Micro-spill structure studies at GSI

2nd IFAST REX collaboration meeting

Feb 17th, 2022

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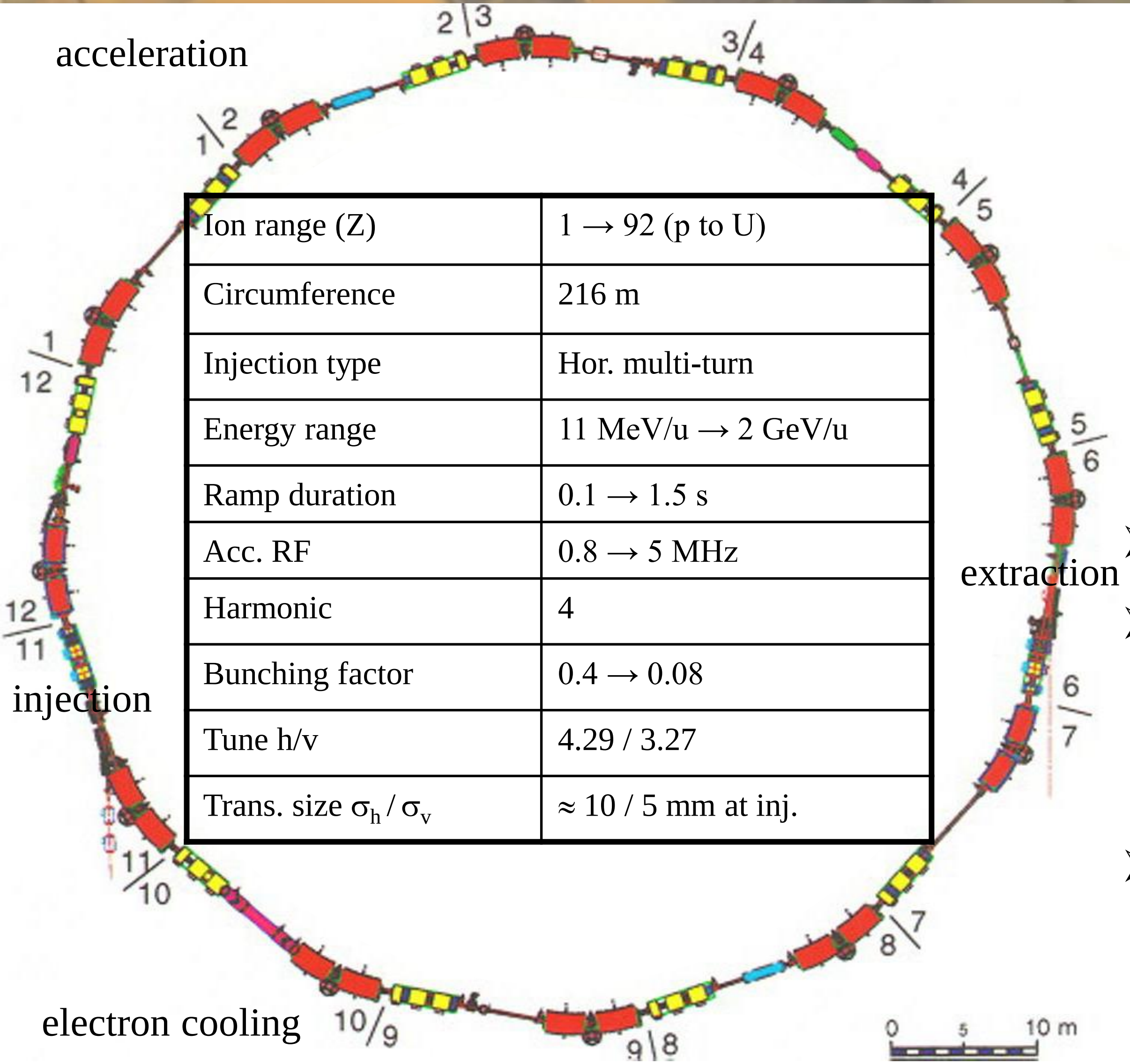
- Beam instrumentation for micro-spill investigations
- Inherent spill smoothing via transit time and enhancement mechanisms
- External tune modulation for spill smoothing

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

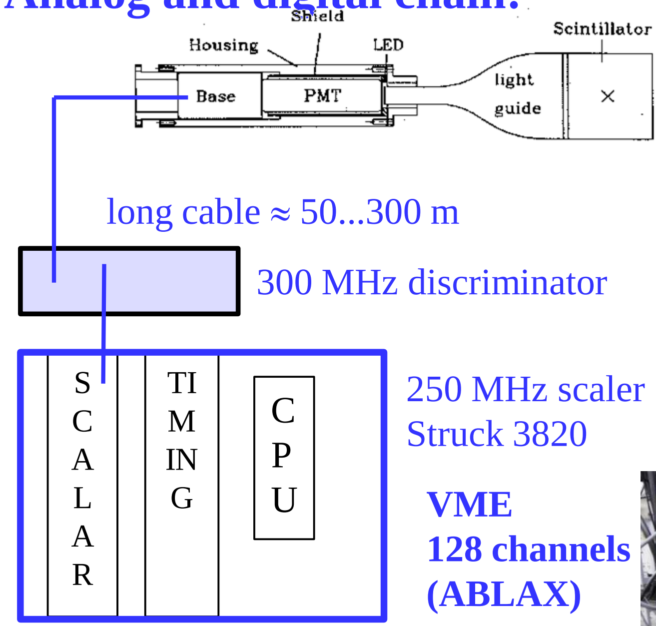


Ion range (Z)	1 → 92 (p to U)
Circumference	216 m
Injection type	Hor. multi-turn
Energy range	11 MeV/u → 2 GeV/u
Ramp duration	0.1 → 1.5 s
Acc. RF	0.8 → 5 MHz
Harmonic	4
Bunching factor	0.4 → 0.08
Tune h/v	4.29 / 3.27
Trans. size σ_h / σ_v	≈ 10 / 5 mm at inj.

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

Standard scintillator data acquisition (Counting in defined intervals)

Analog and digital chain:

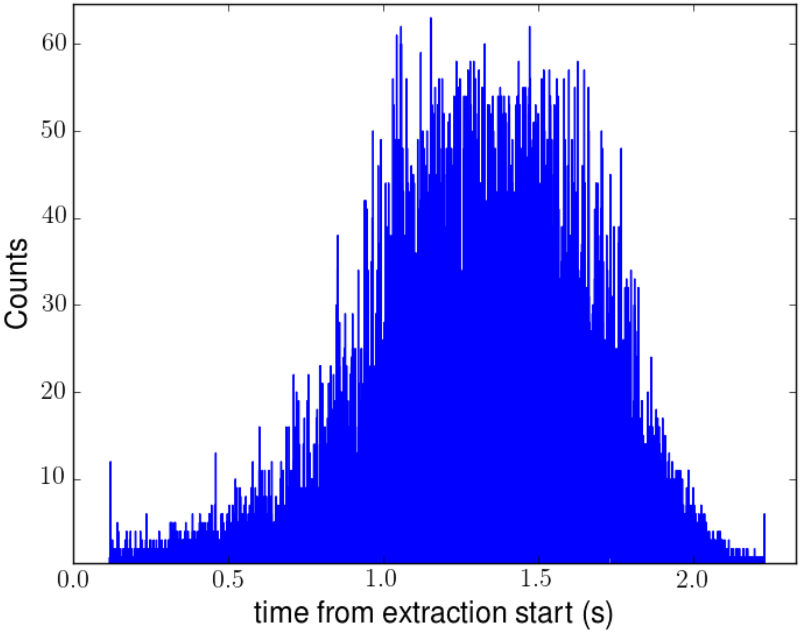


long cable ≈ 50...300 m

300 MHz discriminator

250 MHz scaler
Struck 3820

VME
128 channels
(ABLAX)



T_m : Readout / Meas. resolution= $10\ \mu s$

T_{spill} : Time of extraction = $\sim 2\ s$

Advantage of particle counting:

- every particle detected/counted, **no** noise or background → **could be directly compared to particle simulation**
- **Parallel digitalization of various detectors:** Scintillators, Ionization Chambers, SEM-detectors, diamond detector
- Low amount of data and correlation between various detectors

Spill characterization by counting in defined intervals

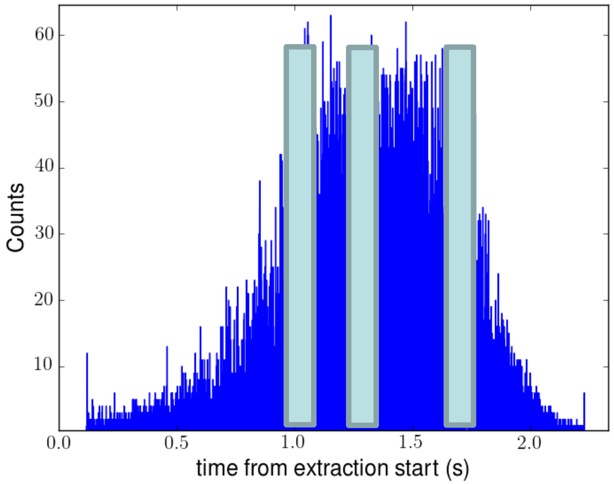
T_m : Readout / Meas. resolution$= 10\ \mu s$

T_{spill} : Time of extraction $= \sim 2\ \ s$

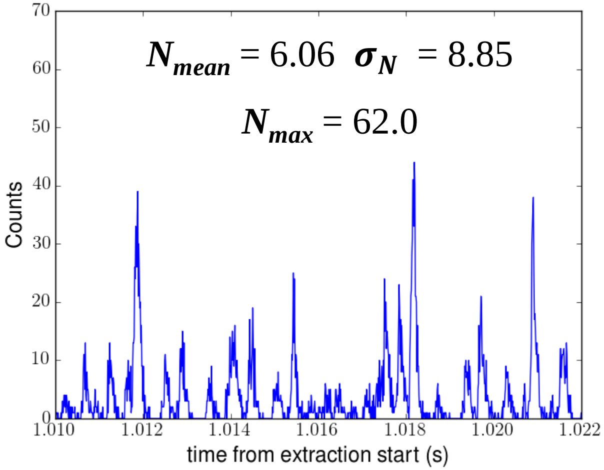
T_{bin} : Characterization resolution $= 10\ ms$

Statistical moments in $T_{bin} = 1000\ T_m$

$N_{mean}, = \langle N \rangle$, Std. dev σ_N, N_{max}

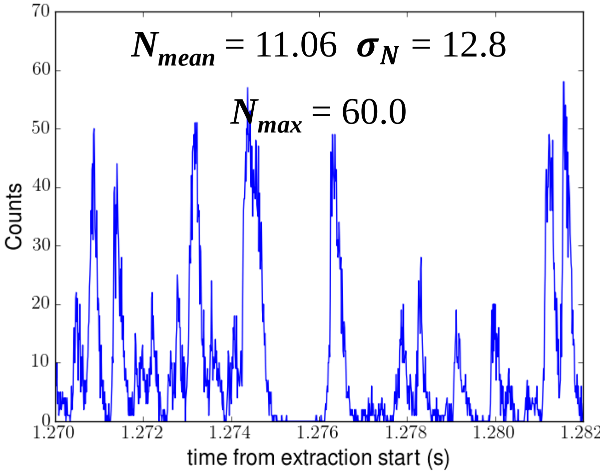


T_1 T_2 T_3


$N_{mean} = 6.06$ σ_N $= 8.85$

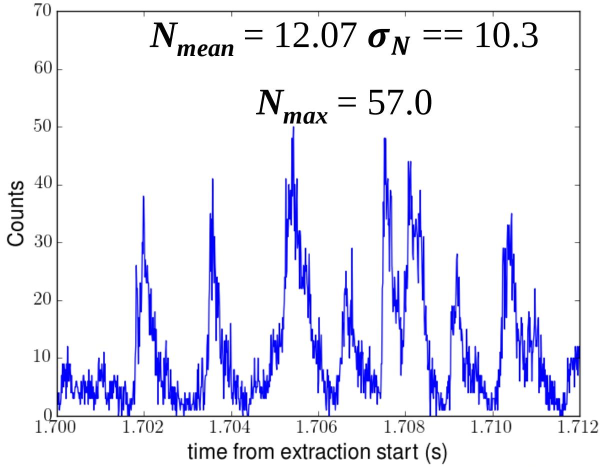
$N_{max} = 62.0$

T_1


$N_{mean} = 11.06$ $\sigma_N = 12.8$

$N_{max} = 60.0$

T_2

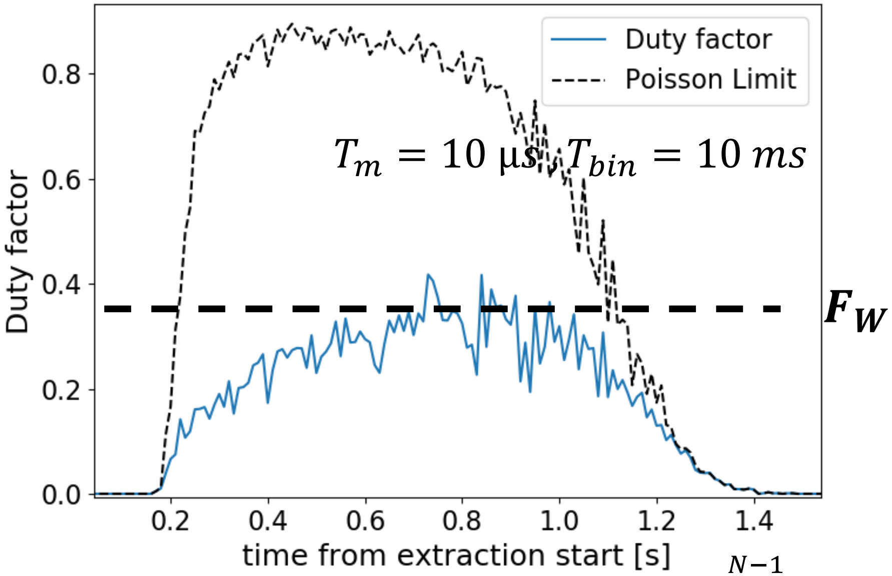

$N_{mean} = 12.07$ $\sigma_N == 10.3$

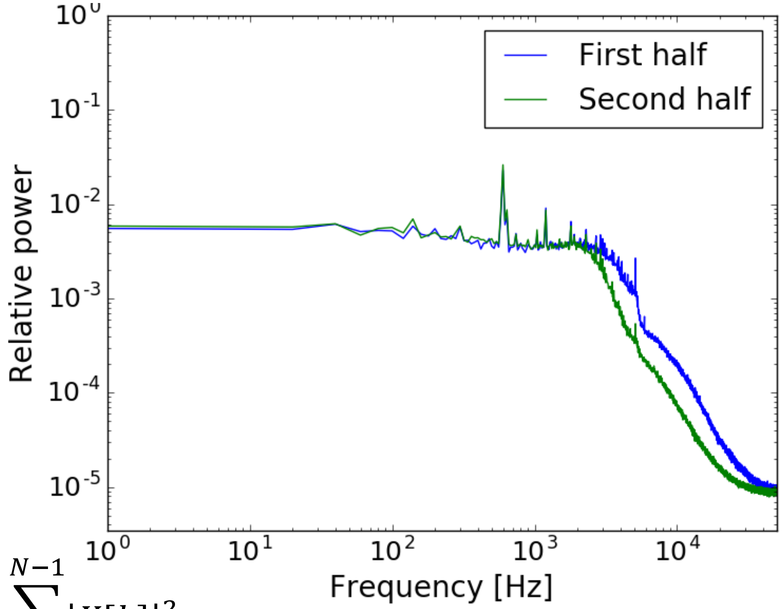
$N_{max} = 57.0$

T_3

Spill characterization by counting in defined intervals

Beam: 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

$$\longleftrightarrow$$

- 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, $\boldsymbol{F_W = \frac{\sum_{k=1}^{n} F_k\langle N\rangle_k}{\sum_{k=1}^{n}\langle N\rangle_k}}$

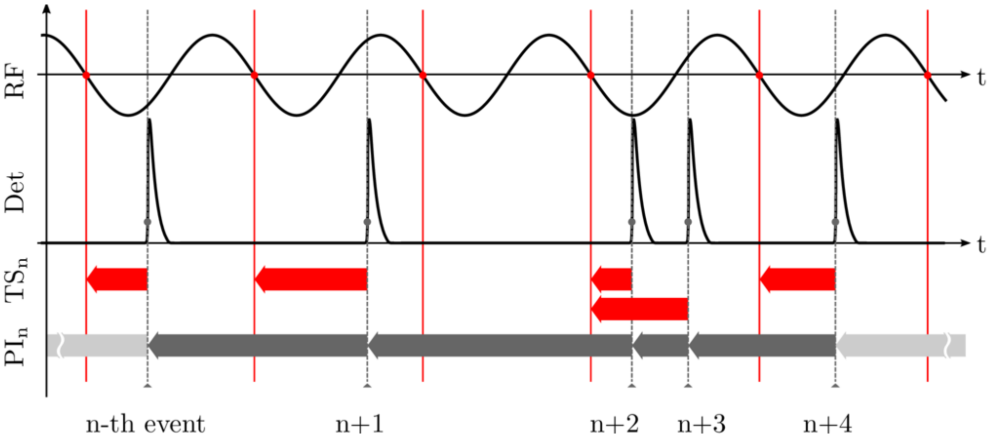
Frequency Domain

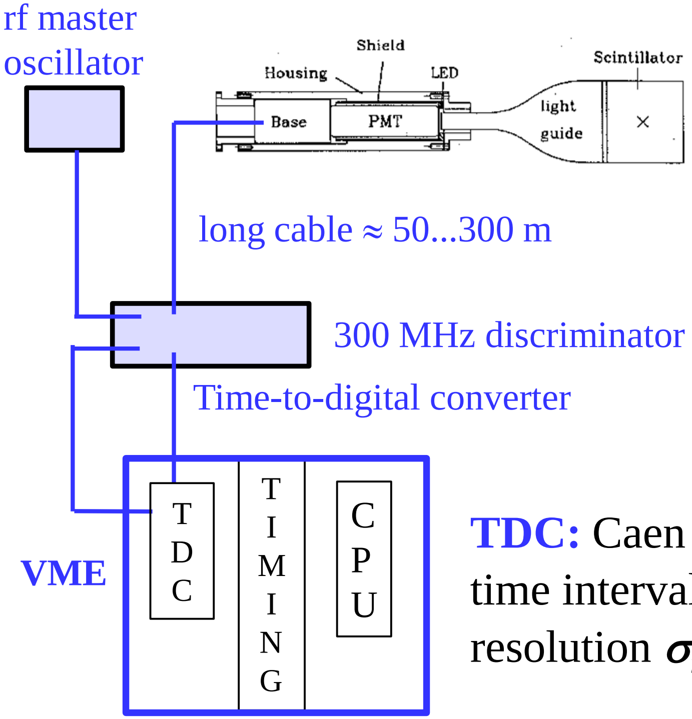
- $\boldsymbol{F_W}$ is equivalent to “DC power” over Total power
- 10- 30% of power in main’s harmonics f = n·50 Hz (peaks at 600 Hz)
- Broadband = noisy beam response up to a “shoulder” at ≈ 3 kHz

Characterization by time of arrival measurements

Measurement technique:

- Particle arrival is measured with respect to the phase of the acc. frequency f_{acc}
- Particle arrival with respect to each other
- **Closer to user detectors → Bunched beam analysis**





rf master oscillator

long cable ≈ 50...300 m

300 MHz discriminator

Time-to-digital converter

VME

TDC

TIMING

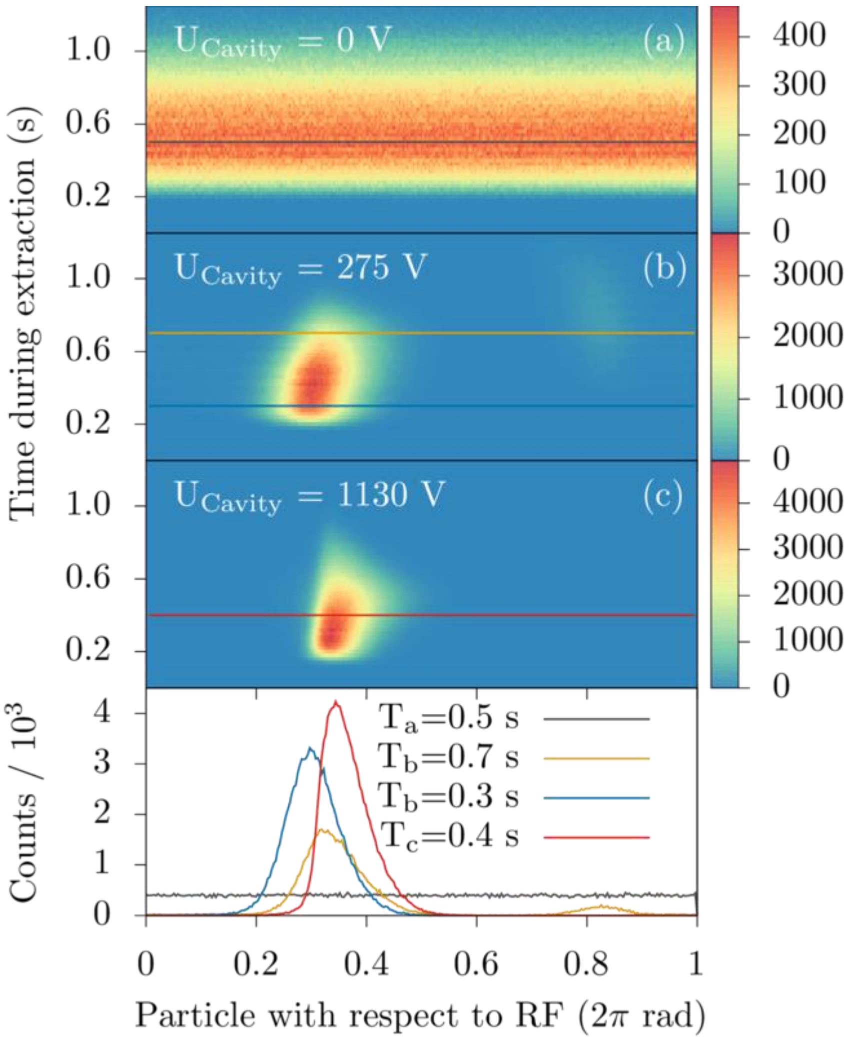
CPU

TDC: Caen V1290N time interval counter

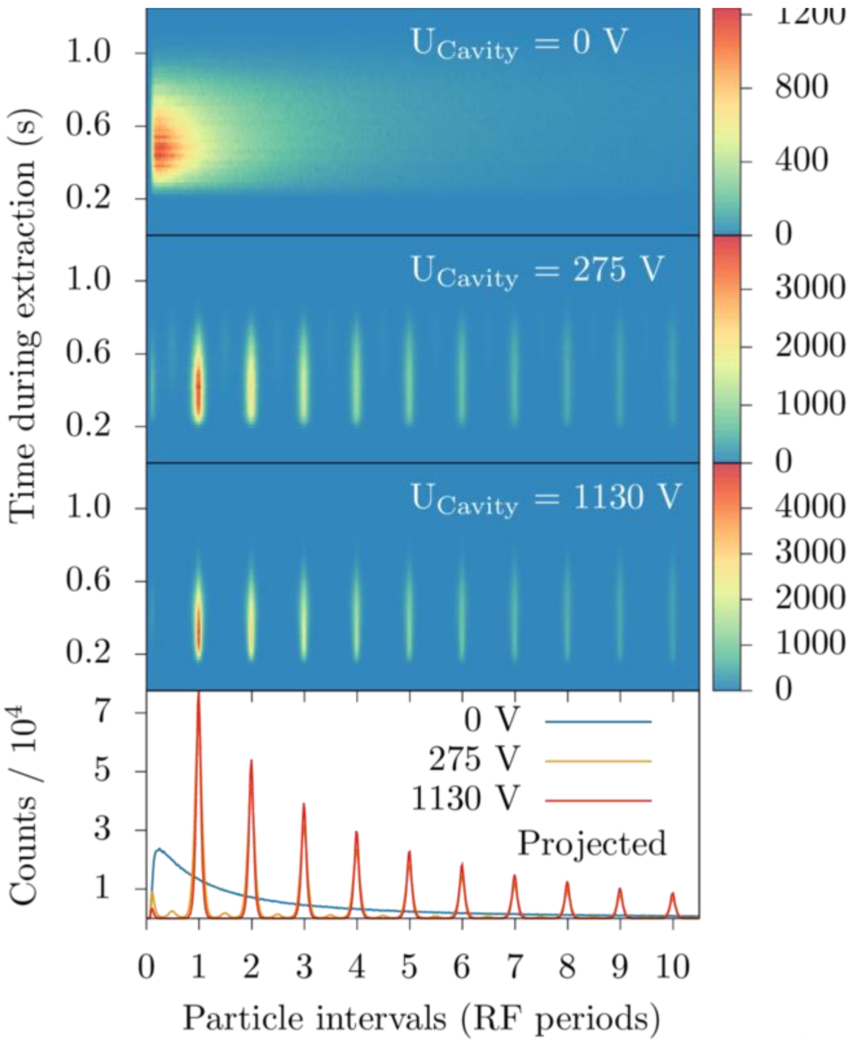
resolution σ_{rms} ~ 50 ps, double hit discrimination 5 ns, Max. count rate ~ 3e6

Particle arrival intervals

Histogram of arrival time w.r.t RF



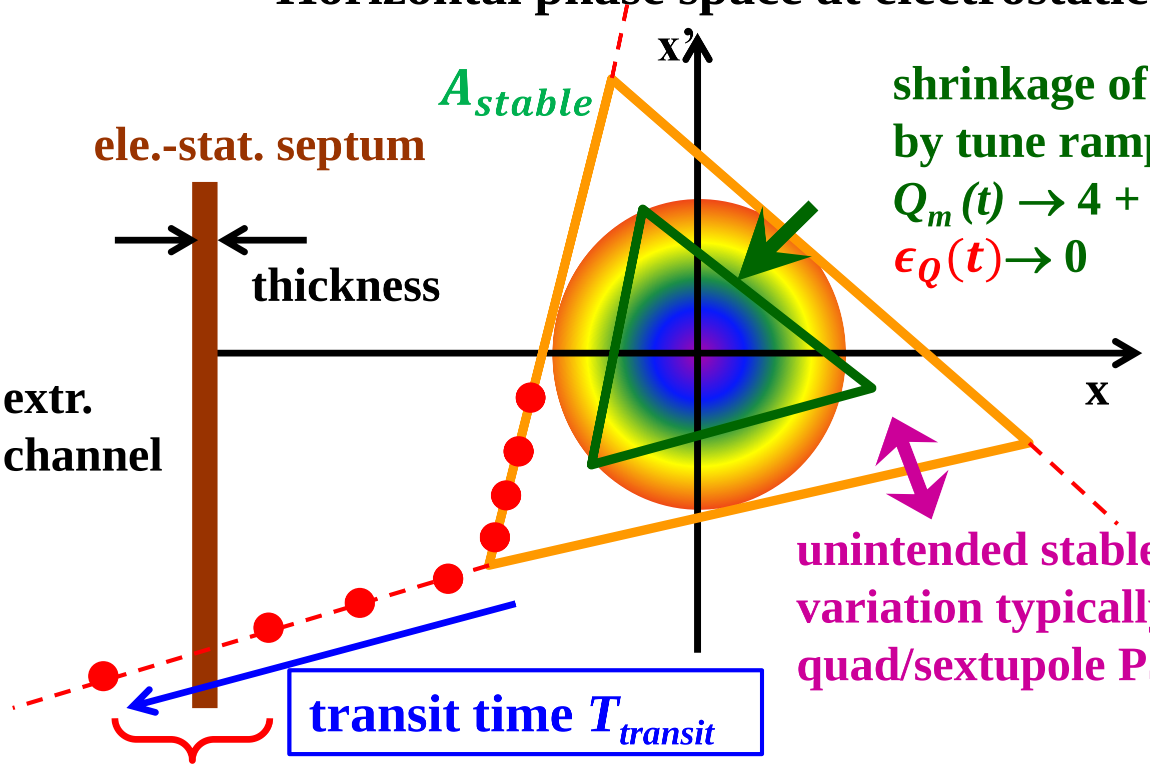
Histogram of time between successive particles



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

Slow extraction by tune ramp (Quad driven)

Horizontal phase space at electrostatic septum



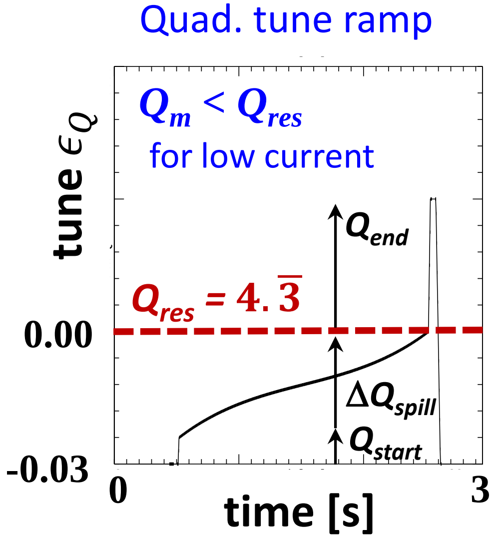
shrinkage of A_{stable} by tune ramp

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

$\epsilon_Q(t) \rightarrow 0$

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

last spiral step x_{step} after 3 turns



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

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

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

Ions' tune spread by chromaticity

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

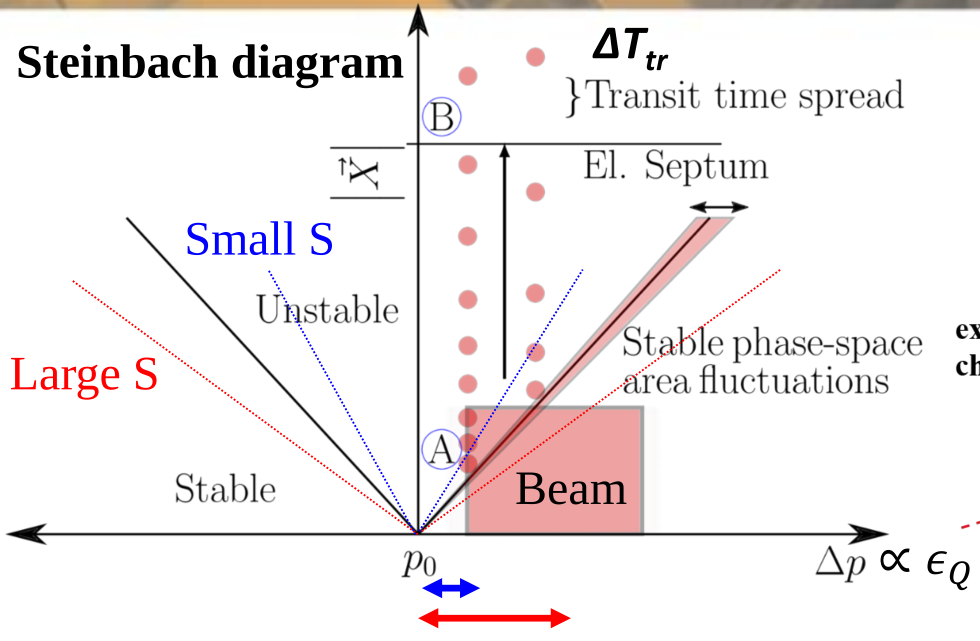
Quad

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

Sextupole

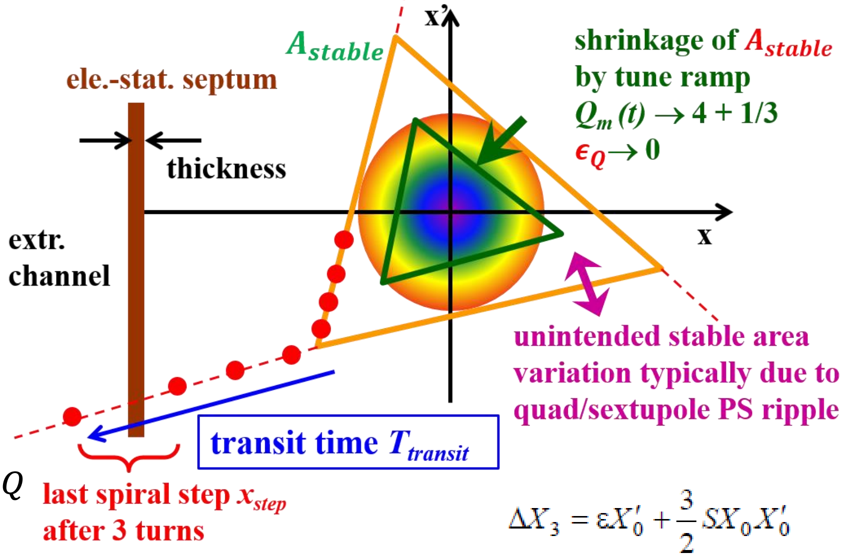
Extraction settings and transit time distribution (Quad driven)

Steinbach diagram



Smaller $S \propto$ Small $\overline{\epsilon_Q}$

Phase space



$$\Delta X_3 = \varepsilon X_0' + \frac{3}{2} S X_0 X_0'$$

$$\Delta X_3' = -\varepsilon X_0 + \frac{3}{4} S\left(X_0^{\,2} - X_0'^{\,2}\right)$$

- For smaller sextupole strength: Tune ramp should start close to resonance for same spill length
- Amplitude dependence on the sextupole fields : For small S and $\overline{\epsilon_Q}$ at any given A→ larger Transit time and smaller spiral step compared to large S. Analytical dependence in Eq. 4.17 in PIMMS.
- 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

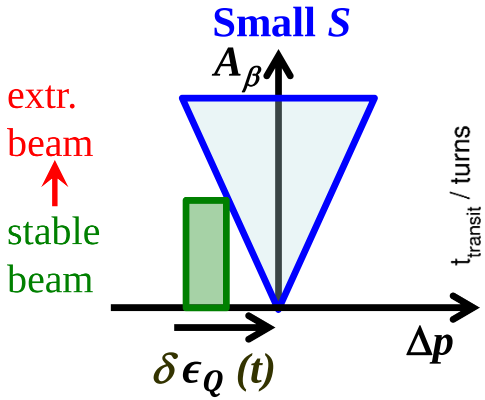
Extraction settings and transit time distribution (Quad driven)

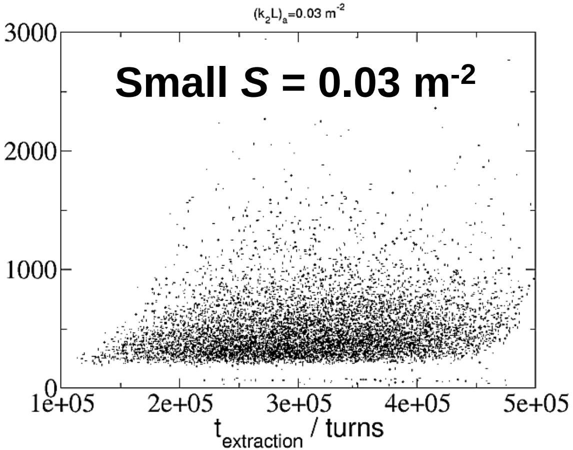
Transit time distribution: Dependence on sextupole strength S & distance to resonance $\epsilon_Q(t)$

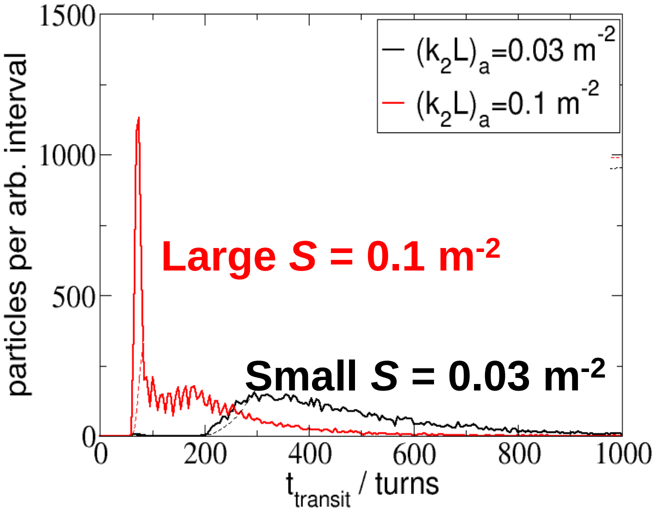
i.e. $T_{transit} = T_{transit}\ (S \text{ or } \epsilon_Q(t))$

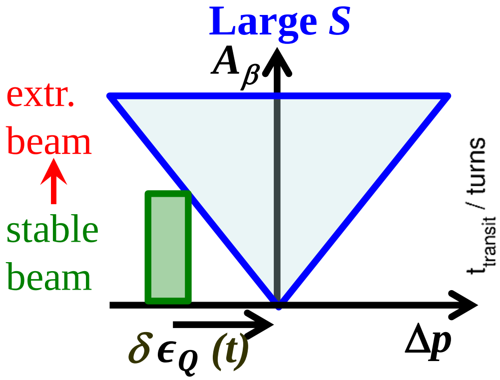
1 turn ~ 1 μs in SIS-18

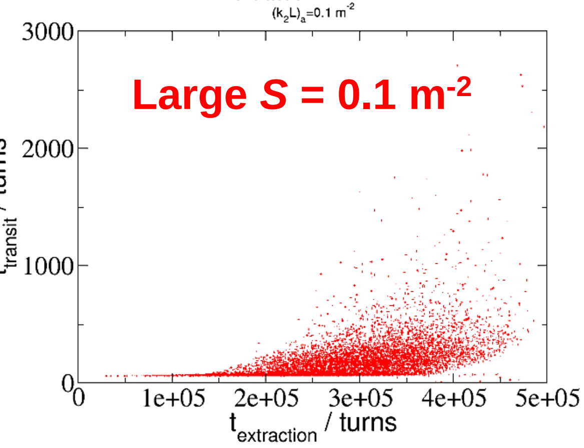
Histogram of transit time $T_{transit}$







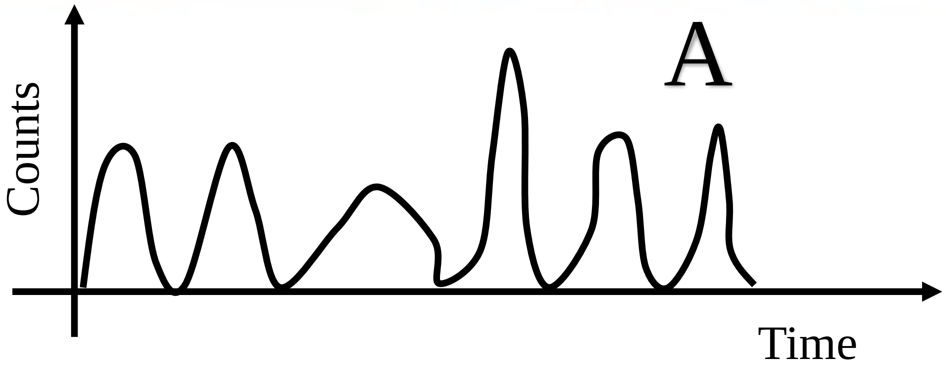


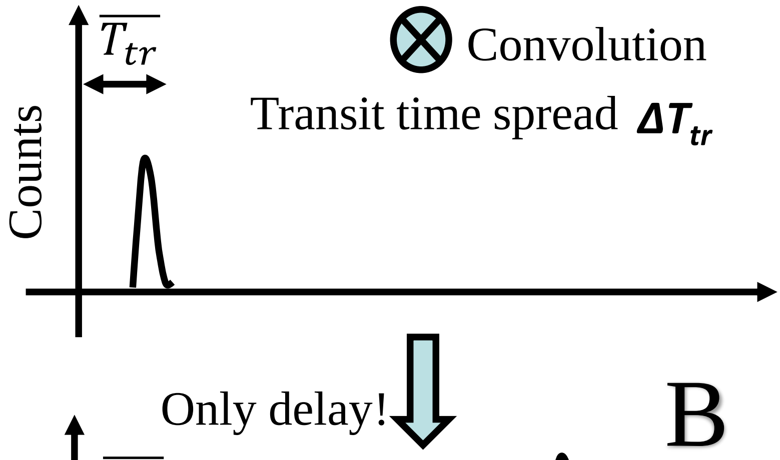


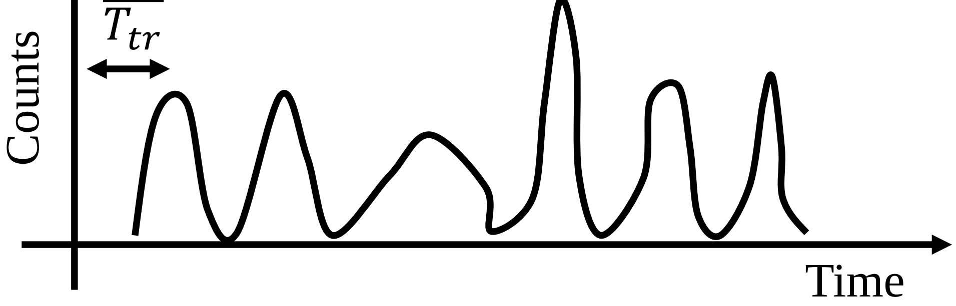
Result:

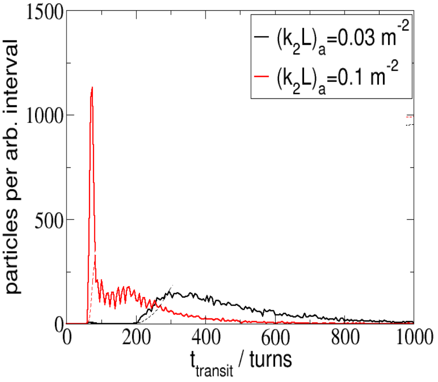
- $T_{transit}$ dist. varies during extraction
- Lower S ⇒ larger mean $T_{transit}$ $(\overline{T_{tr}})$
- Lower S ⇒ larger spread of $T_{transit}(\Delta T_{tr})$

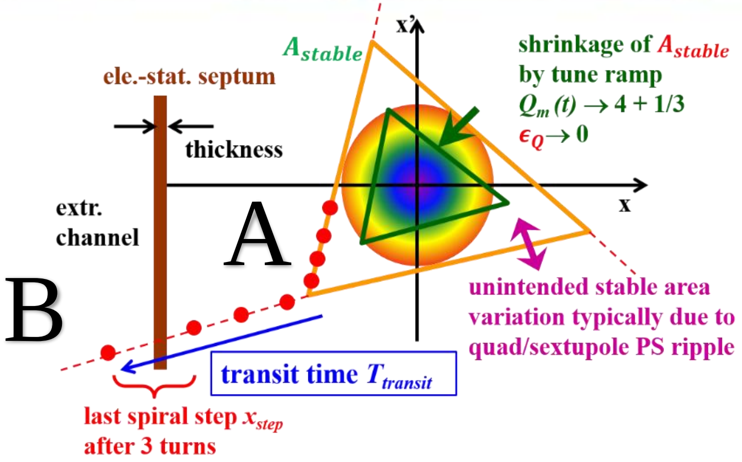
Larger sextupole strength: Effect of transit time on spill

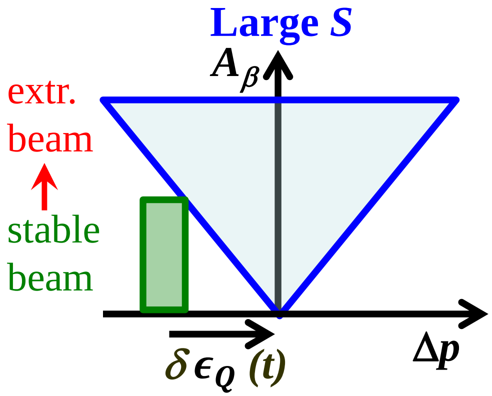




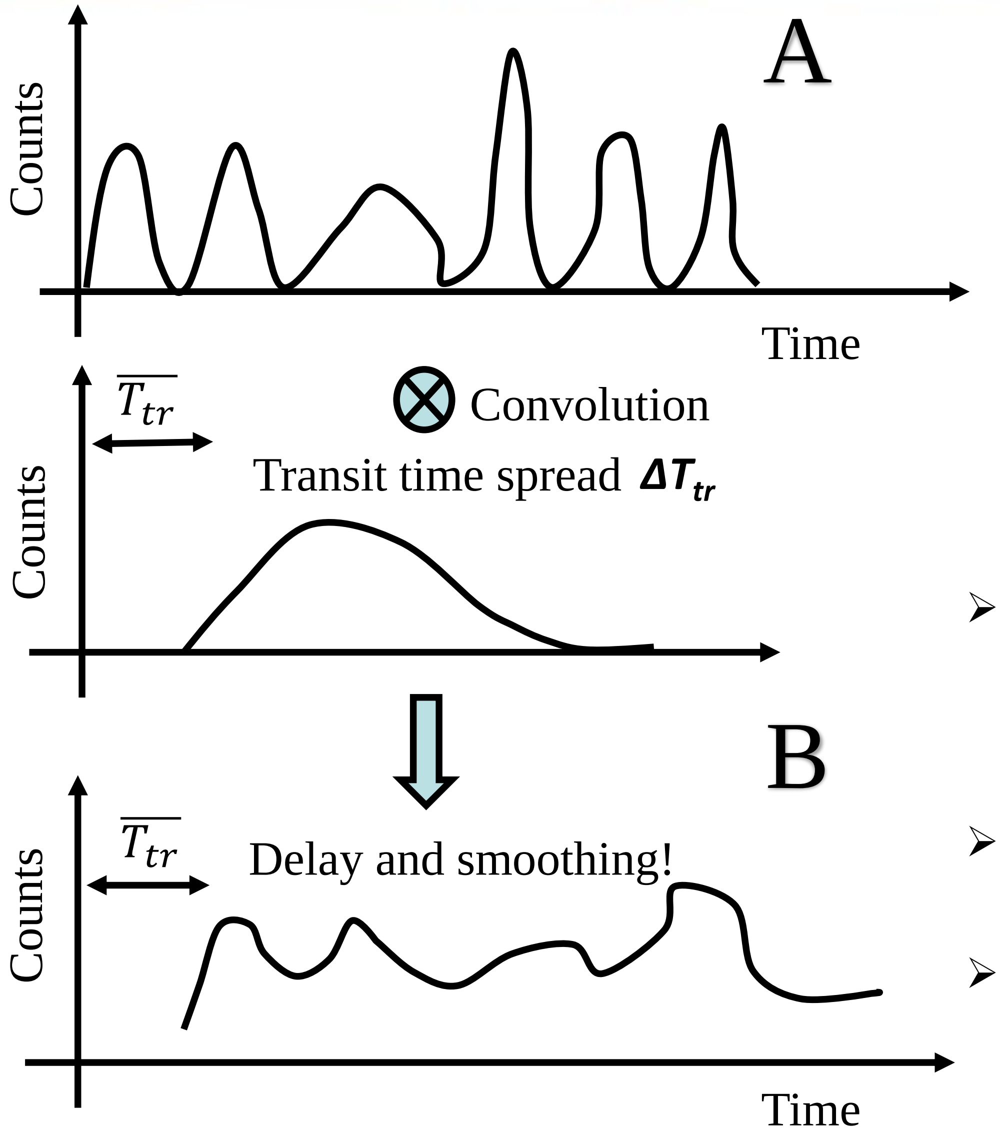


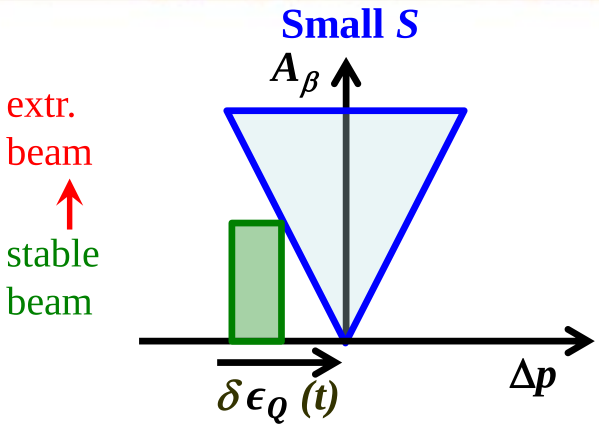






Smaller sextupole strength: Effect of transit time on spill

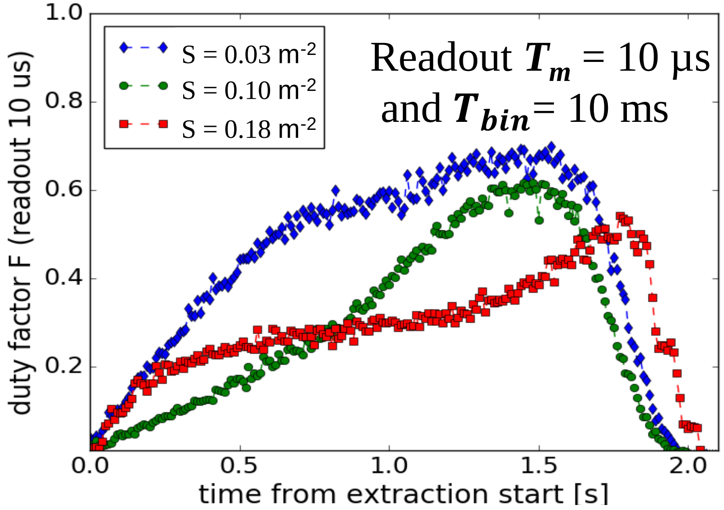




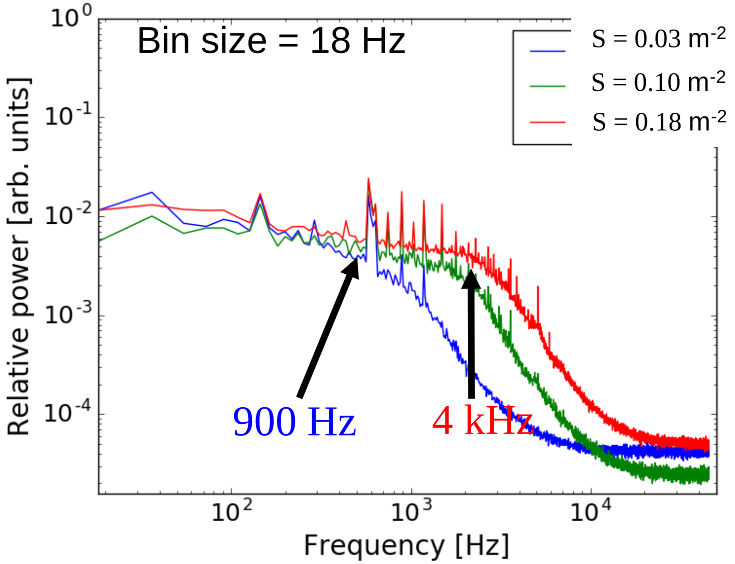
- Sextupole strength (S), distance to resonance $(\overline{\epsilon_Q})$ and Emittance (A) are **NOT independent** parameters because of spill length and shape constraint
- Low pass filtering of stable phase area fluctuations, $f_{cut} \propto 1/\Delta T_{tr} \propto \overline{\epsilon_Q}$
- The transit time induced delay in spill meas. is a problem for microspill feedback control

Experiments: Sextupole strength variation

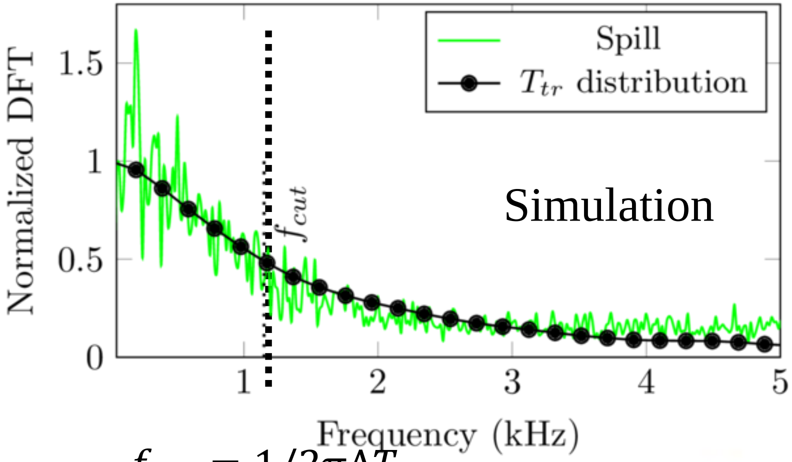
Experiment: Ar^{18+}, 300 MeV/u



Experiment: Fourier transformation



- ➢ Sextupole strength reduction affects duty factor F_W 0.3 → 0.58
- ➢ Duty factor F is time dependent (changing $\overline{\epsilon_Q}$)
- ➢ For lower S, lower cutoff filtering $f_{cut} \propto 1/\Delta T_{tr}$
- ➢ **Lower limit to sextupole strength reduction → spiral step x_{step} becomes too small, leads to beam losses**



$f_{cut} = 1/2\pi\Delta T_{tr}$

Minimize horizontal beam size at extraction

Case 1

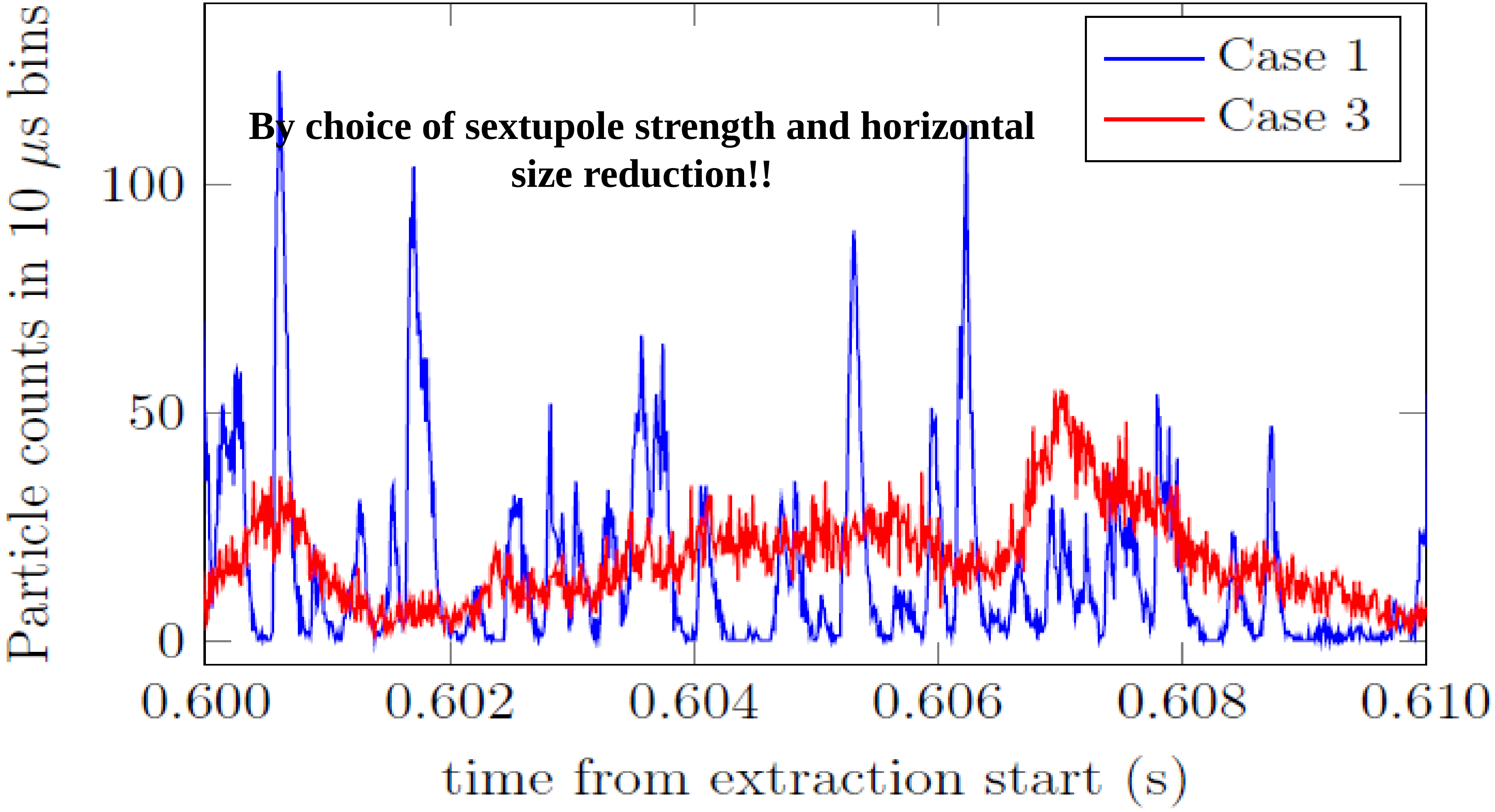
Large *S*

Case 2

Small *S*

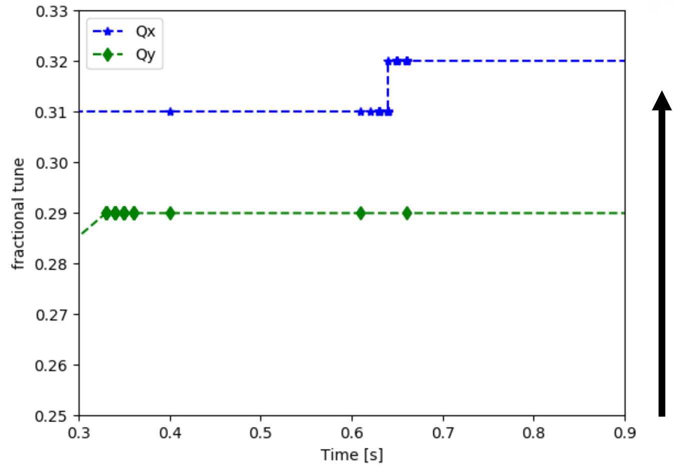
Case 3

Small *S* and Horizontal emittance

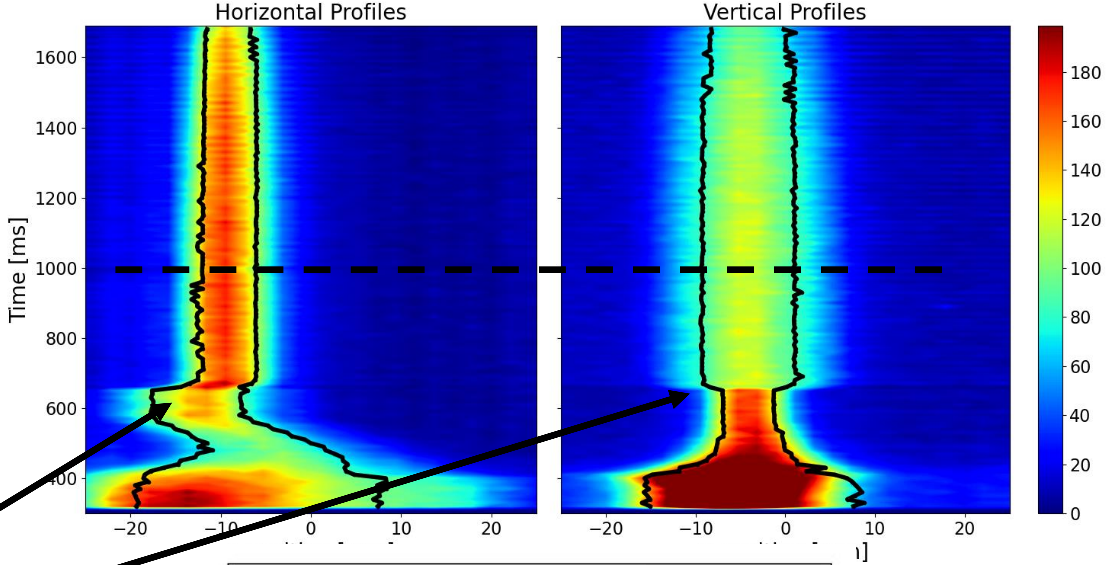


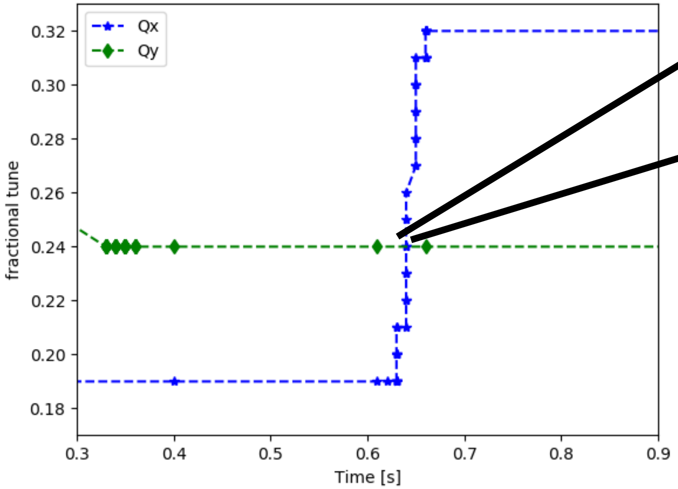
By choice of sextupole strength and horizontal size reduction!!

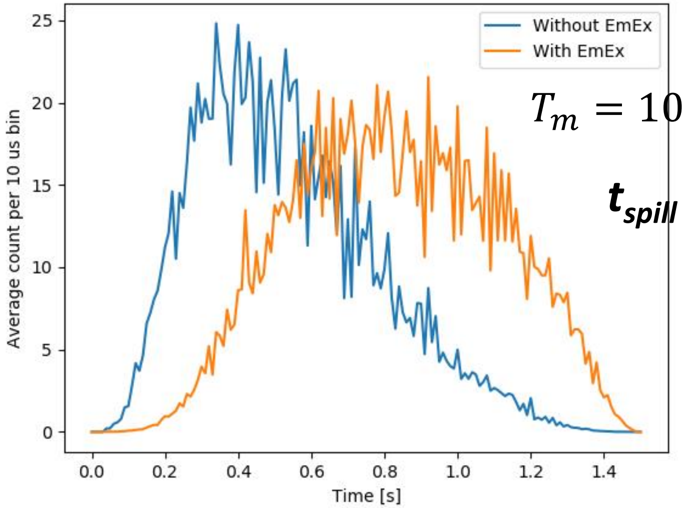
Emittance exchange (EmEx) for spill smoothing



Ionization Profile Monitor





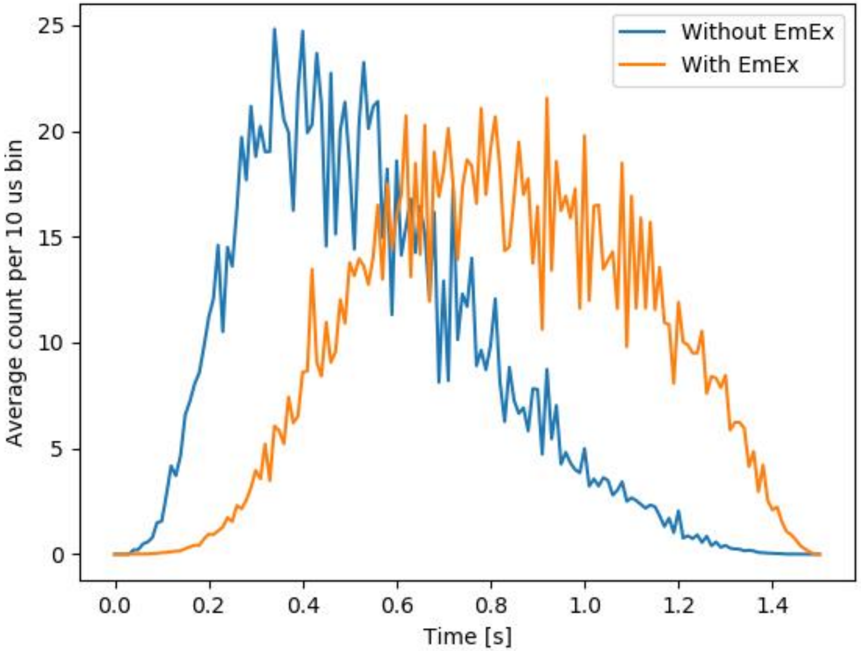


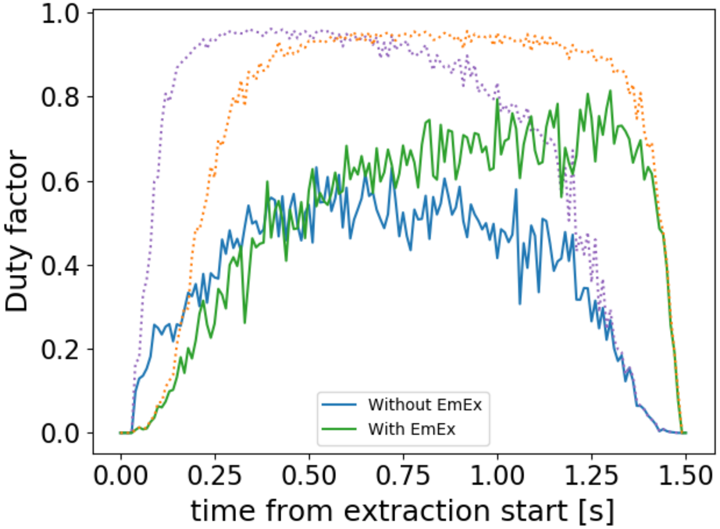
$T_m = 10\ \mu s\ , T_{bin} = 10\ ms$

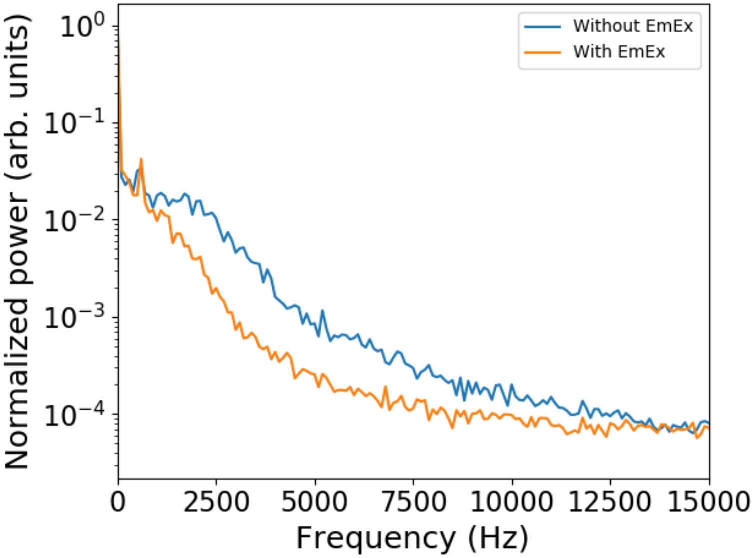
$\boldsymbol{t_{spill}} = 1.2\ \mathrm{s}$

Beam : 300 MeV/u Ar^{18+}

Emittance exchange (EmEx) for spill smoothing

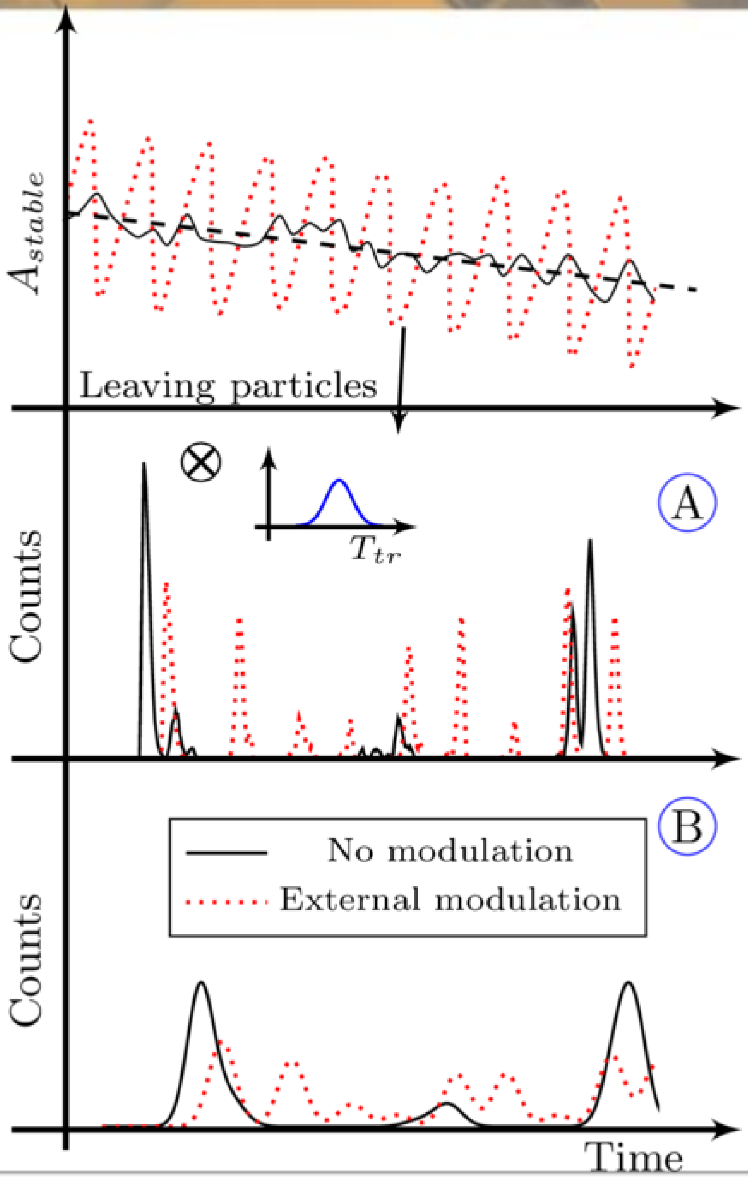


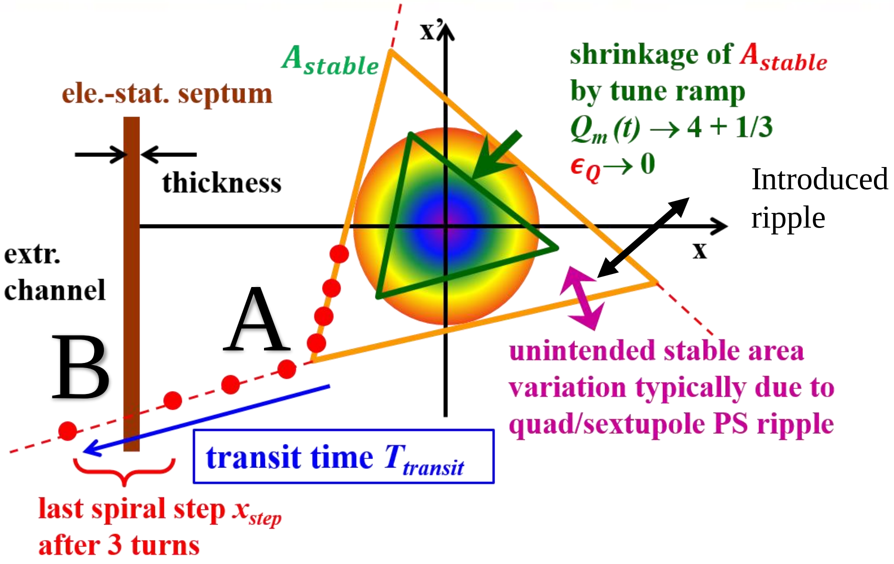




- Did not touch the extraction settings
- Extraction starts a bit later due to smaller horizontal beam size
- Spill quality is **better with EmEx**: Weighted DF increases from 0.49 to 0.64
- The support of SIS-18 colleagues acknowledged!

Transit time dependent external tune modulation



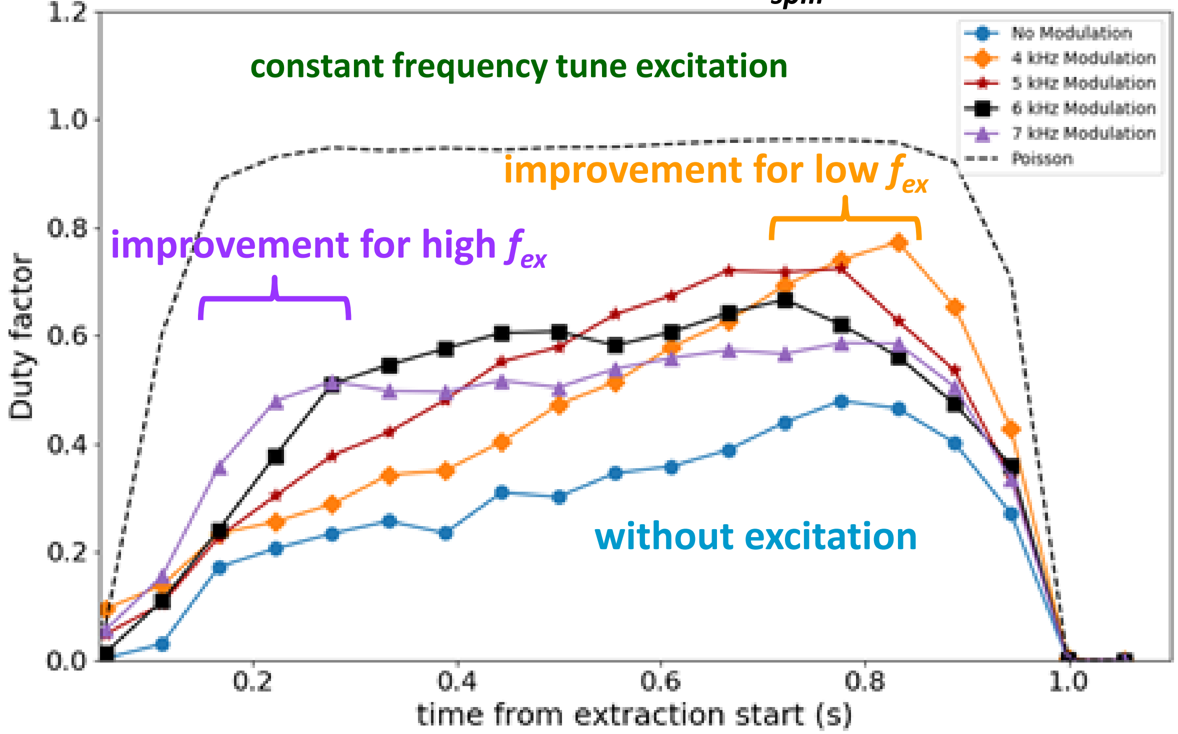


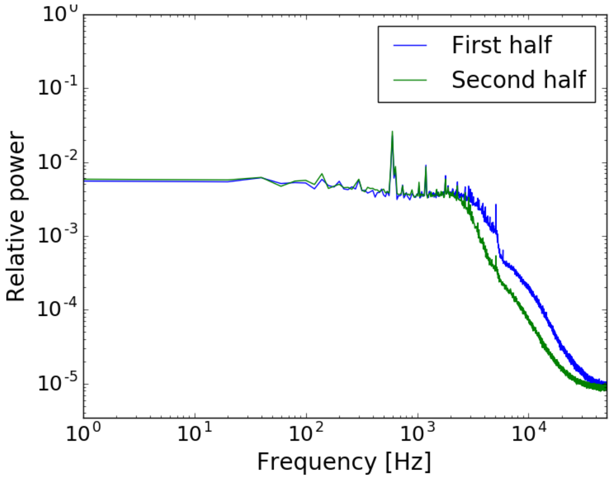
- Modulate tune with a higher frequency 3-5 times the cut-off frequency and amplitude 5-15 times the inherent ripple (1-3% of extraction tune ramp)
- This high frequency A_{stable} modulation does not allow lower frequency inherent fluctuations to “feed” on particles
- Modulation frequency high enough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

R. Singh et al.: ‘*Reducing Fluctuations in Slow-Extraction Beam Spill Using Transit-Time-Dependent Tune Modulation*’, Phys. Rev. Applied 13, 044076 (2020)

Transit time dependent external tune modulation

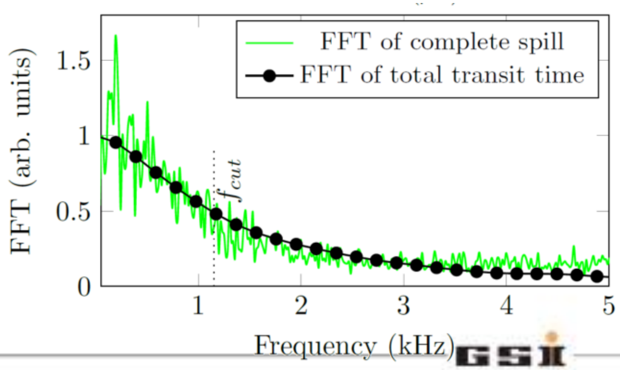
Beam: Ar^{18+}, 300 MeV/u, t_{spill} = 1 s



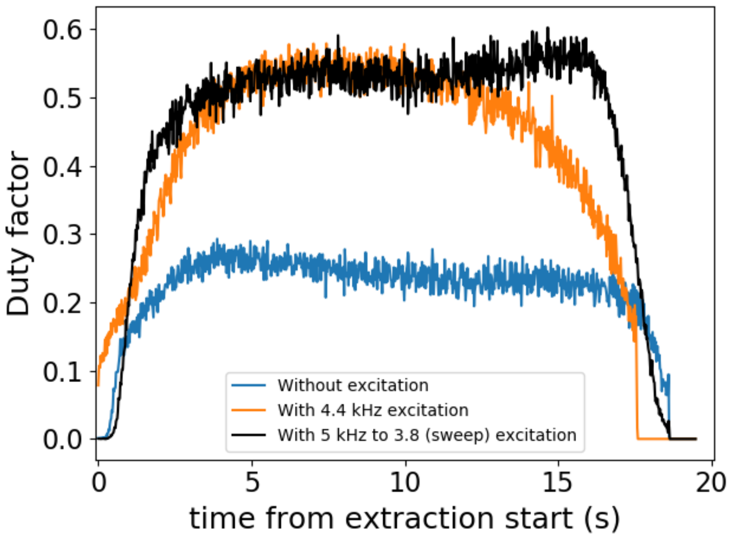


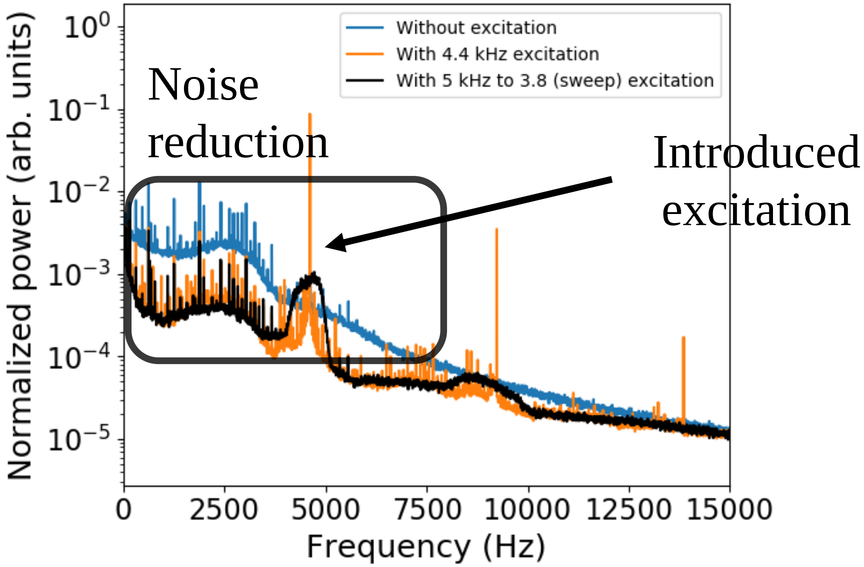
Choice of excitation frequency f_{ex}:

- Lower limit → low pass filtering $\Rightarrow f_{ex} > f_{cut} = \frac{1}{2\pi\Delta T_{tr}}$
- Upper limit → no re-capture of released ions $\Rightarrow f_{ex} < \frac{10}{\overline{T}_{tr}}$
- Optimal frequency $f_{ex} \approx 3\, f_{cut}$ since typically $\frac{\Delta T_{tr}}{\overline{T}_{tr}} \approx 0.3$



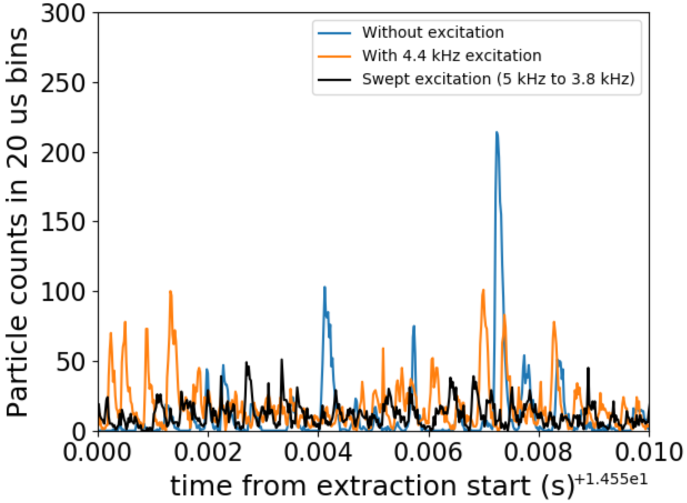
Tune modulation with user/production beam





Noise reduction

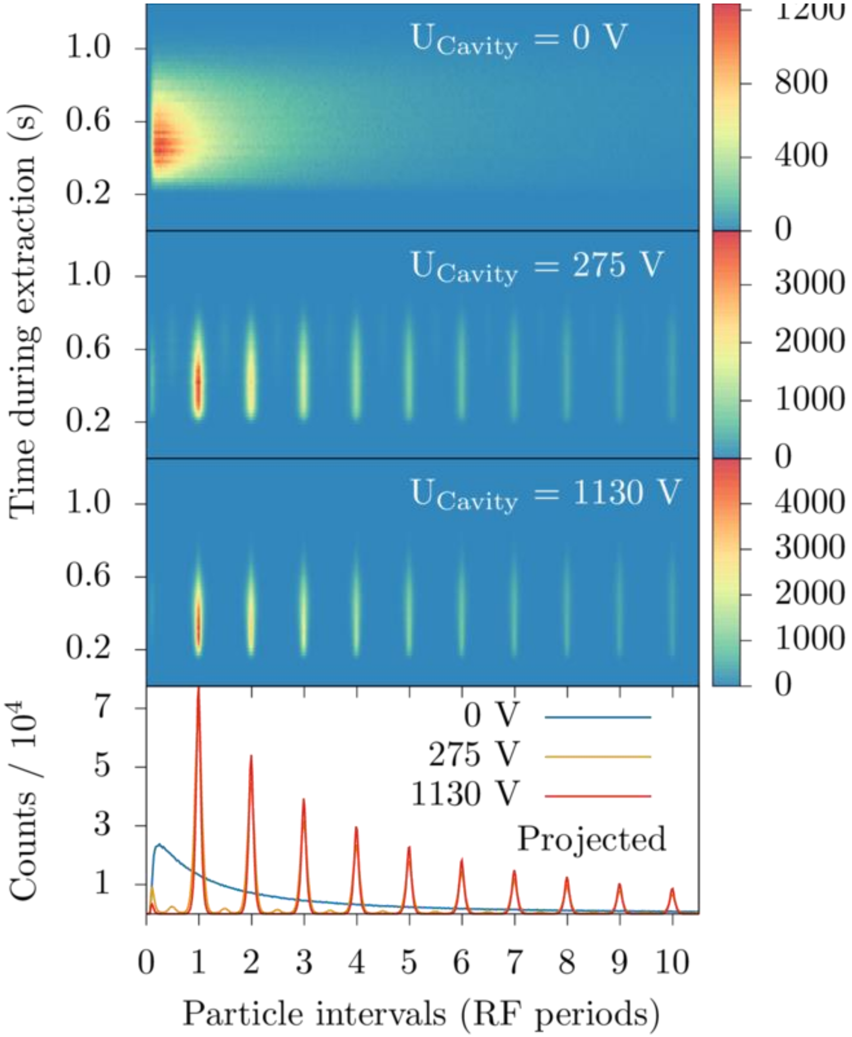
Introduced excitation



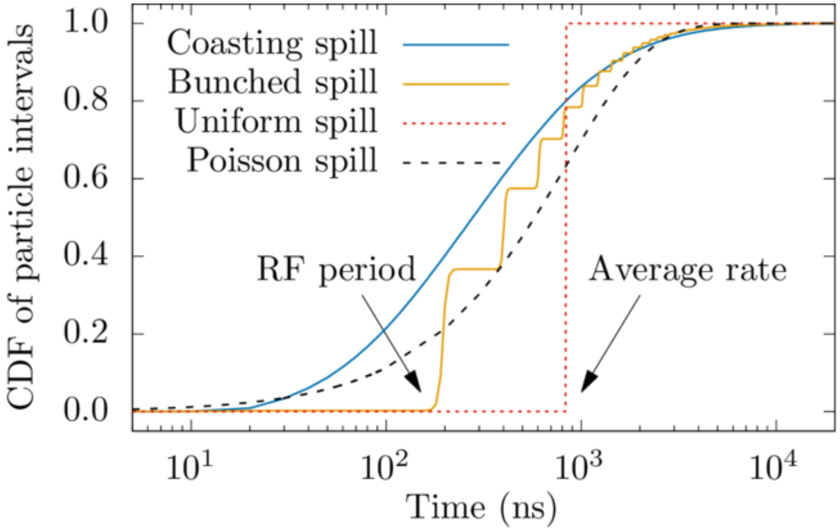
- **Beam :** 1.58 GeV/u Ag^{45+} (HADES experiment)
- The transit time spread evolves (increases from low to high) based on tune ramp, **apply a frequency sweep correlated to transit time spread**
- Amplitude not yet optimized (150 mA applied i.e. 15 times of inherent ripple amplitude at 600 Hz)

Bunched beam extraction

Histogram of time between successive particle arrival



Cumulative distribution of the spills



- **Beam :** Bi^{68+} at 300 MeV/u, quad. scan, bunched beam (detector : Scintillator)
- For some experiments, bunched beam spill can be advantageous over a "Poisson" spill if the RF frequency is matched with the average extraction rate.

T. Milosic et al., sub-ns single particle spill characterization for slow extraction", doi:10.18429/JACoW-IBIC2021-WEPP28, IBIC 2021

Recent slow extraction activities at GSI

Overview of activities → Talk by D. Ondreka at recent slow extraction workshop.

→ A method to identify/verify the septum voltage and problems with sparking was discussed.

→ Challenges for SIS100 extraction presented.

https://conference-indico.kek.jp/event/163/contributions/3142/

Installation of Very High Frequency (VHF) : Refurbished Einzel resonator for SIS-18, increase the effective fill time of SIS while using synchrotron motion for spill smoothing

Simulations by S. Sorge et al. show that it might help in comparison to unbunched beam,

→ creates macrostructures due to synchro-betatron resonances.

→ Generally, a regime or relation is found between transition and synchrotron tune where bunching helps

https://conference-indico.kek.jp/event/163/contributions/3154/

R. Steinhagen et al., Macrospill feedback was developed and tested using experimental detectors. Software aspects were also discussed.

https://conference-indico.kek.jp/event/163/contributions/3155/

Summary

- We are utilizing single particle counting plastic scintillators+PMTs . The data is analysed in counting mode (ABLAX) and particle interval mode (TDC)
- Inherent smoothing mechanisms of the spill have been investigated in detail and now regularly used in the machine operation
- Promising pilot study on utilizing transverse emittance exchange was recently performed
- External tune modulation in dependence to transit time distribution was realized and showed useful improvements for machine users
- Recent results from TDC show, bunched beam extraction is an attractive option for low extraction rate experiments at GSI
- Most investigations are with quad driven extraction and knock-out investigations pending

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