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Sub-Ns Single-Particle Spill Characterization for Slow Extraction

T. Milosic*, R. Singh and P. Forck
GSI Helmholtz Centre for Heavy Ion Research, Darmstadt

GSI FAIR HELMHOLTZ GEMEINSCHAFT

Abstract With the recent developments on improving spill quality at GSI/FAIR, appropriate measurement devices have come into focus again. In contrast to commonly used scaler-based approaches where events at a certain sample frequency are counted, we present a measurement concept resolving single-event detector timestamps in the sub-ns regime leveraging a well-established off-the-shelf TDC VMEbus module. This allows for high-resolution time structure information with respect to the ring RF as well as evaluation of inter-particle separation distributions. This yields insightful information for specific experiments at GSI whose efficiencies are heavily limited by pile-ups and detector dead times. We will present the concept of the measurement setup and exemplary data taken in recent campaigns in context of spill microstructure improvements for slow extraction.

Introduction

- Spill characterization
- Slow extraction: bunched & coasting
- Single-particle measurement
  → Complements scaler approach
- Use of TDC offers new information
- Elementary events as shown in Fig. 1
- Time structure TS_n:
  [prec. slope-sens. zero crossing, det_n]
- Particle-interval PI_n:
  $[det_n,\ det_{n+1}]$

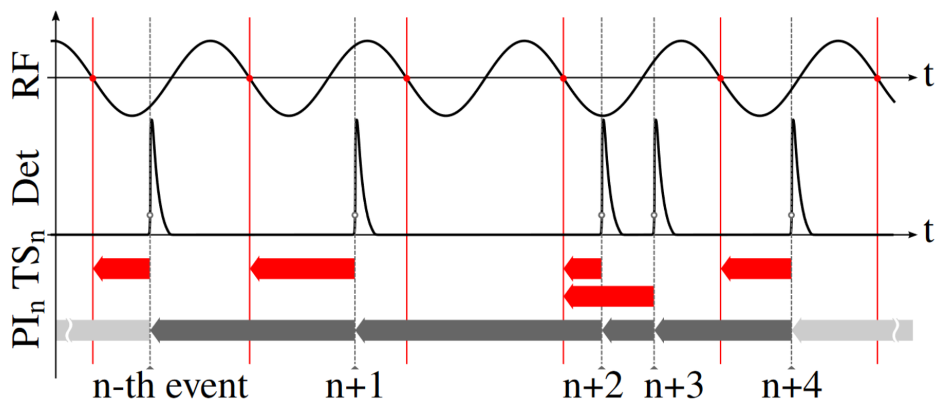

Fig. 1: Single-particle events characterizing spills.

Hardware

- Duagon (MEN) A25 VMEbus controller running a diskless CentOS7 environment
- PMC White Rabbit timing receiver
- CAEN V1290N TDC (CERN's HPTDC ASICs)
- 4 MEvents/s per ASIC
- 21-bit time stamp counter
- LSB ~ 25 ps → dynamic range ~ 50 us
- Resolution ~ 35 ps RMS per input
- Double-hit resolution 5 ns
- Chronological order not guaranteed (misalignments happen frequently at high rates)

Fig. 2: VMEbus mainframe configuration

Implementation

Software stack

- C++ FESA class running on the VMEbus mainframe
- JavaFX GUI for operators, BI and accelerator experts
- Exporter for in-depth offline analysis

Requirements & Challenges

- Online mode required (operating & experiments)
- Complements offline data analysis
- Online data is a challenge at high rates
  - Limitations of TDC module
    - Short full dynamic range ~ 50 us
    - Requires manual overflow correction in order to extent dynamic range (spills up to several tens of seconds)
    - Prerequisite for check $t_{n+1} < t_n$: Restoration of chronological order!

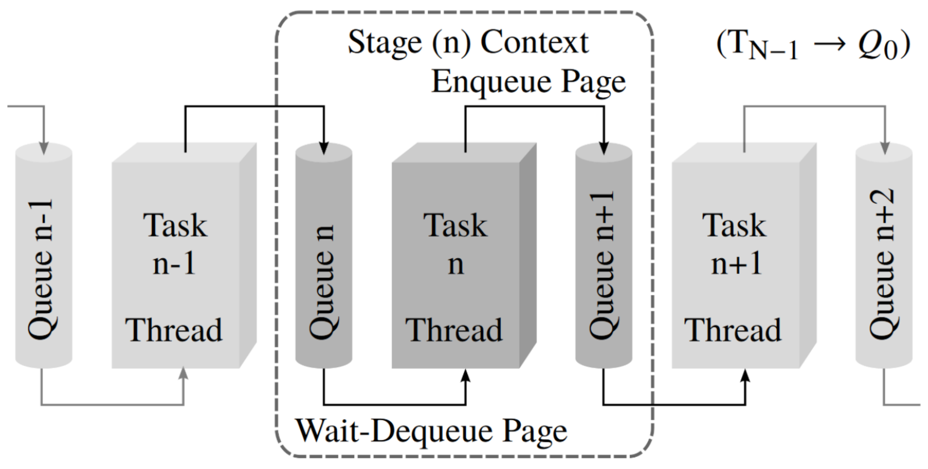

Fig. 3: Pipeline concept with chained stages. Closed cycle: Last N-1 outputs to queue 0 again.

- RF prefetching
- Lots of compute-intensive tasks
  → Avoid stalling the acquisition/processing pipeline
- **Suggests to parallelize the pipeline**

Pipeline

- Divide acquisition into sequential tasks → Stages of a pipeline (Fig. 3)
- Stage context: {2+ queues (in+out), 1 thread}
- Closed cycle, last context outputs to first que ue again.
- Data are ***pages***: basically buffer of a TDC read cycle
- Contiguous memory on the heap, allocated once
  → Low copy and object creation overhead
- Control flow / synchronization:
  Queues in single-consumer single-producer mode
- Maintains ordering of pages
- Great thread coverage for modern multi-core CPUs (Fig. 4)
- Current implementation uses ***2 coupled pipelines***

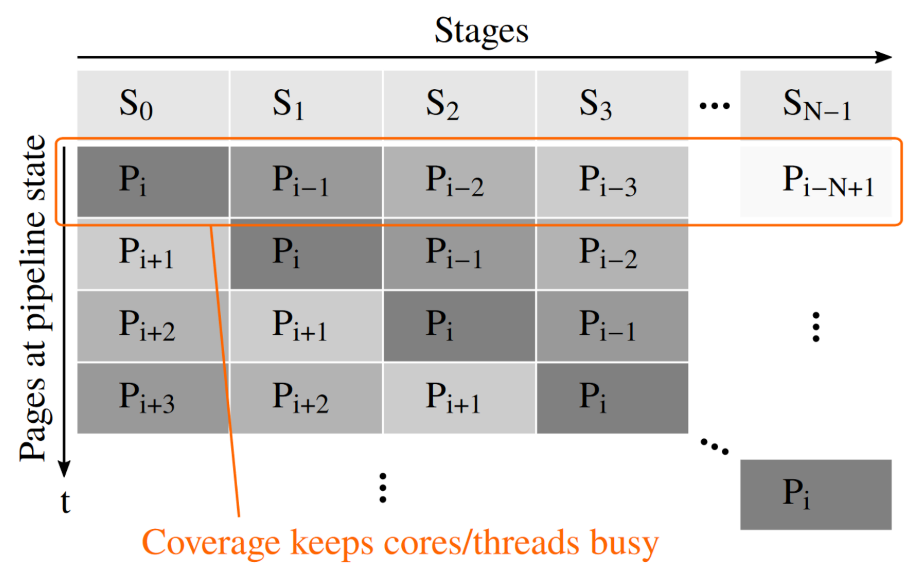

Fig. 4: Coverage diagram for pipeline with N stages.

- Pipeline 1 operates on native 32-bit words
- Pipeline 2 operates on 64-bit words
  → 48 bits of extended time stamp counter
- New dynamic range 51.2 us → 114 minutes
- Figure 5 shows the 2 pipelines and associated tasks
- ASICs capability can be fully used even in online mode at a net detector of rate ~ $3.6 \cdot 10^6/s$.
  Diff is occupied by other TDC events, mostly RF depending on the SIS RF of AUX frequency

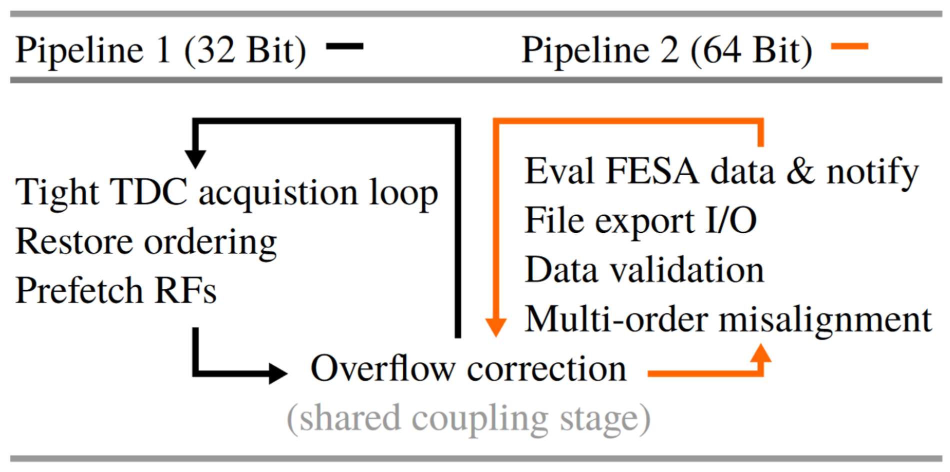

Fig. 5: Data flow and tasks.

Data

- Recorded data contains full event time stamp information
- Feature-rich exporter allows to specify/use e.g.
  - Binning (Time Structure & Particle Interval)
  - Size of time slices
  - Particle-interval range
  - High-resolution current mode
- Supports filters and selection facilities for spill container
- Superimpose/overlay multiple spills to enhance statistics

Measurements

Time Structure

- Bi^{68+} beam at 300 MeV/u with plastic scintillator (Fig 6.)
- Three different cavity voltages {0 V, 275 V, 1130 V}
- Time slices 20 ms, 9 spills superimposed
- Axes: (x) one RF period. (y) Time during extraction
- Bottom shows slices by color reference

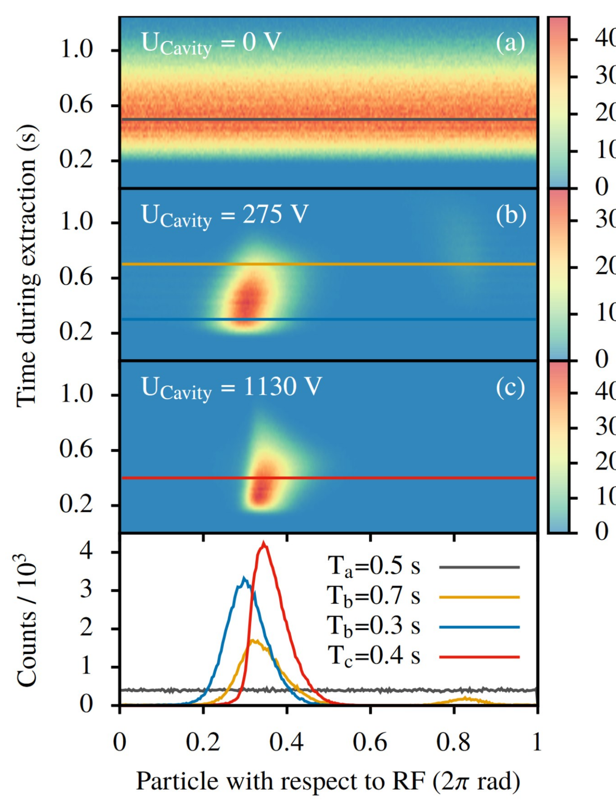

Fig. 6: Time-structure information

- 0 V: No correlation to RF. Unbunched.
- 275 V: Bunched beam. Second smaller bunch emerges
- 1130 V: Only one bunch
- Further interpretation of data outside scope this paper

Particle Interval Distribution

- Same Bi^{68+} data and slicing as time structure (Fig. 7)
- Time slice 20 ms, 9 spills
- Y axis is given in units of RF periods

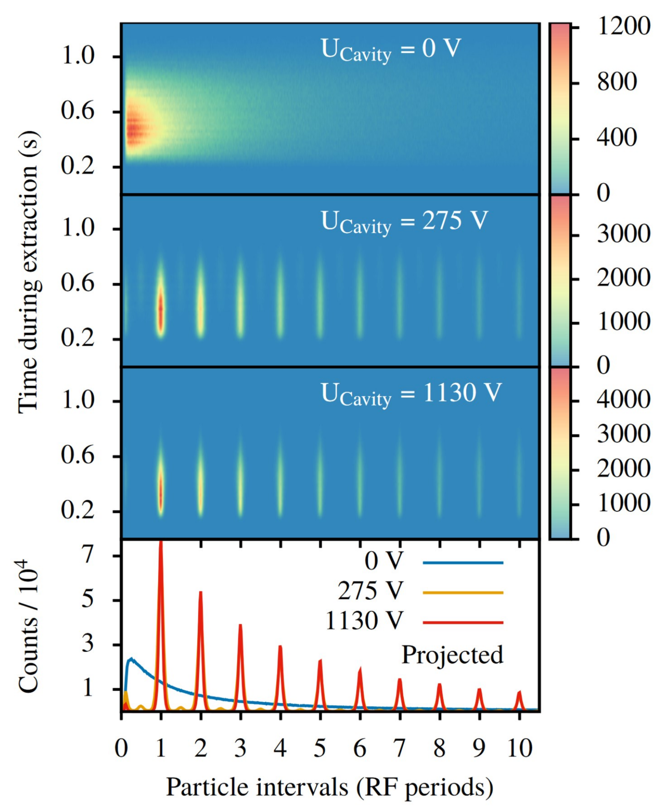

Fig. 7: Particle-interval distribution

- For the uncorrelated case at 0 V cavity voltage, the distribution is governed by a Poisson-like process.
  → Interval distribution is exponential
- At 275 V distinct accumulation regions are apparent evently spaced by the RF plus a second accumulation between the prominent regions.
- For 1130 V only the prominent regions remain

Spill Characterization

- Although duty factor and maximum-to-mean ratio give a measure of the smoothness of the spill, not a quantification of the potential events at detector
- TDC time of arrival provides more direct measure of the usable part of the spill for a given detector response
- Figure 8 shows a cumulative density function for slow extraction coasting, bunched, hypothetical Poisson and uniform spills at a **rate of $1.2 \cdot 10^6/s$**
- Jumps in bunched beam correspond to the 205 ns RF period
- Bunched beam is known to mitigate spill modulation caused by power supply ripple at the cost of introduction high frequency structures at RF frequency
- Evident, that for bunched beams a higher fraction of particles with larger intervals in comparison to coasting beams
- For hypothetical detector of 250 ns dead time, bunched beam would be advantageous even in comparison to the Poisson distribution in Fig. 8.
- Thus, extraction rate and RF period has to be carefully chosen to benefit from bunched beam extraction

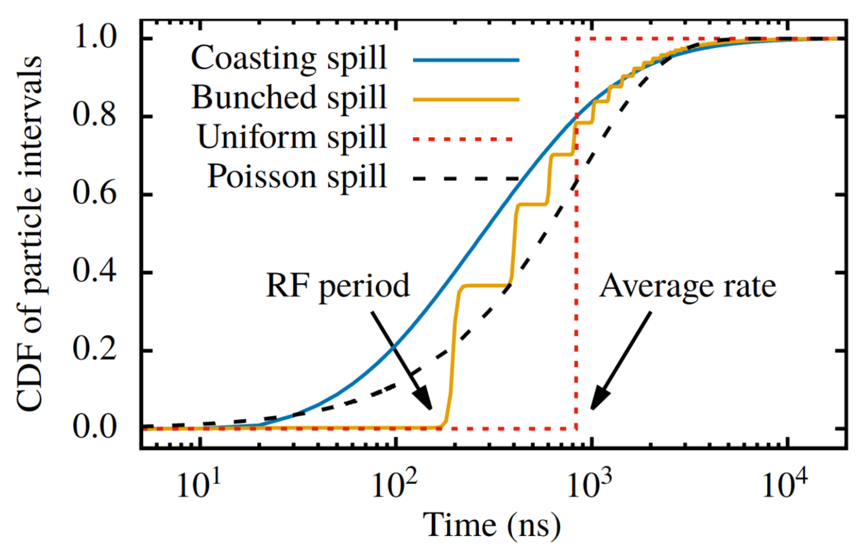

Fig. 8: Cumulative distribution of the spills

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(*) t.milosic@gsi.de

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