Micro-spill activities at GSI

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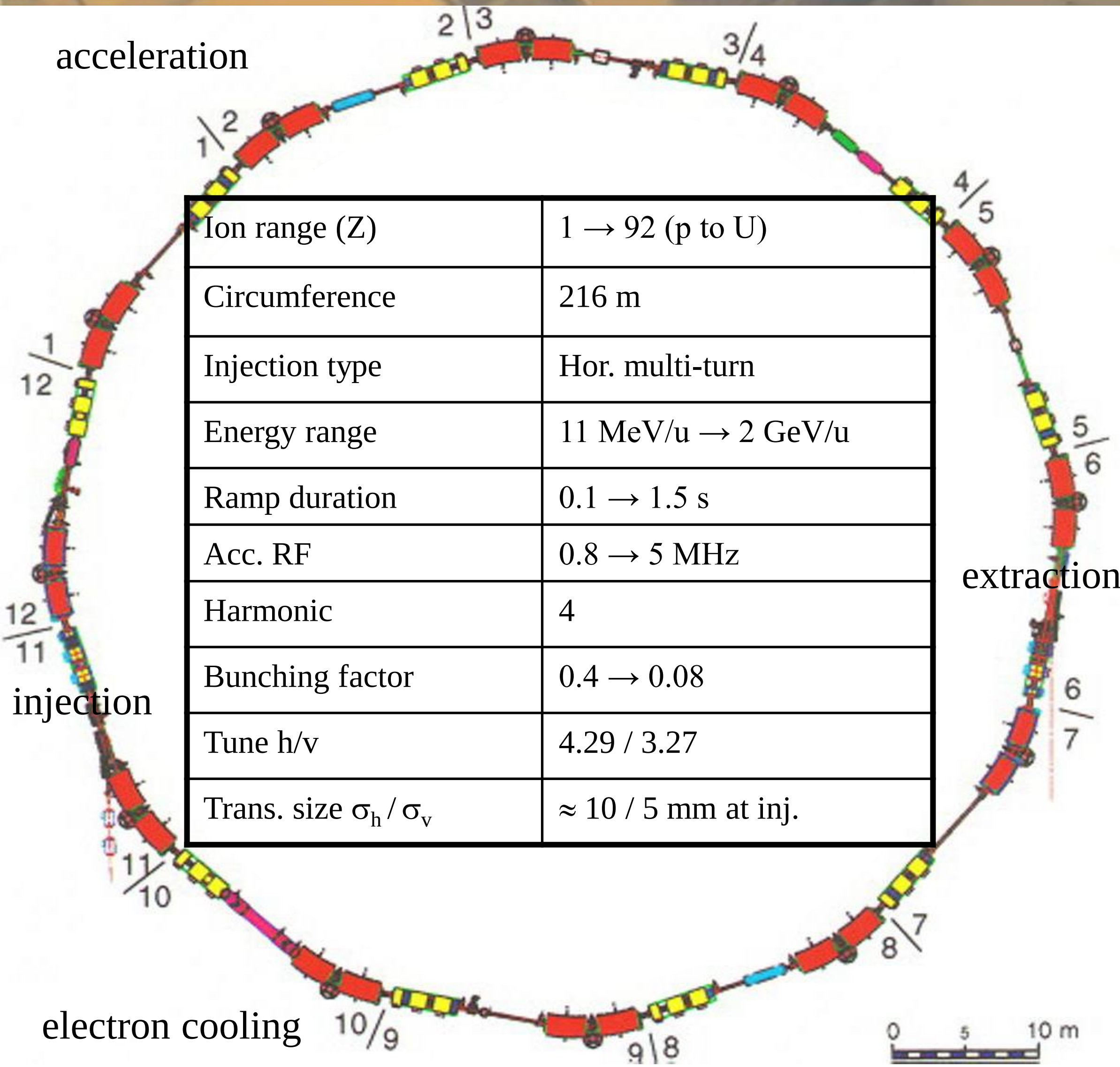
Feb 8th, 2021

I-FAST-REX Kick-off meeting

Feb 8th, 2021

- Beam instrumentation for micro-spill observations
- Recent observations: Effect of extraction settings & beam settings on spill via transit time
- Summary: Slow extraction “transfer function” , feedback and other topics

GSI Heavy Ion Synchrotron SIS18 (Bρ=18 T-m): Overview



Ion range (Z)	1 → 92 (p to U)
Circumference	216 m
Injection type	Hor. multi-turn
Energy range	11 MeV/u → 2 GeV/u
Ramp duration	0.1 → 1.5 s
Acc. RF	0.8 → 5 MHz
Harmonic	4
Bunching factor	0.4 → 0.08
Tune h/v	4.29 / 3.27
Trans. size σ_h / σ_v	≈ 10 / 5 mm at inj.

- SIS18 → booster for SIS-100
- Third order resonance → Quad driven and knock-out extraction → coasting and bunched beams
- Variety of fixed target experiments with detector times from 100 µs to 100 ns → upto 20s spills

Overview on Detectors for slow Extraction

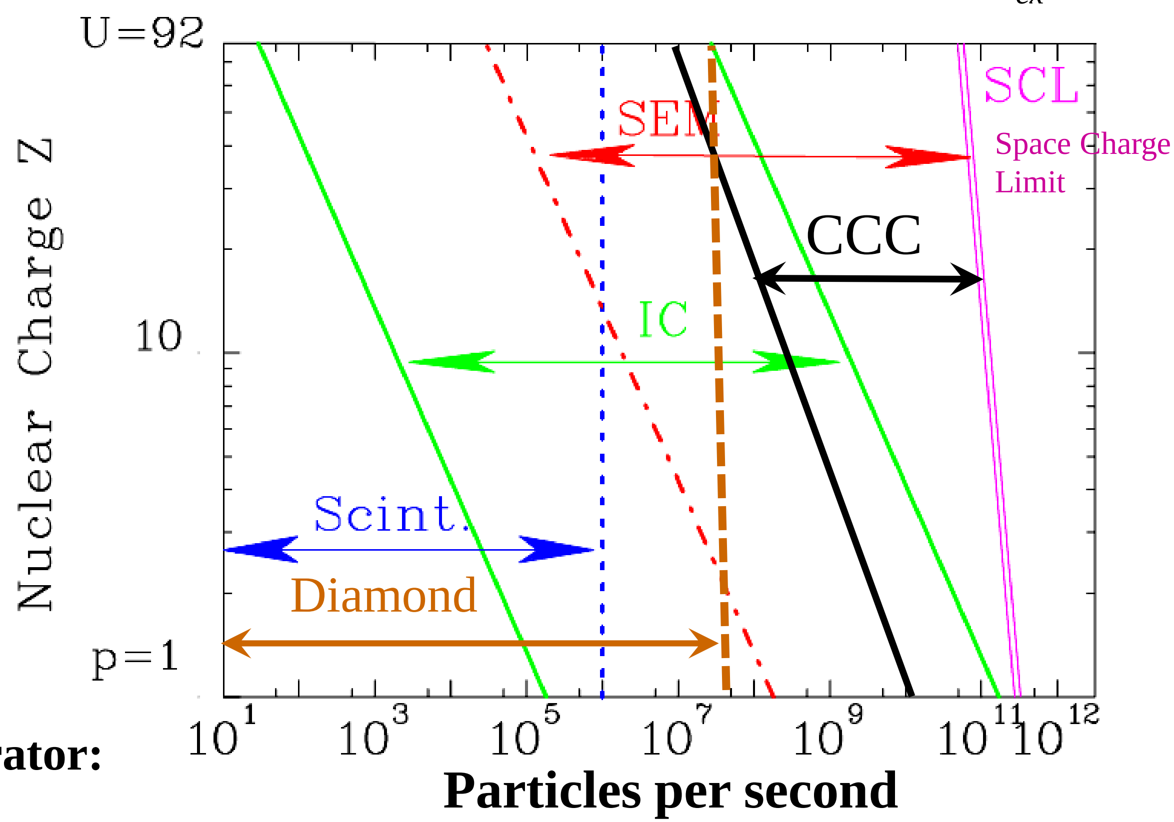
Standard Detectors:

- **Energy loss in gas (IC):**
  - min: $I_{sec} \approx 1$ pA
  - max: $I_{sec} \approx 1$ µA
- **Sec. e– emission:**
  - min: $I_{sec} \approx 1$ pA
- **Particle counting:**
  - max: $r \simeq 5.10^6$ 1/s

Non-Standard Detectors:

- **Cryogenic Current Comparator:**
  - min: $I_{beam} \simeq 2$ nA
- **Diamond counter (e.g. at HADES):**
  - max: $r \simeq 3 \cdot 10^7$ 1/s

Particle detectors for ions of 1 GeV/u, $A = 1$ cm^2, $t_{ex} = 1$ s

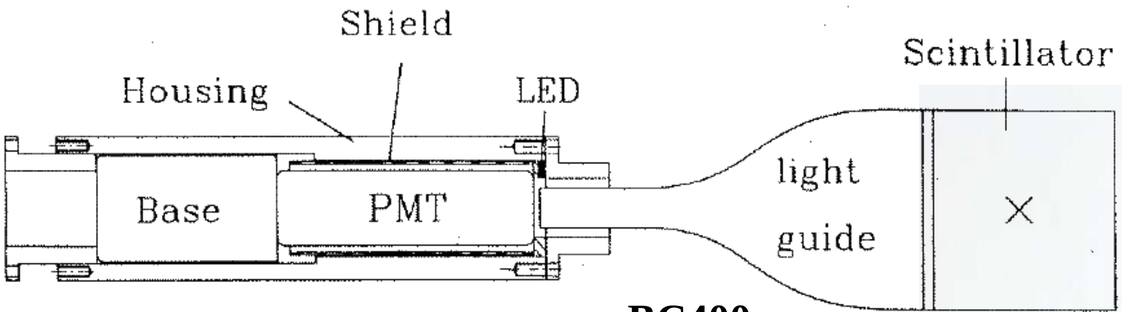


Calibrated against each other → Comparisons in overlapping areas led to well understood detectors

Example of Scintillator Counter

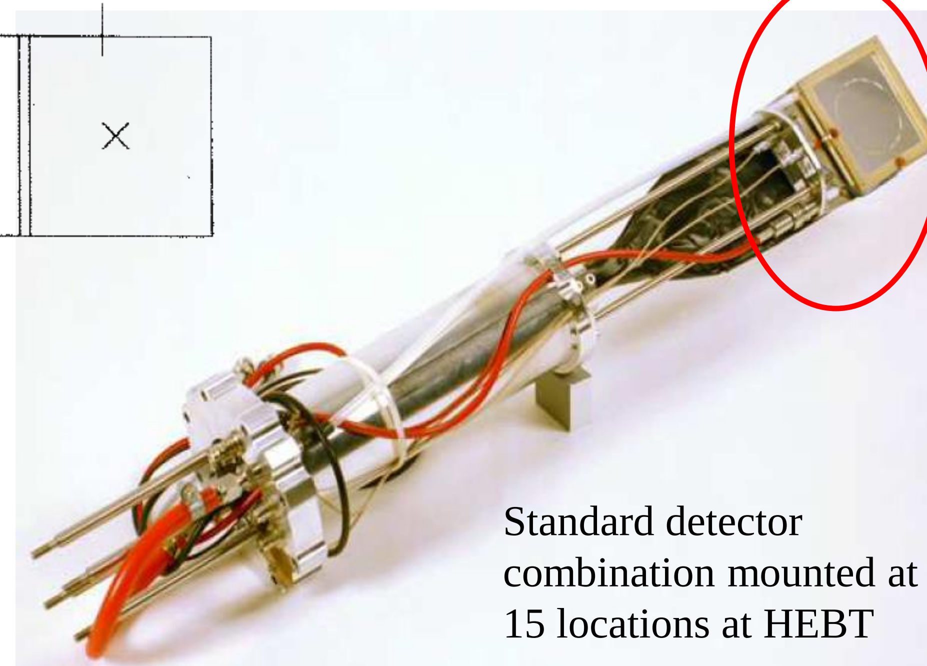
Detector: Plastic Scintillator of 75 x 75 mm² and 1 mm thickness

made of BC 400 (emission λ_{max} = 420 nm, pulse width ≈ 3 ns + cable dispersion)



1” Photomultiplier
Photonis XP2972
gain: 10^6
active base
rise time 1.9 ns
max. **average** count rate 3-5·10^6 1/s

BC400
Scintillator
75 x 75 mm²
1 mm thickness



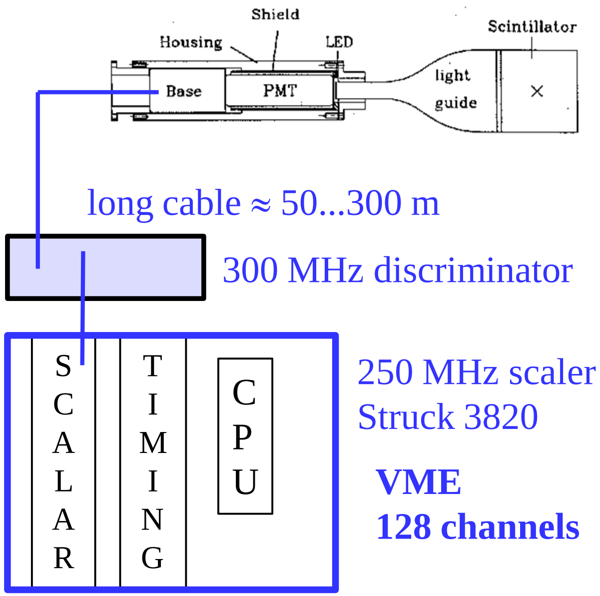
Standard detector combination mounted at 15 locations at HEBT

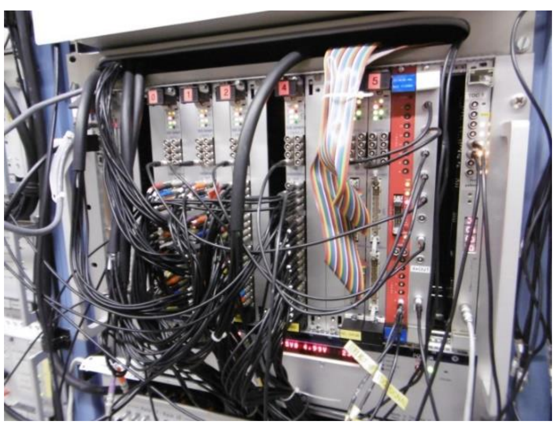
Advantage of particle counting:

- single particle detection
- 100 ps time resolution
- **no** noise or background

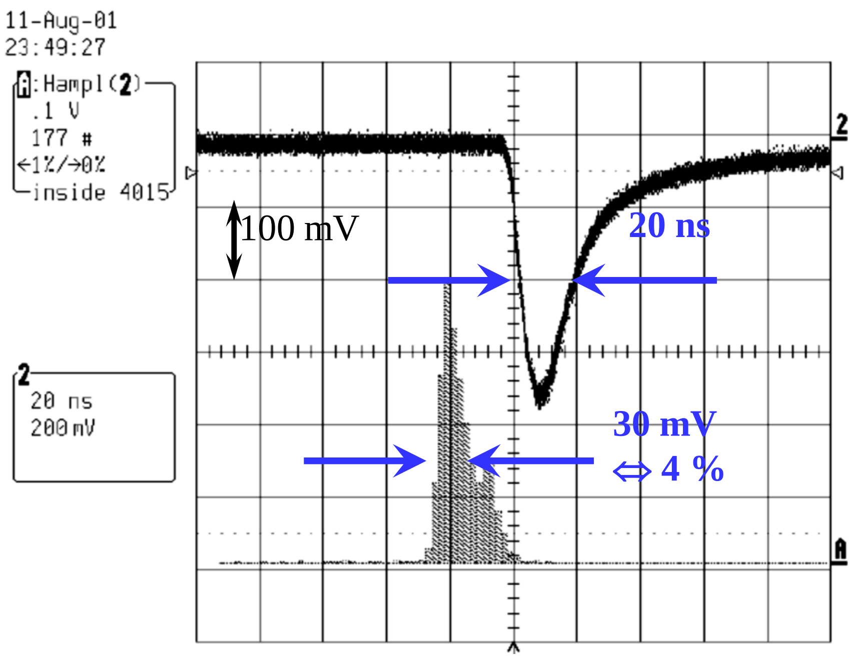
⇒ could be directly compared to particle simulation

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, SEM-detectors
- any detector from experiment e.g. diamond from HADES

Entire cycle stored with min. sample time T_m = 1 μs

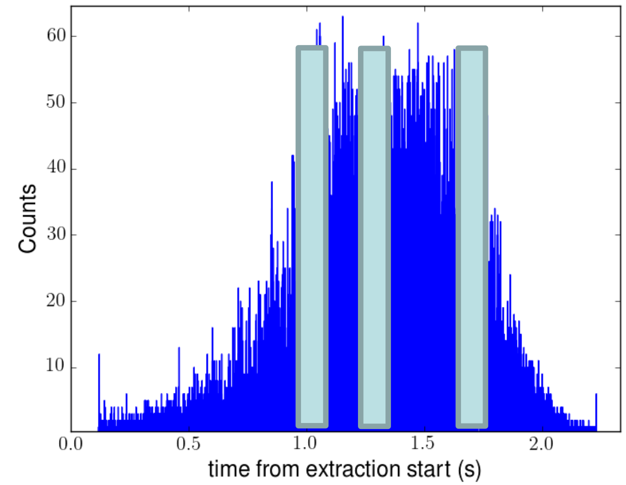
Various <u>online</u> analysis tools

Spill measurement and characterization

T_m : Readout / Meas. resolution= 11 us

T_{bin} : Characterization resolution = 11 ms

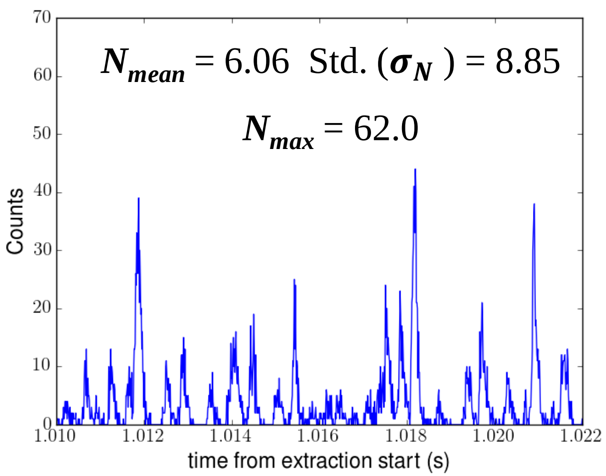
T_{spill} : Time of extraction = 3 s



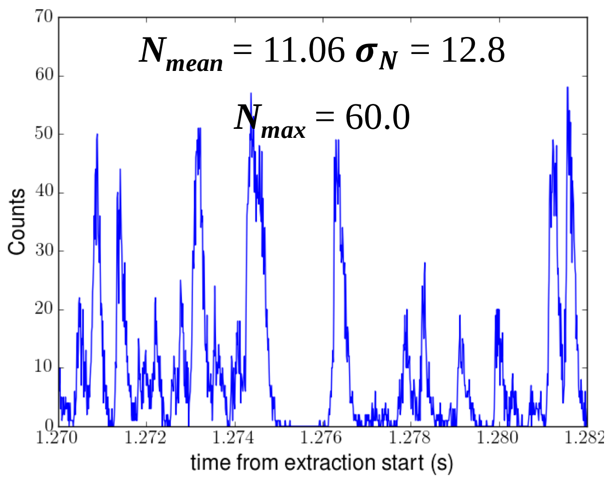
T_1 T_2 T_3

Statistical moments in T_{bin}

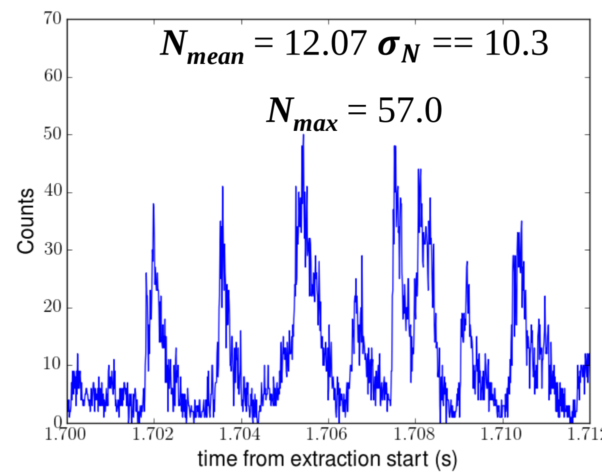
Mean, Max, Std. dev.



T_1



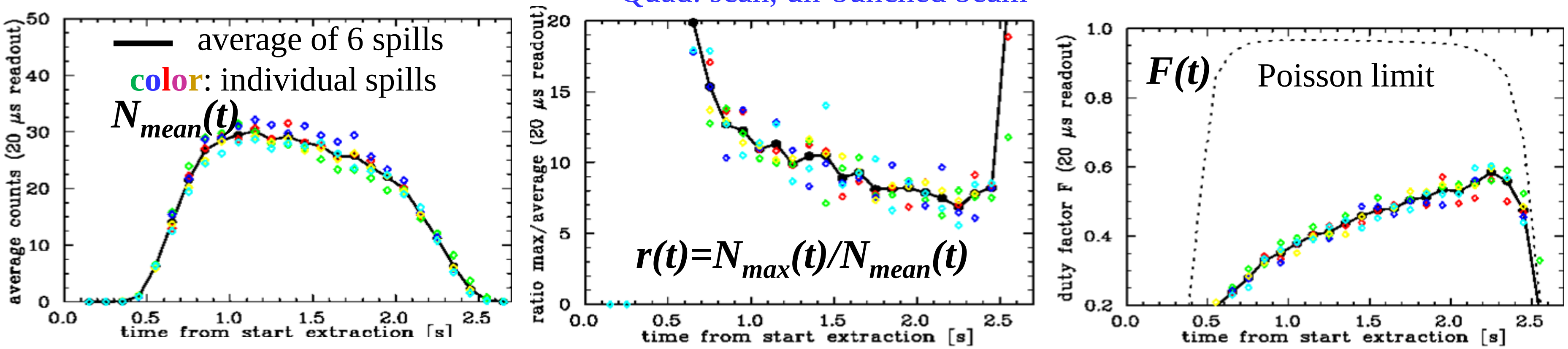
T_2



T_3

Example: C^{6+} at 300 MeV/u, recorded spills in consecutive cycles with same parameters

Quad. scan, un-bunched beam



Readout T_m = 20 μs and T_{bin}= 0.1 s

Determination of:

- $N_{mean} \equiv \langle N \rangle$
- $r = N_{max} / N_{mean}$

relevant for experiments → Easier interpretation

- $F = \frac{N_{mean}^2}{N_{mean}^2 + \sigma_N^2} \equiv \frac{\langle N \rangle^2}{\langle N^2 \rangle}$

called duty factor (PIMMS) → Underlying distribution

Poisson Distribution $\langle N \rangle = \sigma_N^2$

Observation for quad. scan:

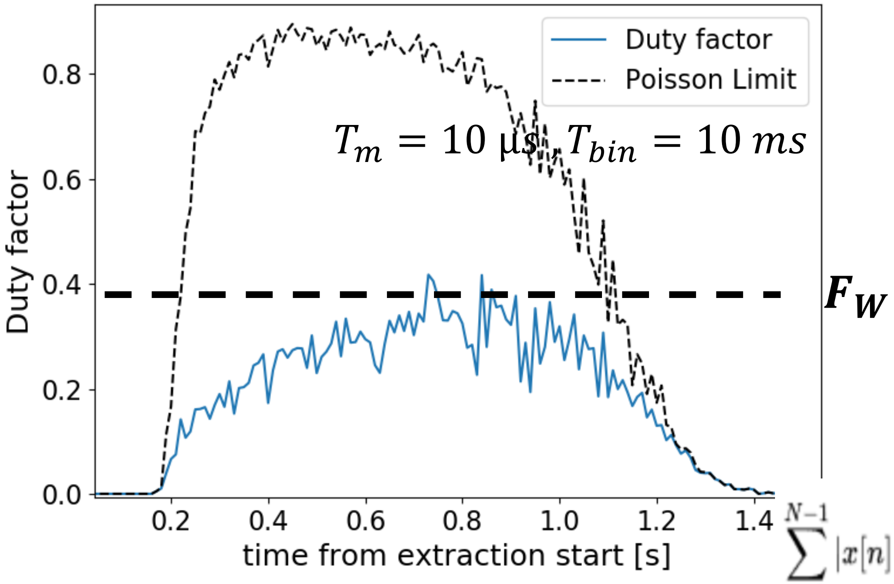
- individual spills have comparable r and F
- r and F are **not** constant
- $r \approx 10$ and $F \approx 0.5$
  far from Poisson limit → fluctuations

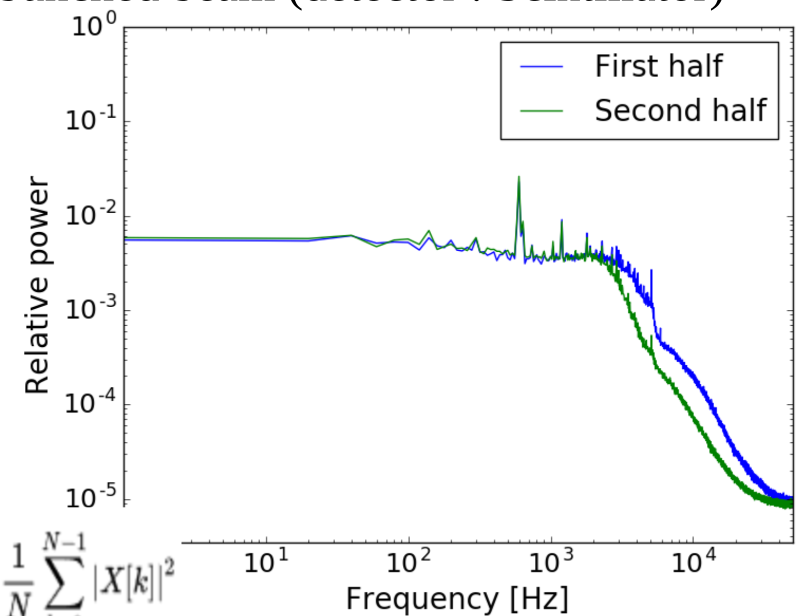
Source of fluctuations?

Microspill quality: One number per spill?

Spill measurement and characterization

Bi^{68+} at 300 MeV/u, quad. scan, un-bunched beam (detector : Scintillator)





$$\sum_{n=0}^{N-1} |x[n]|^2 = \frac{1}{N} \sum_{k=0}^{N-1} |X[k]|^2$$

Time Domain ⟵ Parseval's Theorem ⟶ **Frequency Domain**

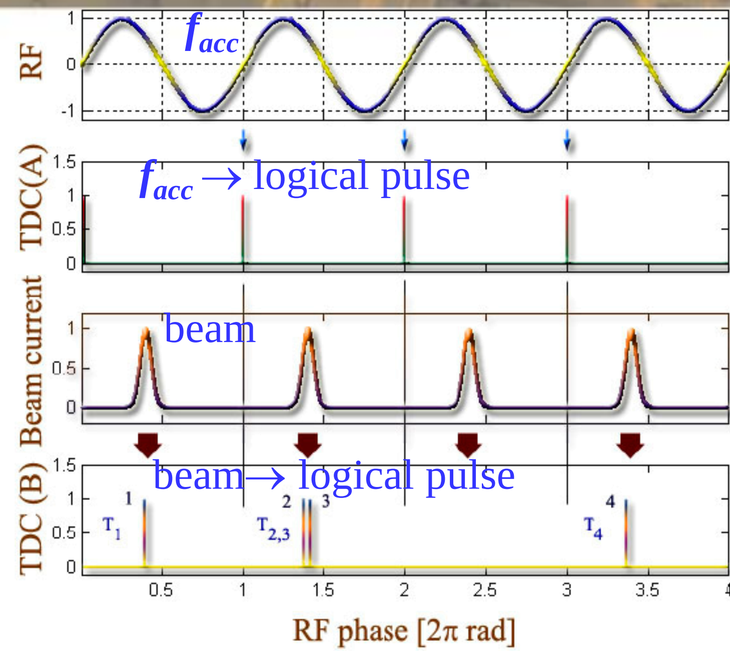
- Duty factor calculated in the chosen interval $\boldsymbol{T_{bin}}$ as $\boldsymbol{F = \frac{N_{mean}{}^2}{N_{mean}{}^2 + \sigma_N{}^2} \equiv \frac{\langle N \rangle^2}{\langle N^2 \rangle}}$
- Poisson duty factor $\boldsymbol{F_{poisson} = \frac{N_{mean}}{N_{mean}+1} \equiv \frac{\langle N \rangle}{\langle N \rangle + 1}}$
- Evolution of F during the spill is visible, weighted duty factor, $\boldsymbol{F_W = \frac{\sum_{k=1}^{n} F_k \langle N \rangle_k}{\sum_{k=1}^{n} \langle N \rangle_k}}$

- $\boldsymbol{F_W}$ is equivalent to "DC power" over Total power
- 10- 30% of power in main's harmonics f = n·150 Hz for f > 20 Hz
- Broadband = noisy beam response up to "shoulder" at ≈ 3 kHz

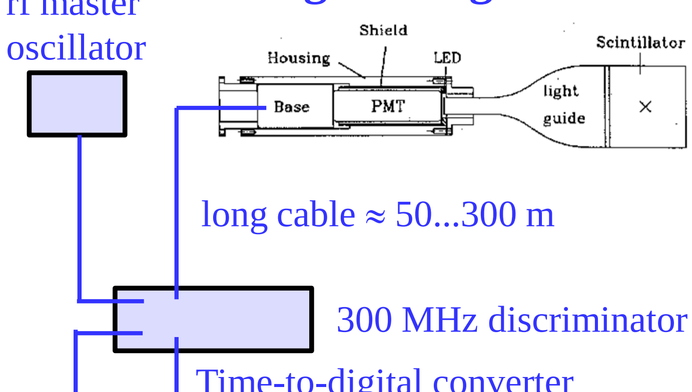
Bunched Beam Observation on sub-ns Time Scale

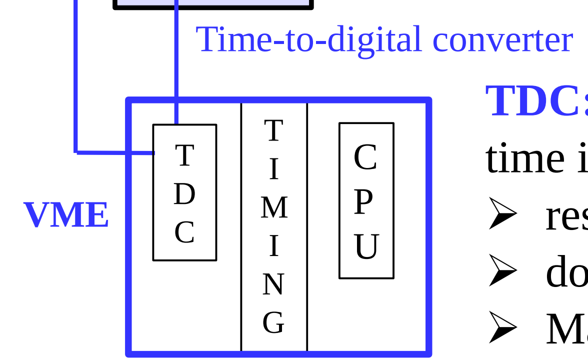
Measurement technique:

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



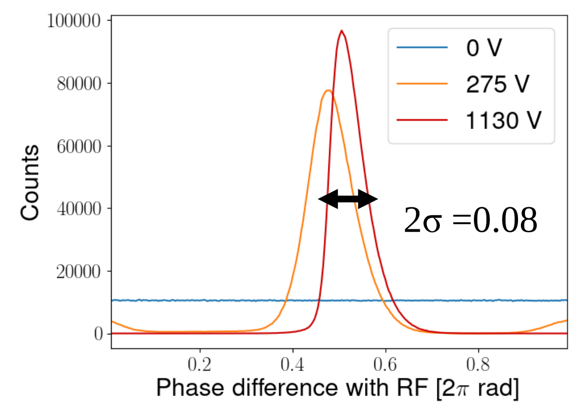
Analog and digital chain:





TDC: Caen V1290N
time interval counter

- resolution σ_{rms} ~ 50 ps
- double hit discrimination 5 ns
- Max. count rate ~ 3e6



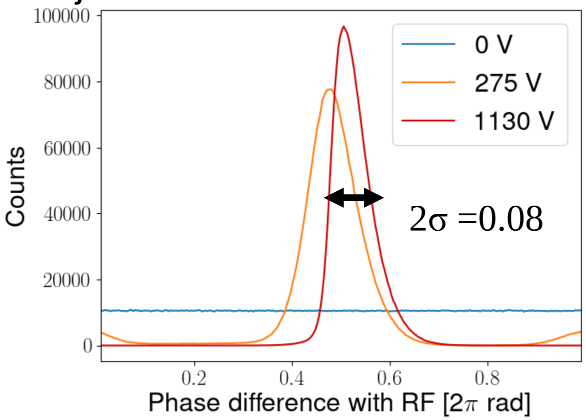
Bi^{68+} at 300 MeV/u, quad. scan, plot from 10 spills of 3e5 particles each

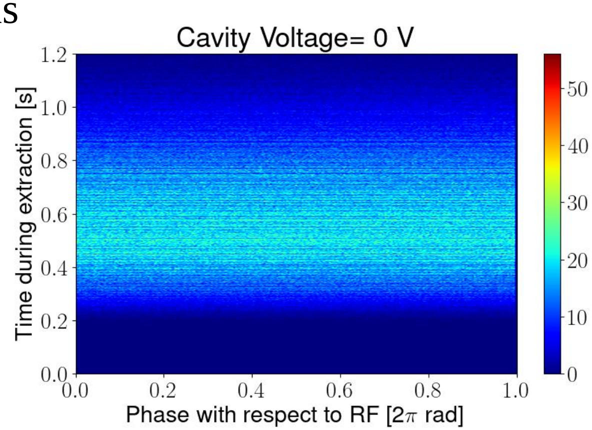
Particle arrival intervals

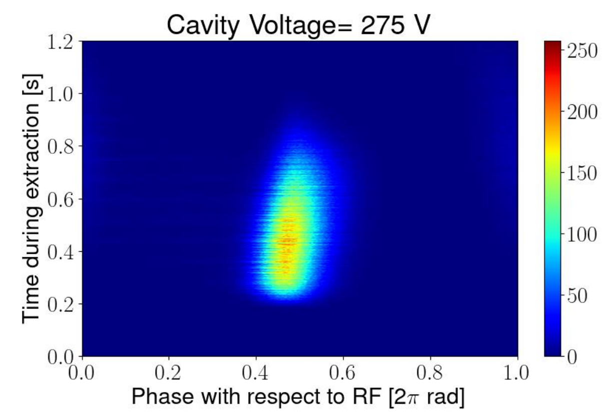
Bi^{68+} at 300 MeV/u, quad. scan, bunched beam (detector : Scintillator)

Histogram of arrival time with respect to RF

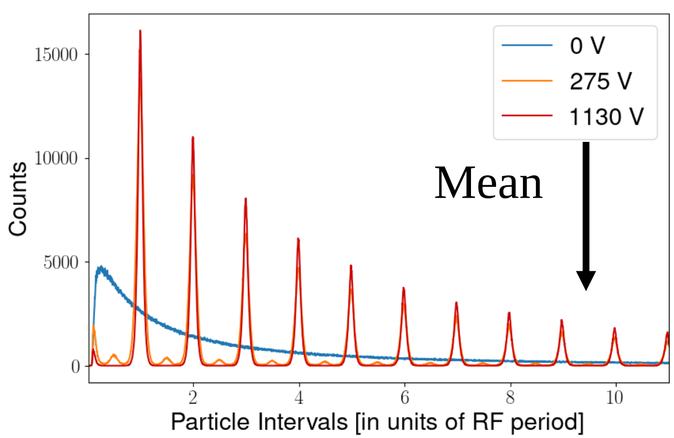
f_{rf} = 3.62 MHz → RF period is 277 ns

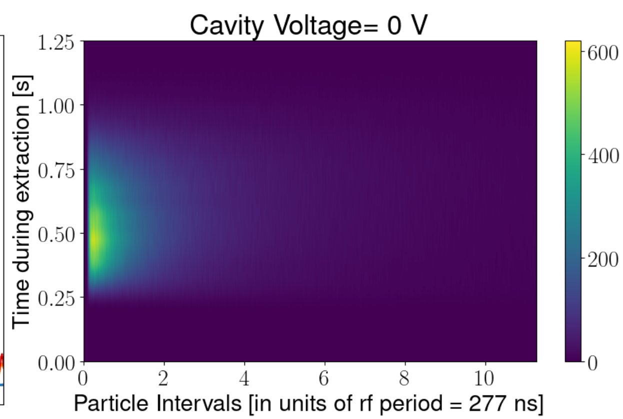


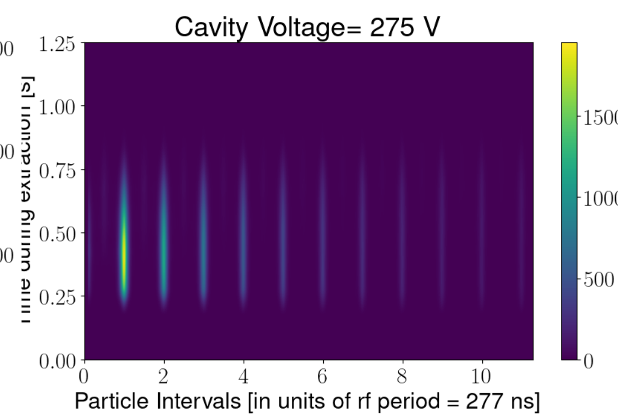




Histogram of time between successive particle arrival

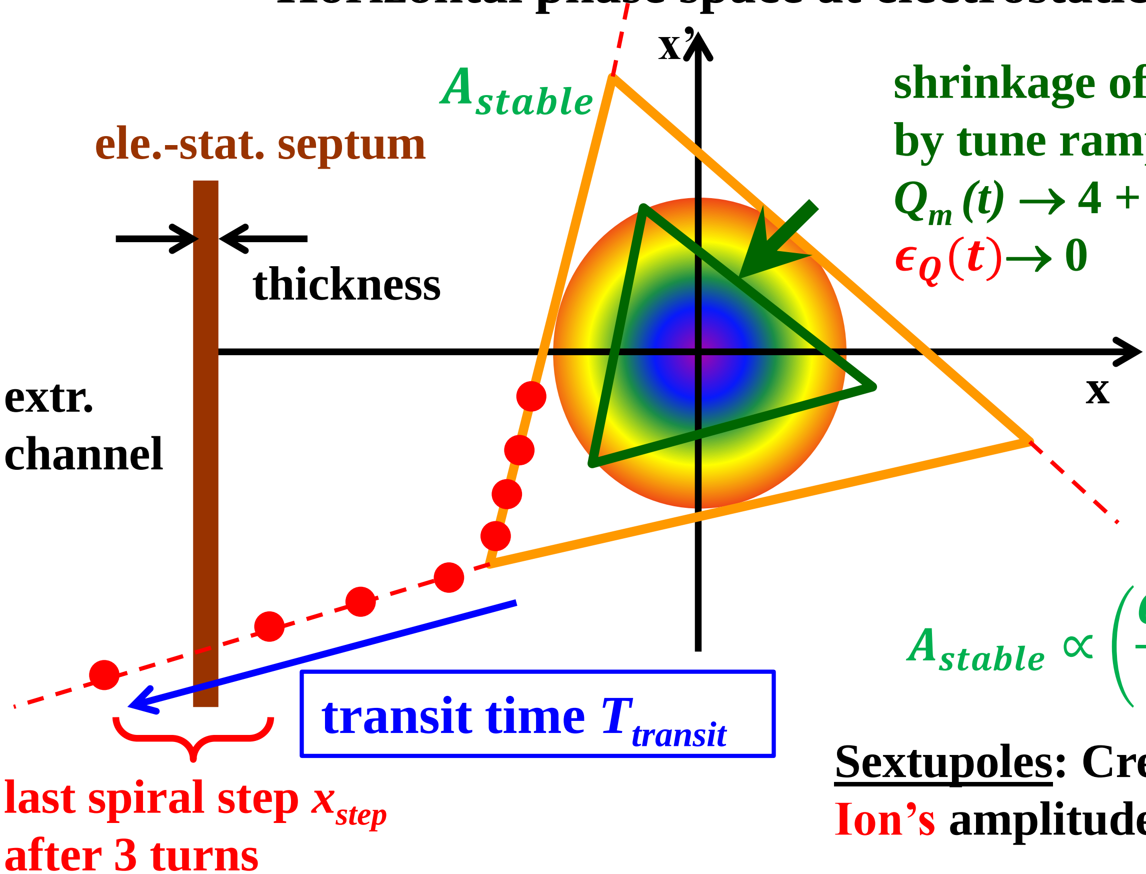




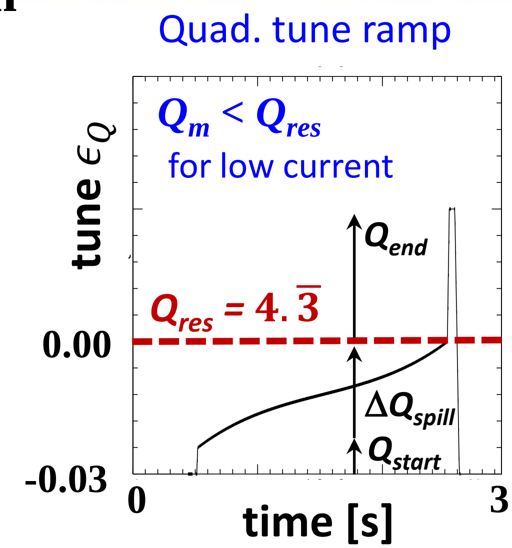


Slow Extraction by Tune Ramp (Quad driven)

Horizontal phase space at electrostatic septum



shrinkage of A_{stable}
by tune ramp
$Q_m(t) \rightarrow 4 + 1/3$
$\epsilon_Q(t) \rightarrow 0$



$$A_{stable} \propto \left(\frac{Q_m - Q_{res}}{S}\right)^2 \propto \left(\frac{\epsilon_Q}{S}\right)^2$$

Sextupoles: Create non-linear fields

Ion's amplitude growth per turn $\Leftrightarrow$ $T_{transit}$ & x_{step}

Ions' tune spread by chromaticity

$$\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p} = -1.0 \cdot (5 \cdot 10^{-4})$$

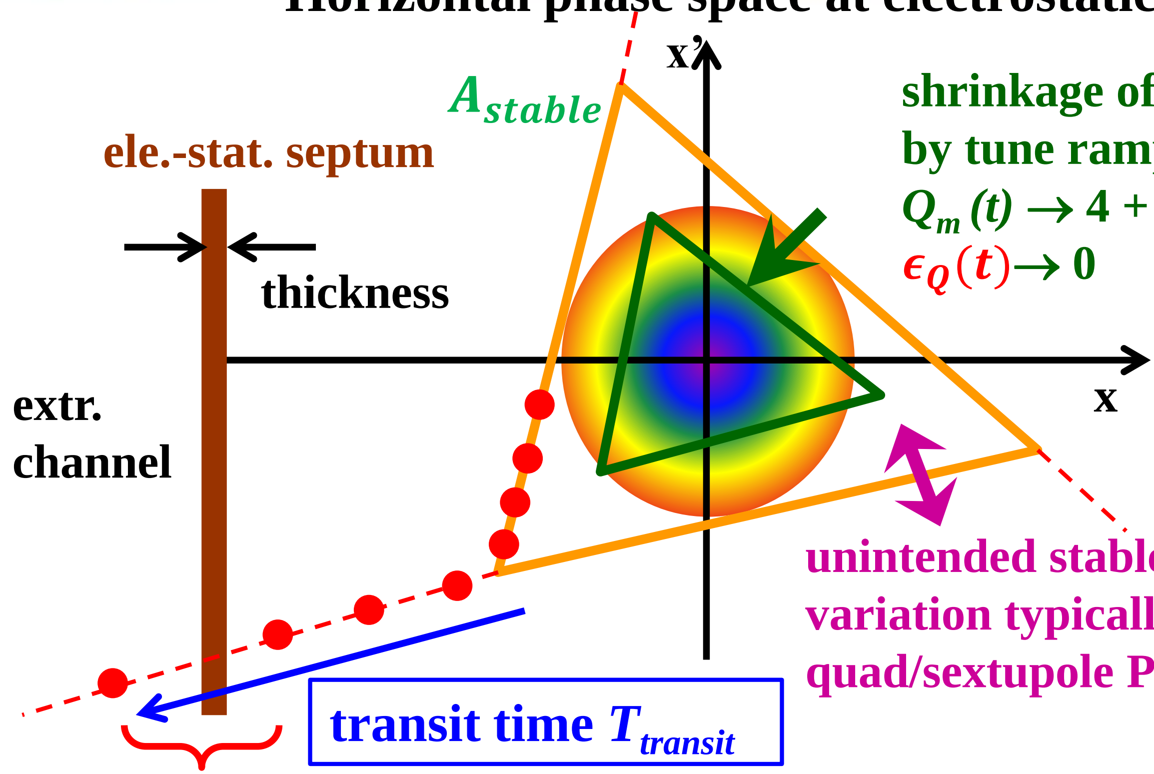
Typical values: $S = (0.08 \pm 0.04)\ m^{-2}$

Abbreviation: $S \equiv (k_2 L)_a$

Amplitude of normalized integrated sextupole field

Slow Extraction by Tune Ramp (Quad driven)

Horizontal phase space at electrostatic septum



shrinkage of A_{stable} by tune ramp

$Q_m(t) \rightarrow 4 + 1/3$

$\epsilon_Q(t) \rightarrow 0$

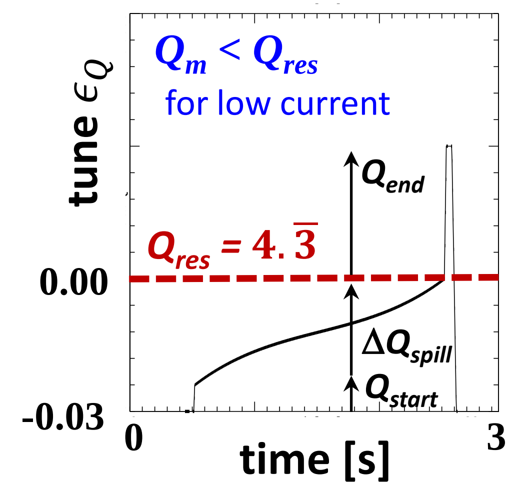
unintended stable area variation typically due to quad/sextupole PS ripple

last spiral step x_{step} after 3 turns

Ions' tune spread by chromaticity

$$\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p} = -1.0 \cdot (5 \cdot 10^{-4})$$

Quad. tune ramp



$$\frac{\Delta Q_m}{Q_m} \sim 10^{-5}/ms$$

$$\frac{\Delta I_Q}{I_Q} \sim 2.10^{-6}/ms$$

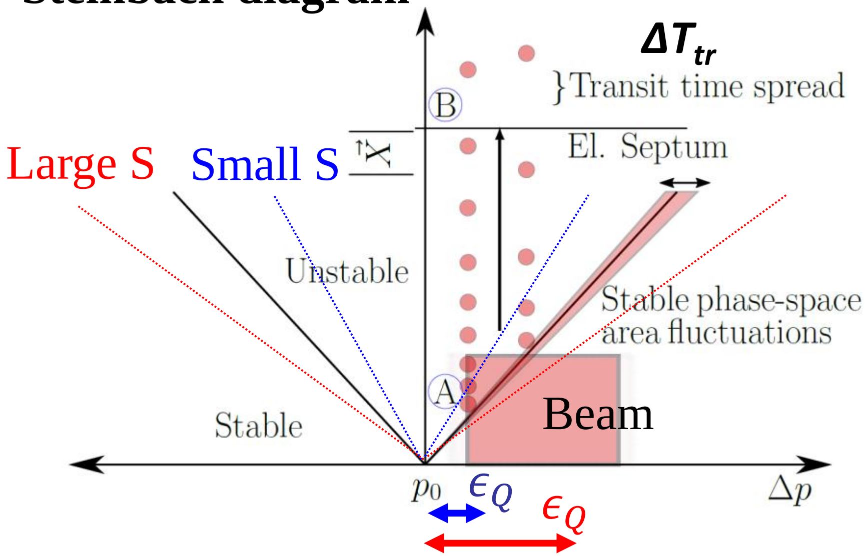
Quad

Sextupole

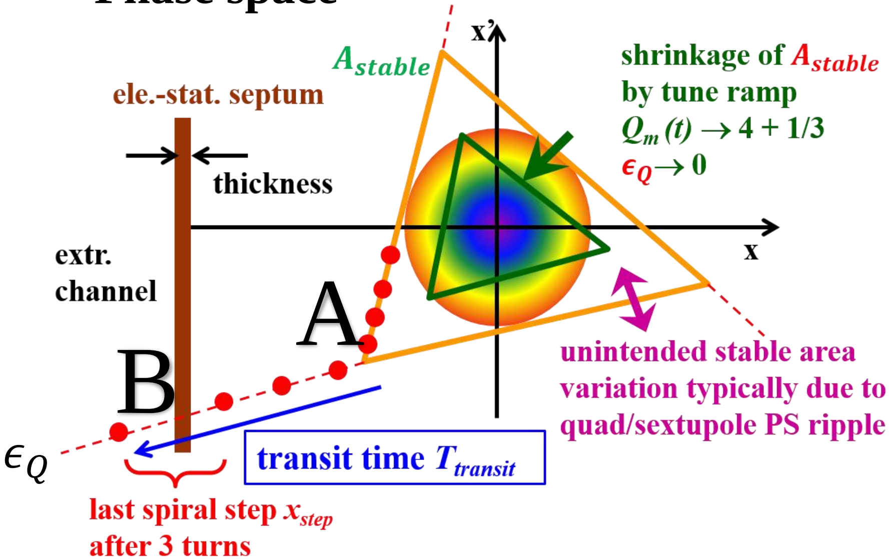
$$A_{stable} \propto \left(\frac{\epsilon_Q}{S}\right)^2$$

$$\delta A_{stable} \propto 2A_{stable}\left|\frac{\delta Q_m}{\epsilon_Q}\right| + \left|\frac{\delta S}{S}\right|$$

Steinbach diagram



Phase space



- For smaller sextupole strength: Tune ramp starts close to resonance to obtain the same spill length
- Sextupole fields has quadratic amplitude dependence, i.e. For smaller S and A → larger Transit time and smaller spiral step
- Small ϵ_Q could result from smaller S and/or transverse emittance (A) → related parameters
- Qualitatively: Transit time distribution broader if we start close to resonance $\overline{T_{tr}} \propto \frac{1}{\overline{\epsilon_Q}}$ $\Delta T_{tr} \propto \frac{\Delta\epsilon_Q}{\overline{\epsilon_Q}^2}$

L. Badano et al., ``Proton-ion medical machine study (PIMMS) part I", CERN/PS/ 99-010 (DI), Geneva (1999).

S. Sorge et al., ``Measurements and Simulations of the Spill Quality of Slowly Extracted Beams from the SIS-18 Synchrotron", J. Phys.: Conf. Ser. 1067 052003, (2018).

R. Singh et al., ``Smoothing of the slowly extracted coasting beam from a synchrotron", https://arxiv.org/abs/1904.09195 (2019).

PIMMS Report part 1

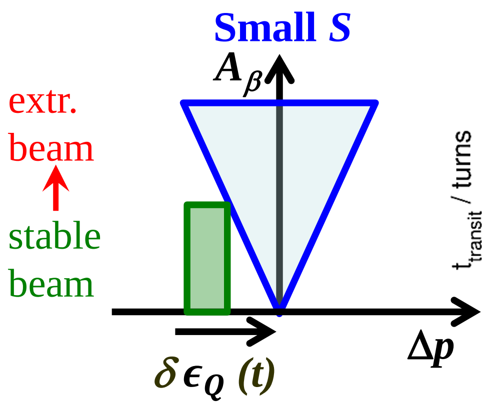
Extraction settings and transit time distribution (Quad driven)

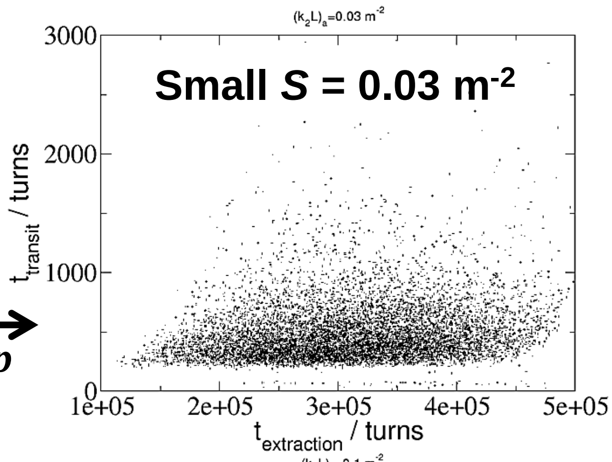
Transit time distribution: Dependence on sextupole strength ***S*** & distance to resonance $\epsilon_Q(t)$

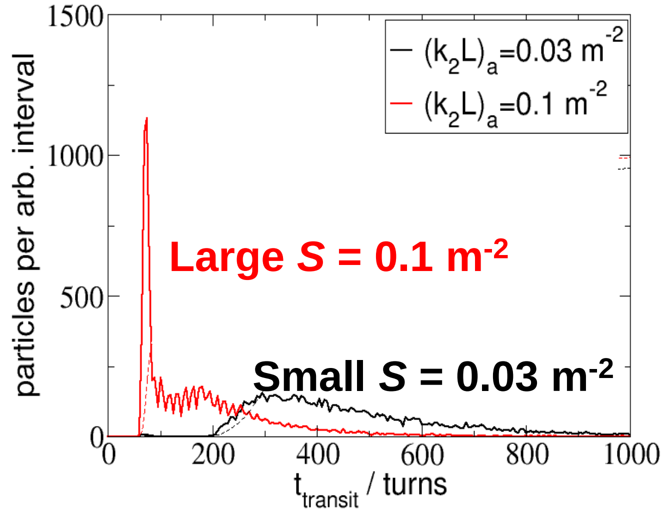
i.e. $T_{transit} = T_{transit}(S \text{ or } \epsilon_Q(t))$

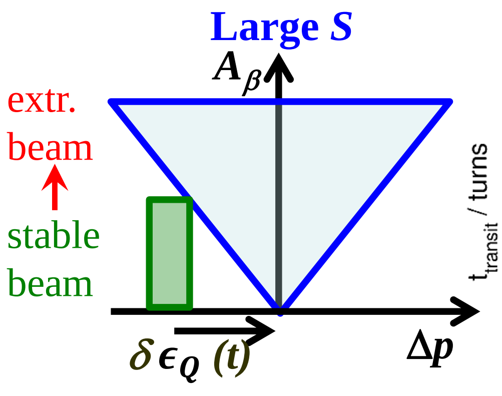
1 turn ~ 1 μs in SIS-18

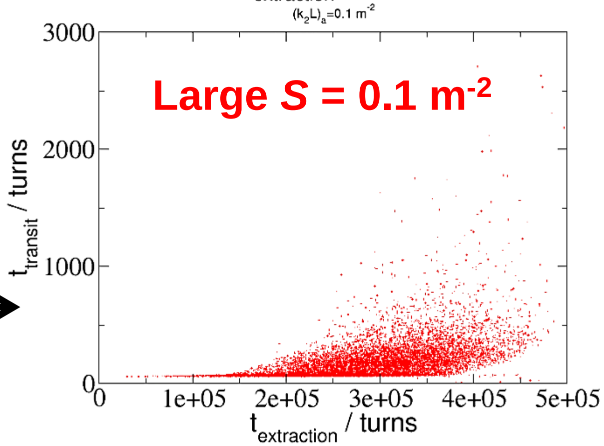
Histogram of transit time $T_{transit}$







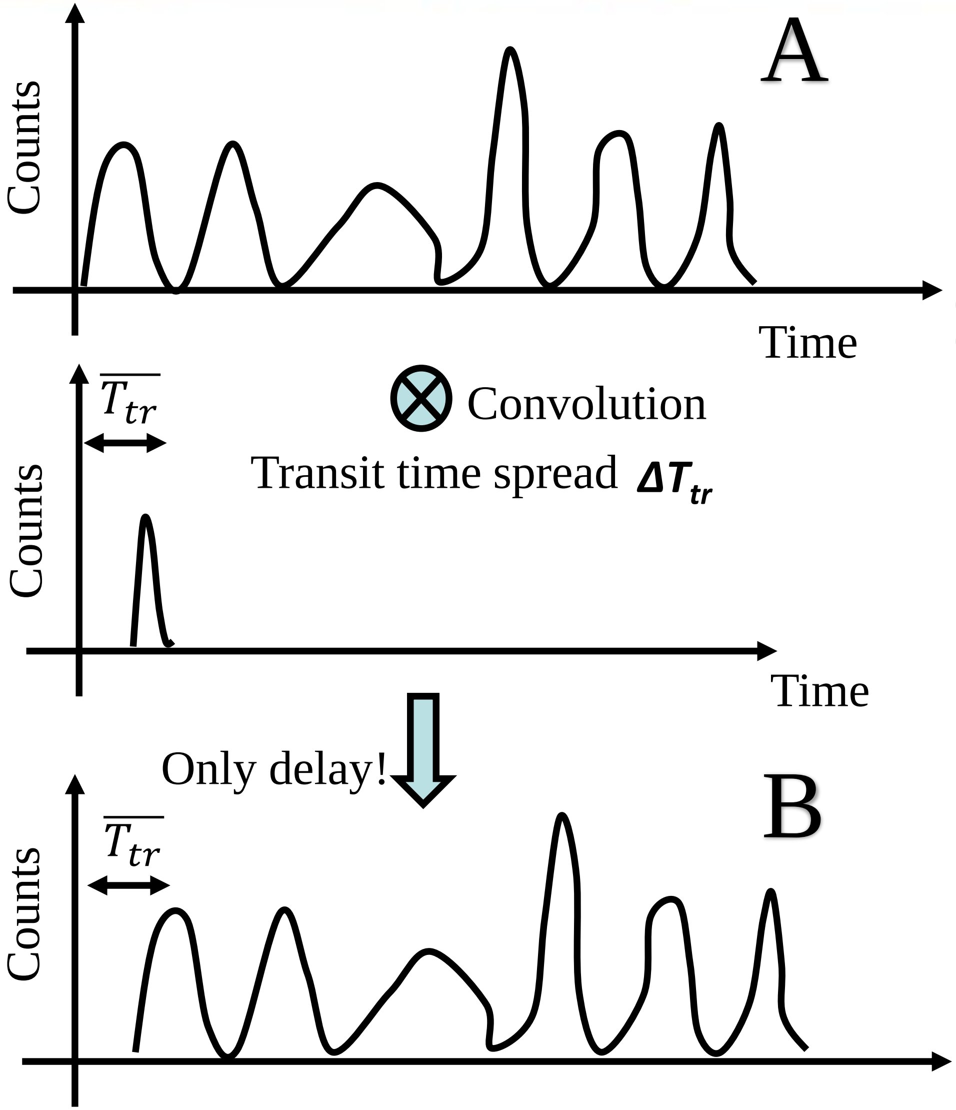


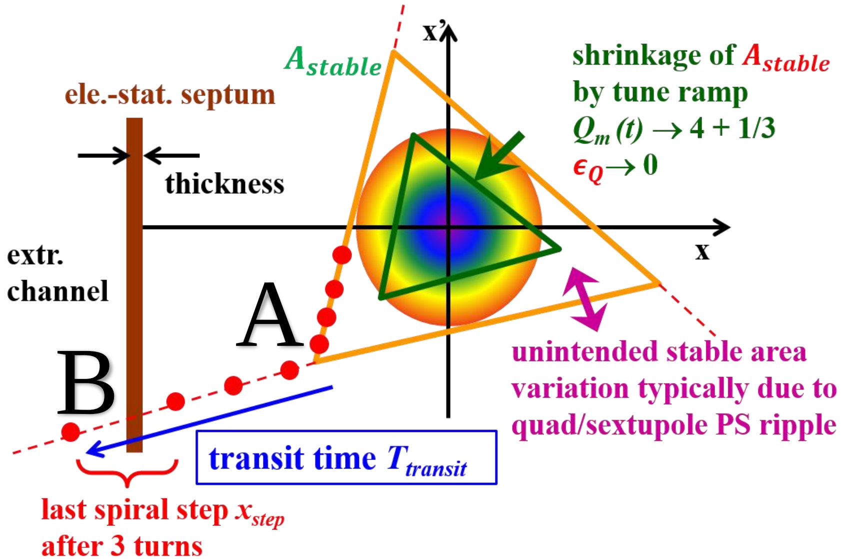


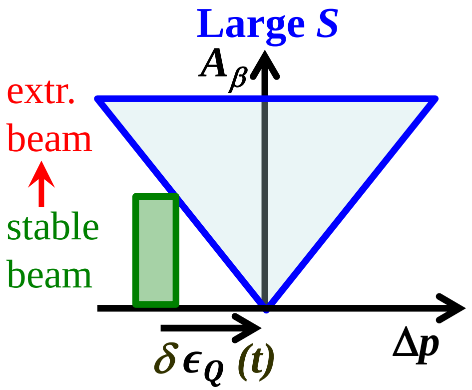
Result:

- $T_{transit}$ varies during extraction
- Lower S ⇒ saturation reached earlier
- Lower S ⇒ larger mean $T_{transit}$ $(\overline{T_{tr}})$
- Lower S ⇒ larger spread of $T_{transit}(\Delta T_{tr})$

Effect of transit time (Quad driven)







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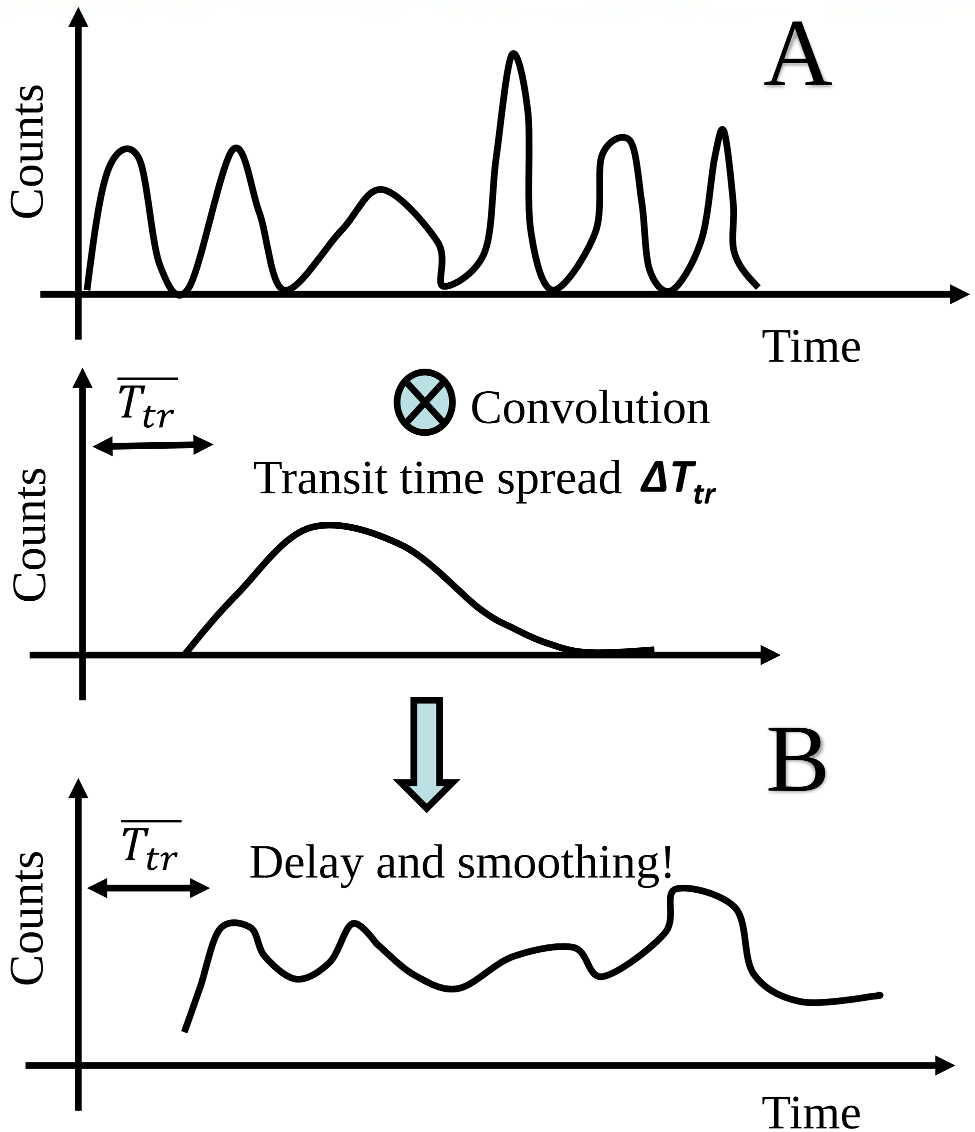
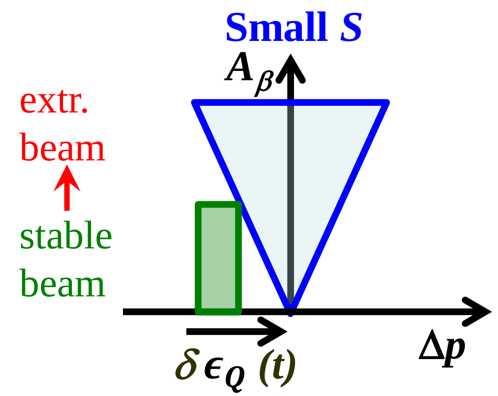
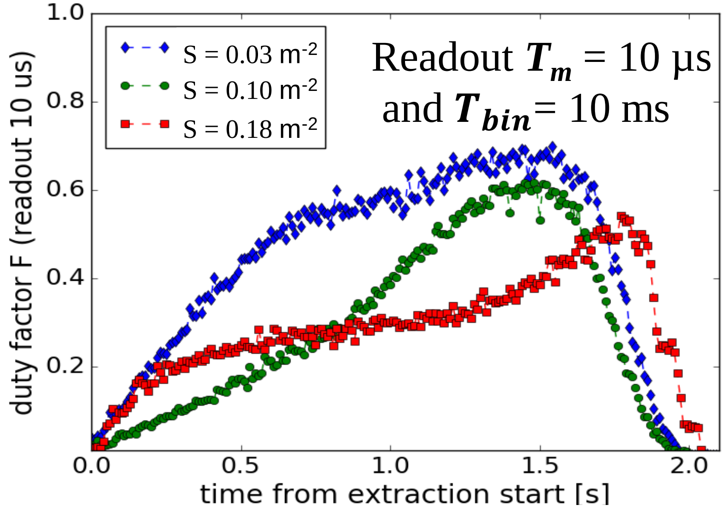


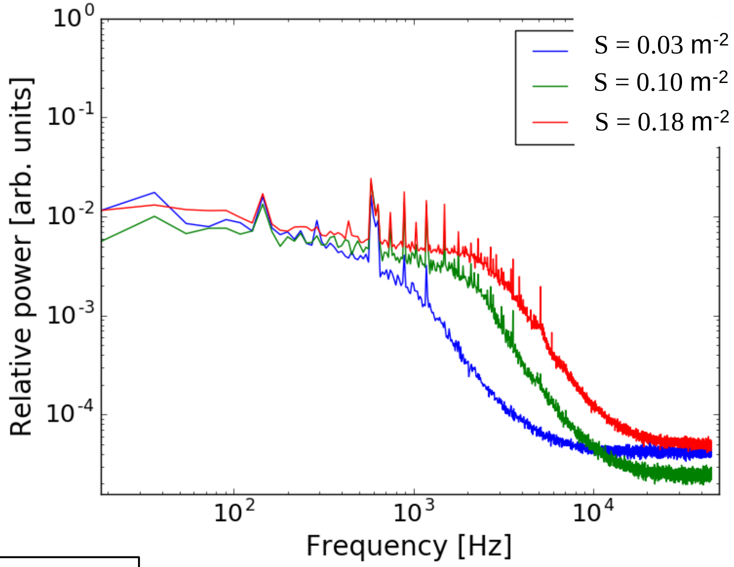


- At smaller sextupole strength, tune ramp starts closer to resonance (small $\overline{\epsilon_Q}$) (to maintain spill length)
- Sextupole strength (S), Emittance (A) and distance to resonance ($\overline{\epsilon_Q}$) are **NOT independent** parameters
- Transit time mean and spread are inversely proportional to distance to resonance($\overline{\epsilon_Q}$)
- Low pass filtering, $f_{cut} \propto 1/\Delta T_{tr}$

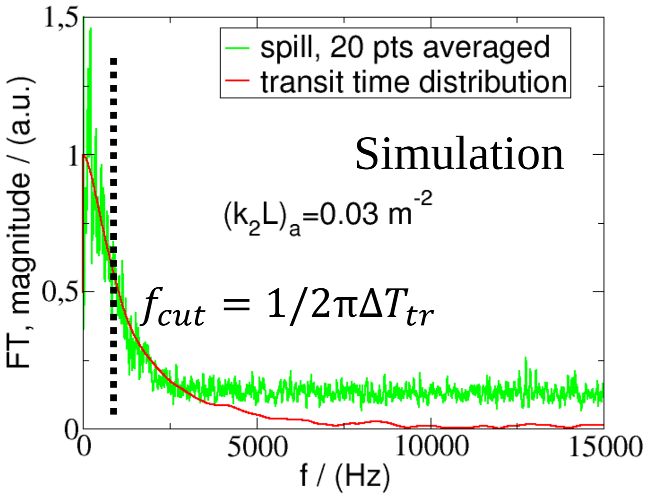
Sextupole Strength Variation: Experiments

Experiment: Ar^{18+}, 300 MeV/u



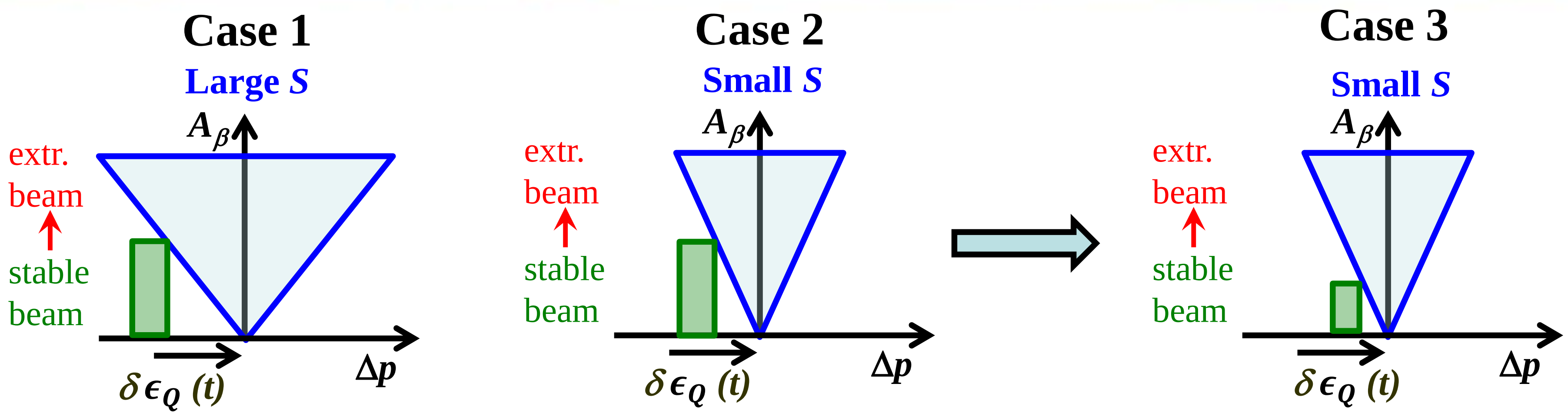


Further lowering sextupole leads to beam losses, spiral step x_{step} becomes too small

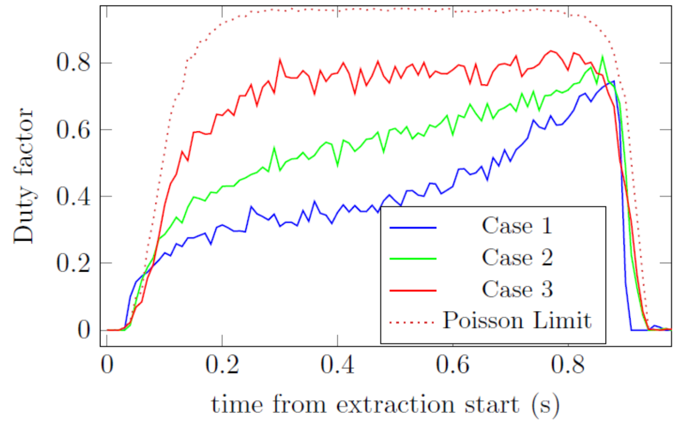


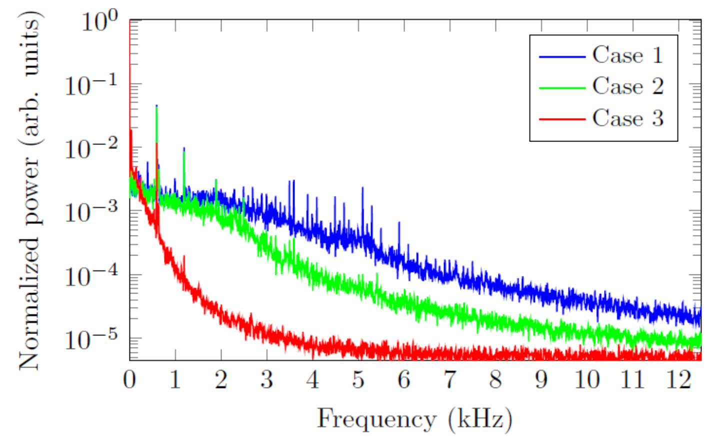
- Sextupole strength has strong effect on duty factor F_W (0.3 → 0.58)
- Duty factor F is time dependent (changing ϵ_Q)
- For lower S, peak duty factor is reached earlier (smaller $\overline{\epsilon_Q}$)
- For lower S high frequencies are damped due to spread in i.e. low pass filtering $f_{cut} \propto 1/\Delta T_{tr}$

Minimize transverse beam size at extraction



Experimental results
(C^{6+}, 300 MeV/u)

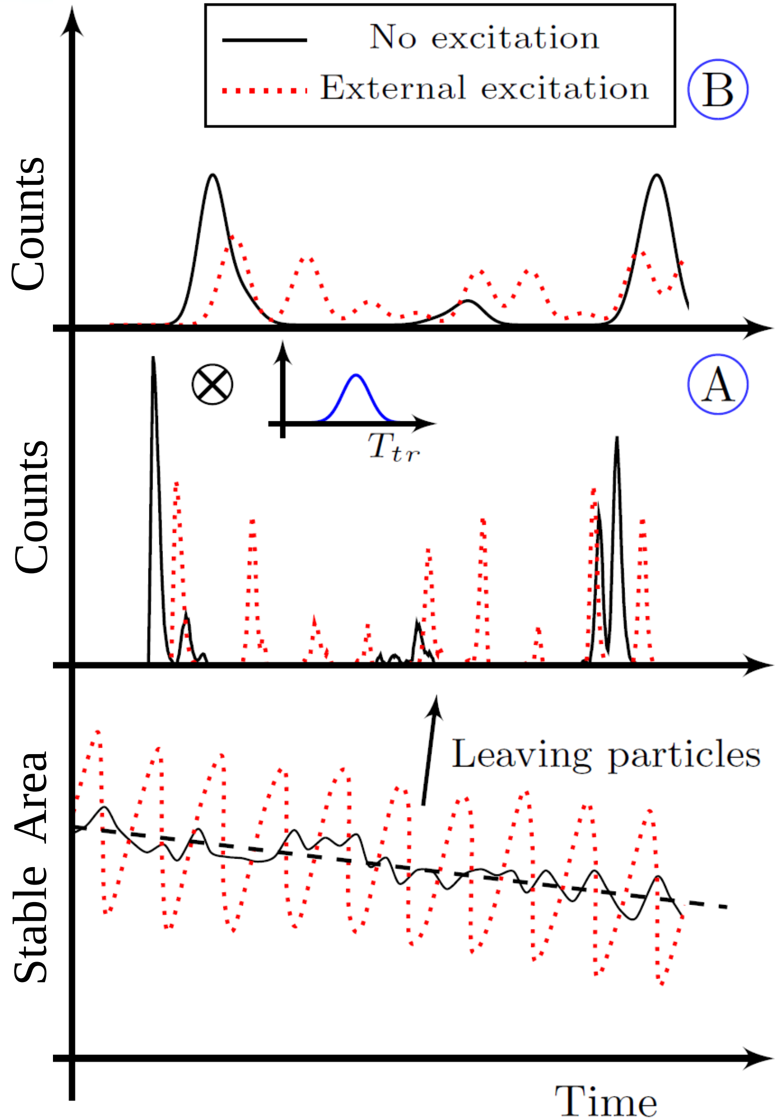


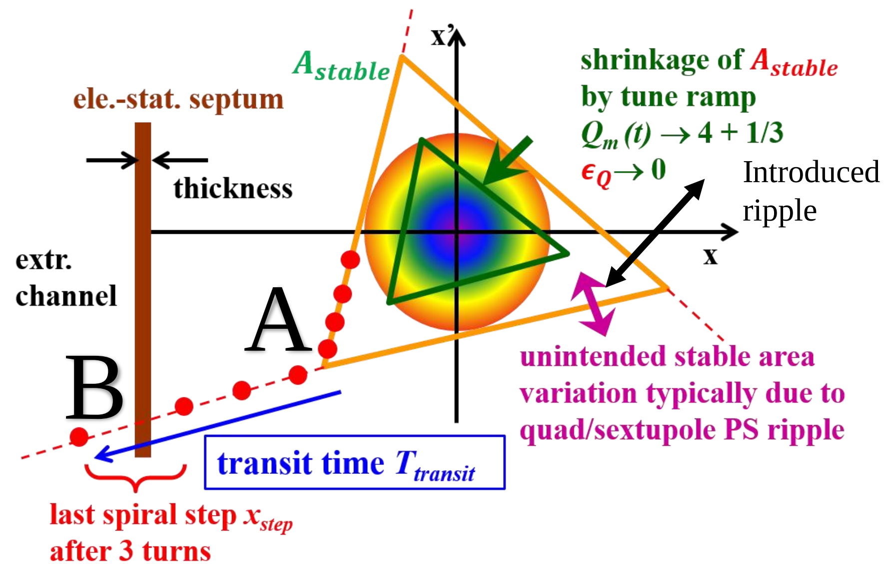


Reduce the transverse beam size and start further closer to resonance

- **Less Turn Injection or Beam cooling → Less statistics**
- **Emittance Exchange: Using the coupled resonance with skew quads and crossing tunes?**

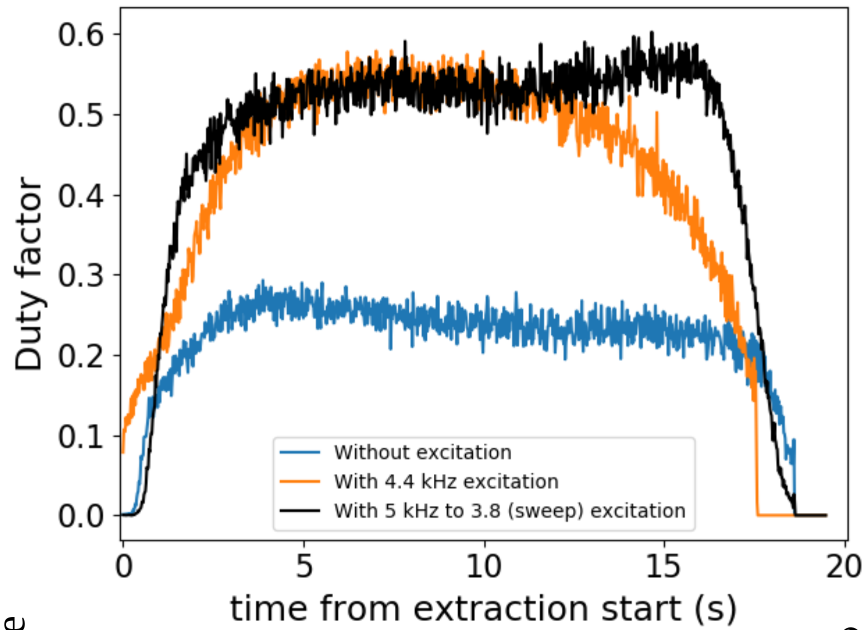
Tune Wobbling: Introduce external tune modulation

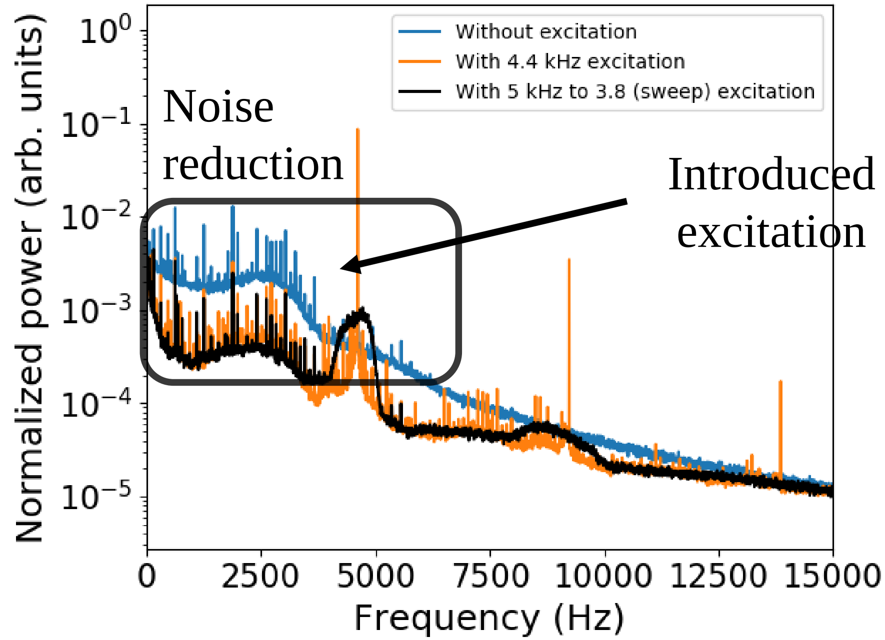


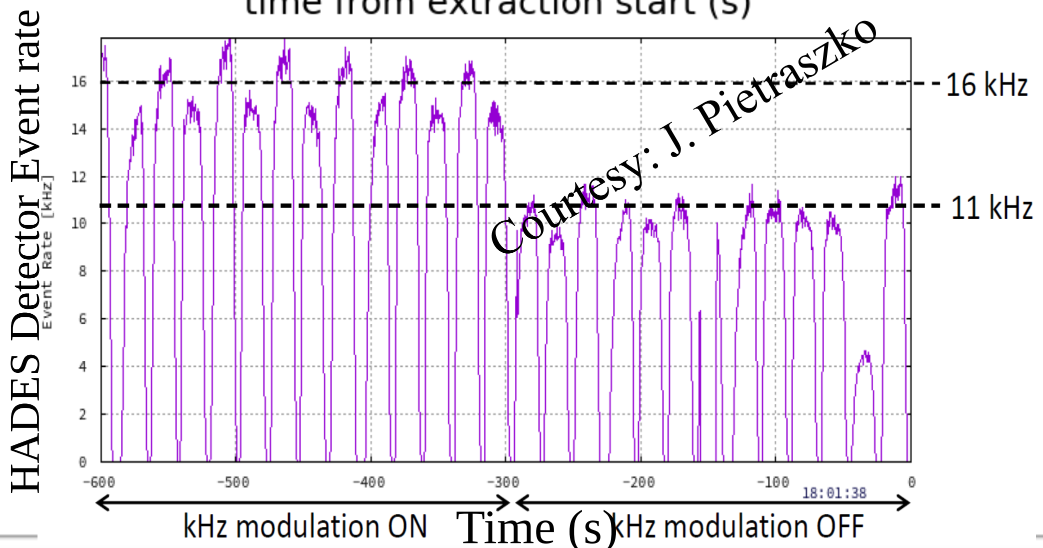


- Modulate tune with a higher frequency 3-5 times the cut-off frequency and amplitude 5-15 times the inherent ripple (1-3% of total tune ramp)
- This high frequency separatrix modulation does not allow lower frequency inherent fluctuations to "feed" on particles
- Modulation frequency high enough such that it is suppressed by transit time spread → but not too high

Tune modulation with 1.58 GeV/u Ag^{45+} (HADES) beam







- The transit time spread evolves (increases from low to high) based on tune ramp, **apply a frequency sweep correlated to transit time spread → Triggered linear sweep applied**
- Amplitude still not optimized (150 mA applied to one quad family i.e. 15 times of inherent ripple amplitude at 600 Hz)

Bunched beam extraction

MEASUREMENTS AND IMPROVEMENTS OF THE TIME STRUCTURE OF A SLOWLY EXTRACTED BEAM FROM A SYNCHROTRON

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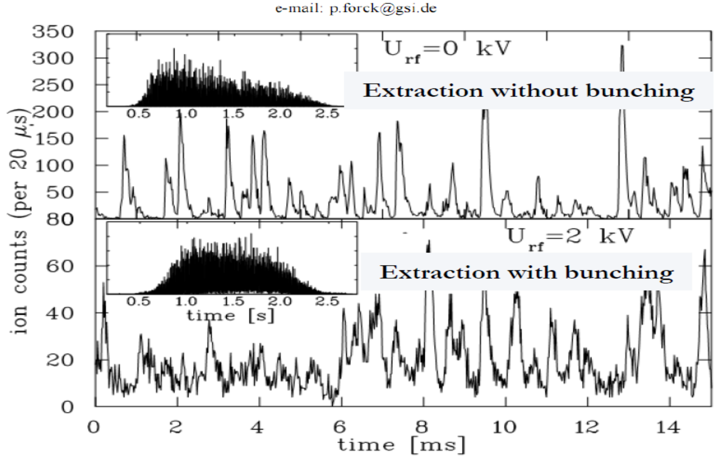
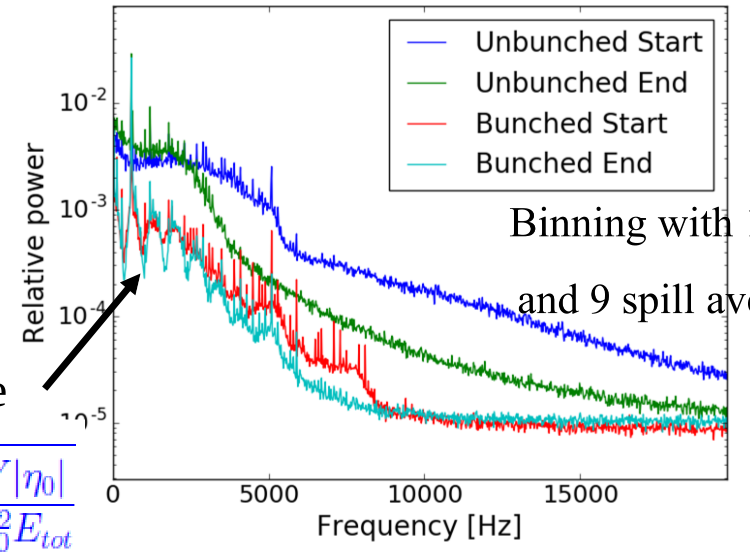
Gesellschaft für Schwerionenforschung GSI, Planck Strasse 1, 64291 Darmstadt, Germany
*Institute for Nuclear Research, Kiev, Ukraine
e-mail: p.forck@gsi.de



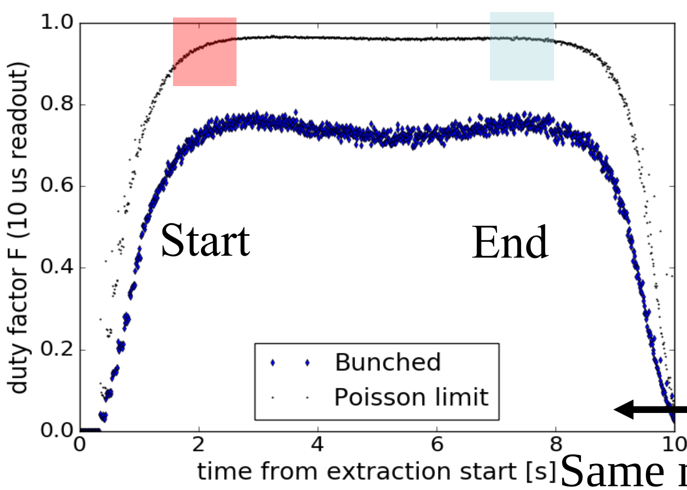


Binning with 10 Hz and 9 spill average

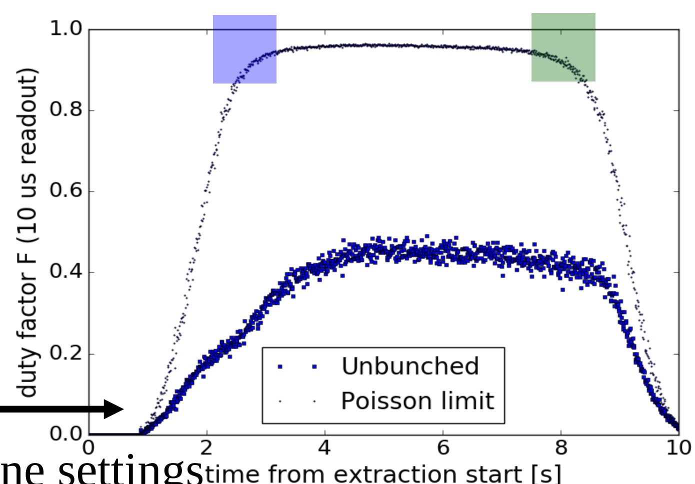
Sync. tune

$$Q_s = \sqrt{\frac{hqV|\eta_0|}{2\pi\beta_0^2 E_{tot}}}$$

Bunched beam: T_m =11 μs, T_{bin} =10 ms



Coasting beam: T_m =11 μs, T_{bin} =10 ms

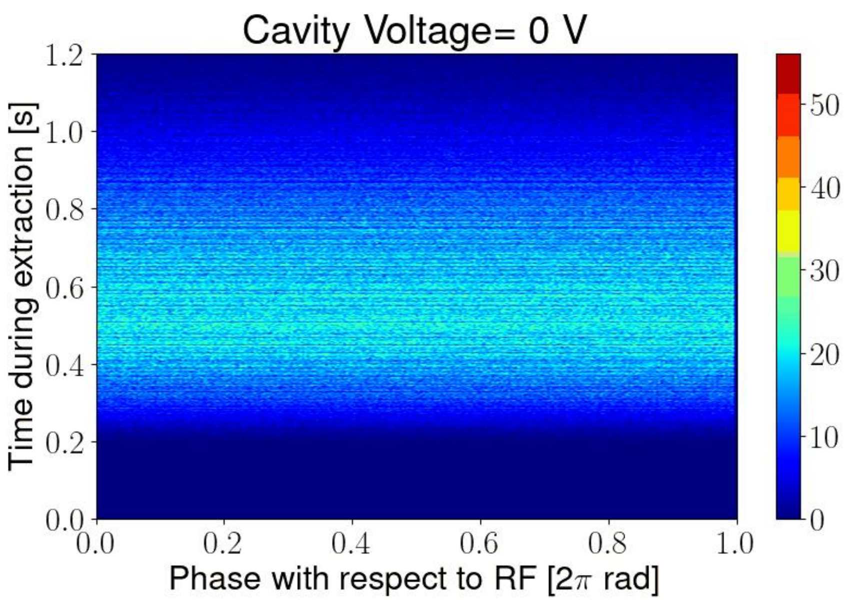


Same machine settings

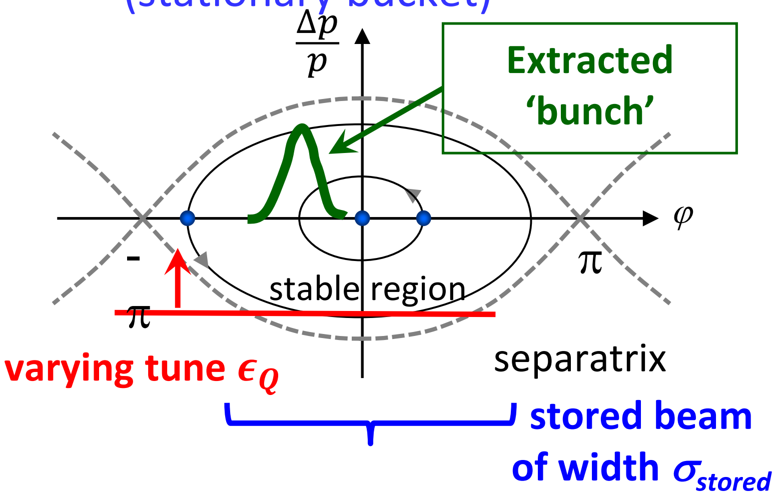
Bunched beam extraction

Bi^{68+} at 300 MeV/u, quad. scan, bunched beam (detector : Scintillator)

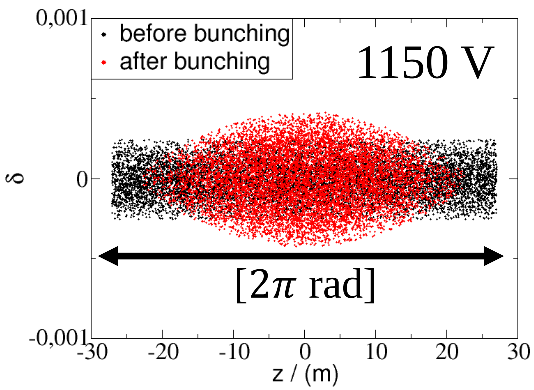
Histogram of arrival time over extraction

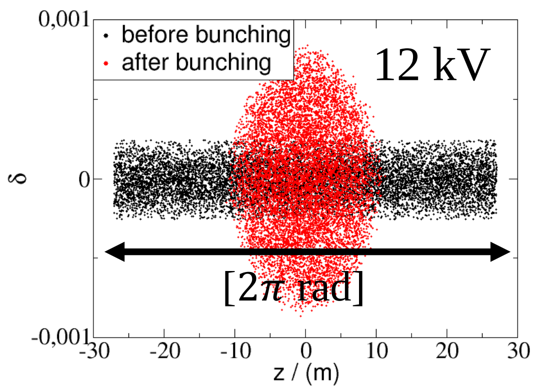


Long. phase space
(stationary bucket)



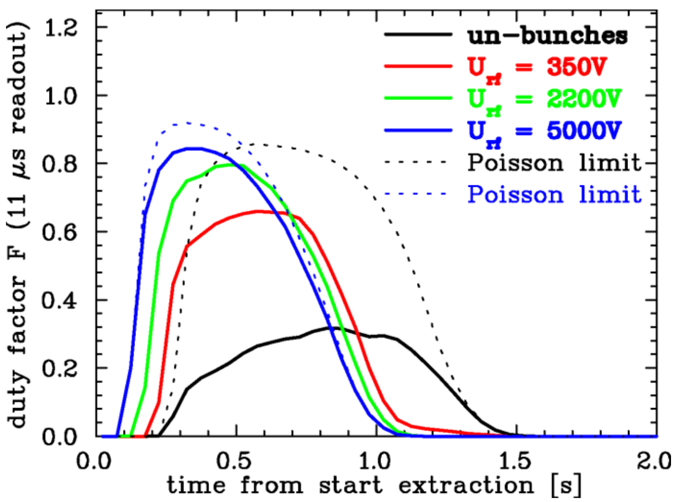
- Extraction starts earlier and structure formation
- 'Bunch' duration at target in the range of 2σ ≈ 5-10% of the RF period
- 'Bunch' duration shorter by factor 2-3 in comparison to bunches inside SIS

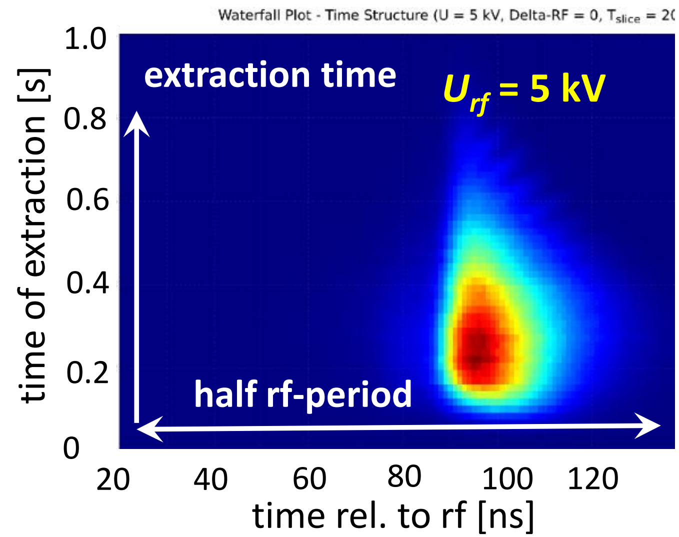


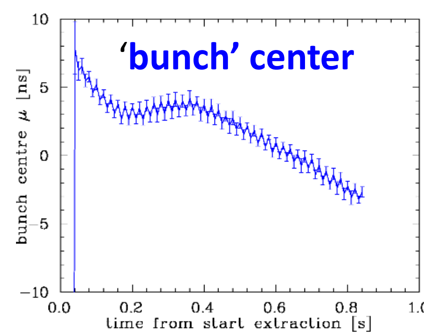


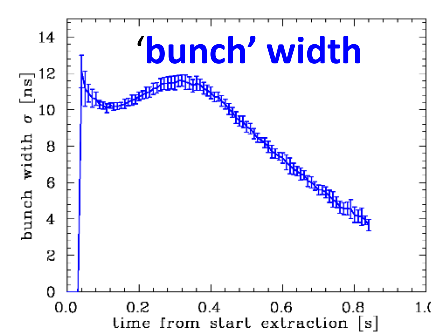
Bunched beam extraction

Bi^{68+} with 300 MeV/u, with f_{rf} = 3.62 MHz









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

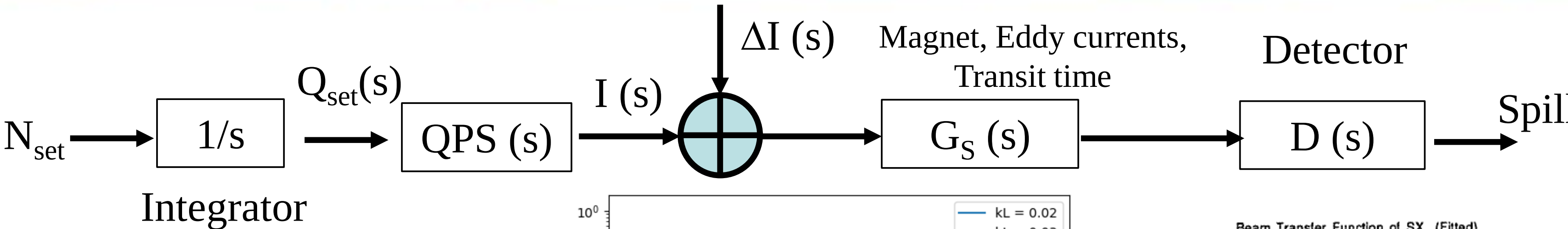
→ **Poisson limit nearly reached**

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

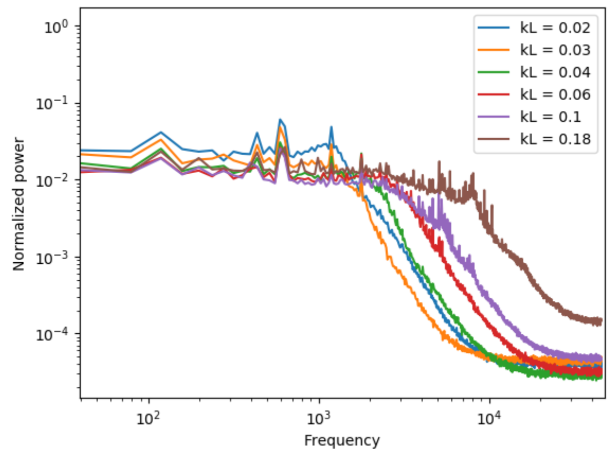
Unacceptable for many users, due to detector dead time $t_{dead} = 0.1 \ldots 10$ μs $\approx 1/f_{rf}$

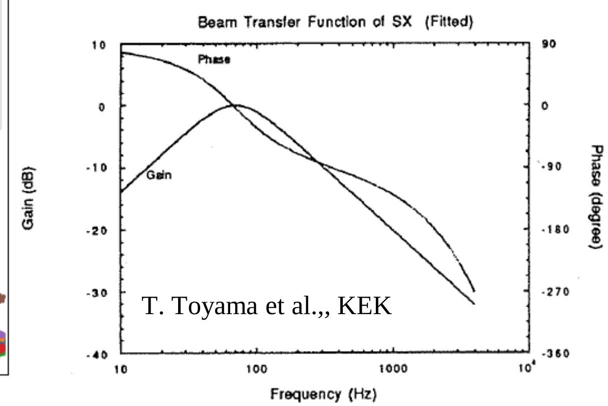
Mitigation: 80 MHz high frequency bunching cavity in preparation by P. Spiller et al.

Slow extraction "transfer function"

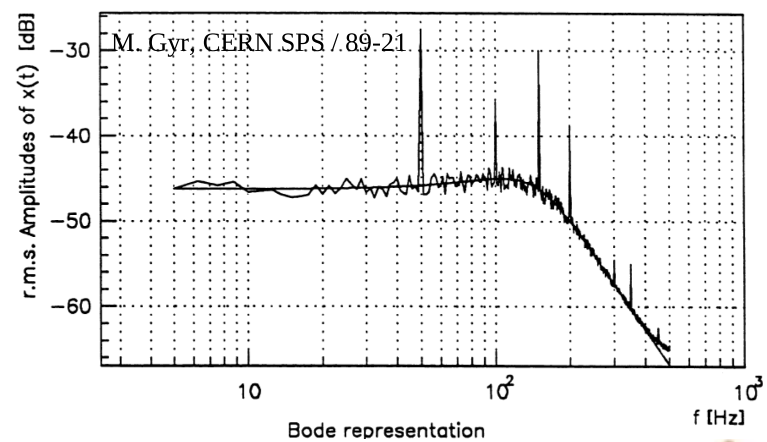


- Transfer function is only defined for linear time invariant (LTI) systems
- The spill spectrum is though to be the magnitude of slow extraction "transfer function"

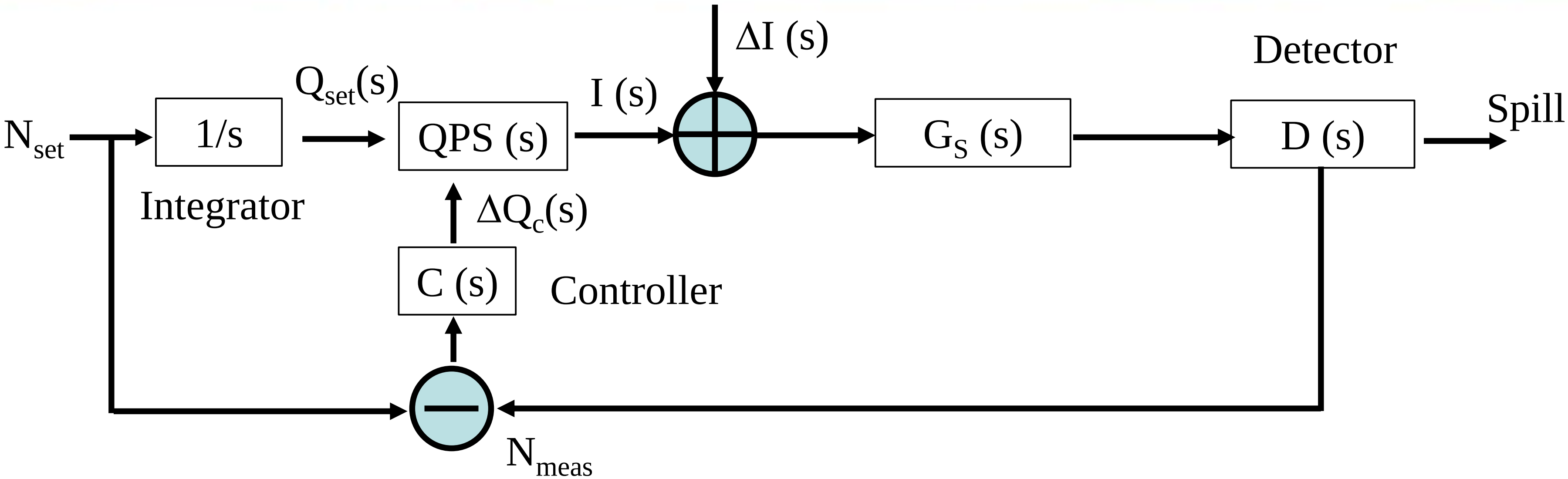




- Slow extraction transfer function is a function of transit time distribution
- There is a large delay in slow extraction transfer function → transit time → dead time

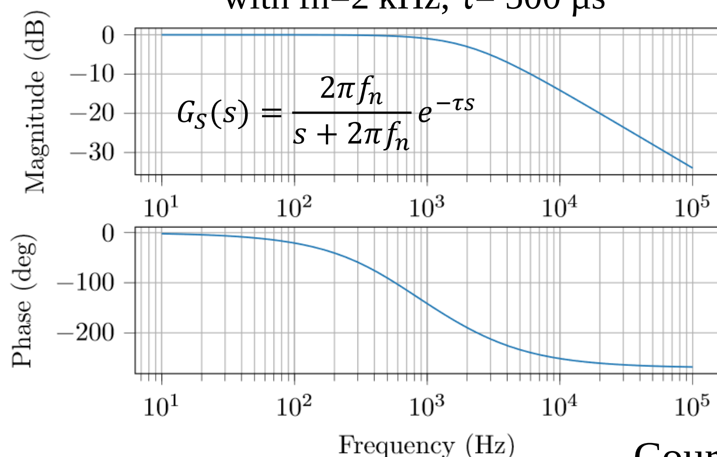


Micro-spill feedback

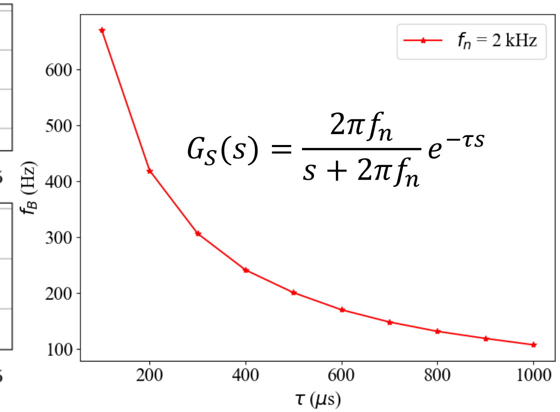


- If we model the G_S (s) with a first order transfer function with a delay
- Calculate optimal controller C(s) and the achievable disturbance rejection
- Disturbance rejection upto ~100 Hz should be possible

Bode plot of first order transfer function with fn=2 kHz, τ= 500 µs

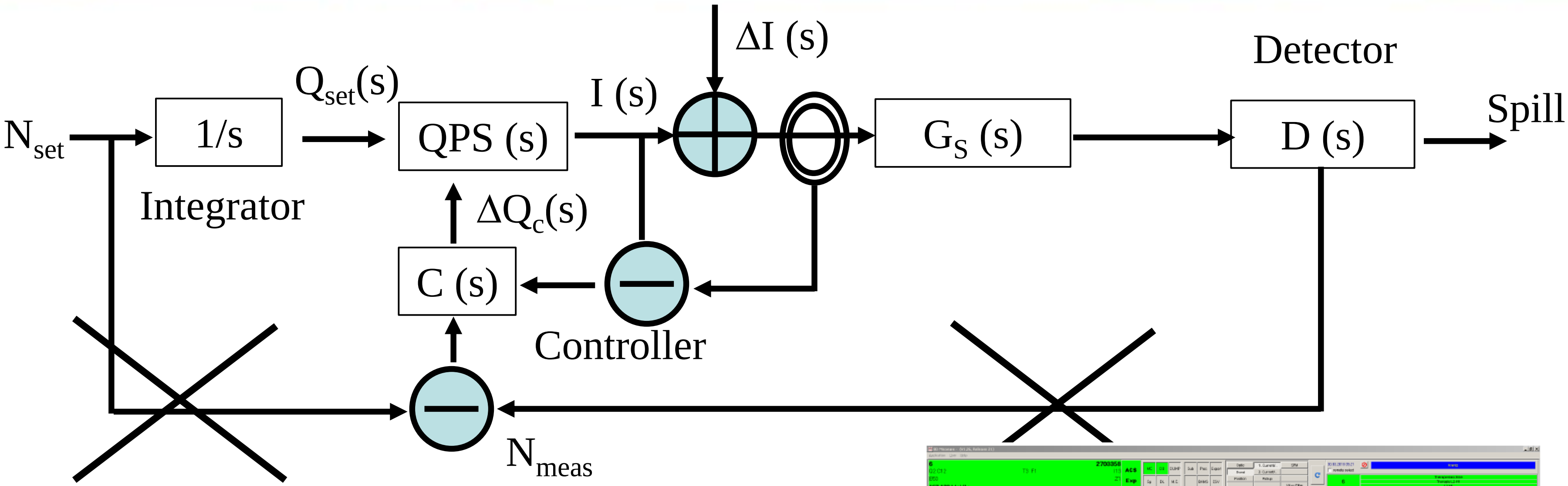


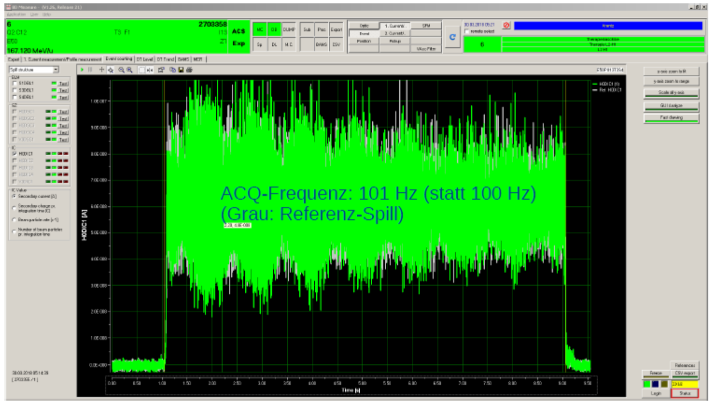
Bandwidth of disturbance rejection for Closed loop



Courtesy: S. H. Mirza

Micro-spill feedback





C. Krantz, HIT-MIT meeting

- Non-linear time variant G_S (s) does not take us very far with disturbance rejection
- Feedback based on tune measurement not an option since tune ripples are very small $\frac{\Delta Q_m}{Q_m} \sim 10^{-3} - 10^{-4}$
- Feedback based on ΔI (s) in reference to I (s) → Good reliable AC current measurement necessary

Also: D. Naito et al, Real-time correction of betatron tune ripples on a slowly extracted beam PRAB 22, 072802 (2019)

Summary and Outlook

SUMMARY

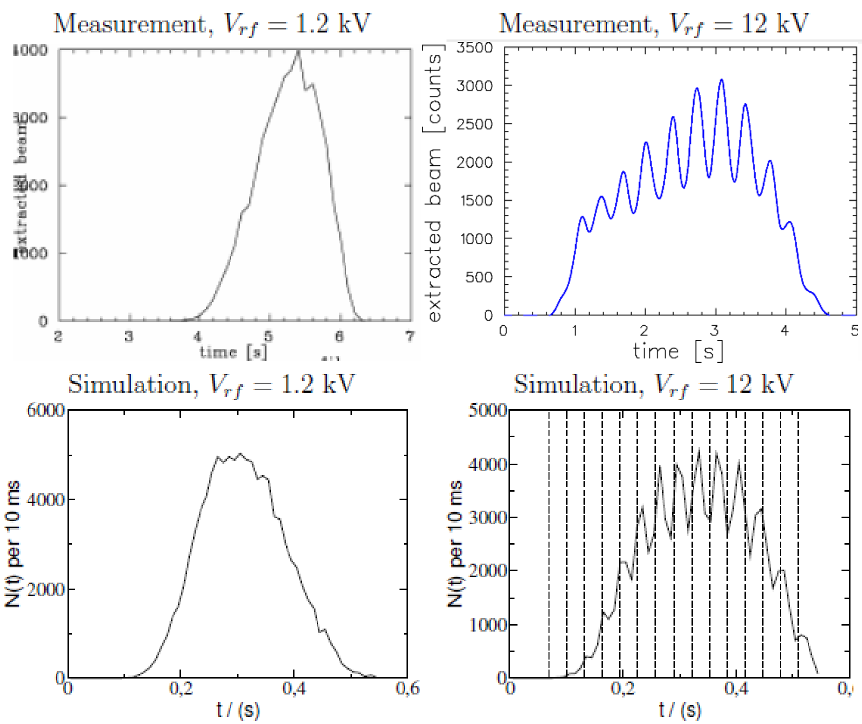
- Beam diagnostics and analysis available for slow-ex measurements and comparisons with simulations
- Optimization of extraction settings, i.e. ϵ_Q, S and beam size for inducing a large transit time spread → provides ``natural" suppression of fluctuations
- Tune modulation at 3-5 f_{cut} with I_{ex}= 5-15 of inherent noise → modulation itself suppressed ... ent fluctuations

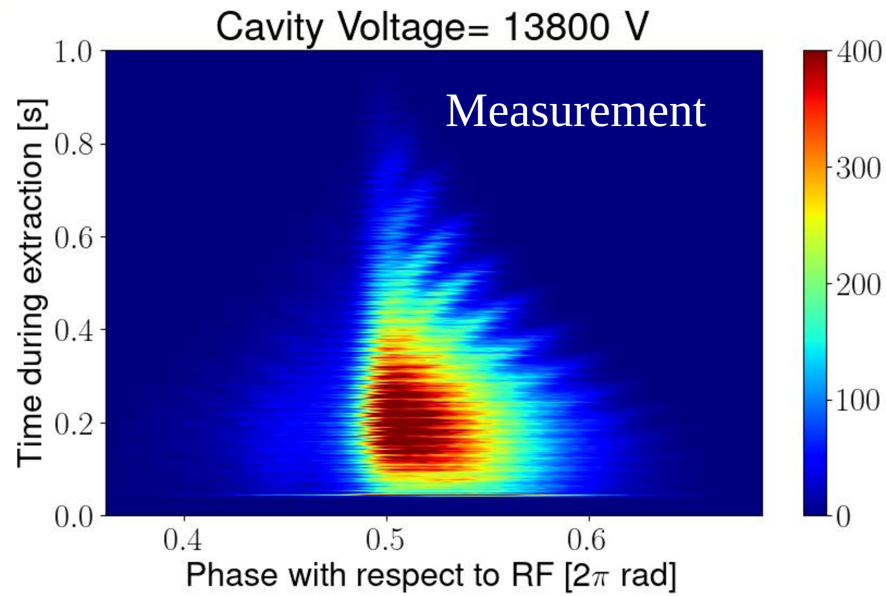
Acknowledgements: A. Stafiniak, W. Orlov, H. Welker, D. Ondreka

OUTLOOK

- Current fl... I_Q ... further improvement of power supplies possible?
- Cancel the resulting tune fluctuations via an extra quadrupole using a feedback system ? Measurement of current ripples $\frac{\Delta I_Q}{I_Q} = \mathbf{10^{-6}}$ reliably → proposal with Bergoz Inst.
- Investigations needed for tune wobbling with knock-out extraction and follow up on KO noise variants → Efficient beam excitation at the highest rigidities → KO excitation front end with Bartel Electonics
- Improvements in detectors to perform higher rate experiments and benchmarking with BLM, IC, CCC, Scintillators

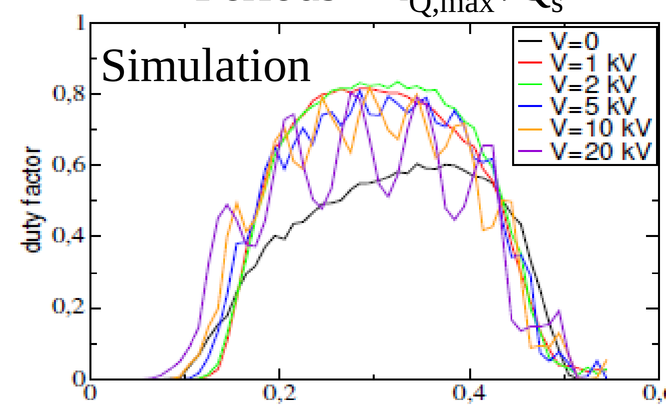
Some details: Bunched beam extraction





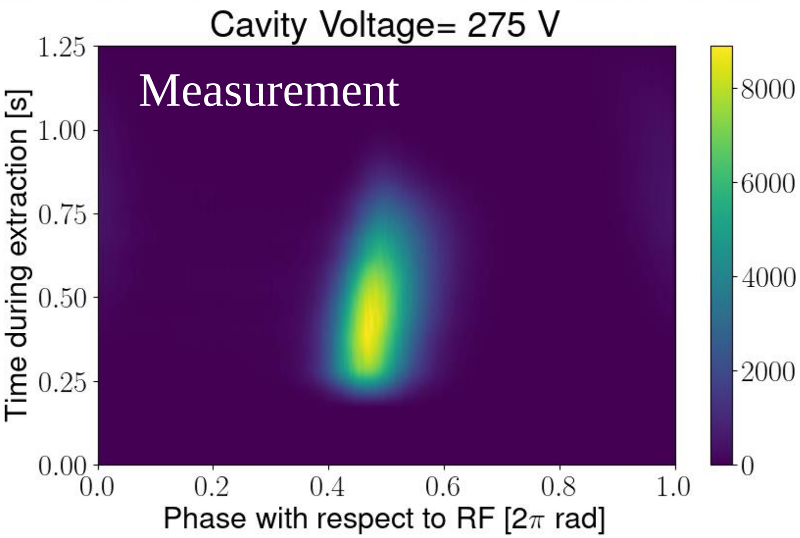
$$Q_s = \sqrt{\frac{hqV|\eta_0|}{2\pi\beta_0^2 E_{tot}}}$$

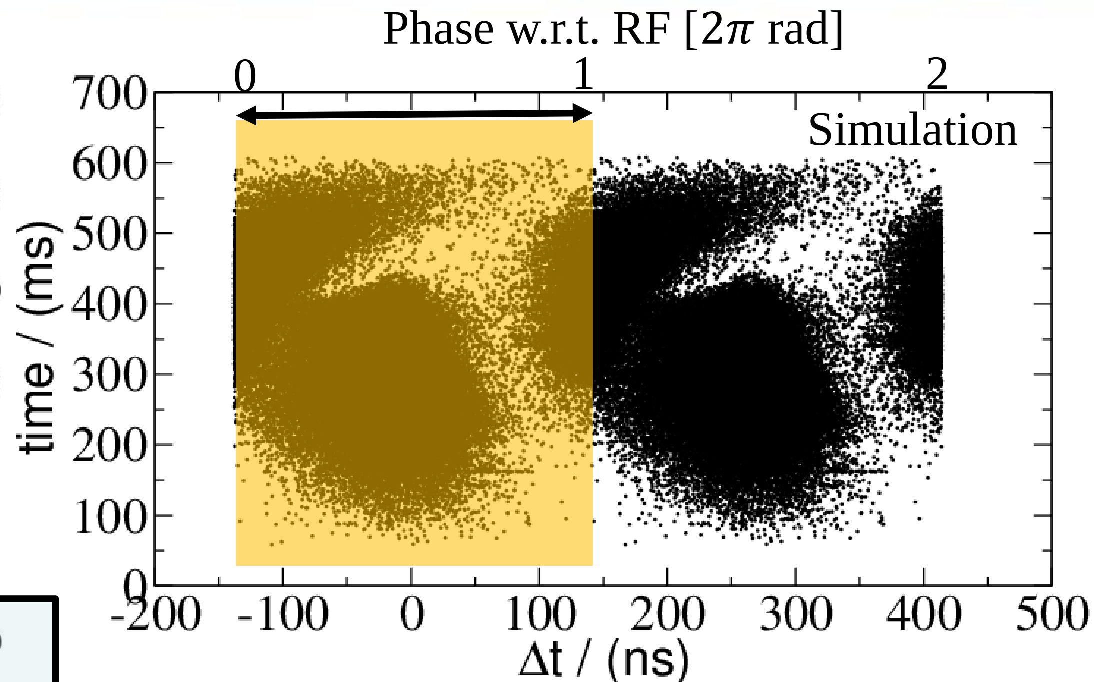
Periods = $\epsilon_{Q,max} / Q_s$

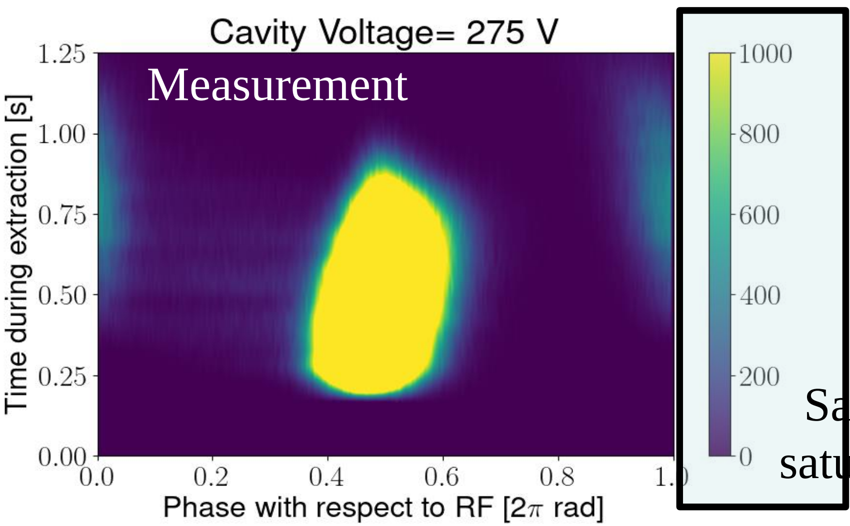


- When transit time(synchrotron period)/4 ~, particles can become stable again due to changing $\frac{\Delta p}{p}$, resulting in "accumulation" in phase space
- Extracted in "packets" when the stop band becomes larger at synchro-betatron resonances → $mQ_x + pQ_s = l$

Details: Bunched beam extraction







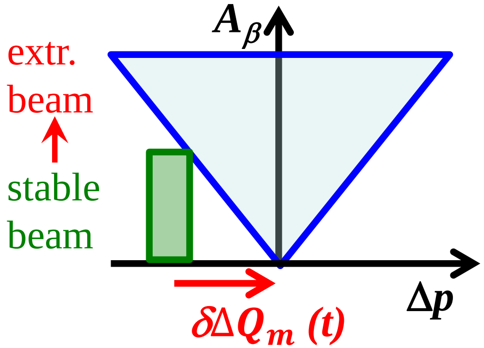
At lower voltages, the extracted widths are larger and uncaptured particles are extracted from edge of buckets

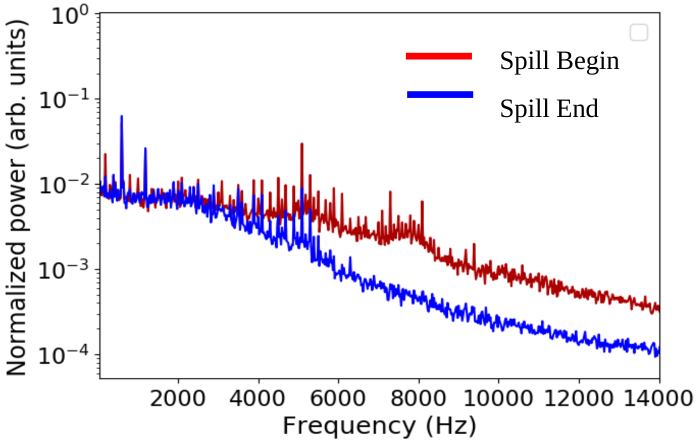
Same figure as above, colormap saturated to highlight lower counts

Quad-driven versus Knock-out Extraction

Quad-driven ⇔

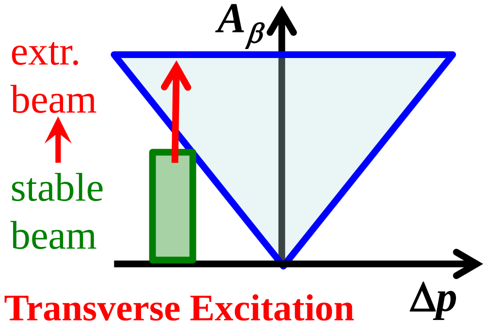
variation of tune by quadrupole field

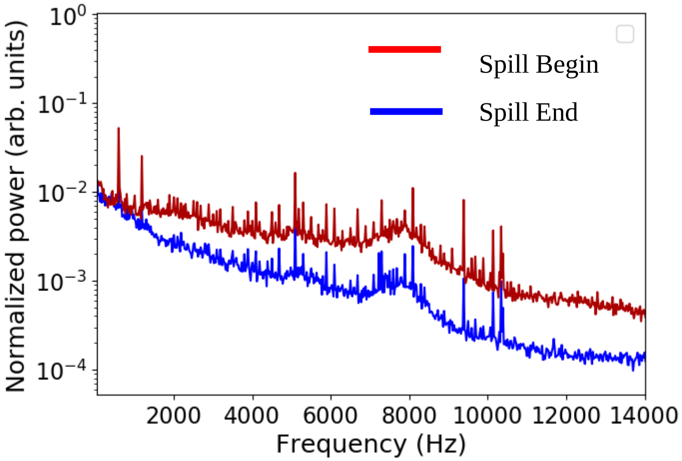




Knock-out ⇔

blow-up of horizontal betatron amplitude





- Transit time spread increase towards the end of spill is the improvement mechanism
- Similar trend for bunched beams

- Fast separatrix crossing towards the end of spill is the improvement mechanism
- **Excitation noise spectrum plays an important role, investigations & improvements at HMIAC, HIT, MIT**

⇒ Both methods suffers from the similar problems and might gain from the same solutions!

Bunched beam Extraction (Quad driven)

Extraction of bunched beam

Method: Leaving the rf on after accel.

⇒ Building of stationary buckets

with oscillation of the particle momentum

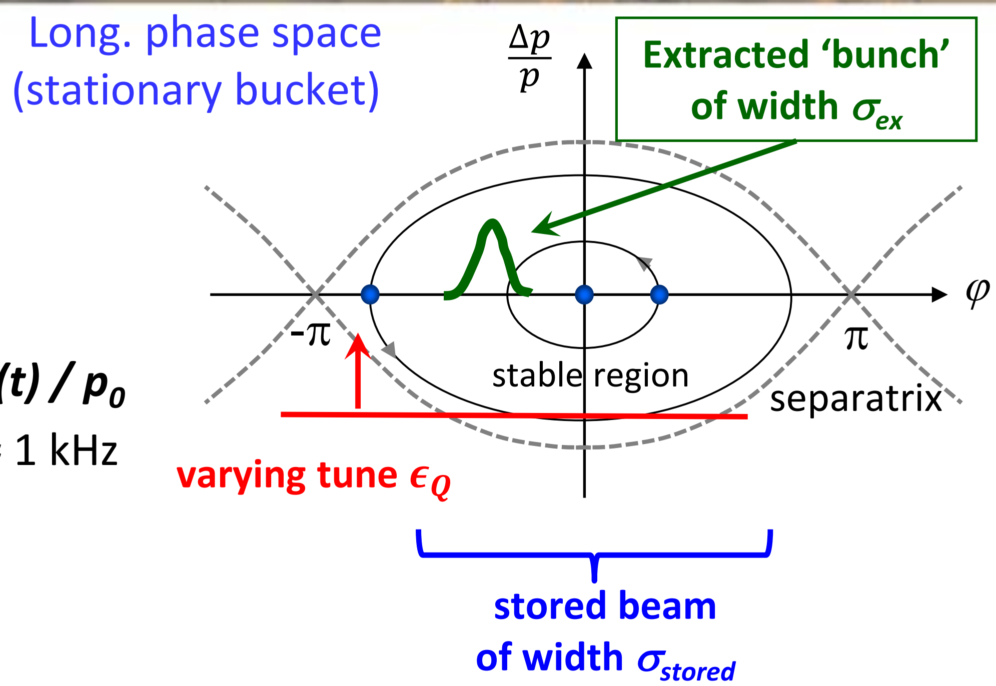
⇒ Enlarged spread of $T_{transit}$ due to

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



Reason: Only ions with $\Delta p/p$ facing the resonance are extracted → there is more to the story!

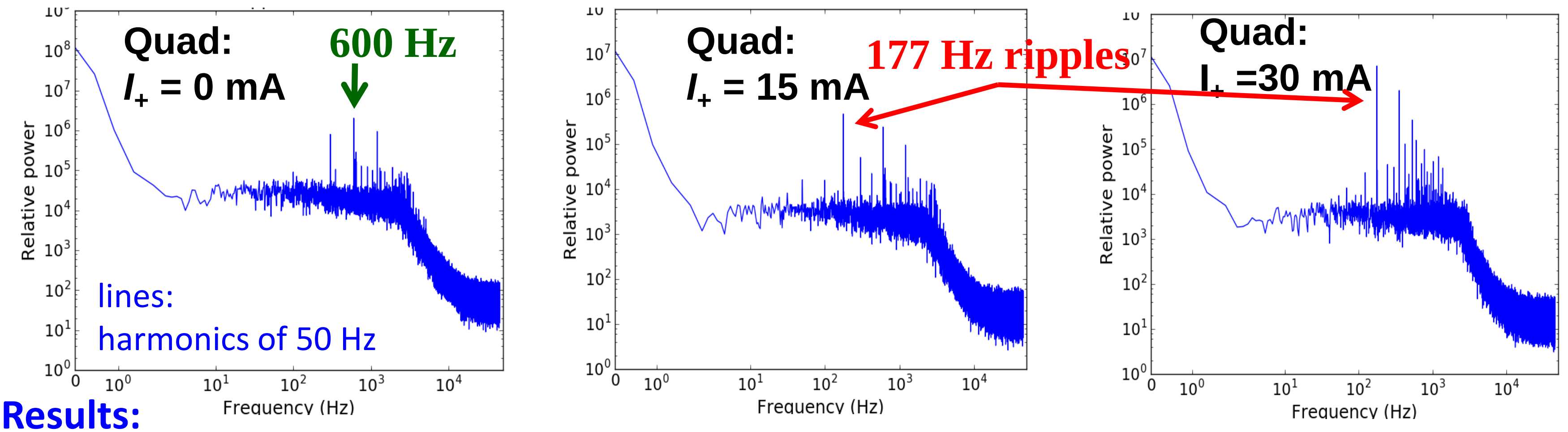
R. Singh et al., 'Slow Extraction Spill Characterization From Micro to Milli-Second Scale', J. Phys.: Conf. Ser.1067 072002 (2018)

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.

Induced Sine-Wave delivers a Ripple 'Calibration'

Quantitative investigations of PS ripple: Injecting 137 Hz (dipole) and177 Hz (quad)

Beam response measurement with scintillator followed by Fourier transformation



Results:

Dipole: Effect for ≈ 200 mA ⇔ 5x10^{-5} FS (3.5kA)

Quad: Effect for ≈ 10 mA ⇔ 5x10^{-6} FS (1.7kA)

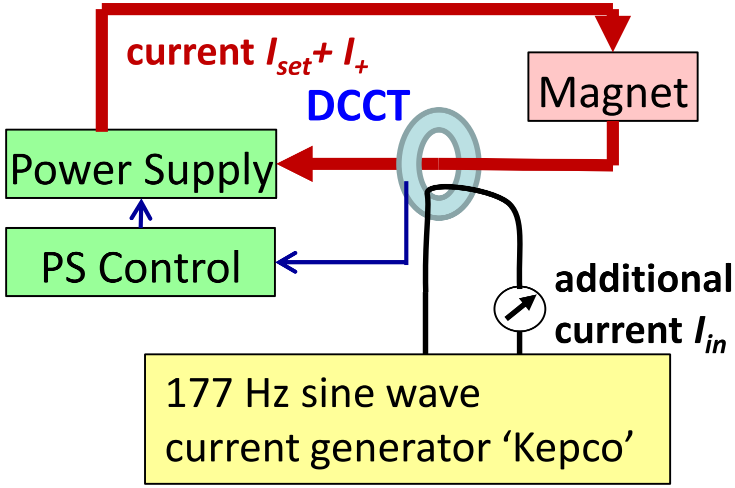
⇒ largest 'natural' line ≈ 5 mA@600 Hz

Sextupole: Effect for ≈ 200 mA ⇔ 5x10^{-4} FS (1 kA)

⇒ micro-structure caused by quadupole PS ripple

Remark: • A power supplier is a complex device e.g. does not behave like a simple low-pass filter

• Data required for realistic MAD-X simulations



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

Systematics : Tune wobbling (quad driven)

$$\overline{T_{tr}} \propto \frac{1}{\overline{\Delta Q_m}} \Rightarrow \Delta T_{tr} \propto \frac{\Delta(\Delta Q_m)}{\overline{\Delta Q_m}^2}$$

Results of 3rd step of mitigation:

- If external frequency $f_{ex} \approx \frac{1}{\Delta T_{transit}}$

  $\Rightarrow$ improvement of quality

Choice of excitation frequency f_{ex}:

- Lower limit $\rightarrow$ low pass filtering

  $\Rightarrow f_{ex} > f_{cut} = \frac{1}{2\pi \Delta T_{tr}}$

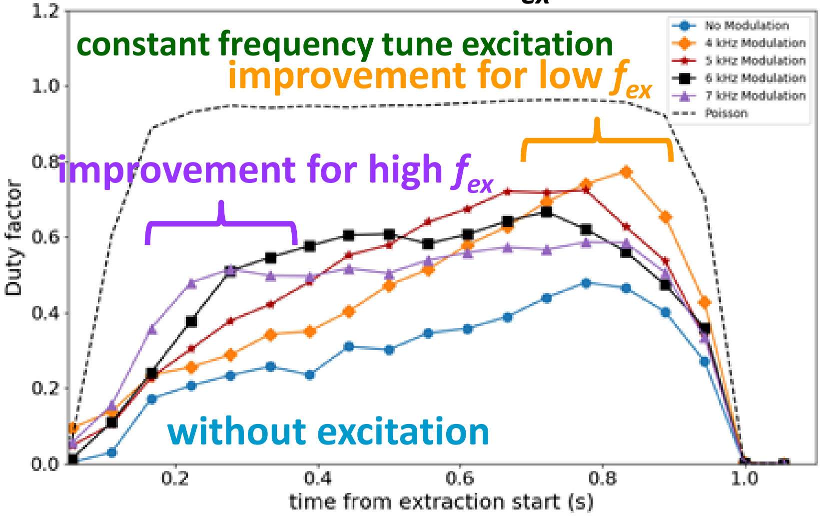
- Upper limit $\rightarrow$ no re-capture of released ions

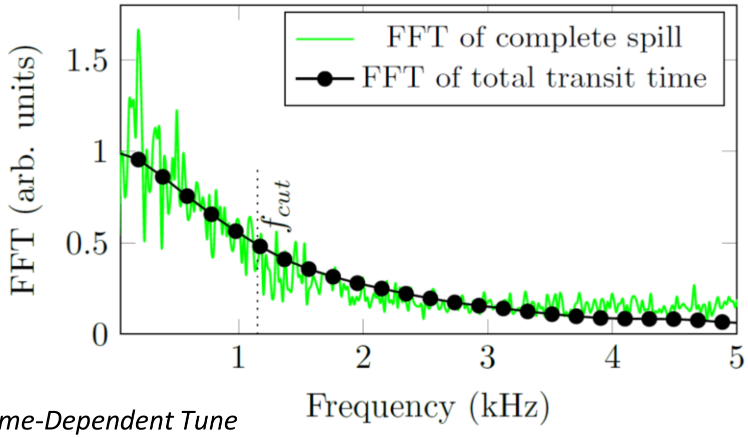
  $\Rightarrow f_{ex} < \frac{10}{\overline{T_{tr}}}$

- Optimal frequency $f_{ex} \approx 10n\, f_{cut}$

  where $n = \frac{\Delta T_{tr}}{\overline{T_{tr}}} \approx 0.3$ typically

Beam: Ar^{18+}, 300 MeV/u, t_{ex} = 1 s

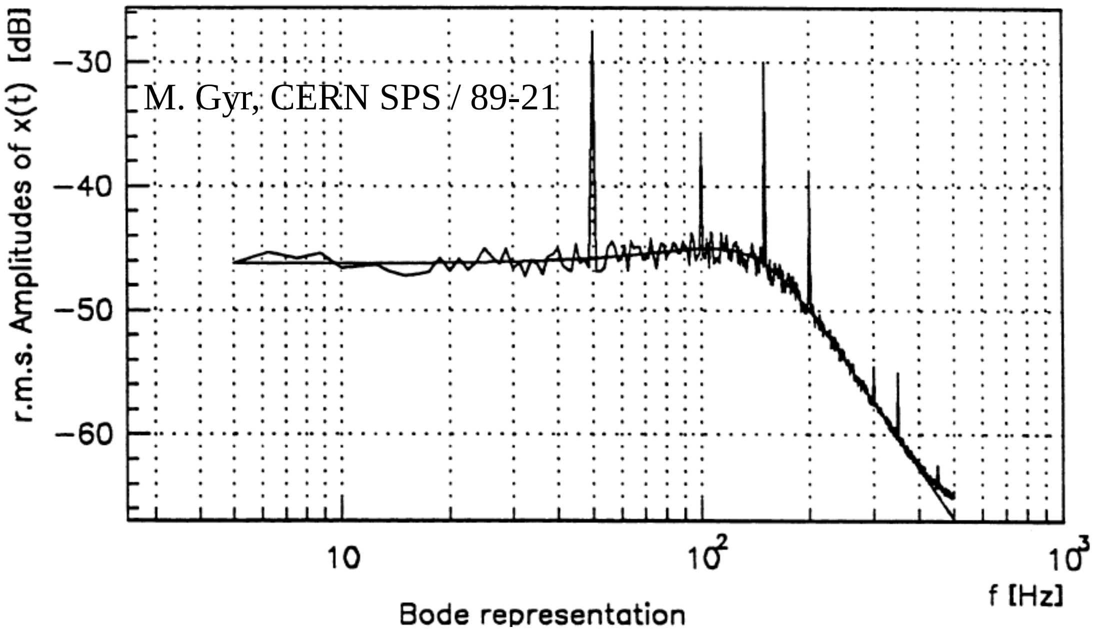


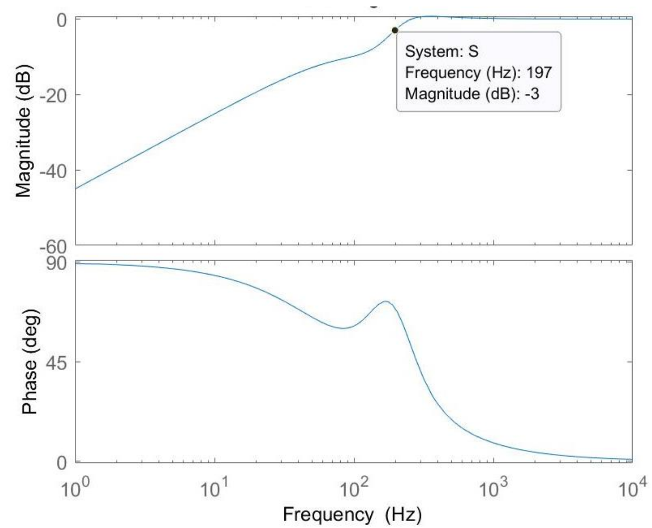


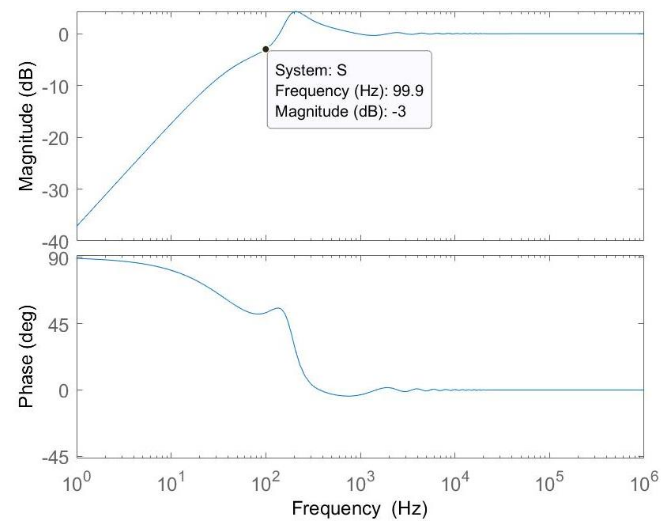
Experimental verification and simulations published:

- R. Singh et al.: '*Reducing Fluctuations in Slow-Extraction Beam Spill Using Transit-Time-Dependent Tune Modulation*', Phys. Rev. Applied 13, 044076 (2020)
- R. Singh et al.: '*Smoothing of the slowly extracted coasting beam from a synchrotron*' arXiv:1904.09195

Micro-spill feedback







C=pidtune(sys,’PID’)

Design optimal controller for the second order system for two delays → Maximum disturbance rehection bandwidth (sensitivity fucntion) is 100 Hz for 500 us delay or transit time

Event rates: Coasting vs bunched beam

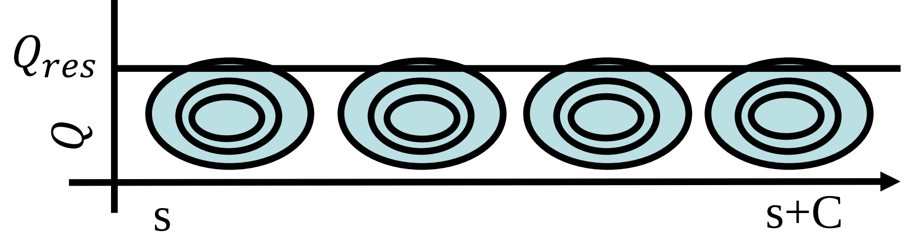
Key terms: $\boldsymbol{N_{rate}}$ Extraction rate ; $\boldsymbol{r}$ Max-to-mean ratio; $\boldsymbol{T_{det}}$ Detector time resolution; $\boldsymbol{T_{rf}}$ RF period; $\boldsymbol{B_f = 2}$ σ width of „extracted" bunch normalized to RF period

Instantaneous Tune (Q) distribution along the synchrotron

Coasting beam extraction

Maximum event rate
$\boldsymbol{N}_{\text{rate}} = \boldsymbol{1/(r\ T_{det})}$

Bunched beam extraction



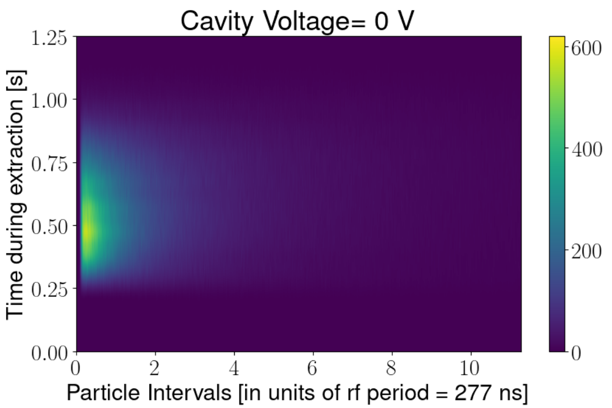
Maximum event rate
$\boldsymbol{N}_{\text{rate}} = \boldsymbol{1/(r\, T_{rf})}$

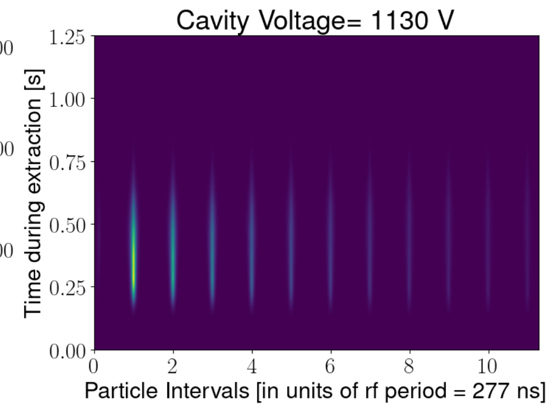
- Reduction in $\boldsymbol{r}$ for coasting beams converts directly to event rate $\boldsymbol{N}_{\text{rate}} \sim \boldsymbol{N_{max}} = \boldsymbol{1/\ T_{det}}$
- Bunched beam useful for micro-spill smoothing only if $\boldsymbol{T_{rf}} < \boldsymbol{T_{det}}$ even if there is a reduction in $\boldsymbol{r}$. Narrow bunches, i.e. low $\boldsymbol{B_f}$ lead to further challenges
- For therapy: acceptable because time resolution of any detector >> some µs and irrelevant for treatment. For experiments: not acceptable due to 'long breaks' of almost one rf period (SIS max. $\boldsymbol{f_{rf}}$ = 5 MHz)

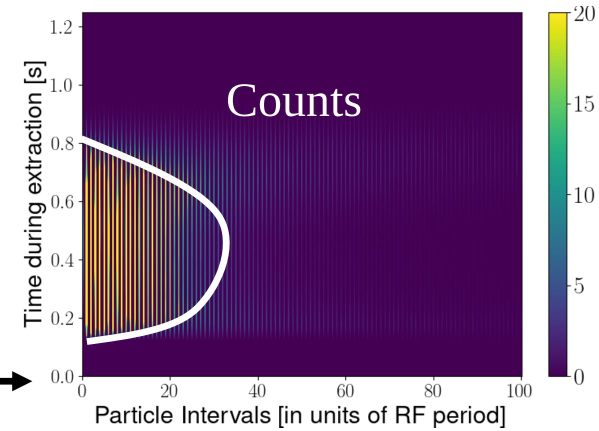
Particle arrival intervals

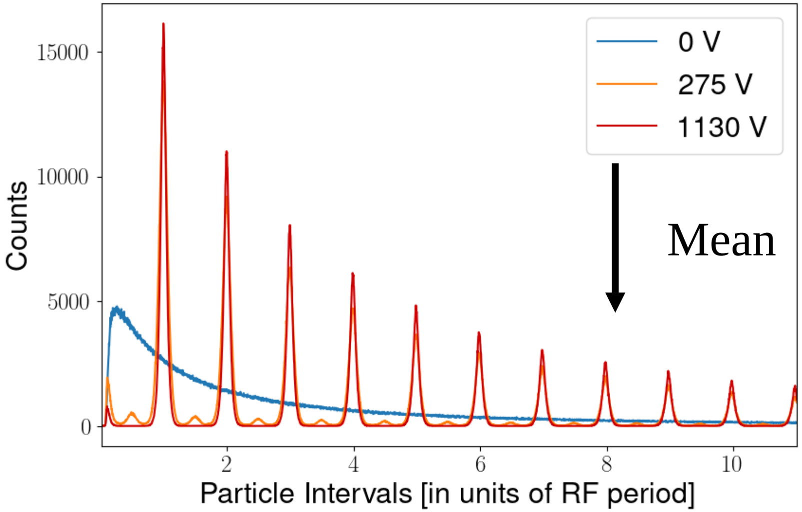
Example: Bi^{68+} at 300 MeV/u, quad. scan, bunched beam (detector : Scintillator)

Histogram of time between successive particle arrival









- The fluctuations in arrival times is 5-10% of bucket width
- Mean and std. deviation of the distribution are inversely proportional to instantaneous count rate
- Uncaptured particles arrive from the edge of buckets

Momentum Variation for Quad-driven Extr: Stored Beam

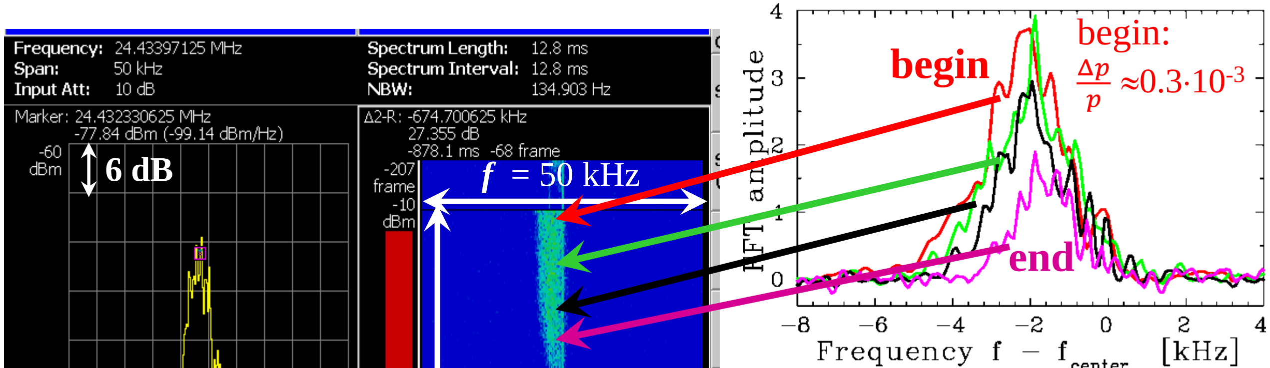
Example for longitudinal Schottky spectrum for quadrupole-driven slow extraction:

- 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 : $\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$

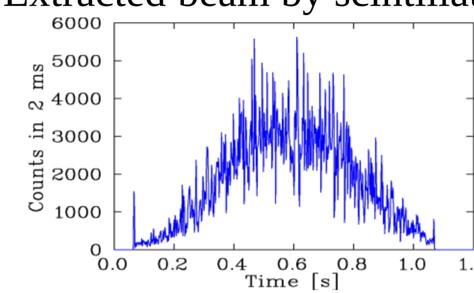
⇒ Lower momentum ions extracted first & variation of extraction angle at dispersive section in transfer

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

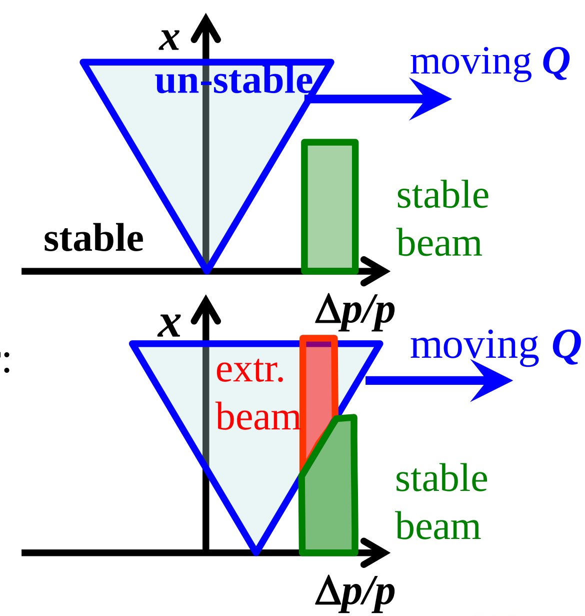
Beam parameter: GSI-synch. C^{6+} at 300 MeV/u ⇔ f_{rev} = 0.95 MHz, Schottky for h =26, Δf = 1.6 kHz (1σ)



Extracted beam by scintillator:



Steinbach diagram:

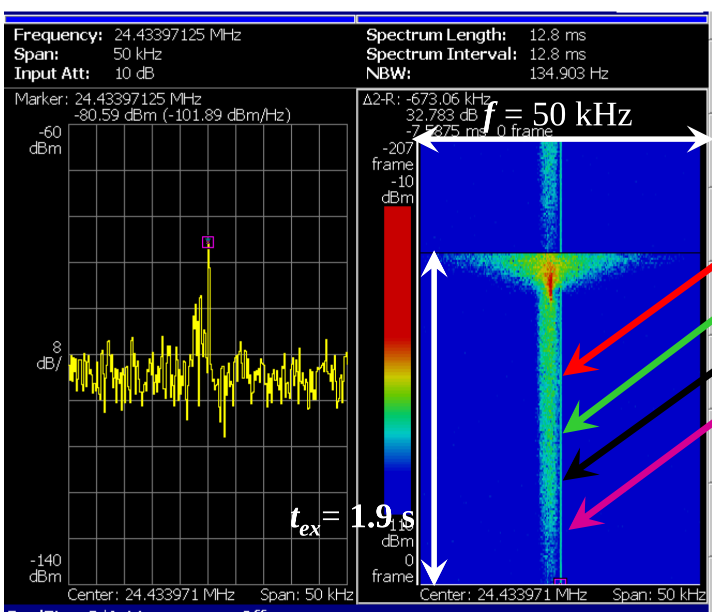


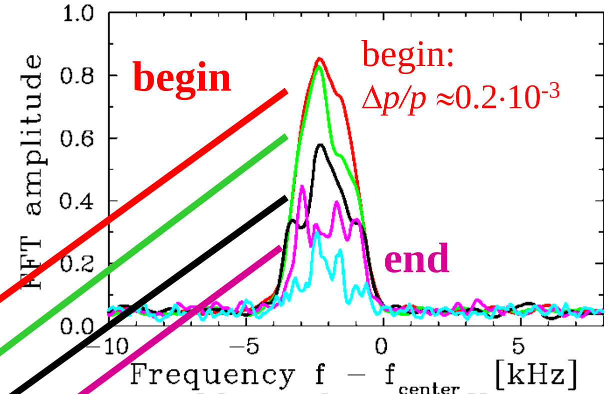
Momentum Variation during Knock-out Extraction

Example for longitudinal Schottky spectrum for KO slow extraction:

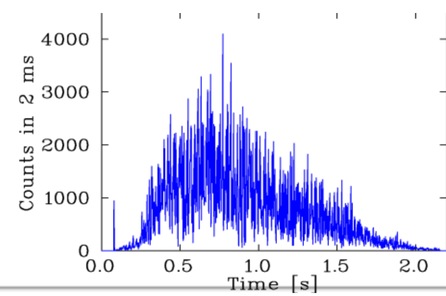
- Momentum spread before extraction here $\frac{\Delta p}{p_0} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{h\, f_0} = 0.2 \cdot 10^{-3}$ (1σ)
- Chromaticity (here ξ=-1.5) i.e. coupling tune ↔ momentum spread : $\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$
- Slow extraction by knock-out extraction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

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

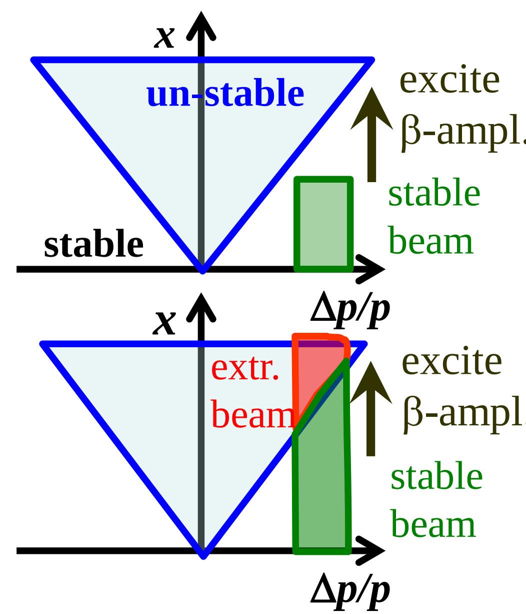




Extracted beam by scintillator:



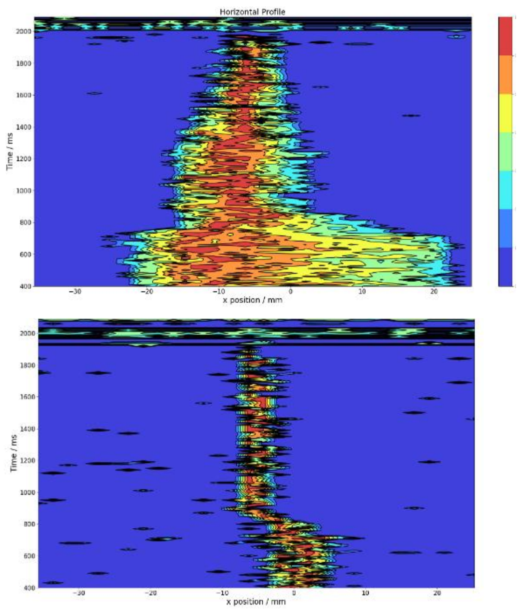
Steinbach diagram:



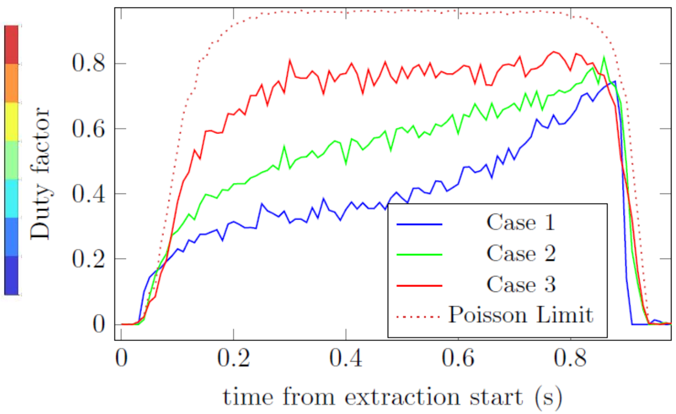
Minimize transverse beam size at extraction

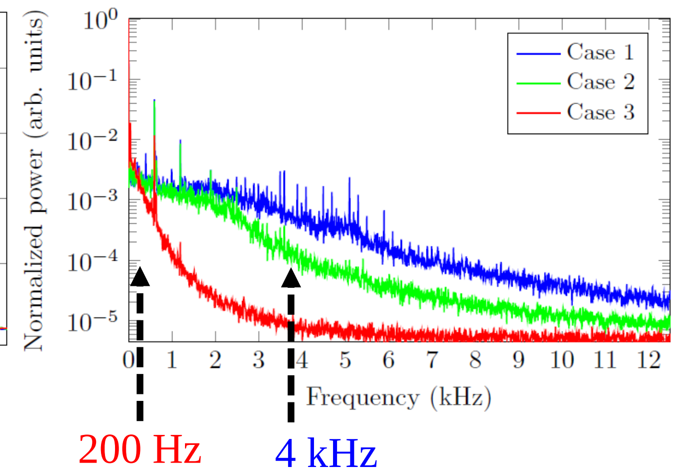
Beam size measurements

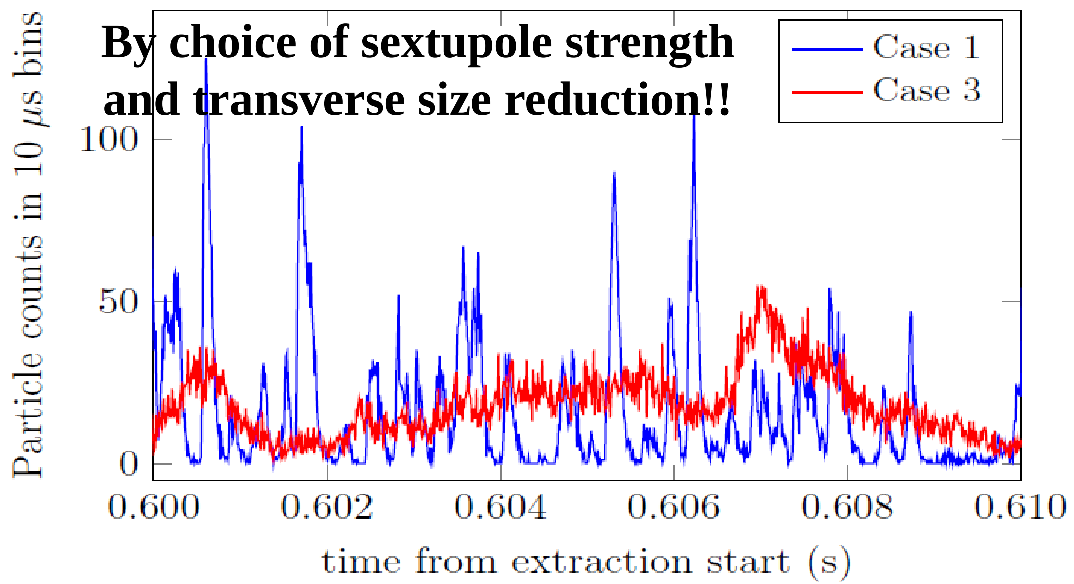
Experimental results (C^{6+}, 300 MeV/u)



10 mm







Case 1: S = 0.06 m^{-2}, ~10 mm (2σ)

Case 2: S = 0.03 m^{-2}, ~10 mm (2σ)

Case 3: S = 0.03 m^{-2}, ~2 mm (2σ)