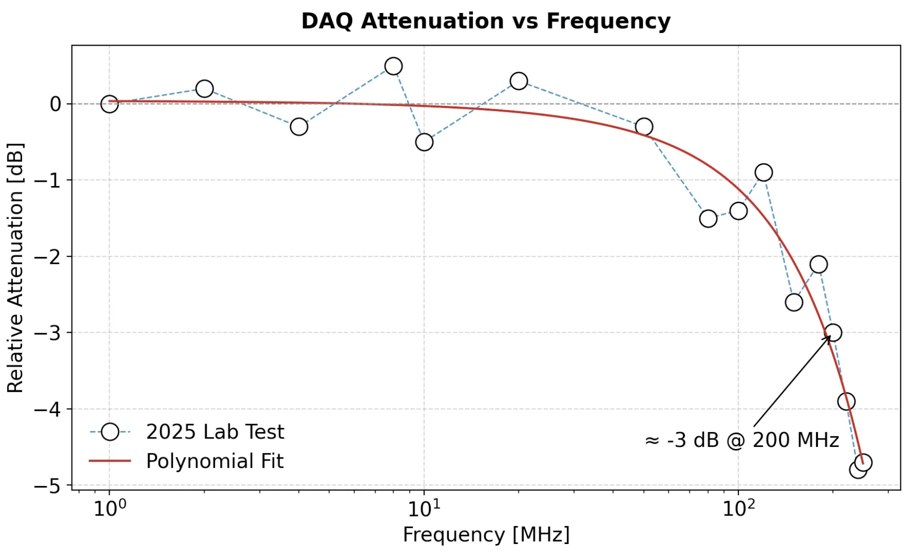
Service Area (surface)

Frequency Response

Lab measurements based on fast pulsed laser (<1ns) shined on PMT —> long cable —> FE amplifier



Lab measurements (no PMT, no cables, only DAQ electronics, all stages)



Overall Monitor Status - Recap

- Equipped since 2024 with **VME DAQ integrated** to CERN control system
- FESA control SW (‘słów’ and ‘fast’ acquisitions)
  - **Slow mode ~‘operational’** allows going up to few MHz. Control and readout via FESA ‘operational’ . Data logged, both time spill and FFT results

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  - **Fast mode for up to 250MHz**: working in ‘**expert/manual**’ setup. To make it operational: Gate-ware needs to be optimised to sustain large data size and high data transfer —-> ultimate reach to be confirmed —> will likely yield to: new DAQ (e.g. PCIe, SoC) needed
  - **Ultra Fast mode 800MHz final FW/SW implementation missing**
- **Since June 2025: OTR screen always IN** (it is ~transparent to operation in term of losses and transverse blow-up —> SW interlock (Active for most CERN screen systems to inhibit their use with high intensity —> high losses) was removed
- Still ‘suffering’ (or profiting?) of **losses directly generating signal,** also with screen out
- Lab measured BW + down-mixing config —> system expected to fulfil requirements up to 800 MHz

Next slides: examples to assess where we are in probing the performance and operational status

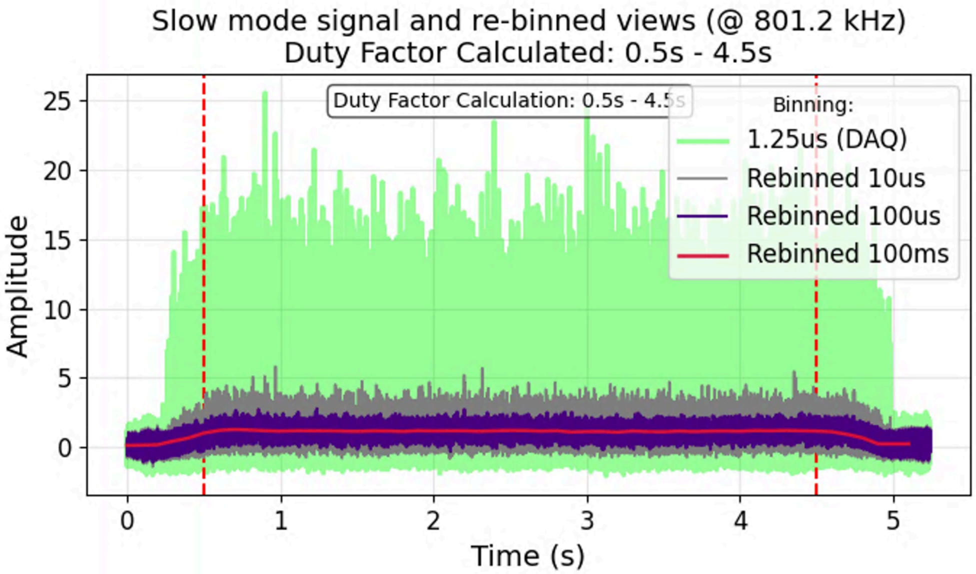
Slow mode example

- This is basically available on line up to 4MHz*, integrated in CERN control system, continuously logged
- Being ported to SW based processing to feed forward HW based 50-100 Hz compensation

*Above 4 MHz:

-more work on gate-ware needed

-on demand measurements (like example presented later) via expert tools

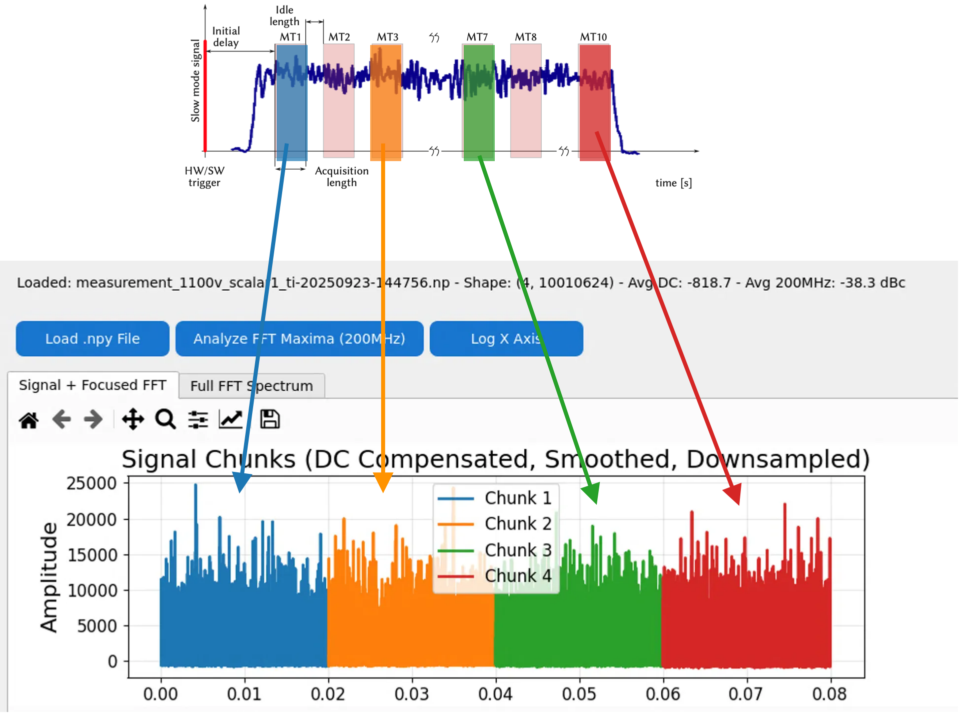


Duty Factor Statistics (Time Range: 0.5s - 4.5s)

Bin Size	N	Mean/bin	Duty Factor
1.25us	1600000	0.01	0.62
10us	400000	0.02	0.84
100us	40000	0.24	0.95
100ms	40	240.03	1.00

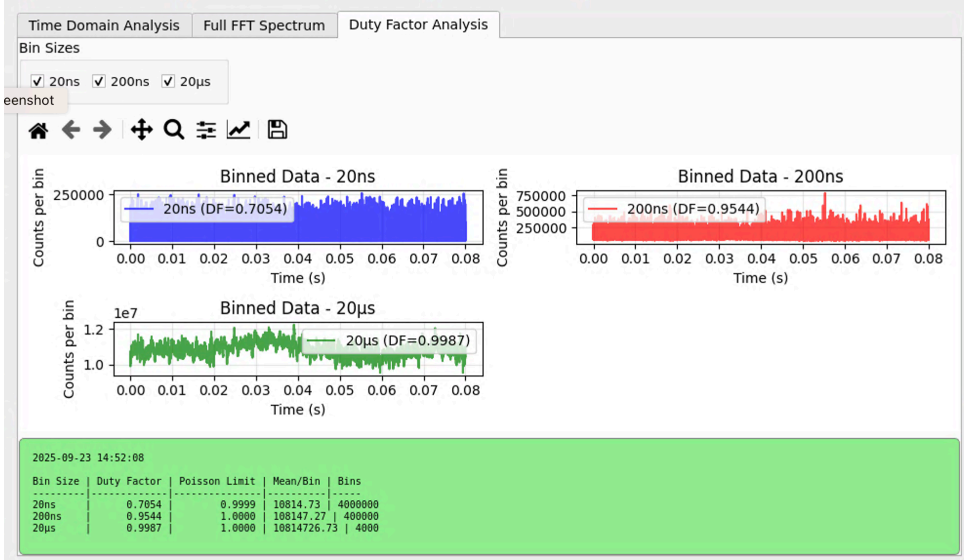
Fast mode measurement examples

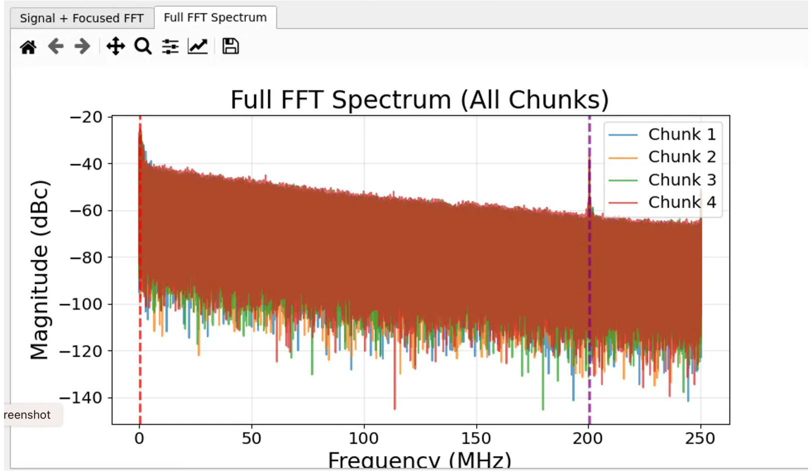
- Spill data acquired in ‘chunks’ (as per eng. specs) and processed on the fly by FW to infer frequency spectrum
- 500 MS/s, 20ns sampling
- Allows reconstructing spectrum **up to 250MHz** harmonic

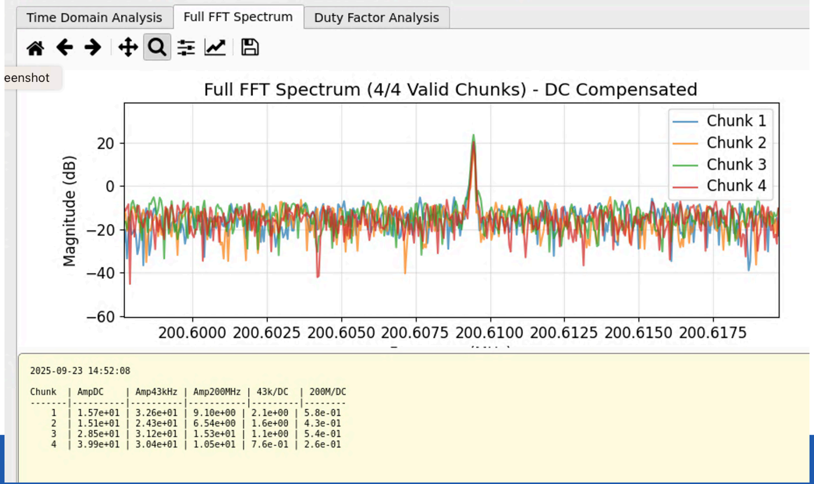


200 MHz measurements

- Example of one spill processing



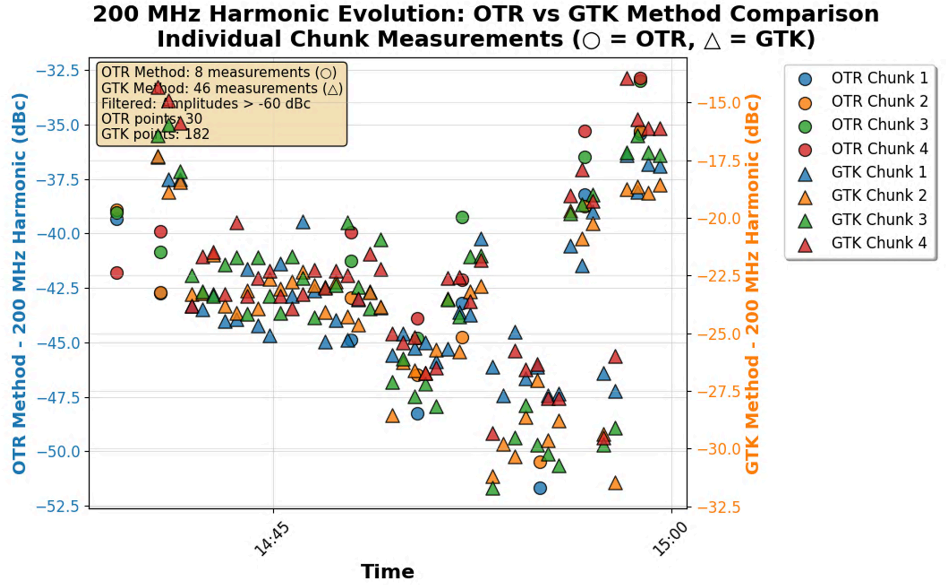




200 MHz measurements

4 chunks of the full spill analysed for both OTR and GTK systems

- Few weeks ago - Pablo Arrutia with BI expert
- Scanned SPS 200MHz RF cavity frequency to artificially inject 200MHz harmonic in extracted beam intensity
- Registered data with
  - SY-BI OTR-PMT system
  - NA62 experiment GTK* system

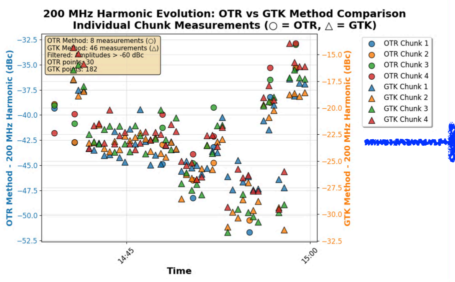


***In NA62** the GTK (GigaTracker) measures the time, momentum and direction of each incoming 75 GeV kaon at rates up to ~10^9 particles/sec with ≈ 100 ps timing precision per track.

Link for more details: GTK, NA62 — CERN na62.web.cern.ch

Operational experience: we need Pablo to see 200 MHz ;-)

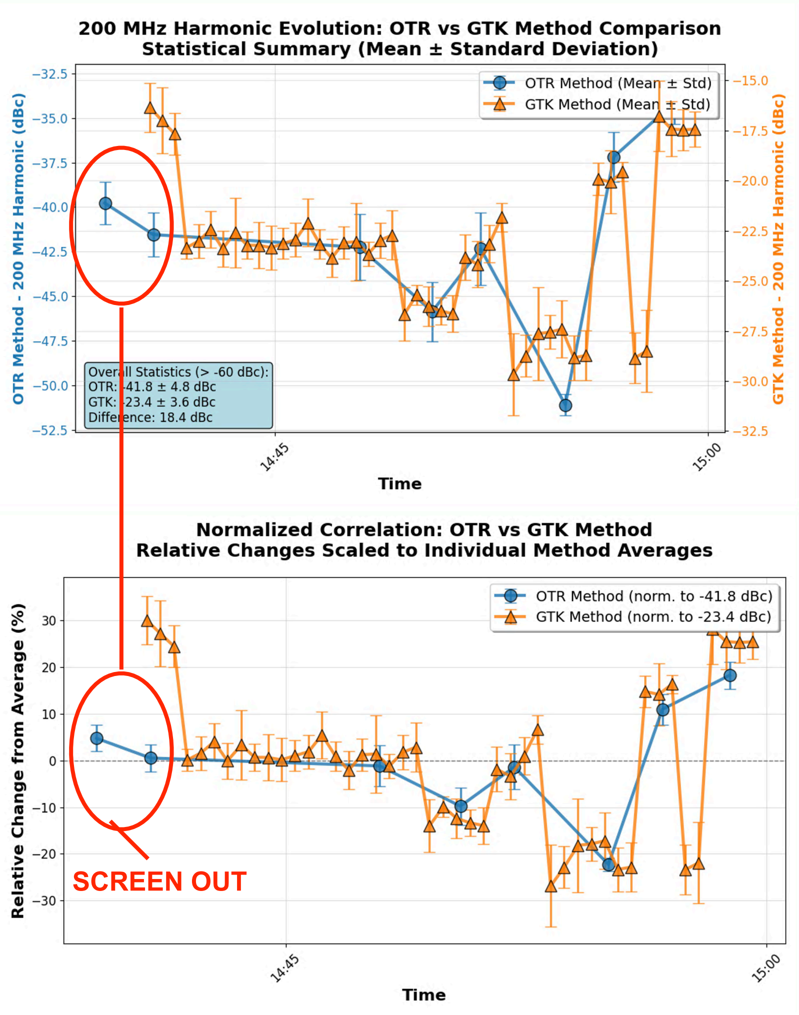
200 MHz measurements



Average and spread of 4 chunks

Absolute

Relative



Operational experience: measurement based only on losses (no OTR) has **limited BW** (see spare slides)

Summary

- OTR-PMT spill monitor on line, ~operational up to few MHz, available to OP for 50-100Hz corrections
- PMT see losses
  - Signal usable also without screen up to ~13 MHz (see spare slides)
  - OTR needed for higher frequencies
- Recent experiment with injecting 200MHz: present detector + DAQ able to resolve residual bunching from SPS RF. Ultimate sensitivity tbc

Outlook of next steps

:

- **Bring 'low rate' mode fully operational** and test its use for 50-100 Hz compensation
- **Study ultimate sensitivity** systematically, compare to BSI (secondary emission detector, slower than OTR-PMT and in principle more noisy)
- Study **PMT ageing** (HV scans)

- Update gate-ware and SW —> assess ultimate reach with present DAQ
- Propose / implement new DAQ - not VME ? SoC ?

For > 1=GHz: collect final ECN3-ShiP requirements. Assess need for different detector type or DAQ type

- **Photon counting techniques** instead of integrating ?
- Explore different detectors (Cherenkov based system presented last year, we did not work on it this year

Anybody else already with or is developing > 100MHz spill measurements ?

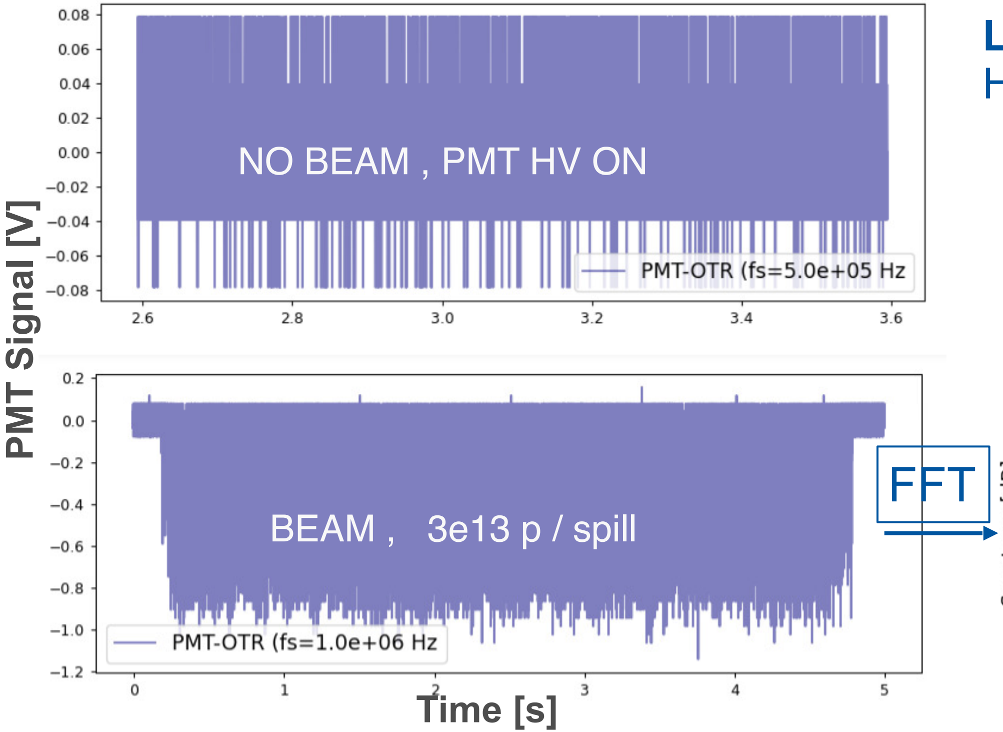
BACKUP / SUPPORT / REFERNECE SLIDES

Plans towards xx GHz range (DAQ side)

On-going studies (conceptual + few lab tests for the moment

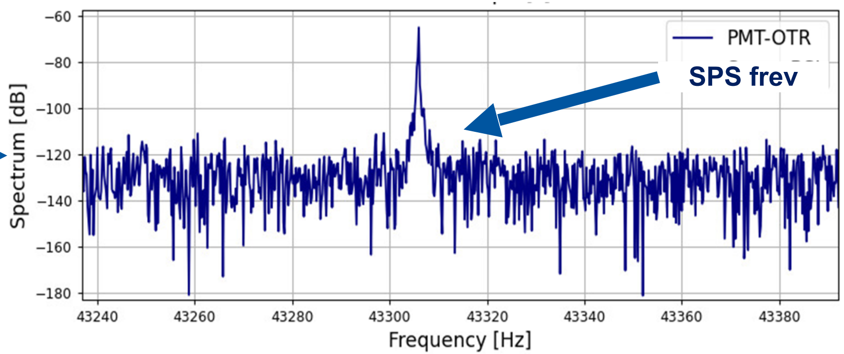
Option	Pros	Cons
ATCA	High-speed communication channels, used in CERN experiments	Expensive, requires minimum configuration, not cost-effective for isolated system
SoC (RFSoC)	Flexibility in choosing ADCs, local communication between ARM CPU and FPGA	Existing modules have low memory, limited availability of larger memory options
PCIe	Widely used standard, high-speed data transfer, supports DMA	Requires PCIe form-factor FPGA carrier with sufficient memory, limited module options with large memory

OTR – PMT (example with fs=1MHz)



Low noise.
Here, with no beam and PMT HV ON

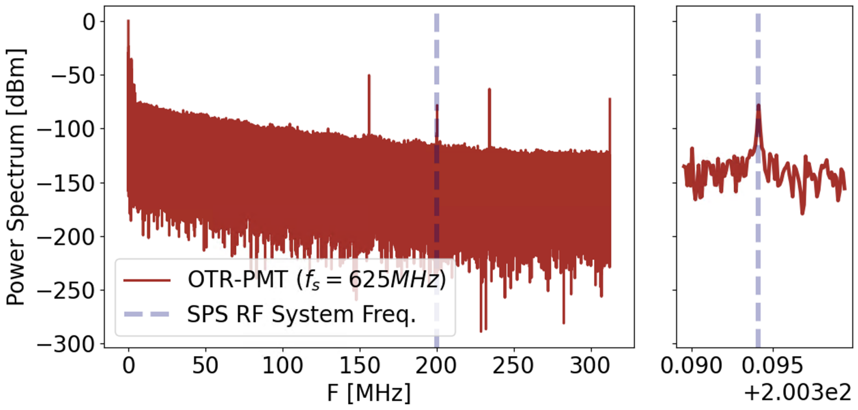
- **SNR**~=0.9/0.160=**5.6** in this example
- Similar to SEM, but here there is no low pass filter

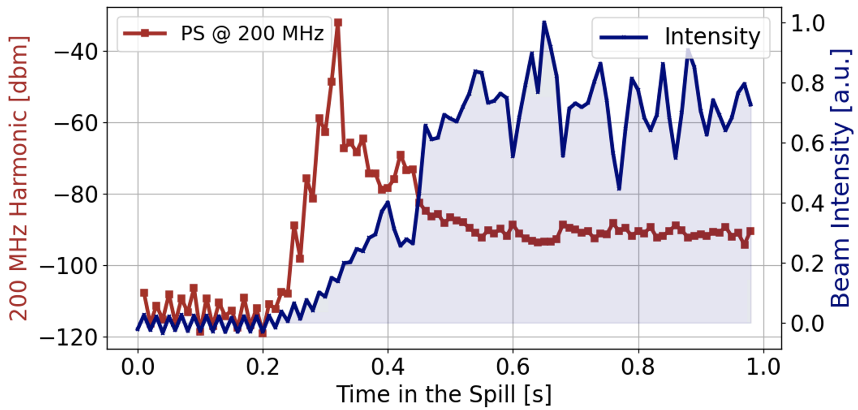


OTR – PMT (example with fs=625 MHz)

High frequency acquisition on a ‘chunk’ to study presence SPS RF (nominal=200.3941 MHz) in spill intensity

Scanned trigger delay to measure 200 MHz harmonic along the spill (here only first part of the spill)





Geometric Bandwidth Limit from Loss Localization Uncertainty

- A single loss monitor sensitive to losses along a 10 m line sees losses convolved over the proton flight time:

$$\tau = \frac{L}{v} \approx \frac{10\ \text{m}}{c} \approx 33.3\ \text{ns}$$

- The signal = beam intensity ⊗ rectangular window (width = τ)
  → frequency response is sinc-shaped low-pass

$$|H(f)| = \left|\frac{\sin(\pi f \tau)}{\pi f \tau}\right|$$

- Effect: fine temporal structure in beam intensity is blurred out.

The monitor integrates losses over ~33 ns, acting as a sinc low-pass filter.

Bandwidth of a 10 m Integrated Loss Monitor

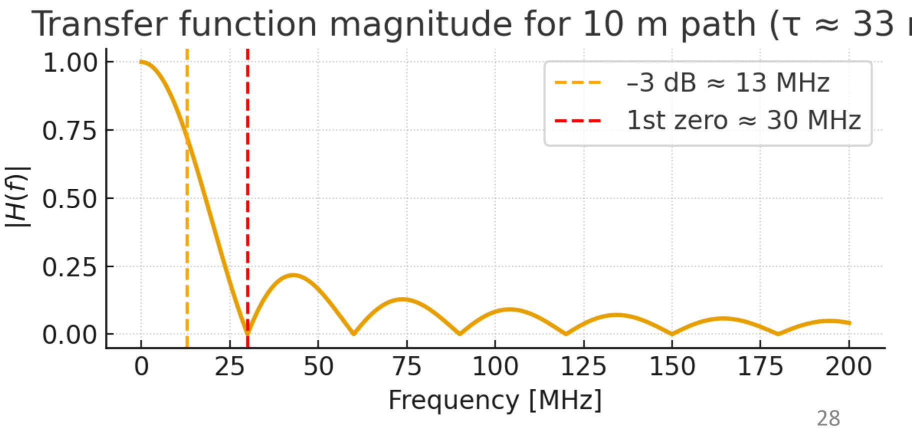
• First zero: f_0 = 1/τ ≈ 30 MHz
• –3 dB point: f_3dB ≈ 0.443/τ ≈ 13 MHz
• At 200 MHz: |sinc(πfτ)| ≈ 0.041 → –28 dB (undetectable)
→ 200 MHz beam harmonics cannot be inferred; effective bandwidth ≈ 10–20 MHz for L = 10 m.

Design rule:

L ≲ v / f_t (first zero above f_t)

L ≲ 0.443 v / f_t (–3 dB above f_t)

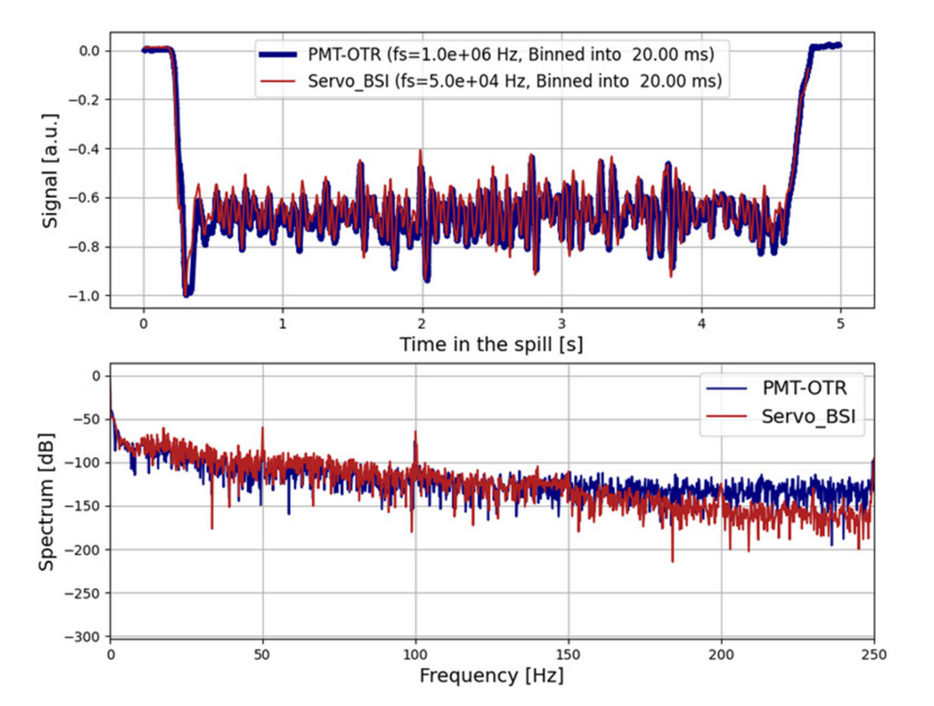
For 200 MHz → L < 1.5 m (zero), L < 0.66 m (–3 dB).



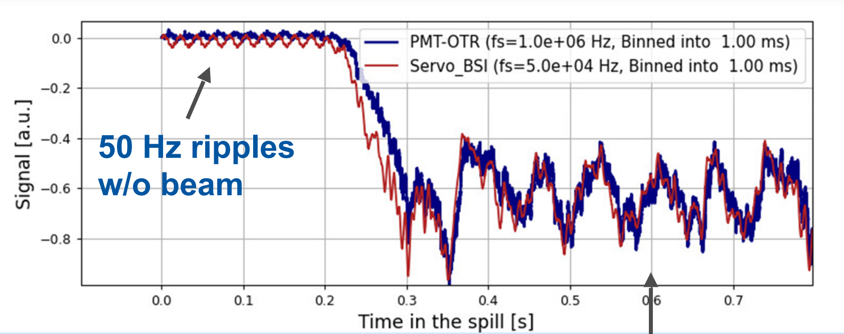
OTR-PMT vs SEM

Binning both monitors in equal time intervals

@ 20 ms



@ 1 ms (Zoom on Start of the Spill)

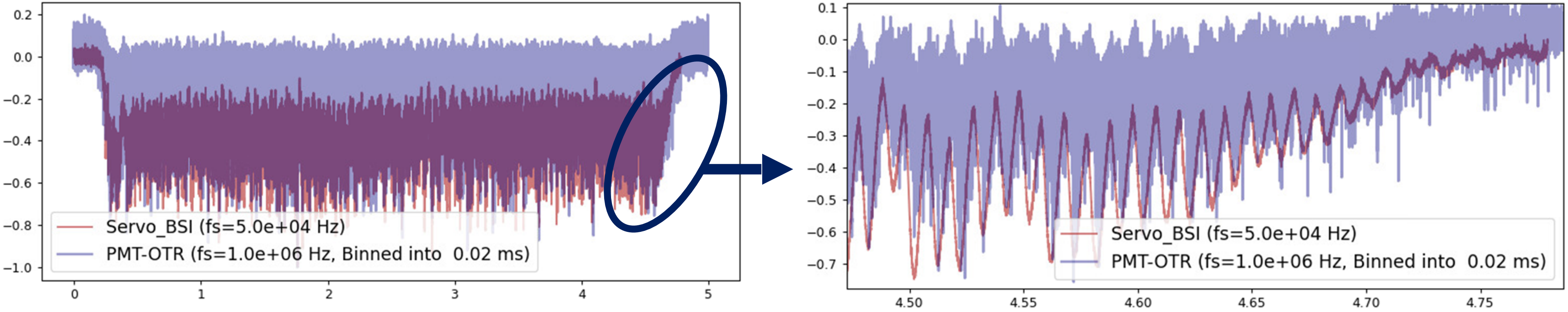


10 Hz beam intensity modulation

Impressive agreement between two systems based on different detector, DAQ and 30m apart

OTR-PMT vs SEM

SEM @ 50 kHz (20us), no binning
OTR-PMT @ 1MHz binned @ 50 kHz (20us)



As expected from **SEM** setup**: low pass filter (1kHz) reduces overall BW**, even when sampling at higher rate (50 kHz in this example)

OTR-PMT gives same envelope (100Hz beam intensity fluctuations) **but also measures higher frequency** beam intensity fluctuations

DAQ – from Functional to Engineering Specs

Acquisition Mode	Sampling Rate	Storage Needed	Ccomments / Remarks
Slow	> 200kHz	32 Mbits	• Suitable for ADCs with a sampling frequency > 200kHz. • Can increase sampling rate and memory for better frequency or temporal resolution.
Fast (up to 200MHz)	≥ 400 MHz	64 Gbits	• Requires ADC with minimum 400 MHz sampling rate and sequential triggering mechanism to reduce data storage needs.
Ultra-fast (800MHz)	≤ 1.6 GHz	Depends	• Can be under-sampled if the ADC and signal path support it. • Alternatively, a fast ADC at > 1.6 GHz can be used, or the 800 MHz frequency can be down-mixed to a compatible band for Fast mode.

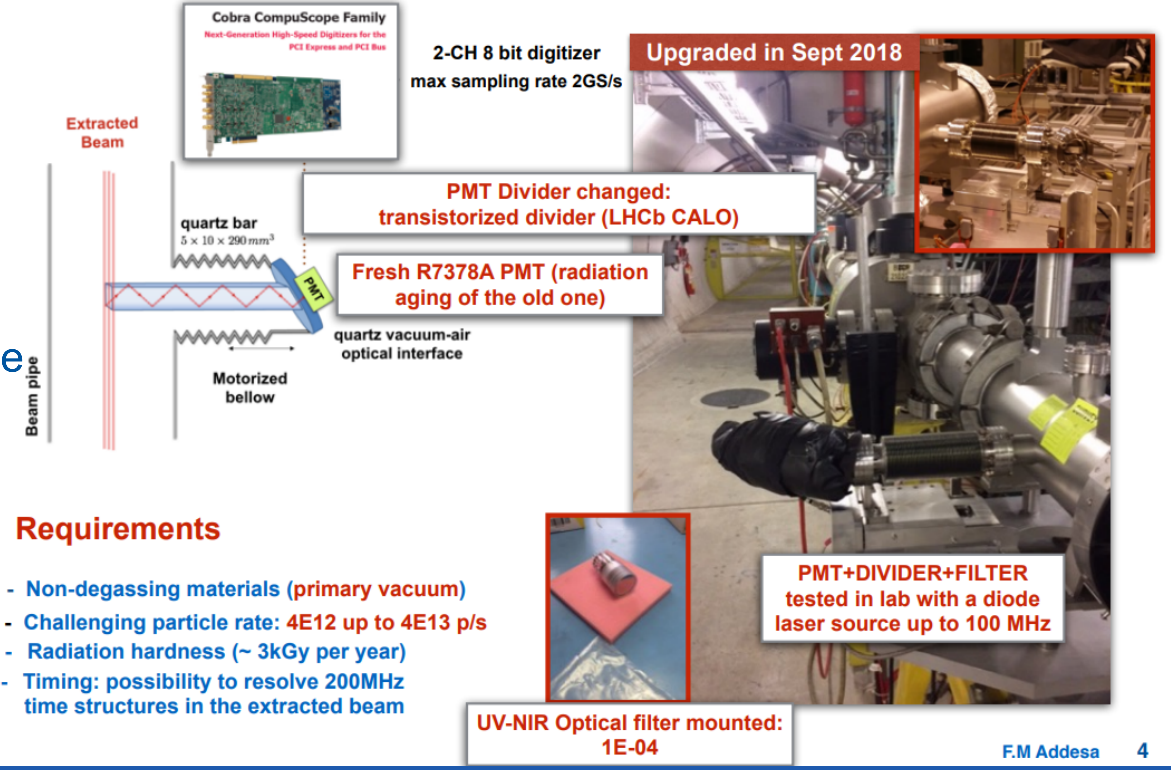
Plans towards xx GHz range (Detector side)

Cherenkov detector for proton Flux Measurement(CpFM)

F. M. Addesa et al. “In-vacuum Cherenkov light detectors for crystal-assisted beam manipulations,” https://cds.cern.ch/record/2661725

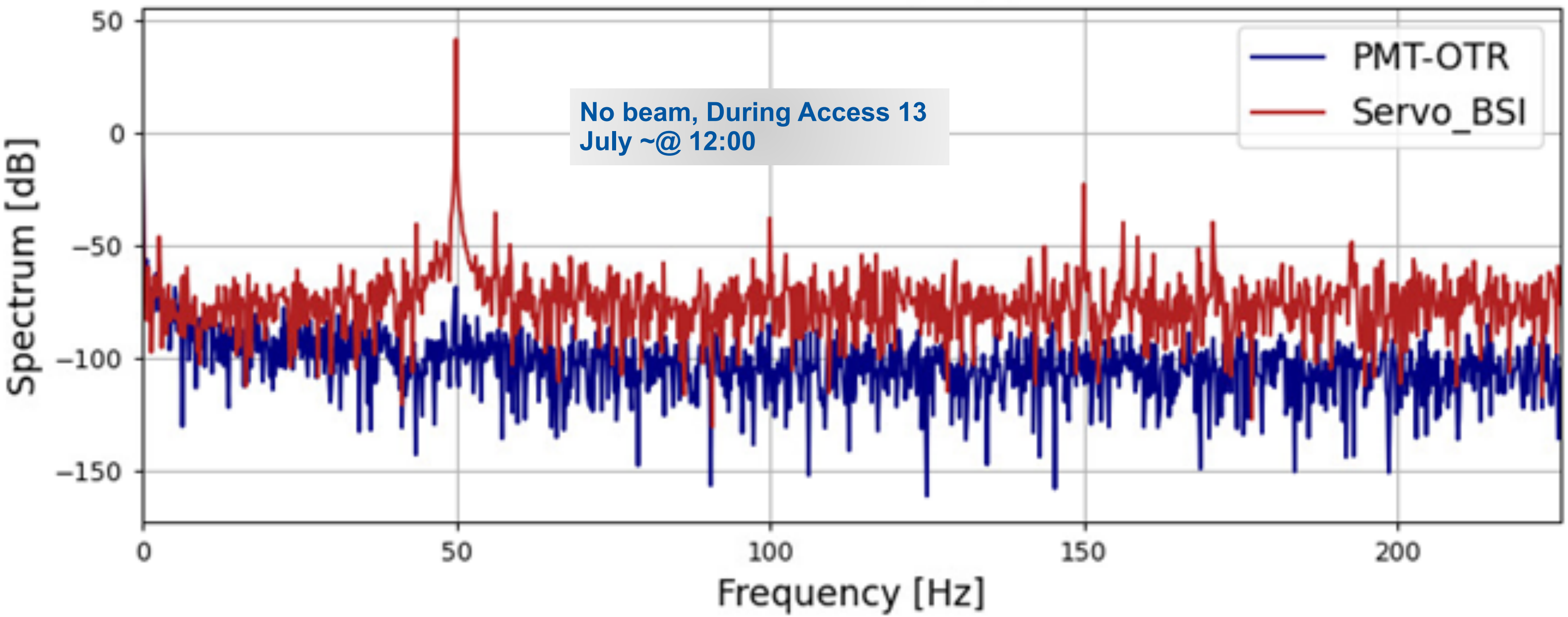
In vacuum quartz bar producing Cherenkov light

- System evolution of one used with low particle flux for crystal assisted extraction
- **Can go to few GHz at least (as OTR-PMT, but with better SNR)**
- Validated in 2018 with custom made DAQ



Plan

- Resurrect system
- Study ultimate bandwidth
- Propose ~standard DAQs


No beam, During Access 13 July ~@ 12:00
PMT-OTR
Servo_BSI
Spectrum [dB]
50
0
−50
−100
−150
0
50
100
150
200
Frequency [Hz]