Work-package 4: Spill Detector Developments and Analysis

-- Status at GSI & Perspectives for the Work-package --

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IFAST-REX 2nd Collaboration Meeting, 17th Feb. 2022

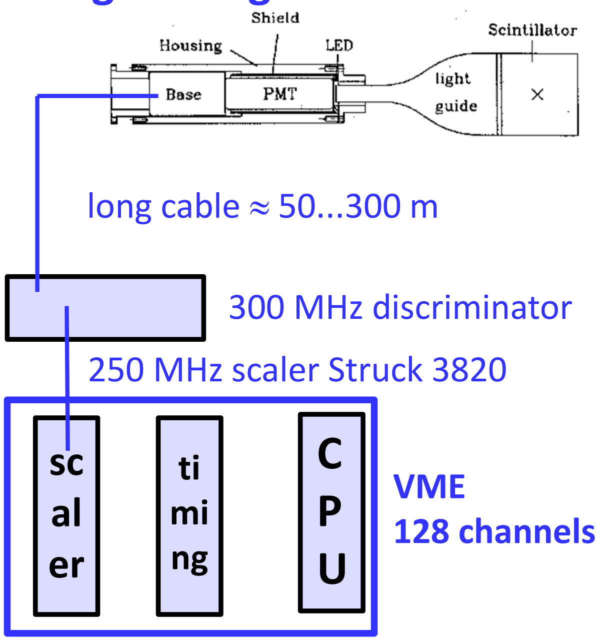
Status at GSI:

- Detector types (plastic and inorganic scintillators)
- Scaler and TDC-based data acquisition
- Data analysis
- Ideas concerning Machine Learning

Vision for work-package 4

Standard Scintillator, Electronic and Data Acquisition

Scintillator at HEST: Analog and digital chain:



Signal chain:

- Plastic scintillator
- Scaler readout
- Entire cycle stored with typ. sampling t_{read} = 10 µs
- Further detectors & SIS current
- Various **online** analysis tools

Restriction:

- Maximum **average** count rate:

  $r_{aver} \approx 3 \cdot 10^6$ 1/s

  due to pulse length, PMT property and cable dispersion
- Very low radiation tolerance of plastics

Advantage of particle counting:

- Single particle detection, well to be triggered
- Prompt detector response, better 1 ns
- **No** noise or background

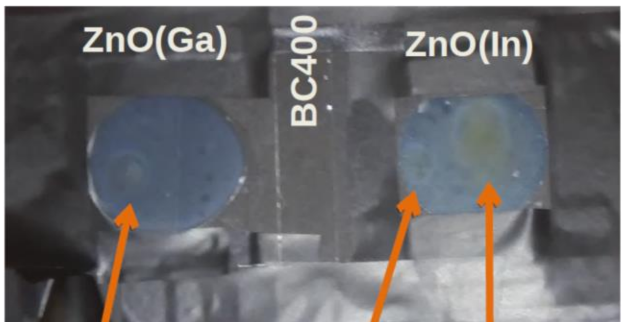
$\Rightarrow$ **Could be directly compared to MADX tracking simulation**

Development of inorganic ZnO:In Scintillators

Requirements:

- Short pulses smaller than few ns
- Moderate energy resolution for stable discriminator level
- **Radiation hardness**

⇒ Test of inorganic ZnO:In as ceramics (first test with ∅5mm)



Xe, Ø5 mm

Xe

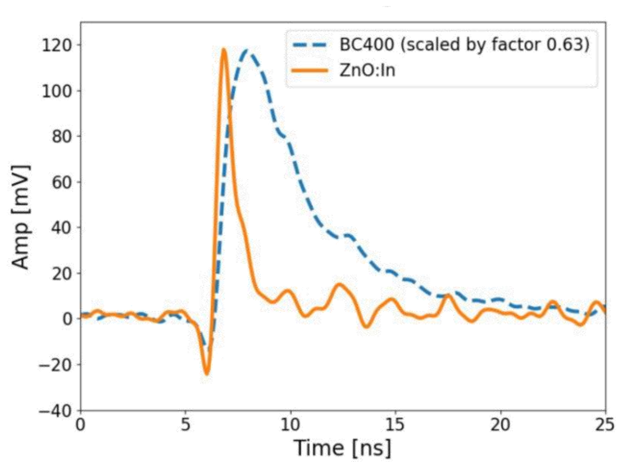
U not collimated
beam Spot c.a 7x9 mm²

Example for fast pulses

Beam: U at 300 MeV/u

→ FWHM < 1 ns (short cable)

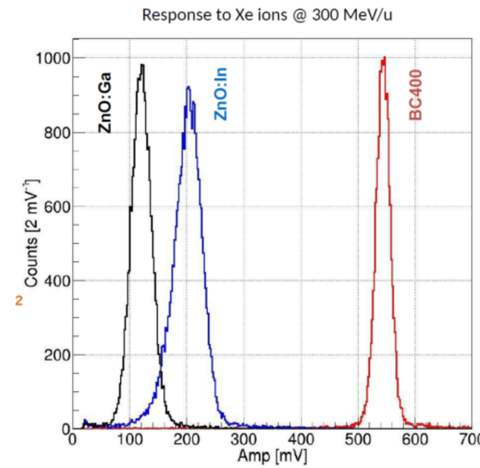
Using fast PMT (Hama. H13661)



Example pulse height spectrum

Beam: Xe at 300 MeV/u

→ Energy resolution sufficient!

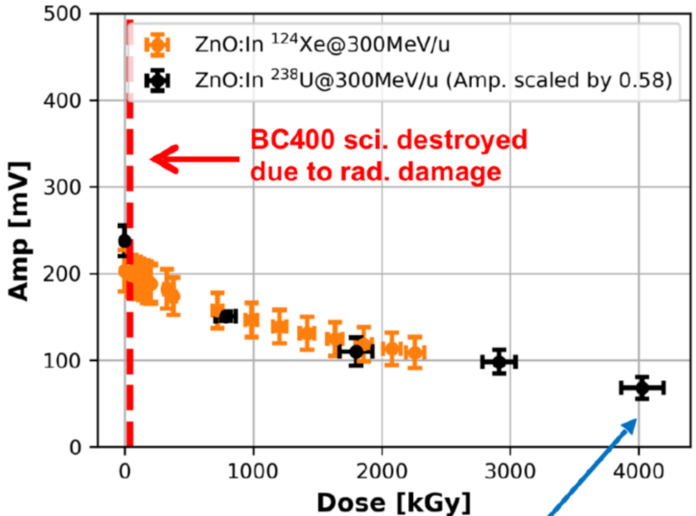


P. Boutachkov, M. Saifulin (GSI) in collaboration with Russian and Latvian institutes

Radiation Hardness of inorganic ZnO:In Scintillators

Example: Beam: : U and Xe at 300 MeV/u

IBIC-2019, P. Boutachkov et. al.
https://doi.org/10.18429/JACoW-IBIC2019-MOPP005

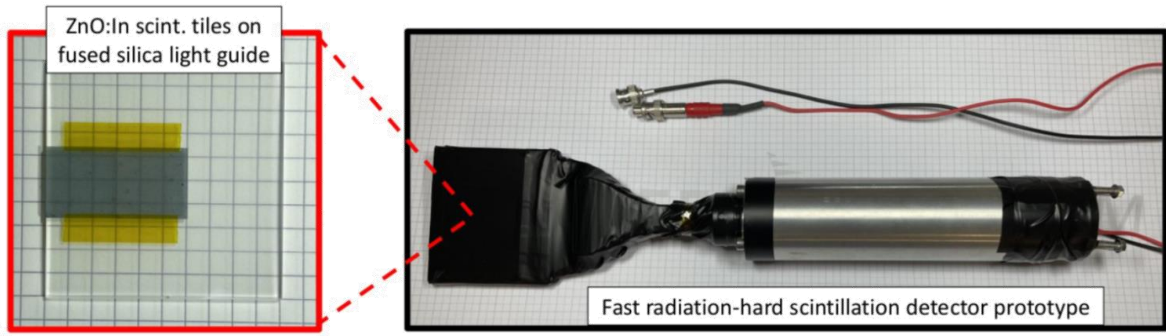


1E+12 ^{238}U/cm^2, or 3E+12 ^{124}Xe/cm^2

Development:

- Large area 50x50 mm^2 needed
- Compilation of e.g. 15 mm^2 tiles

Two scintillator tiles detector,
detector active area 30x15 mm^2



Preliminary: ^{78}Kr @ 300 MeV/u, 98% efficiency compare to BC400

Advantage:

- Much higher radiation hardness
- Fast counting with $r_{aver} = 10^7$ 1/s
- Can be used as detector for spill characterization

Development: Large area detector possible!

Possible restriction: Too low output for protons and light ions (?)

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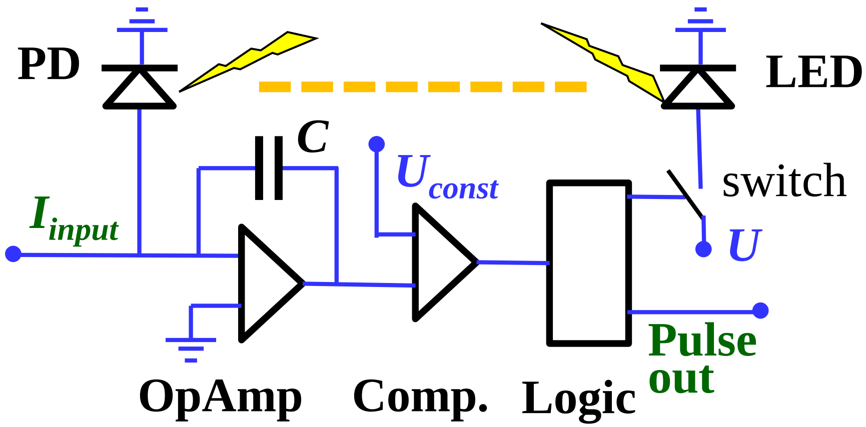
Ionization Chamber Measurement

Read-out of IC:
Current-to-frequency converter:

$I_{input} \rightarrow$ charging of integration capacitor
when threshold of Q = 100 fC reached:

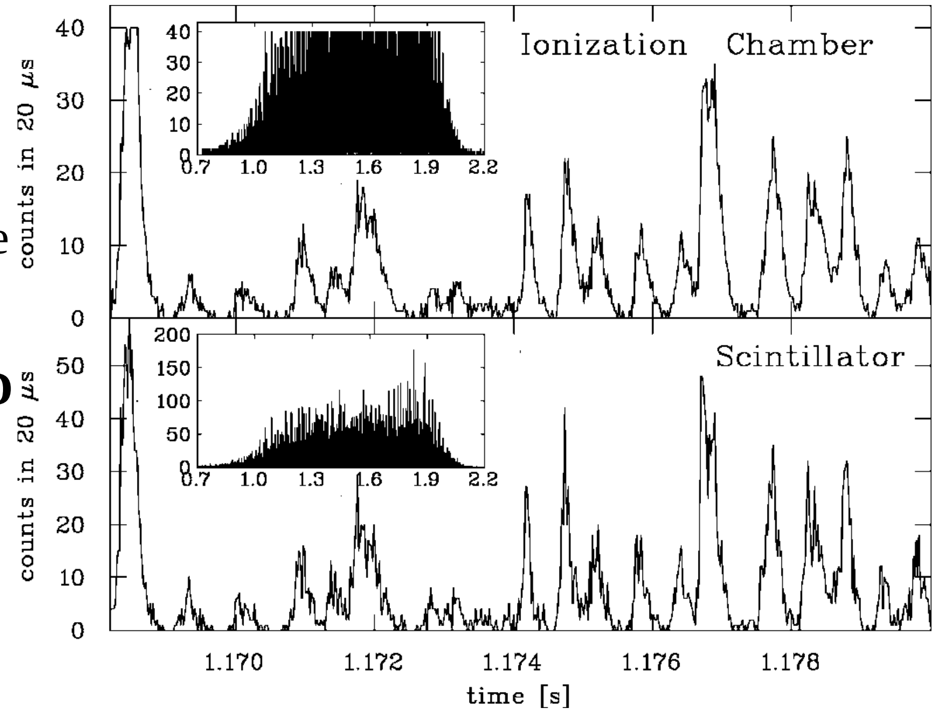
1. one pulse out
2. clearing of capacitor via opto-coupler

GSI type: conversion: 0.1 / 1 / 10 pC/pulse
max. rate: 1 MHz



Advantage: bipolar noise cancelation
best performance concerning
sensitivity and bandwidth

Example: Beam: Bi^{67+} at 250 MeV/u, un-bunched beam
quad. scan t_{read} =20 µs, $r_{aver} \approx 0.5\cdot10^6$ 1/s



Observation:

- same time structure measured with IC & Scint.
- sensitivity & noise reduction required

Usage of Beam Loss Monitors for high Current Beams

Basic idea for Beam Loss Monitors BLM usage:

A lost ion impacting on vacuum pipe or insertion

$\Rightarrow$ detection of shower by scintillator based BLM

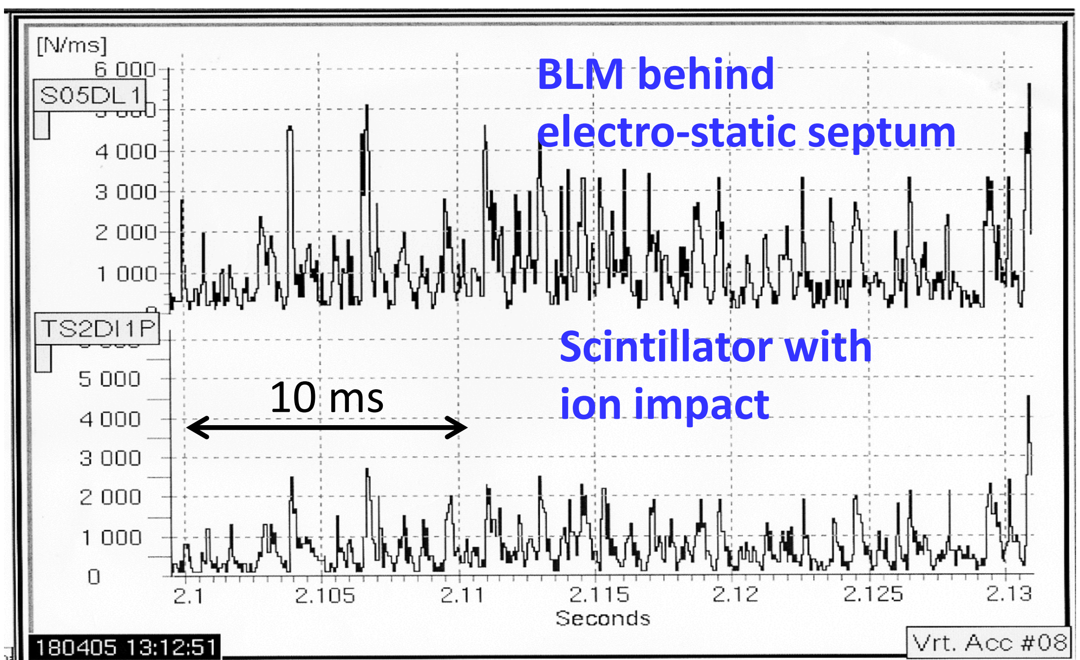
Advantage: cheap system, very large dynamic range

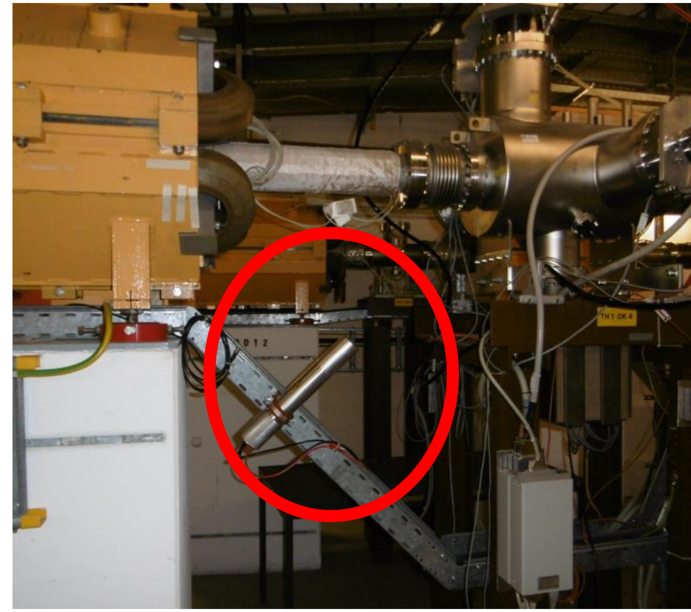
$\Rightarrow$ could be used for high ion currents

Restriction: $r_{aver} < 3 \cdot 10^6$ 1/s

Status: Detailed test pending

Example: Beam: : Kr^{34+} at 900 MeV/u, un-bunched beam





The signal for the BLM by lost ions,

while scintillator detects trans. ions

Observation:

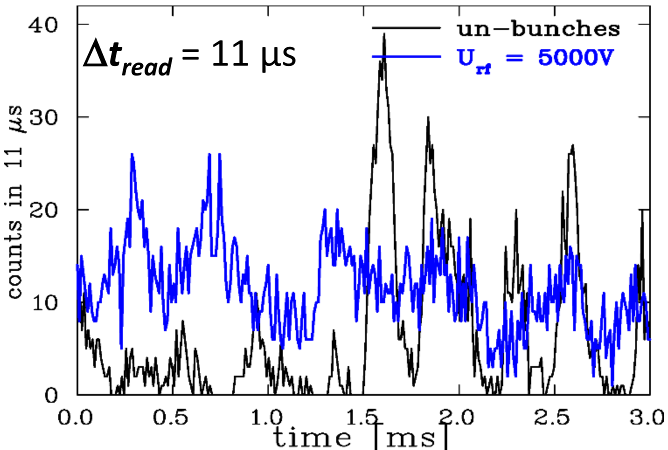
Same time structure is observed

$\Rightarrow$ BLM serves as a representative for micro-structure

Characterization for Micro-Structure

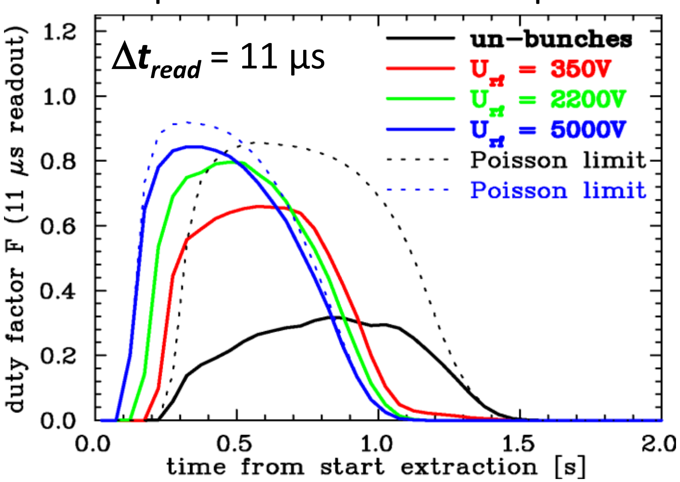
Example for bunched beam extraction

Beam: Bi^{68+} with 300 MeV/u, with f_{rf} = 3.62 MHz
Time domain recording with Δt_{read} = 11 µs



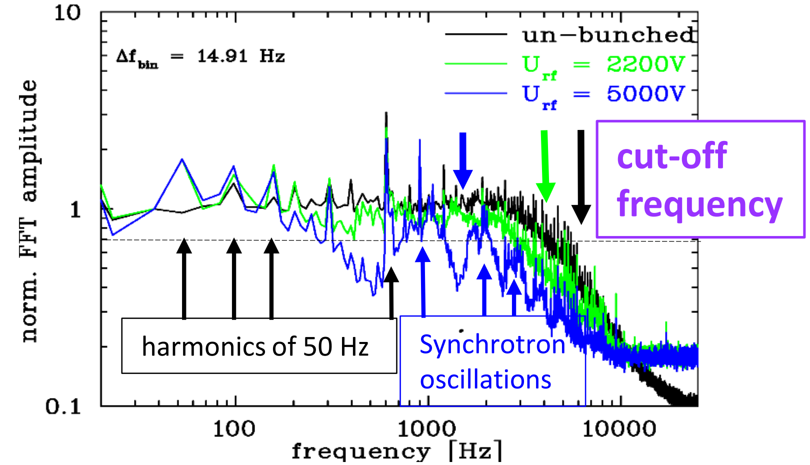
Calculation of duty factor: $F = \frac{c_{mean}^2}{c_{mean}^2 - \sigma_c^2}$

Care: Due to chromaticity, extraction parameter must be adapted



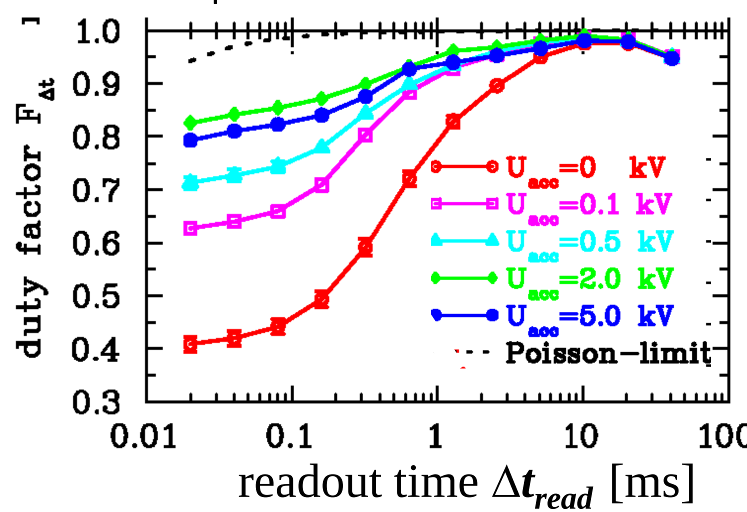
Calculation of Fourier Transformation

→ Steep rise time ⇔ larger cut-off frequency



Duty factor depends on readout time → binning of data

Care for comparison of measurements from different acc.



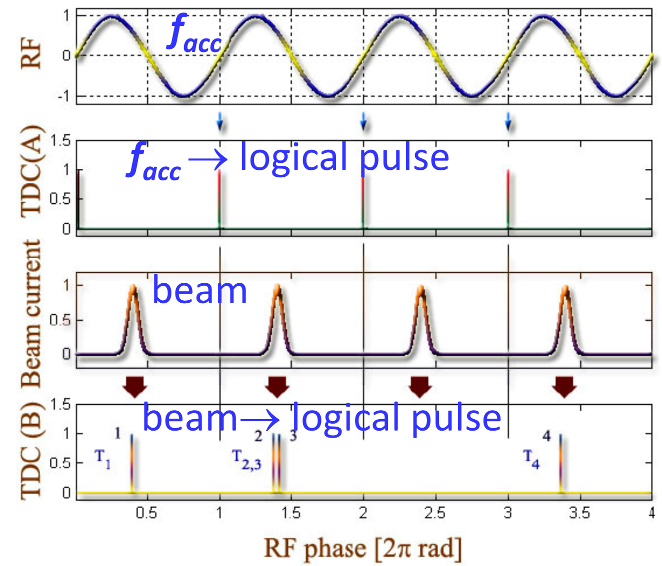
This plot: Different beam parameters

Bunched Beam Observation with 1 ns Time Scale

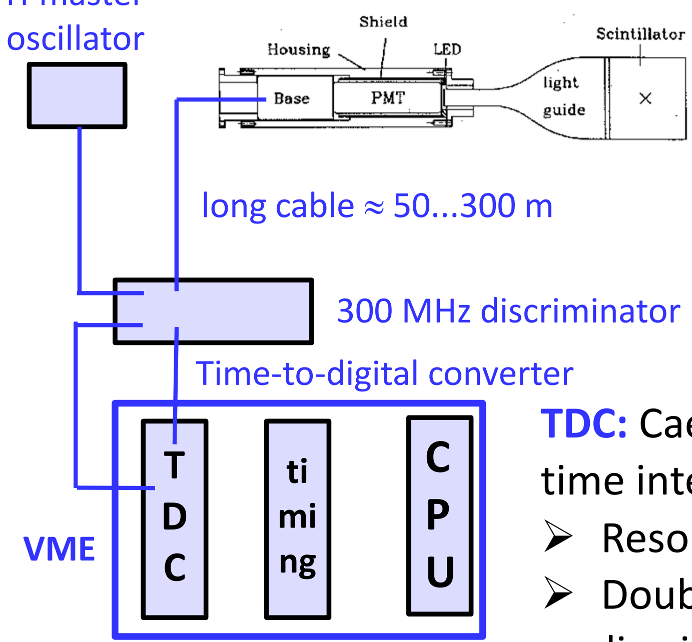
Bunched beam leads to short 'bunches' of the extracted beam

Measurement technique:

Particle arrival is measured with respect to the phase of the acc. frequency f_{acc} & with respect to the successive particle



Analog and digital chain:



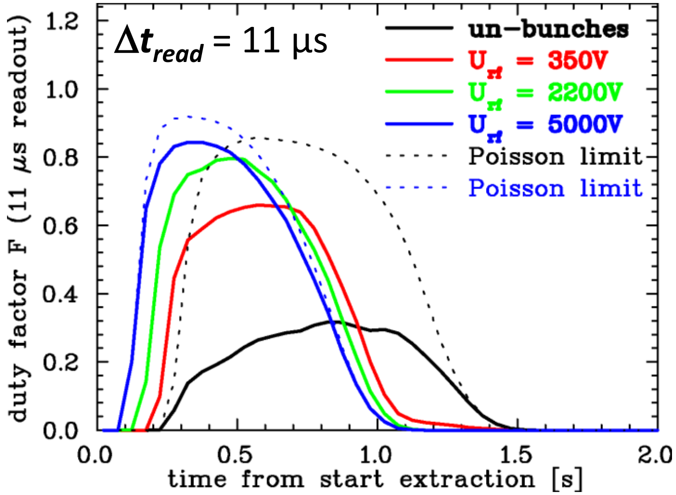
TDC: Caen V1290N time interval counter

- Resolution σ_{rms}= 35 ps
- Double hit discrimination 5 ns
- Max. count rate $r_{aver} < 3\cdot10^6$ 1/s

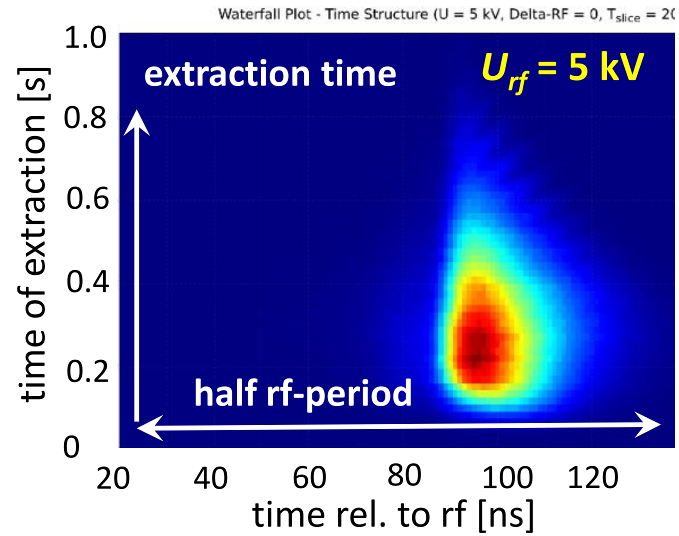
Timo Milosic et al. (GSI), IBIC 2021

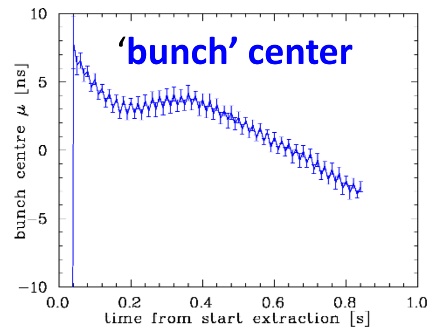
Effect of bunched Beam Extraction

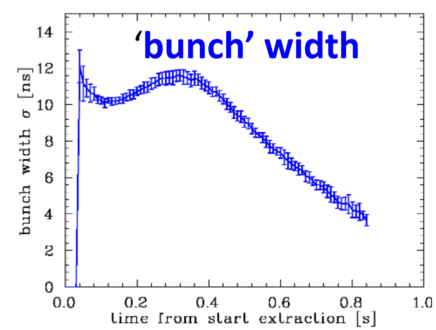
Bunched beam extraction by tune scan:
Beam: Bi^{68+} with 300 MeV/u, with f_{rf} = 3.62 MHz



Short 'bunches' extracted with
$\sigma_{ex} < 10$ **ns** $\ll \sigma_{stored}$ of beam in synch.







Result:

- Large improvement of duty factor by bunching
- Better for higher bunching freq. (within some range)

→ **Poisson limit almost reached**

[improvement only if $T_{transit} \approx \frac{1}{f_{synch}}$]

Beam diagnostics demand:
Faster detector needed
as Poisson limit depends on count rate

However: This is unacceptable for many users,
due to detector dead time $t_{dead} = 0.1 \ldots 10\ \mu s \approx 1/f_{rf}$

Additional mitigation to be installed ≈ 2013:
80 MHz high frequency bunching cavity

Bunched beam Extraction (Quad driven)

Extraction of bunched beam:

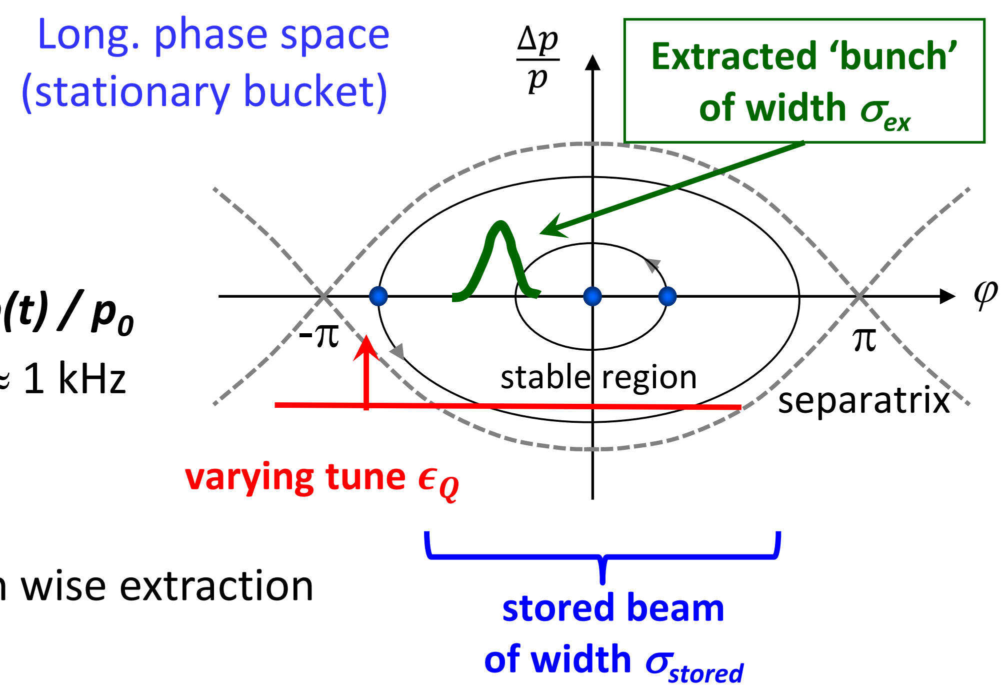
⇒ Building of stationary buckets
with oscillation of the particle momentum

⇒ Enlarged spread of $T_{transit}$ due to
time dependent tune via $\Delta Q(t) / Q_0 = \xi \cdot \Delta p(t) / p_0$
within a synchrotron period $t_{synch} = 1/f_{synch} \approx 1$ kHz

⇒ improvement **if** $t_{synch} \approx T_{transit}$

⇒ increase of $\Delta T_{transit}$ without re-capture

⇒ Shift of bunch center due to momentum wise extraction

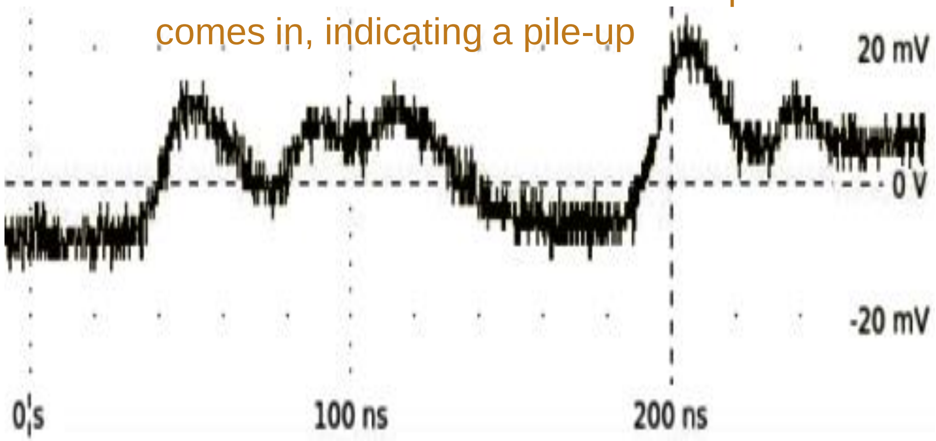


P. Forck et al., 'Measurements and Improvements of the Time Structure of a slowly extracted Beam from a Synchrotron, Conference Proceeding EPAC2000, p. 2237, Vienna 2000.

R. Singh et al., 'Slow Extraction Spill Characterization From Micro to Milli-Second Scale', J. Phys.: Conf. Ser.1067 072002 (2018)

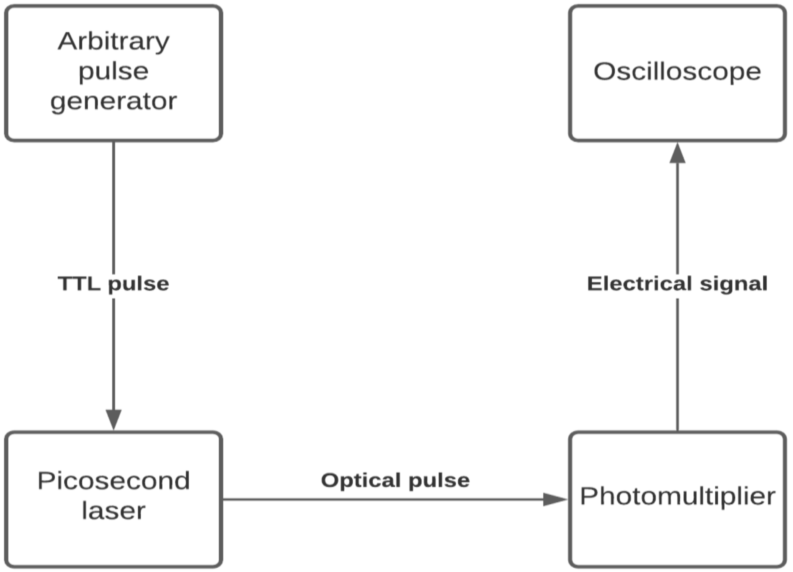
Particle Counting for pile-up Rejection using Machine Learning

Peak doesn't return to baseline before a new peak comes in, indicating a pile-up



Example of a piled-up, baseline shifted signal

Synthetic training/test data generation



Development:

- Detector signals occur very close in time
  → difficulties in their separation and identification
- Comparison: traditional threshold algorithms to template matching and convolutional neural networks (CNN)
- Focus on accuracy and computational complexity for implementing in FPGAs
- Hardware: Fast digitizer from Teledyne SP or Caen

Example:

- 1ch digitizer
- 1-5GSa/s
- 14 bit

R. Singh & P. Boutachkov (GSI) , S. Engel, H. Raza and V. Mohan (University of Essex)

Work-package 4 on detectors: Status and Vision

Status at GSI:

- Detailed investigations with scintillators, very high time resolution
- Development of inorganic scintillators, high radiation hardness
- DAQ: TDC $\rightarrow$ recent FESA-based code finished, Scaler $\rightarrow$ outdate software

  Drawback: Not directly portable to other facilities
- Ideas related to ML pile-up and baseline correction

Visions for the work-package 4:

- Comparable results from all facilities

  Vision: Comparison of spill quality from all facilities $\rightarrow$ **much progress by Florian Kühteubl !**
- Common experimental campaign at several facilities (GSI: shutdown mid 2022-mid 2023)

  Vision: Experiments with similar detector and data acquisition
- **Vision:** Versatile data analysis e.g. in Python available for experts
- **Vision:** Measurements for general understanding of improvements

Proposals for next steps:

- Online meeting with detector experts from all facilities in the up-coming month
- Comparison of experimental data and common data analysis

$\Rightarrow$ Please propose or confirm interested delegates for the work-package 4

Thank you for your attention!