Measurements of the spill structure on a wide time range at GSI

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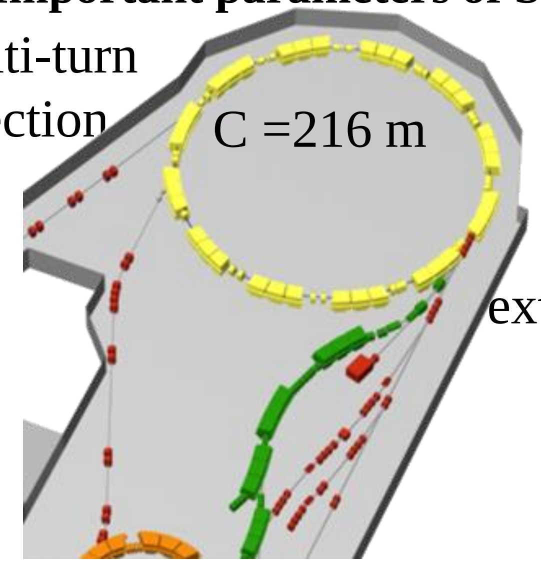
Spill diagnostics for slow extraction @GSI:

- Spill duty factor and spectra
- „Ripple transfer function" of power supplies & spill quality results
- Quadurpole driven extraction of coasting and bunched beams:
  Extraction length, sextupole strengths, momentum spread
- Measurements with 100 ps time resolution for bunched beams

GSI Heavy Ion Synchrotron: Overview

Important parameters of SIS-18:



Ion (Z)	1 → 92 (p to U)
Circumference	216 m
Inj. type	Multiturn
Injection energy	11 MeV/u
Max. final energy	≈ 2 GeV/u
Ramp duration	0.1 → 1.5 s
Acc. RF	0.8 → 5 MHz
Tune	4.30(h), 3.25(v)

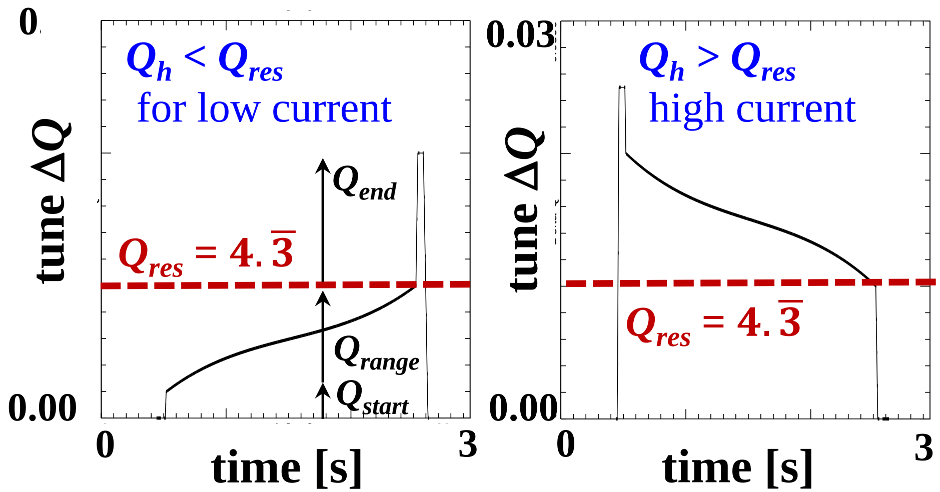
Extraction: $Q(t)$ by 3rd order polynomial

for constant macro-time structure

→ adapted for each experiments

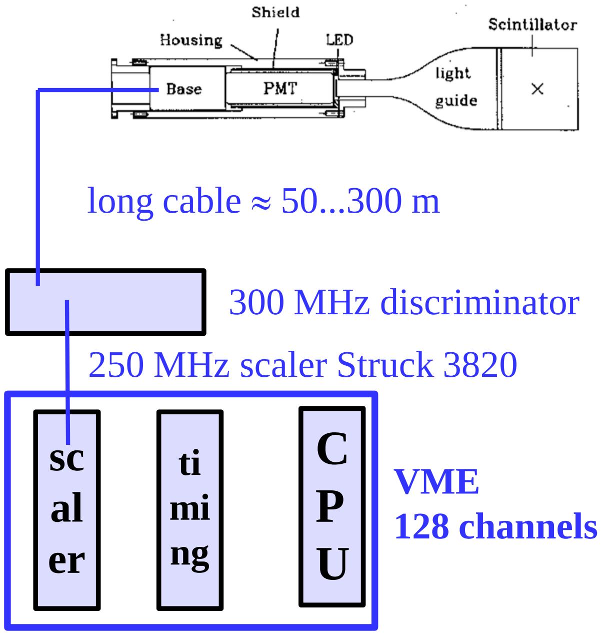
Q_{start} , Q_{range} , Q_{end} and $Q(t)$

Tune ramps by 'fast' quadrupole

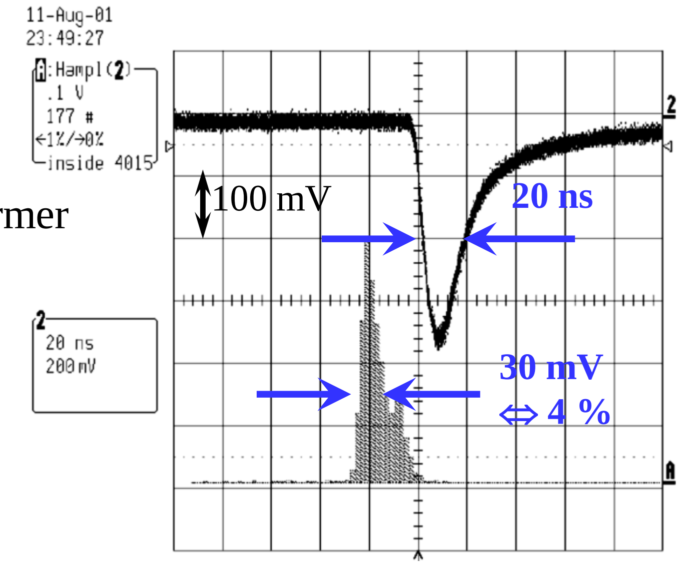


This talk: Data for $Q_h < Q_{res}$

Analog and digital chain:



***Example*:** Analog pulses from a plastic scintillator with 200 m cable for 300 MeV/u Kr beam



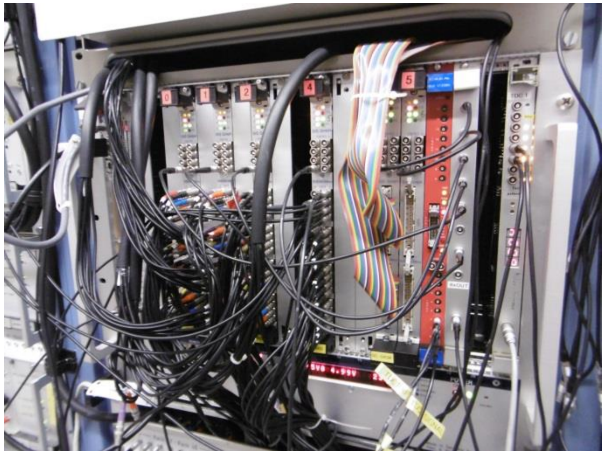
Parallel digitalization of:

- Scintillators
- Ionization Chambers
- synchrotron current transformer
- any detector

Entire cycle stored with

typ. sampling t_{read} = 1...100 µs

Various <u>online</u> analysis tools



Advantage of particle counting:

- single particle detection, well to be triggered
- 100 ps time resolution possible
- **no** noise or background

⇒ could be directly compared to particle simulation

Example for 'Spill Micro-Structure' coasting Beam

Extraction: Quadrupole variation (standard at GSI)

Detector: Scintillator, readout time t_{read} = 20 µs

Single extraction measurement with $r_{mean} \approx 10^6$ 1/s

Observation:

- Breaks and peaks of $t \approx 100$ µs
- High peaks with steeper rising edge (as expected)

Time domain characterization:

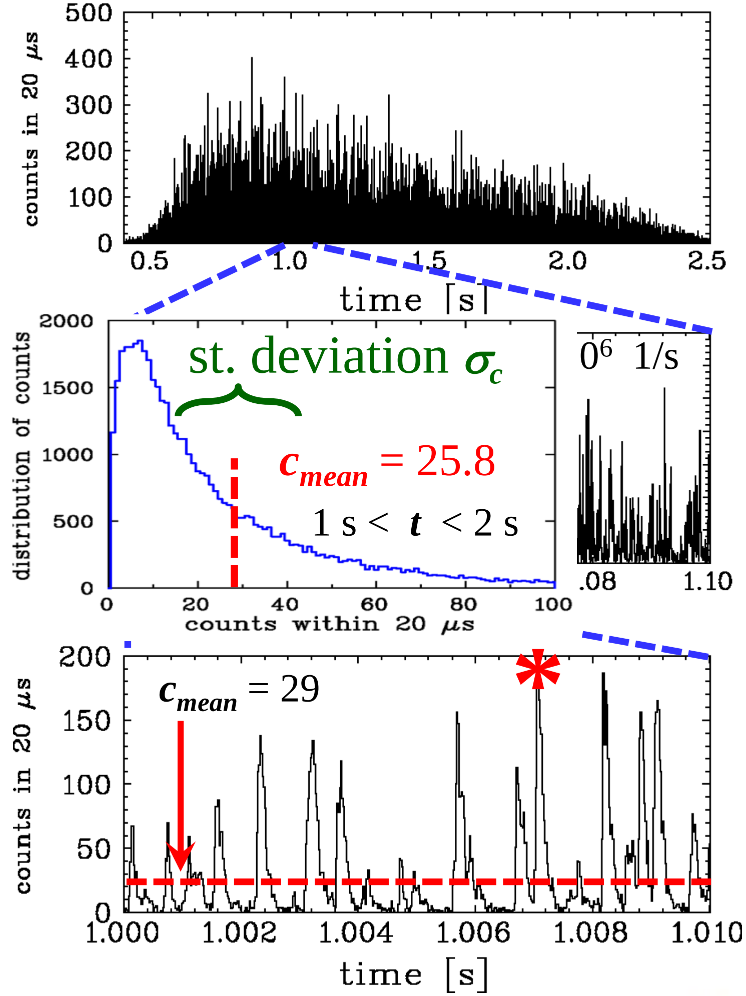
The entire spill quality has to be characterized

- Creation of time intervals of e.g. Δt = 10 ms
- Determination of maximum-to-average ratio
  i.e. calc. mean $c_{mean}(\Delta t)$ & search for max. $c_{max}(\Delta t)$
  $\rightarrow$ calculation of ratio $r(\Delta t) = c_{max} / c_{mean}$
  Advantage: depictive quantity
- Calculation of duty factor
  by standard deviation σ_c of counts/20µs within Δt

$$F_{\Delta t} = \frac{c_{mean}^2}{c_{mean}^2 + \sigma_c^2}$$

Advantage: statistical description for entire interval Δt

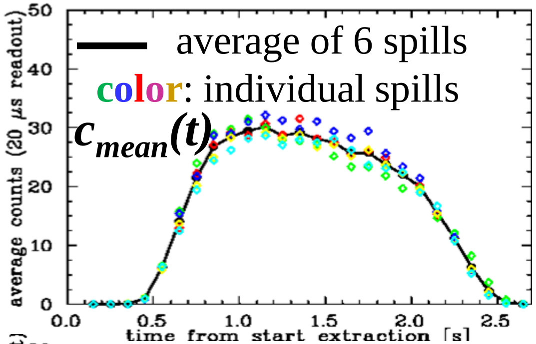
Example: C^{6+} at 300 MeV/u
Quad. scan, un-bunched beam

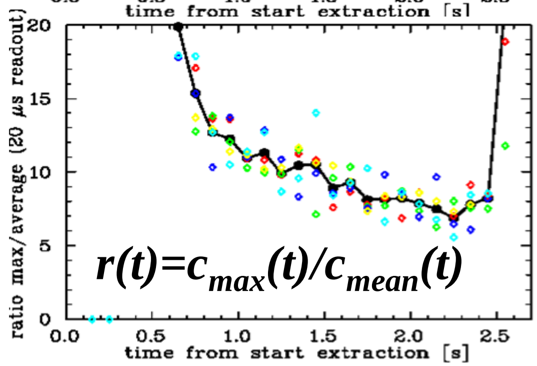


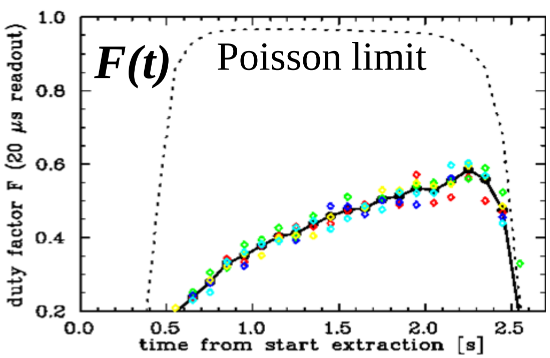
Examples for Ratio max/mean & Duty Factor

Example: C^{6+} at 300 MeV/u, recorded within same day i.e. same beam parameter except extraction

Quad. scan, un-bunched beam







Readout t_{read} = 20 µs

Determination with e.g. Δt = 0.1 s:

- mean: $c_{mean} \equiv \langle c \rangle$
- max/main: $r = c_{max} / c_{mean}$
- duty factor $F = \frac{c_{mean}^2}{c_{mean}^2 + \sigma_c^2} \equiv \frac{\langle c \rangle^2}{\langle c^2 \rangle}$
- Poisson: $F_{poisson} = \frac{c_{mean}}{c_{mean}+1} \equiv \frac{\langle c \rangle}{\langle c \rangle + 1}$

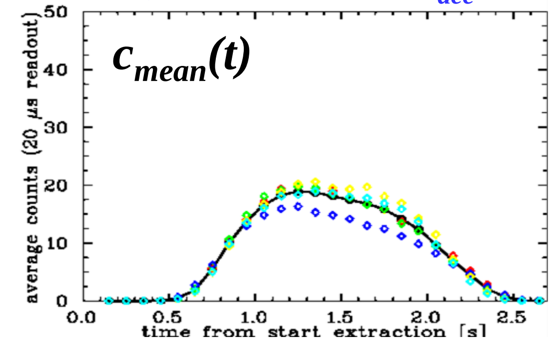
Observation for quad. scan:

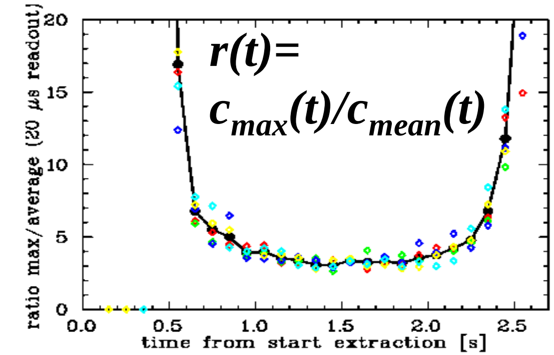
- individual spills have comparable r and F
- r and F are **not** constant
- r (t_{read} =20 µs) ≈ 10
- F (t_{read}=20 µs) ≈ 0.5 < $F_{poisson}$

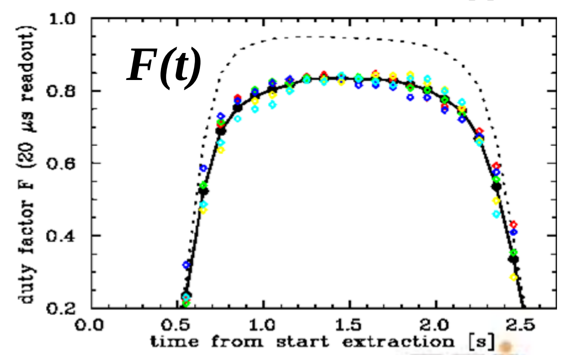
Observation for quad. scan & bunched beam:

- r and F are **not** constant
- r (t_{read}=20 µs) ≈ 4
- F (t_{read}=20 µs) ≈ 0.8 < $F_{poisson}$

Quad. scan., bunched beam U_{acc}=2 kV







Results for bunched Beam Extraction

Comparison of results for different time scale:

Binning of data by offline analysis

i.e. numerical variation of 30 µs < t_{read} < 60 ms

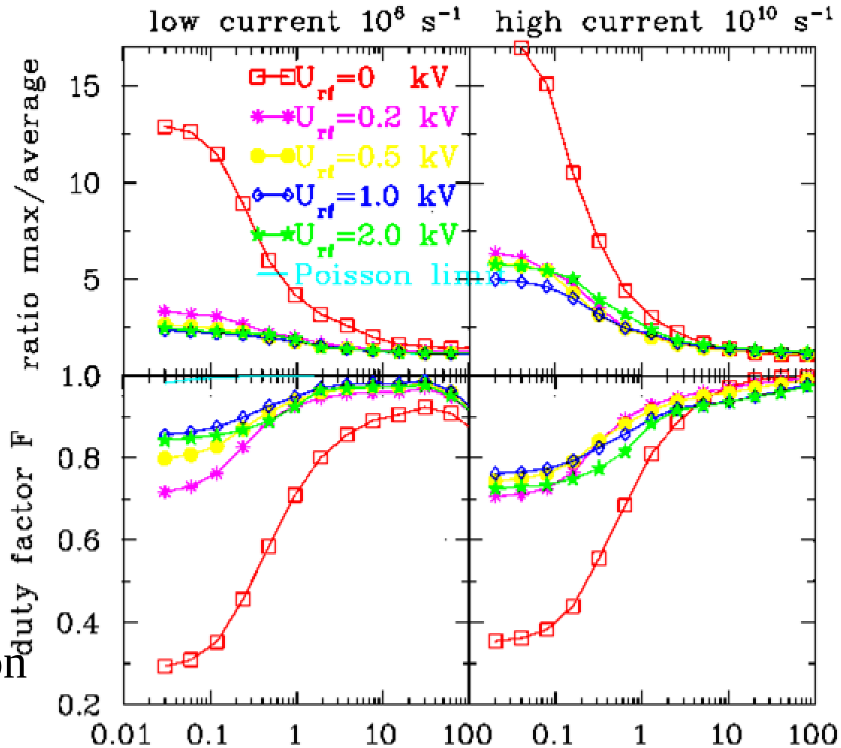
Reason: Comparison of different measurement

Observation:

- Significant improvement for bunched beam
- Moderate bunching leads to significant improvement (maximum U_{acc} = 14 kV)
- Low variation for 20 µs < t_{read} < 100 µs
- **General behavior independent on beam current !**

High current measurement with Cryogenic Current Comparator

Example: Ar^{18+} at 300 MeV/u, different current ranges, quad. scan, bunched beam 0 kV < U_{acc} < 2 kV

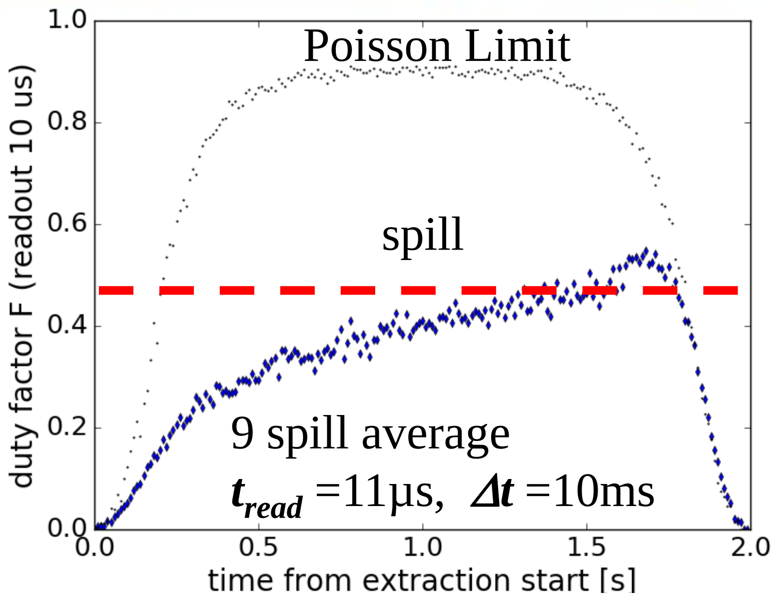


readout time t_{read} [ms]

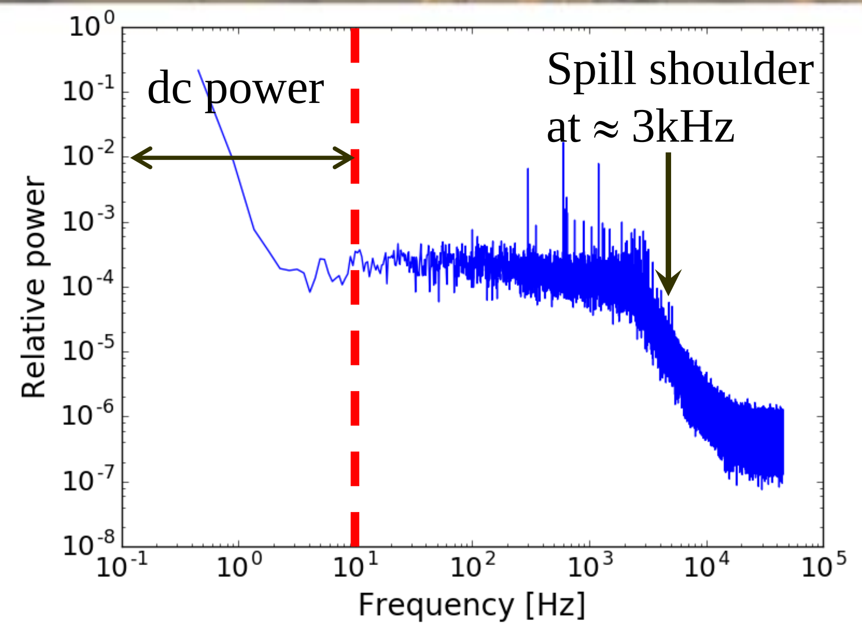
Application:

- Sufficient improvement for therapy application
- **However:** It leads to short 'bunches' with t < 10 ns & $1/f_{acc}$ repetition at target → see below
- **Proposal:** Bunching at higher frequency e.g. 80 MHz, larger ξ (talk by P. Schmid)

Duty Factor and Spill Spectrum



Time Domain



Frequency Domain

- Duty factor calculated in the chosen interval Δt

  as $F = \frac{c_{mean}^2}{c_{mean}^2 + \sigma_c^2} \equiv \frac{\langle c \rangle^2}{\langle c^2 \rangle}$

- Poisson duty factor $F_{poisson} = \frac{c_{mean}}{c_{mean}+1} \equiv \frac{\langle c \rangle}{\langle c \rangle + 1}$
- Evolution of F during the spill is visible

- Time Domain duty factor is equivalent to 'dc power' (f < 10 Hz) divided total power
- **'Narrowband':** ≈ 20- 50% of power in main's harmonics $f = n \cdot 150$ Hz for f > 20 Hz
- **'Broadband':** Noisy beam response up to "shoulder" at ≈ 3 kHz (i.e. pink noise)

'Narrowband' ↔ 'broadband' response not modelled but simulations are comparable, see talk by S. Sorge

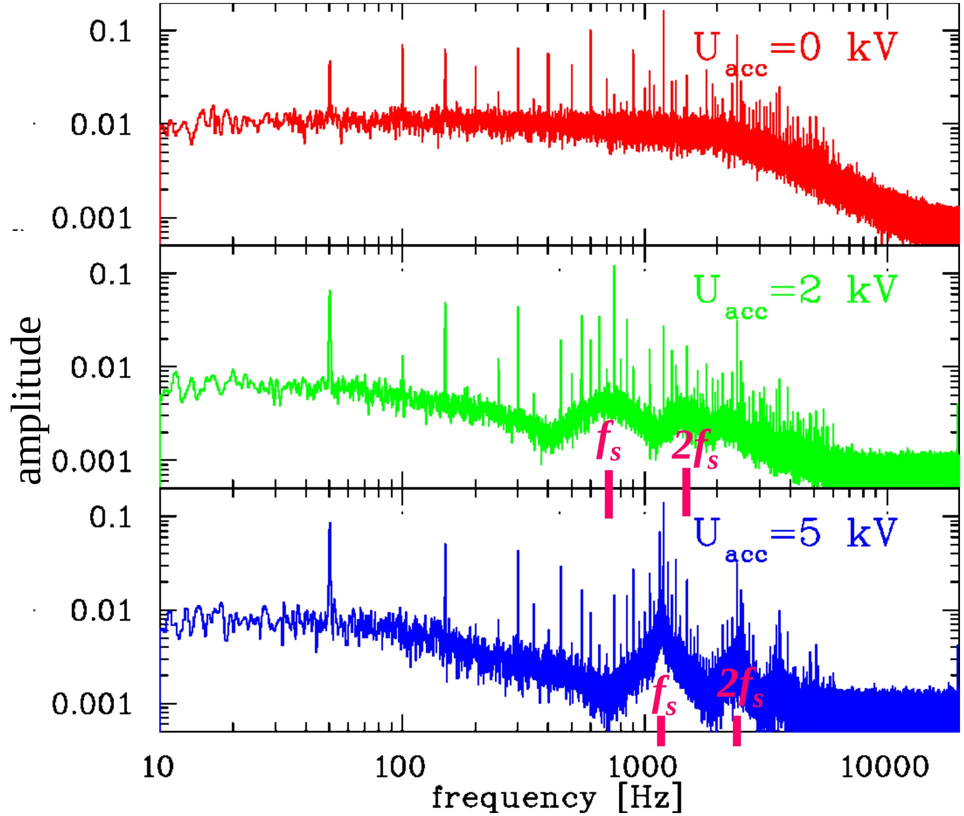
Fourier transformation shows the repetition of the signal:

Observation:

Spectrum comprises on

- Lines related to 50 Hz main frequency linewidth smaller 1 Hz (resolution limit)
- Low pass response up to $f_{cut} \approx 4$ kHz
- Flat part is equivalent to noise-like response! What does this mean e.g. for power supplier specifications **?**
- For bunched beam: broad peaks at synchrotron frequency $f_S \propto \sqrt{U_{acc}}$

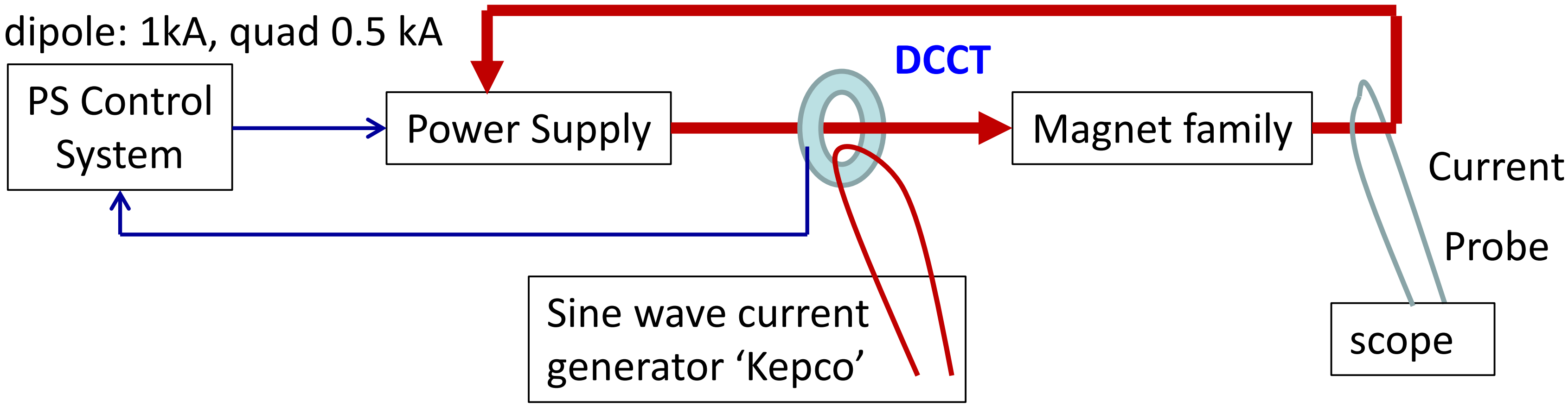
Example: C^{6+} at 300 MeV/u,
t_{ex} = 2 s, readout step t_{read} = 20 µs, 5 spills average
Quad. scan, bunched beam 0 kV < U_{acc} < 5 kV



Remarks:

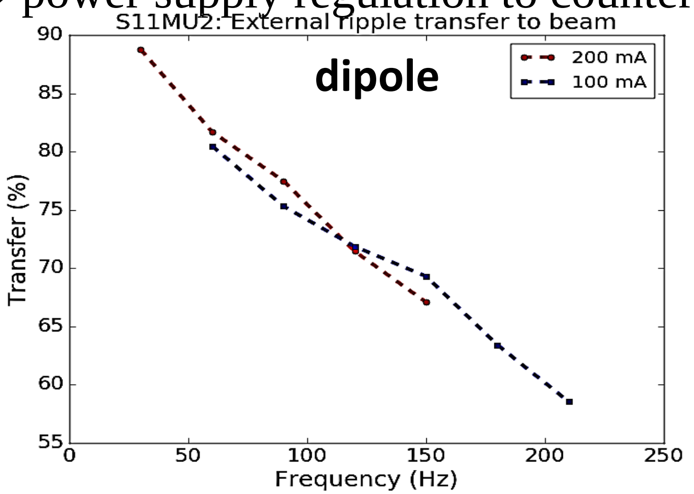
- Spectrum resolution: 2 s sampling with 20 µs i.e. $N = 10^5$ sample points & f_{max} = 25 kHz $\Rightarrow$ resolution $\Delta f = f_{max}/N$ = 0.25 Hz
- Measurement performed in 1998 different power-suppliers used today $\Rightarrow$ main line are multiple of 150 Hz

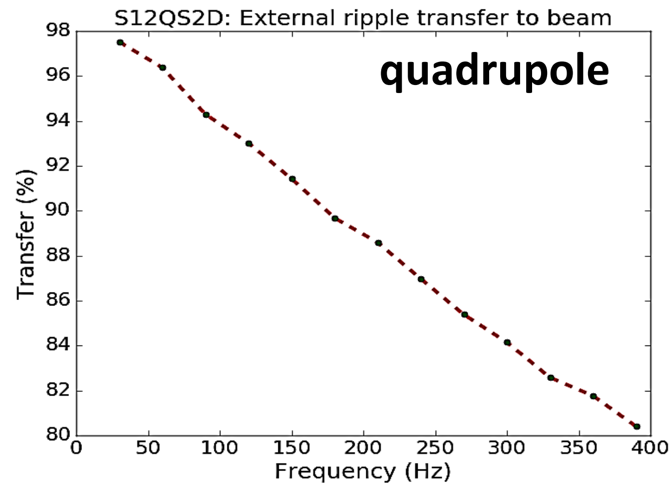
Goal: Determination of power supplier ripples and their influence on the spill



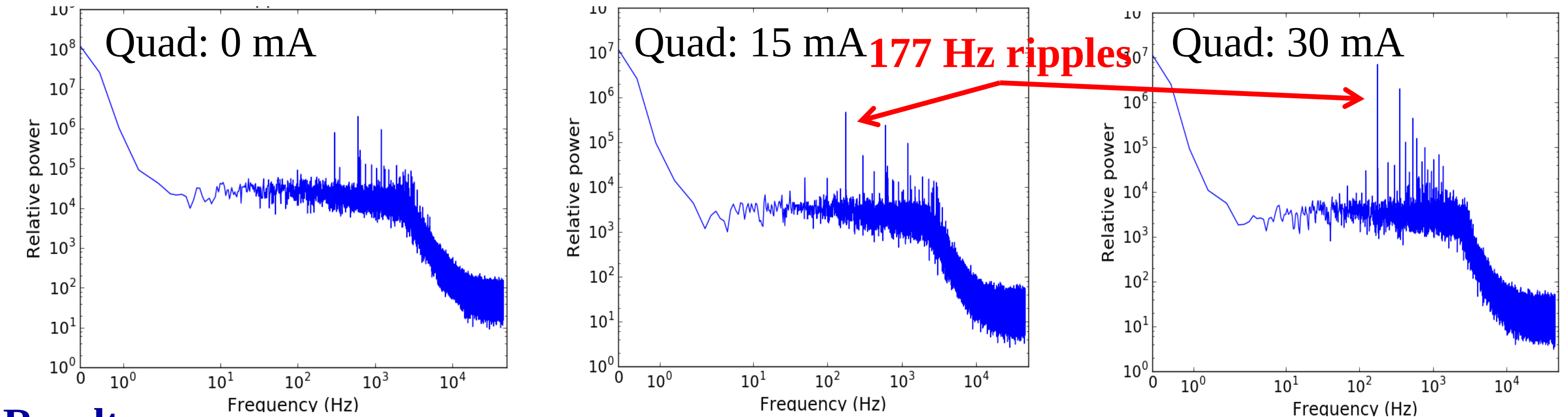
Sine waves of I = 0.1...0.2 A in range from 30 Hz to 400 Hz were fed to the dc-transformer

⇒ power supply regulation to counteract ⇔ measure of 'transfer function'





Quantitative investigations concerning PS ripple: 137 Hz (dipole) and177 Hz (quad) injection



Result:

Dipole: Effect for ≈ 200 mA ⇔ $2x10^{-4}$ FS (3.5kA)

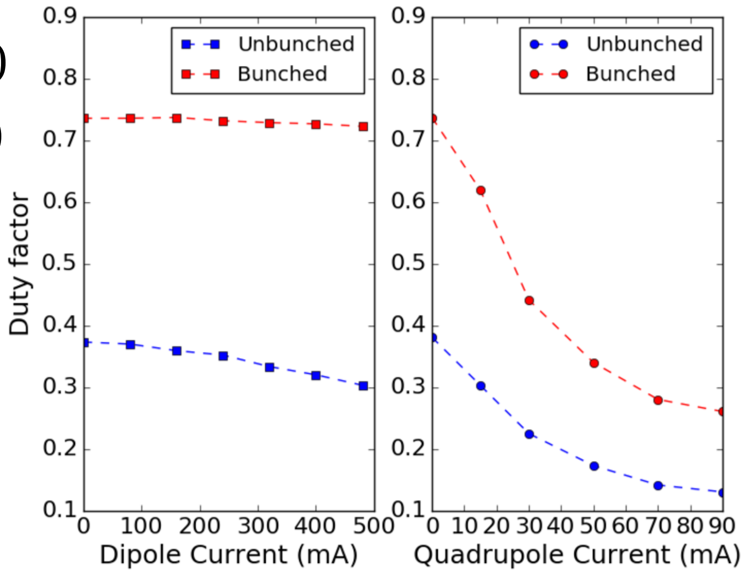
Quad: Effect for ≈ 10 mA ⇔ $2x10^{-5}$ FS (1.7kA)

largest 'natural' line ≈5 mA@600 Hz

⇒ power supplies can't be improved

⇒ micro-structure caused by PS ripple

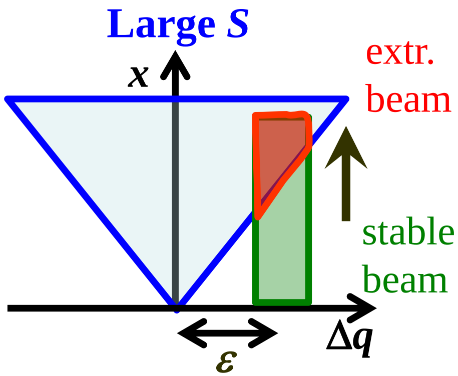
Sextupole: not tested yet

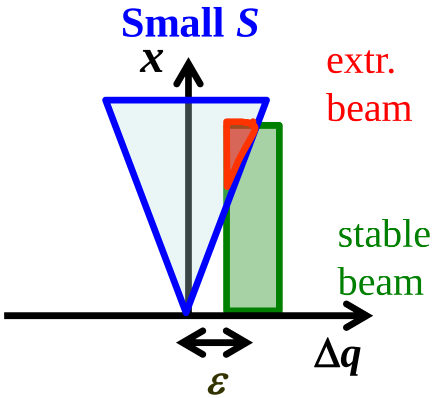


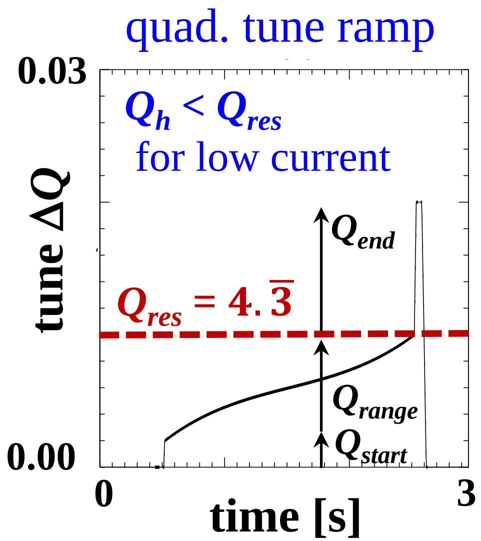
Experiments with slow Extraction Parameter Variation

- Systematically changed several beam parameters to determine the cause of "spill shoulder" -> Suspicion was transit time
- Qualitative effect of distance to resonance ε and sextupole strength S on transit time

i.e. $T_{transit} = T_{transit}(S, \varepsilon)$





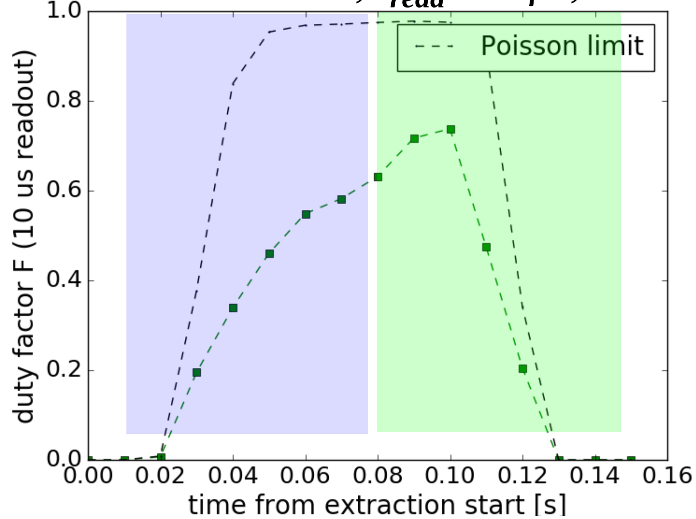


When sextupole strengths are changed, start & speed of quadrupolar ramp has to be adjusted to obtain a similar spill length.

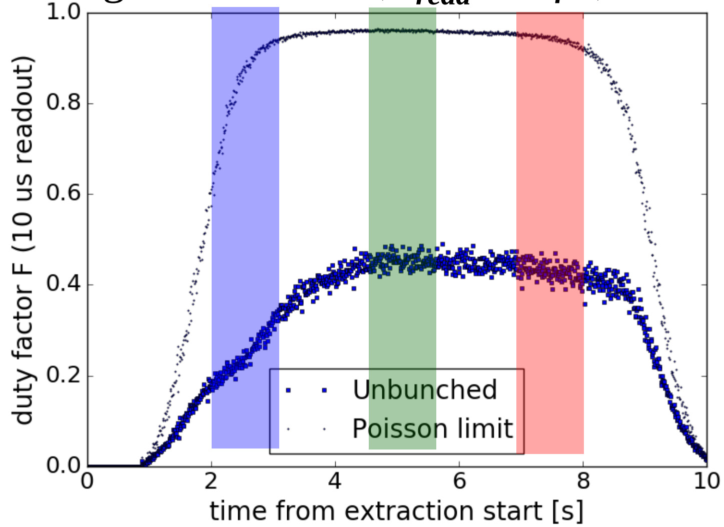
⇒ For lower sextupole strength, both the transit time and its spread would be higher.

Coasting Beam: Extraction Time versus Duty Factor

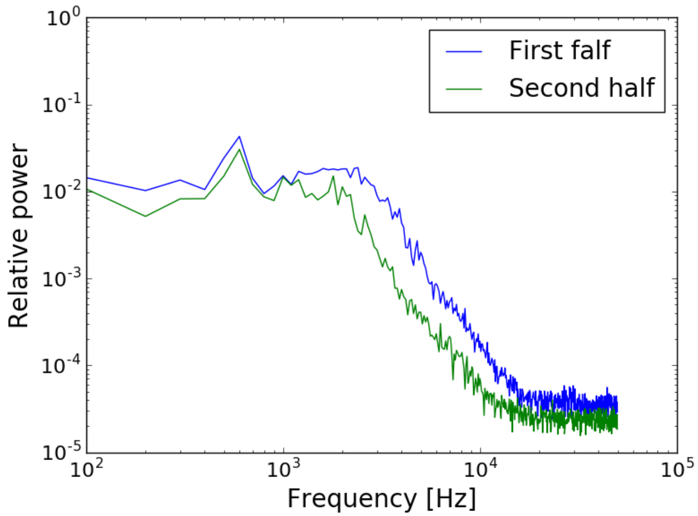
Short extraction 0.1 s, t_{read} =11µs, Δt =10 ms



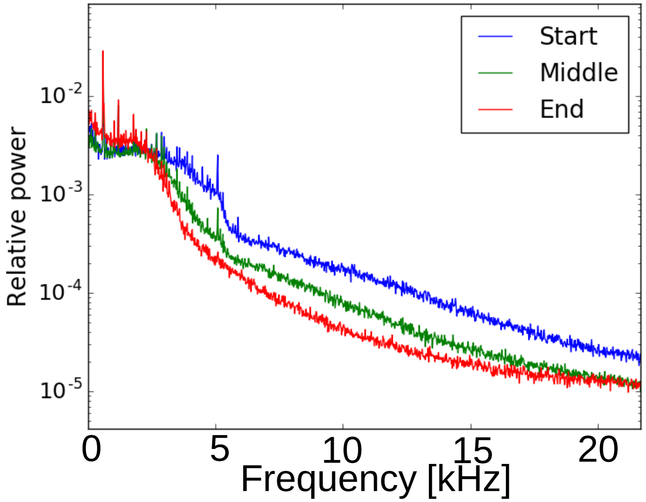
Long extraction 9 s, t_{read} =11µs, Δt =10 ms



Bin size is 50 Hz and 9 spill average

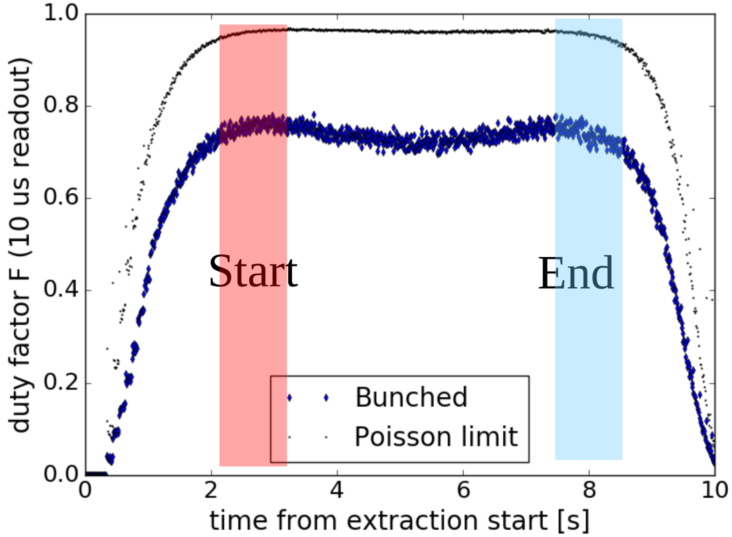


Bin size is 10 Hz and 9 spill average

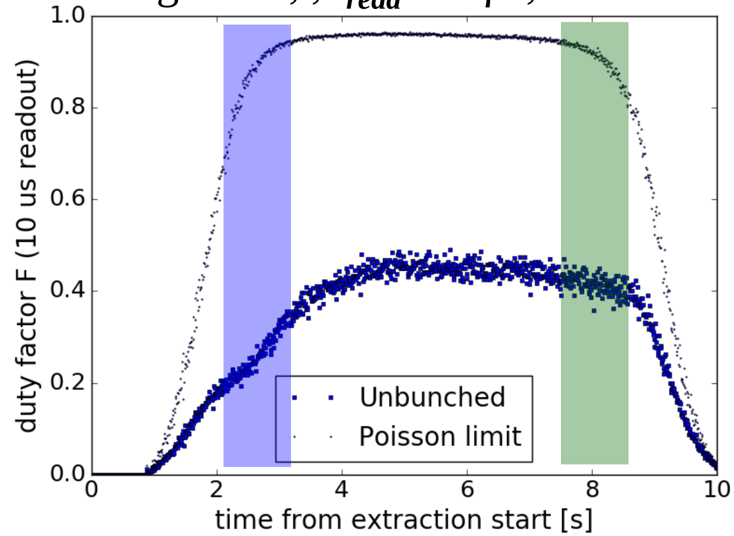


Bunched versus coasting Beam

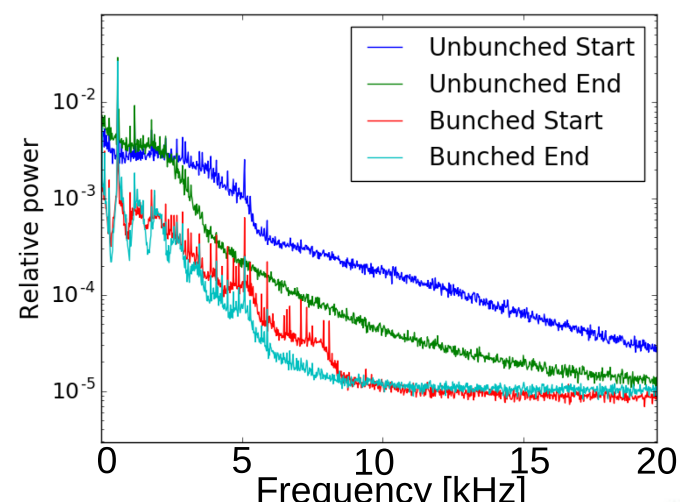
Bunched beam, , t_{read} =11µs, Δt =10 ms



Coasting beam, , t_{read} =11µs, Δt =10 ms

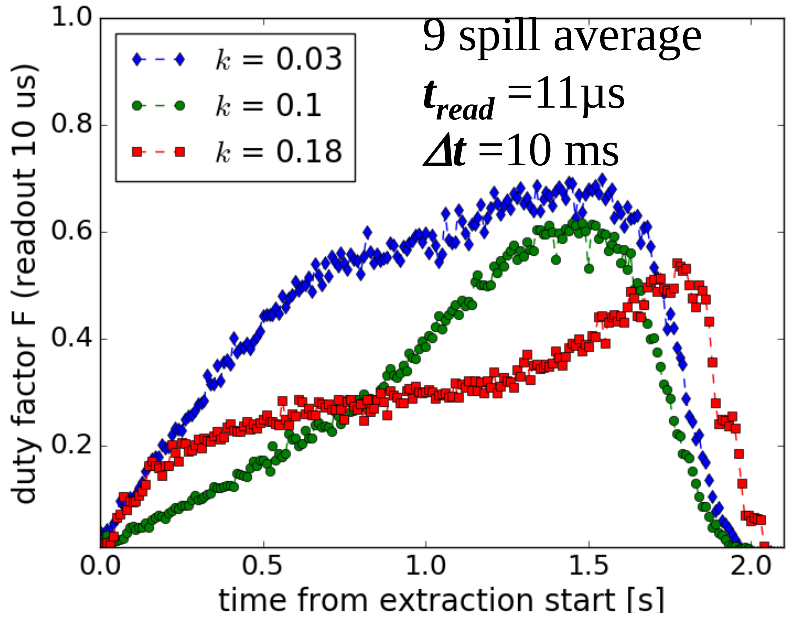


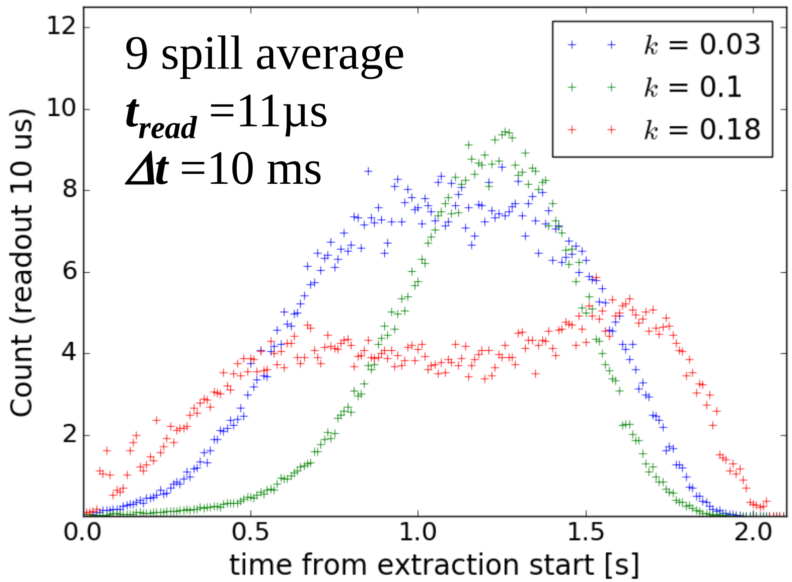
Bin size is 10 Hz and 9 spill average



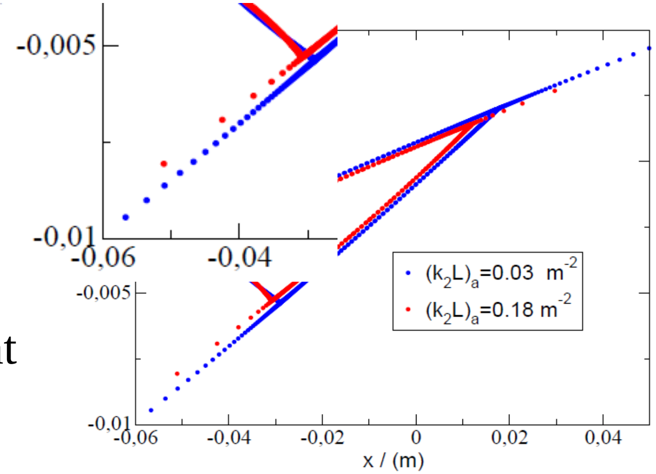
- Higher frequencies are cut-off towards the end of spill for bunched and unbunched beams
- Bunched beam spectrum shows synchrotron tune frequencies
- The coherent lines and the incoherent band are not uncorrelated

Sextupole Strength Variation



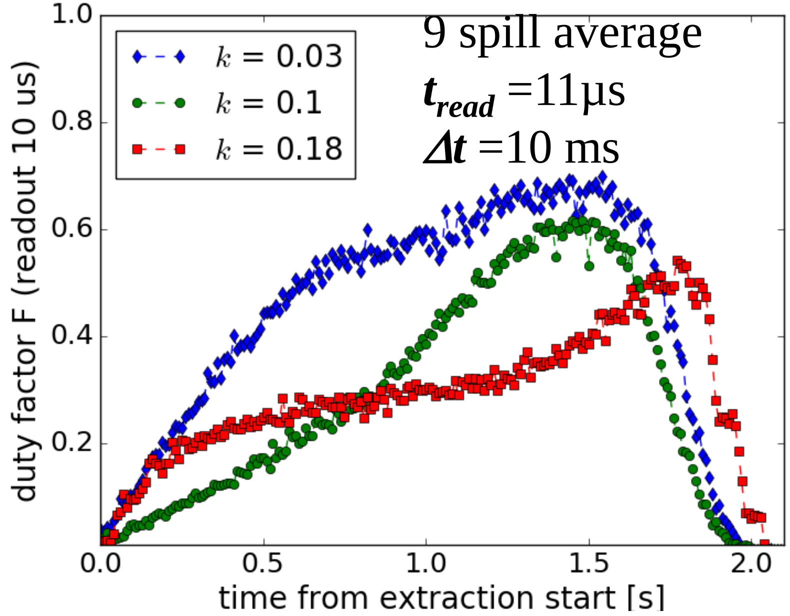


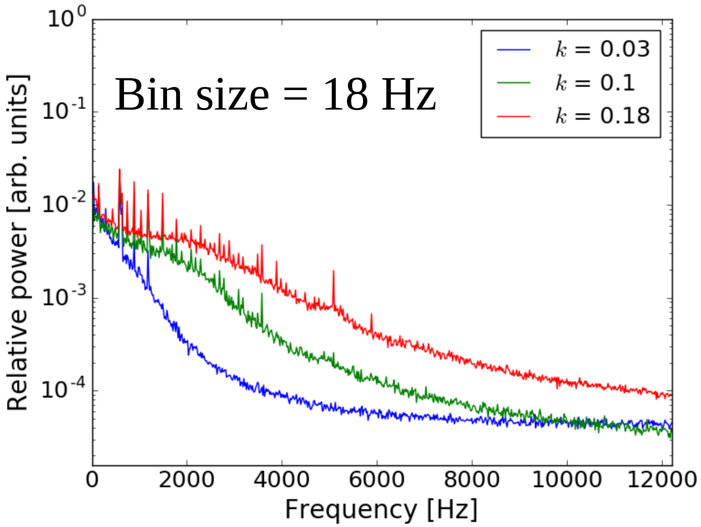
Phase space: Simulation by Stefan Sorge



- Sextupole strength ***k*** has effect on duty factor & shoulder in spectra; lower ***k*** preferred
- Reduction in sextupole strength leads to longer transit times & suppression of high freq. (confirmed by simulations, see talk by S. Sorge)
- **But:** Large sextupole strength ***k*** required to prevent for losses at ele. septum i.e. **not** free parameter

Sextupole Strength Variation





- Sextupole strength ***k*** has effect on duty factor & shoulder in spectra; lower ***k*** preferred
- Reduction in sextupole strength leads to longer transit times & suppression of high freq. (confirmed partly by simulations)
- **But:** Large sextupole strength ***k*** required to prevent for losses at ele. septum i.e. **not** a free parameter

Bunched beam extraction improves the spill structure on 10 μs time scale

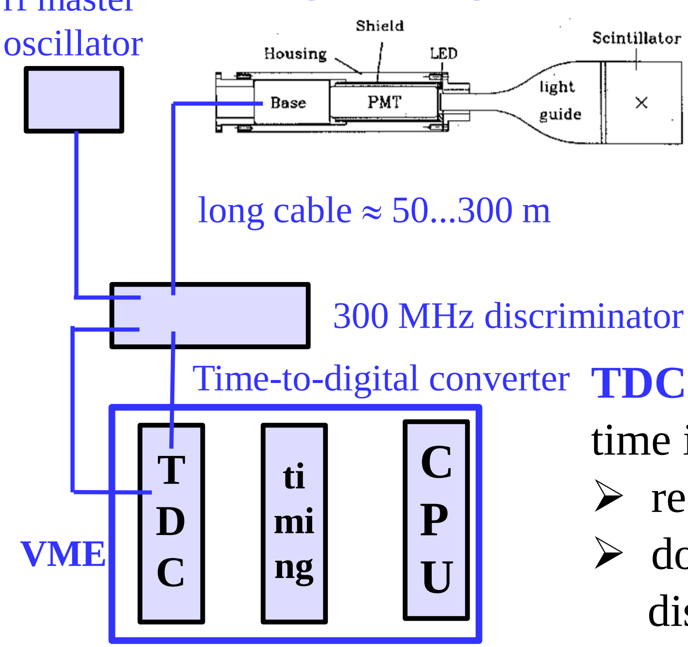
but leads to short ‘bunches’ of the extracted beam

Measurement technique:

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

Analog and digital chain:

rf master oscillator

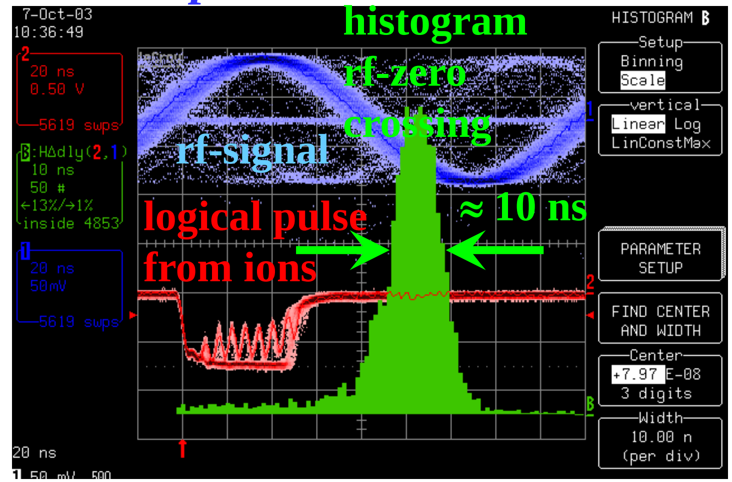


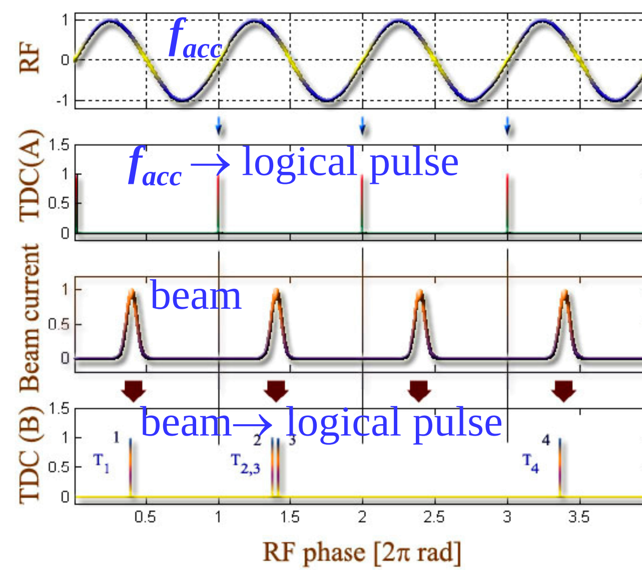
TDC: Caen V1290N

time interval counter

- resolution σ_{rms}= 35 ps
- double hit discrimination 5 ns

***Example*:** Ni^{26+} at 600 MeV/u

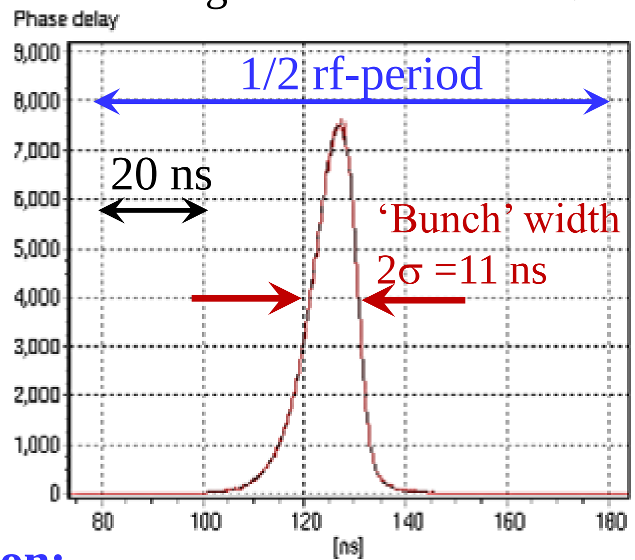




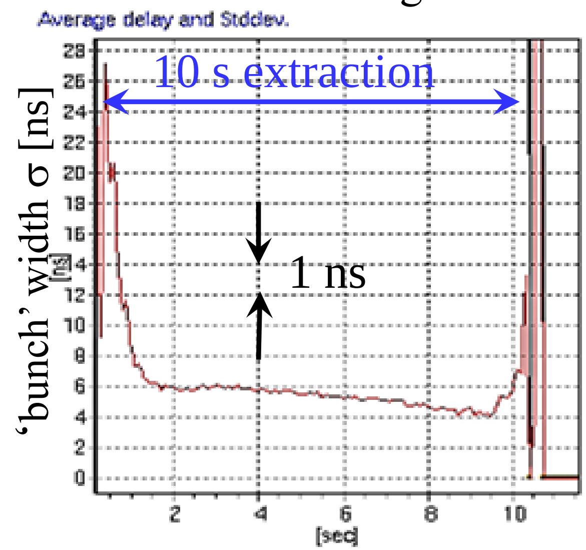
Arrival time measurement for bunched beam

Example: Ar^{18+} at 1750 MeV/u, quadupole variation, bunched beam

Histogram of arrival time:



'Bunch' duration during extraction:



Observation:

- 'Bunch' duration at target in the range of $2\sigma \approx 10 \ldots 30$ ns even for energies of some 100 MeV/u
- 'Bunch' duration at target much shorter than bunch length inside SIS
- Reason: Only ions wit extreme value of $\Delta \boldsymbol{p}/\boldsymbol{p}$ are extracted

Application:

- For therapy: acceptable because time resolution of any detector >> some μs
- For experiments: not acceptable due to 'long breaks' of almost one rf period (SIS max. f_{rf} = 5 MHz)
- Idea to be theoretical and experimentally investigated: High frequency bunching of ≈ 80 MHz

Slow extraction: Complex due to interplay of many parameters
Measurements for μs and ns time resolution:

- Particle counting: no background nor broadband noise , max. average rate: some 10^6 1/s
- Analysis of entire spill: Time domain → duty factor & frequency domain

Results (quadrupole driven extraction):

- Power supplier ripple amplitudes are related to spectrum, PS can't be improved
- Bunched beam extractions improves spill on 100 μs scale, but worsen on 100 ns scale
  80 MHz cavity might shift it to 10 ns scale (see talk by P. Schmid)
- Duty factor increase during spill as related to increase of transit time
  ⇔ Frequency spectrum: higher frequencies are less excited for longer transit times
- Sextupole amplitude has a major influence to increase transit time and its spread
- Momentum spread has no influence on micro-structure
  (as well as chromaticity for coasting beam)
- Further extraction methods will be investigated

Thank you for your attention !

Space slides

Momentum Variation for Quadrupole-driven Extr: Stored Beam

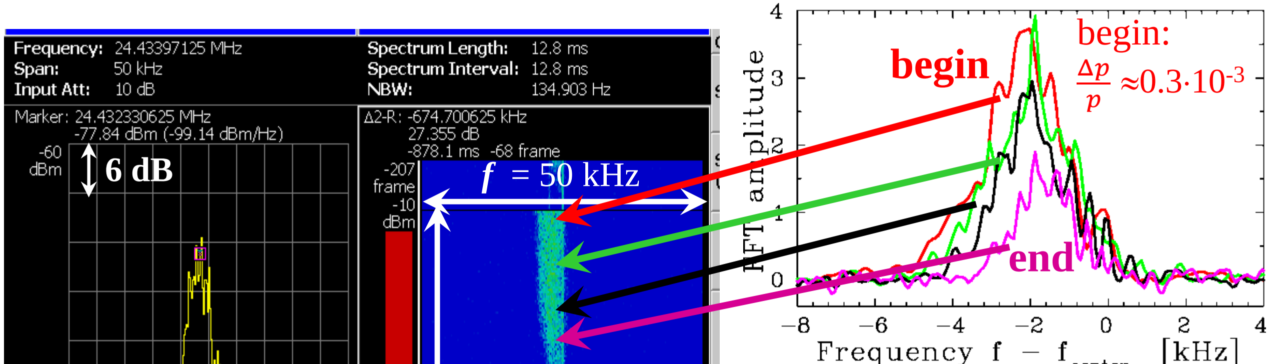
Example for longitudinal Schottky spectrum for quadrupole-driven slow extraction:

- Momentum spread before extraction here $\frac{\Delta p}{p_0} = 0.15 \cdot 10^{-3}$ (1σ)
- Chromaticity (here ξ=-1.5) i.e. coupling tune ↔ momentum spread : $\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$

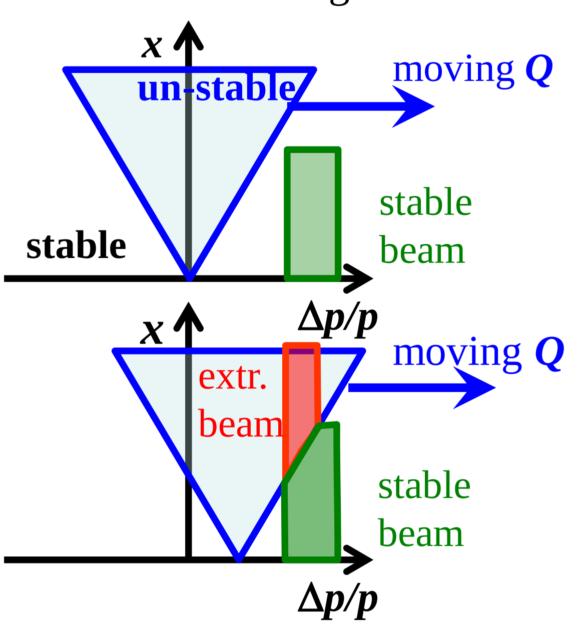
⇒ Lower momentum ions extracted first & variation of extraction angle at dispersive section in transfer

⇒ **No** improvement for micro-structure ! (small momentum interval during e.g. 1 ms)

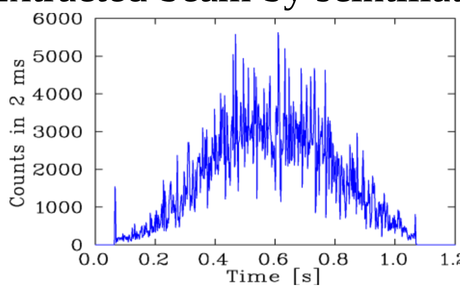
Beam parameter: GSI-synch. C^{6+} at 300 MeV/u ⇔ f_{rev} = 0.95 MHz, Schottky for h =26, Δf = 1.6 kHz (1σ)



Steinbach diagram:

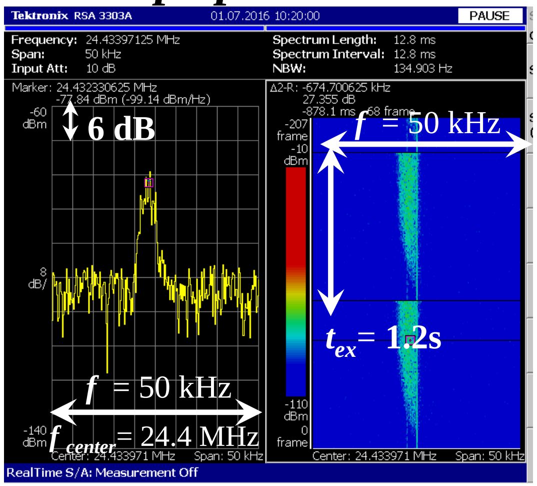


Extracted beam by scintillator:

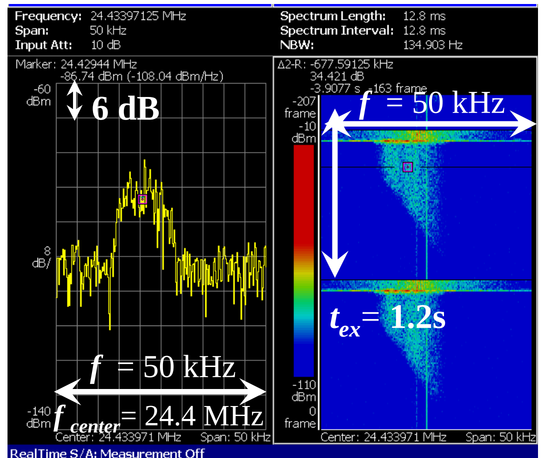


Momentum Variation for Quadrupole-driven Extr: Extracted Beam

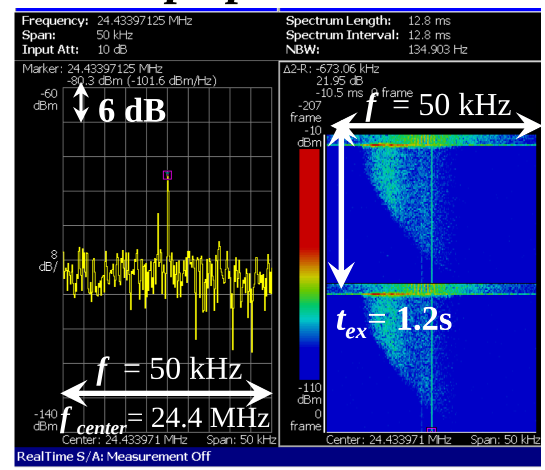
rf-power 0 kV
$\Rightarrow \Delta p / p \approx 0.15 \cdot 10^{-3}$



rf-power 1.0 kV
$\Rightarrow \Delta p / p \approx 0.45 \cdot 10^{-3}$



rf-power 2.0 kV
$\Rightarrow \Delta p / p \approx 0.45 \cdot 10^{-3}$

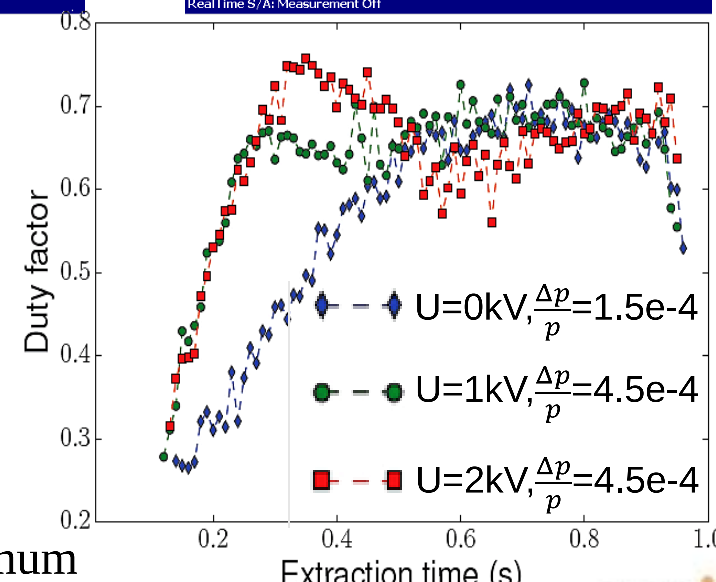


- $\Delta p / p$ was blown-up **prior** to extraction
- by $f = 2880$ kHz $\neq n f_{rev}$ & variable amplitude

$\Rightarrow$ **no** variation of micro-structure

Reason:

within time ≈ ms only one $\Delta p / p$ slice extracted

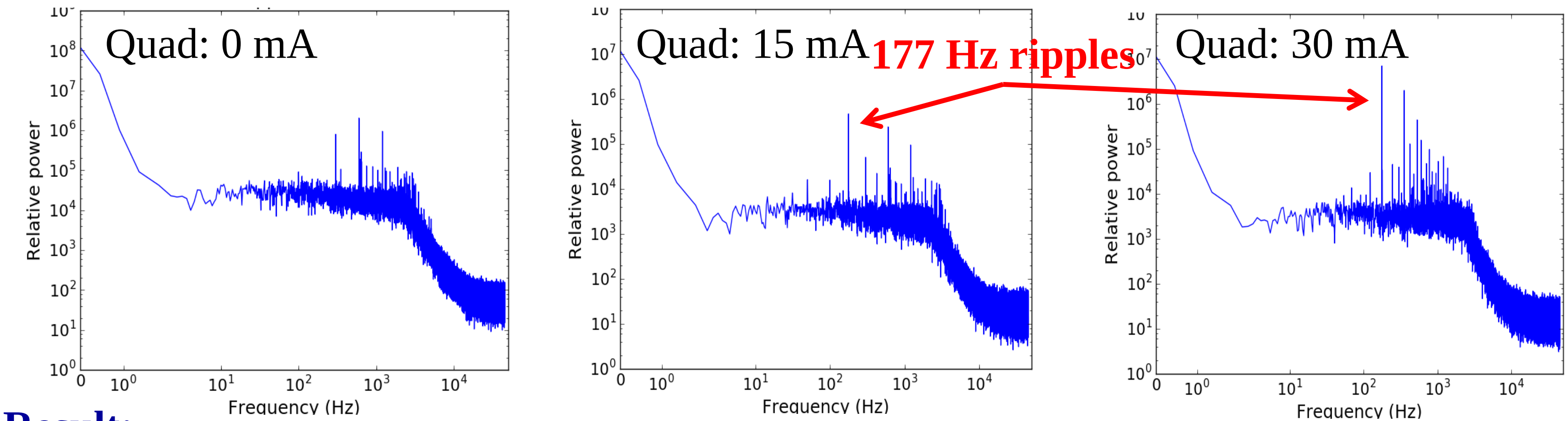


Remark: Non-Gaussian distribution

Width determination by σ_{rms} with a cut of 5 % of maximum

Induced Sine-Wave delivers a Ripple 'Calibration'

Quantitative investigations concerning PS ripple: 137 Hz (dipole) and177 Hz (quad) injection



Result:

Dipole: Effect for ≈ 200 mA ⇔ 2x10^{-4} FS (3.5kA)

Quad: Effect for ≈ 10 mA ⇔ 2x10^{-5} FS (1.7kA)

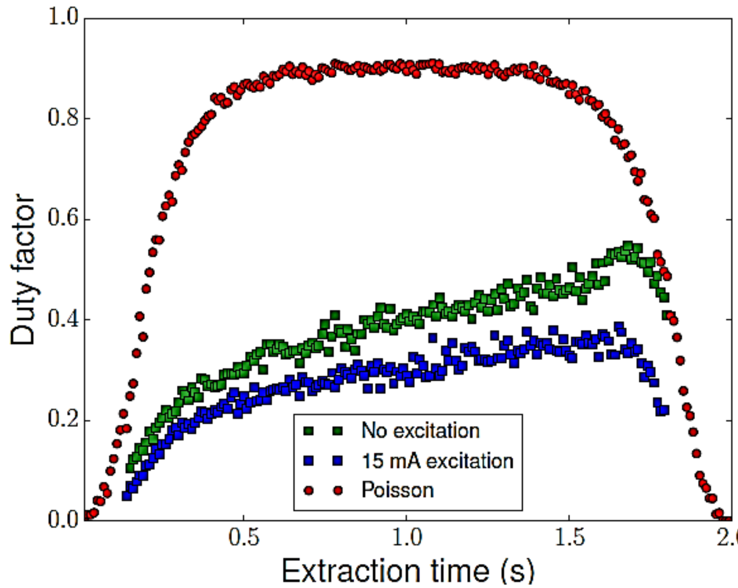
largest 'natural' line ≈5 mA@600 Hz

⇒ power supplies can't be improved

⇒ micro-structure caused by PS ripple

Sextupole: not tested yet

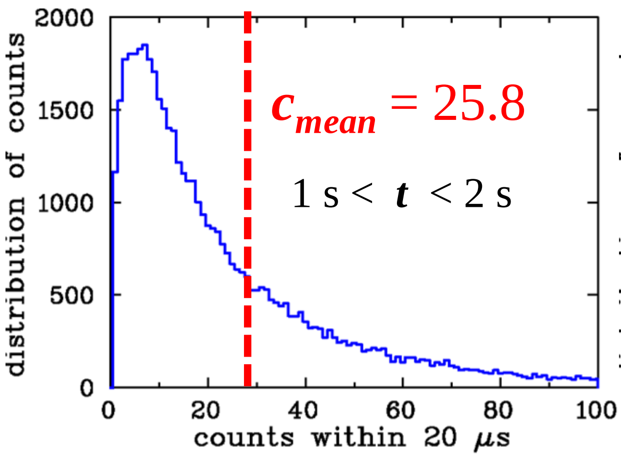
Remark: Beam response comprises of narrow lines & broadband up to ≈ 3 kHz

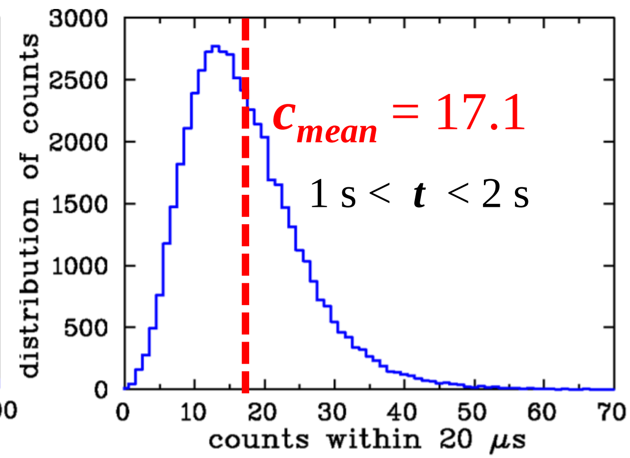


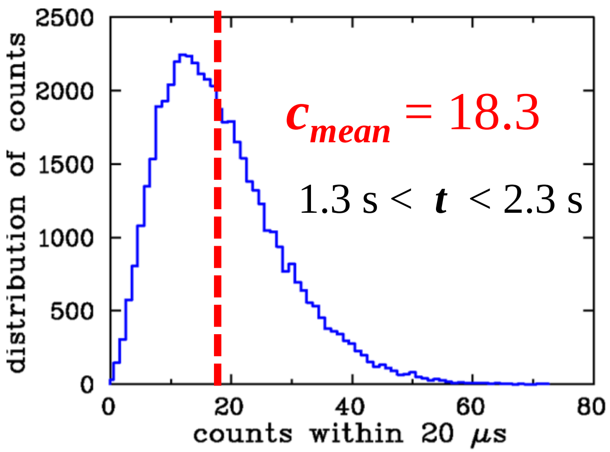
Histogram over the counts: Distribution of counts during spill as characterization
Goal: Narrow distribution centered around mean value c_{mean}

Example: C^{6+} at 300 MeV/u, t_{ex} = 2 s, readout step t_{read} = 20 μs

	Quadrupole scan	Quadrupole scan	Knock-out
Extraction:	Quadrupole scan	Quadrupole scan	Knock-out
Bunching:	un-bunched beam	bunched beam 2 kV	bunched beam 2 kV



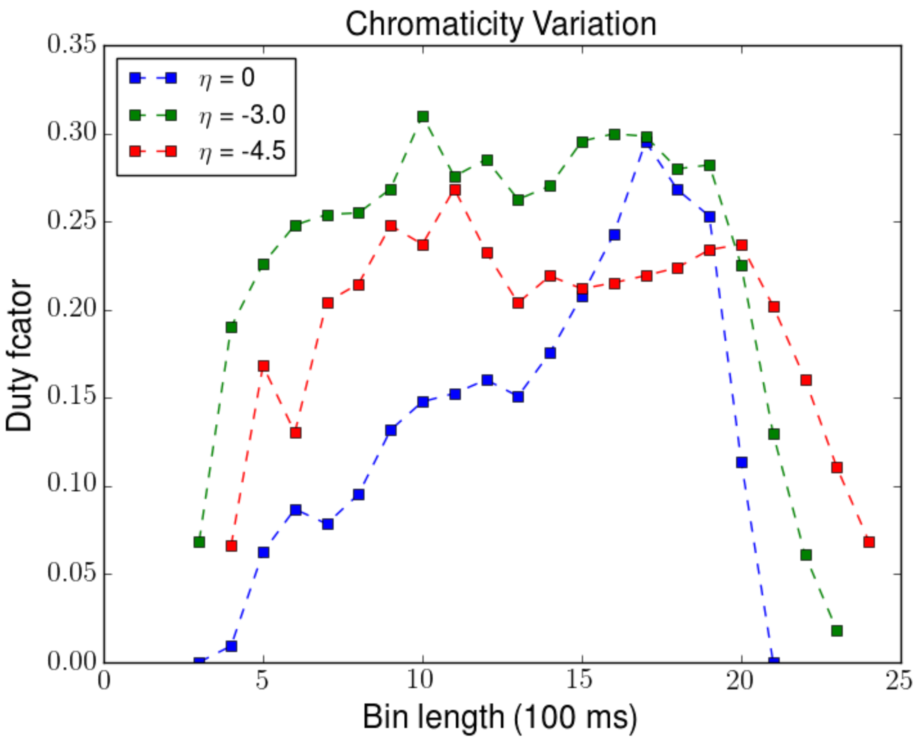


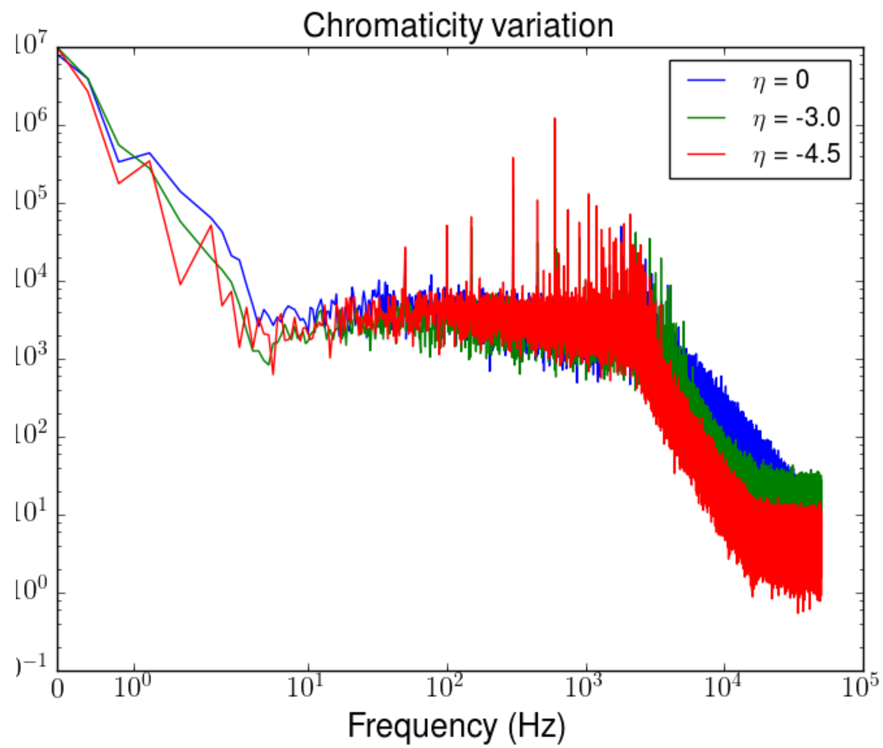


Observation:

- Un-bunched beam: strong variation with breaks (large probability of low counts) & long tail with high counts
- Bunched beam: no breaks, short tail with high counts ⇒ better centered around c_{mean}
- No significant differences concerning quadrupole variation ↔ knock-out extraction
- Ongoing tests for knock-out: Tests with 'better' noise source, dual-harmonics excitation

Coasting Beam: Chromaticity Variation





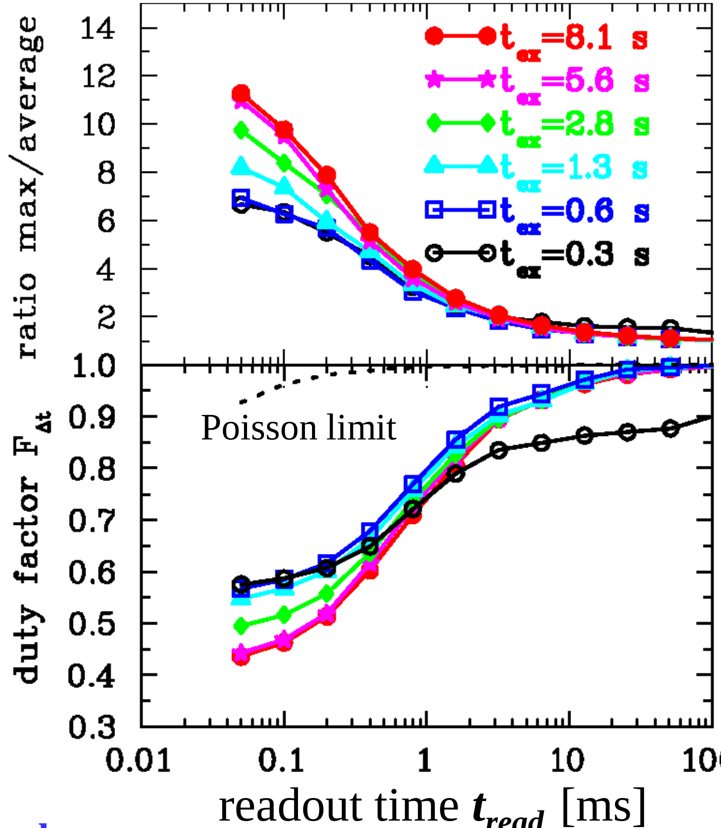
- ➢ No significant effect of chromaticity on the duty factor while the spill shoulder shows slight dependence on Chromaticity
- ➢ Particle numbers in each spill were maintained within 20%

Results for variation of Extraction Duration

Example of further investigations:
Variation of extraction time:
Results: Shorter extraction time
⇒ better micro-structure, but no simple scaling

Further investigations:
- Dependence on beam energy
  but change of further beam parameters
  like emittance and $\Delta p/p$
- Variation of $\Delta p/p$ during extraction
- 'Stochastic' extraction e.g. a COSY
  i.e. longitudinal 'knock-out'
- Air-coil quadrupole to 'soften' separatrix
- Knock-out: different types of noise
- Knock-out: dual harmonics excitation

Example: Pb at 250 MeV/u, 0.3 s < t_{ex} < 8.1 s
quadrupole scan, un-bunched beam
t_{read} =50 µs, r_{mean} ≈ 1 to 0.3·10⁶ 1/s



Remark:
- count-rate differs by factor 3
- count-rate matching influenced the transverse emittance

Example for 'Spill Micro-Structure' bunched Beam

Extraction: Quadrupole variation & bunching
Detector: Scintillator, readout time t_{read} = 20 μs
Observation:

- No breaks & height of peaks decreasing
- No significant regular or periodic structure

Sufficient quality for therapy (position readout at 100 μs)

Depictive reason:

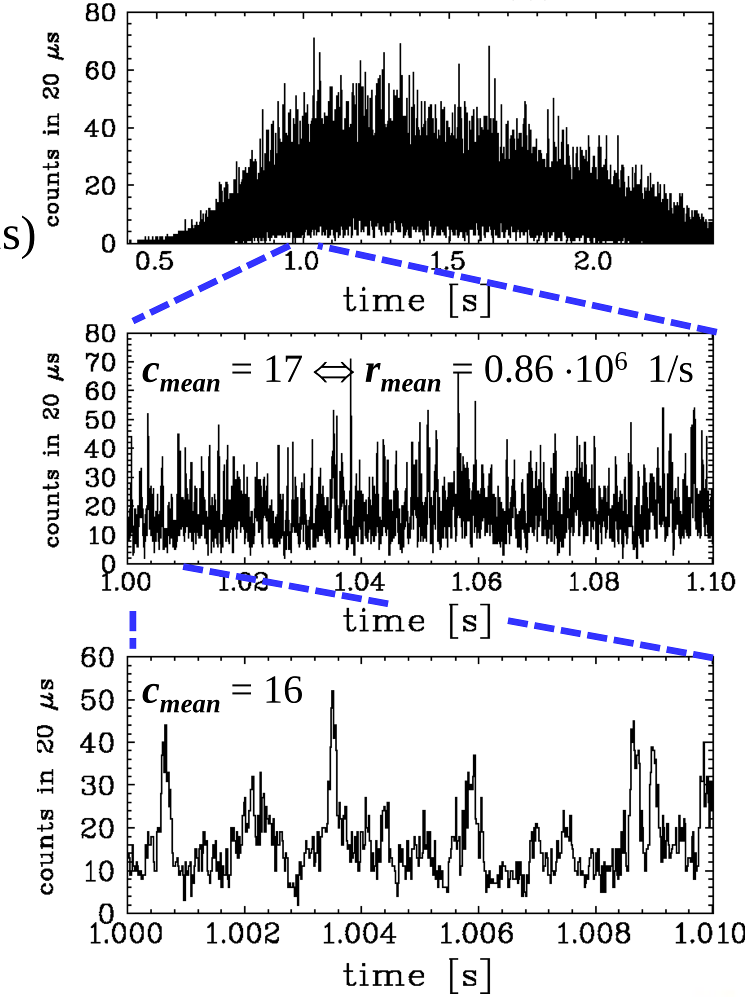
- Variation of $\Delta p(t)$ by synchrotron oscillation $f_S \propto \sqrt{U_{acc}} \approx$ some kHz
- Coupling via chromaticity ξ

$$\frac{\Delta Q(t)}{Q} = \xi \frac{\Delta p(t)}{p}$$

- unstable ions could become stable again

Time between separatrix crossing and ES arrival is *occasionally* comparable to synchr. period $1/f_s$

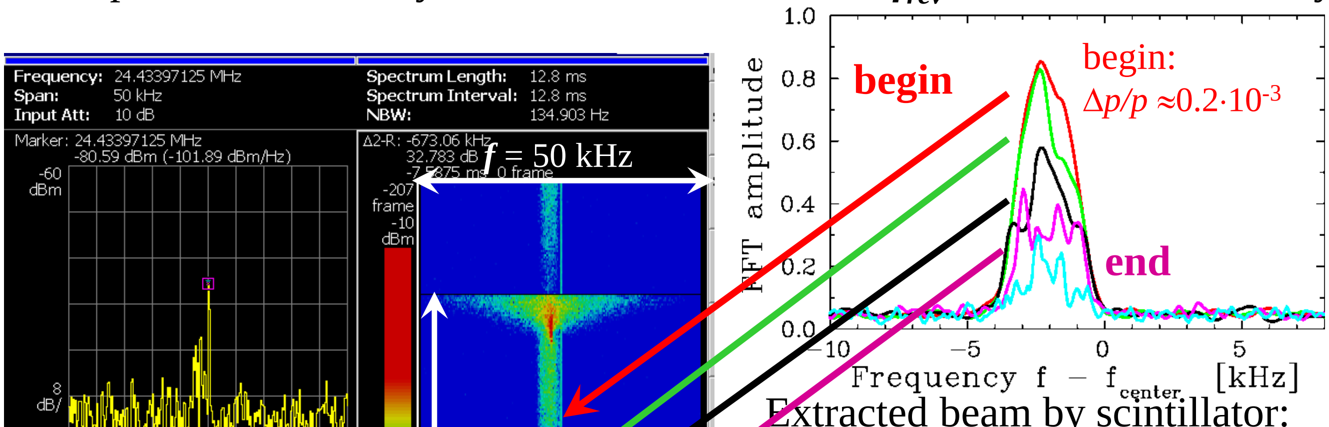
Example: C^{6+} at 300 MeV/u
Quad. scan, bunched beam U_{acc}=2 kV



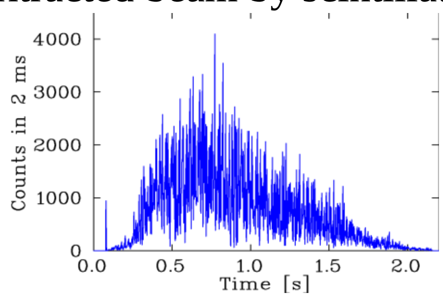
Example for longitudinal Schottky spectrum to visualize slow extraction:

- Momentum spread before extraction here $\frac{\Delta p}{p_0} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{h\, f_0} = 0.2 \cdot 10^{-3}$ (1σ)
- Chromaticity (here ξ=-1.5) i.e. coupling tune ↔ momentum spread : $\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$
- Slow extraction by knock-out extraction i.e. only trans. amplitude growth ⇒ **no** momentum dependent

Beam parameter: GSI-synch. C^{6+} at 300 MeV/u ⇔ f_{rev} = 0.95 MHz, Schottky for h =26, Δf = 1.0 kHz (1σ)



Extracted beam by scintillator:



Steinbach diagram: