Horizontal beam response for the slow extraction at HIT’s synchrotron

I.FAST-REX Collaboration Meeting

Cristopher Cortés
Heidelberg Ion-Beam Therapy Centre

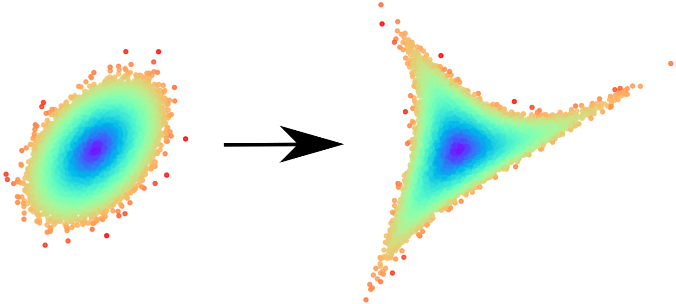
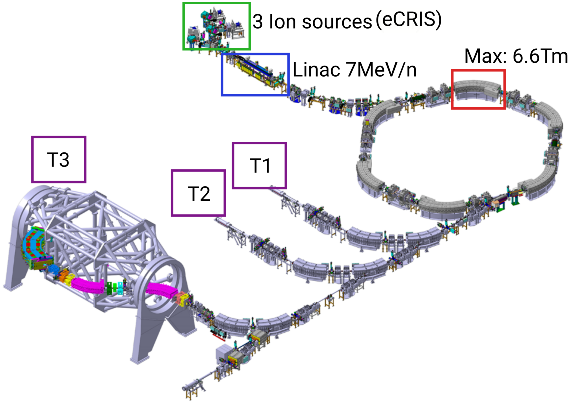


Table of Contents

Table of Contents

Heidelberg Ion-Beam Therapy-Center



Parameter	Value
Ion species	p^{+}, He^{2+}, C^{6+}, O^{8+}
Depth range	2 - 30 cm
Beam size	3.4 - 32.4 mm
Max. dose	2 Gy min^{-1} l^{-1}
Irradiation field	20×20 cm^2
Intensity	10^6-10^9 part./s

Table: Beam characteristics at the HIT facility.

Typical spill at HIT

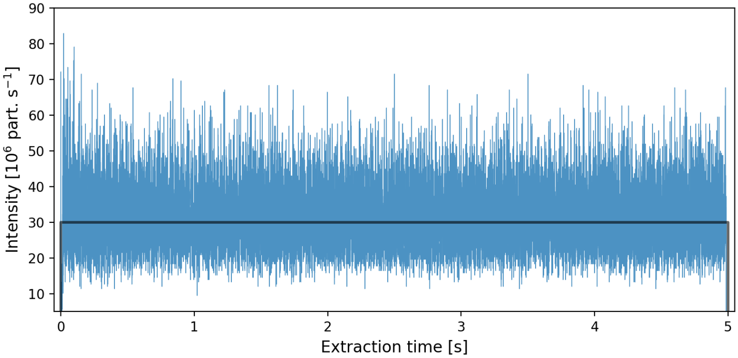


Figure: Typical spill at HIT.

C^{6+} Beam

E_{kin} = 251.24 MeV/u

Spill quality

$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

Typical spill at HIT

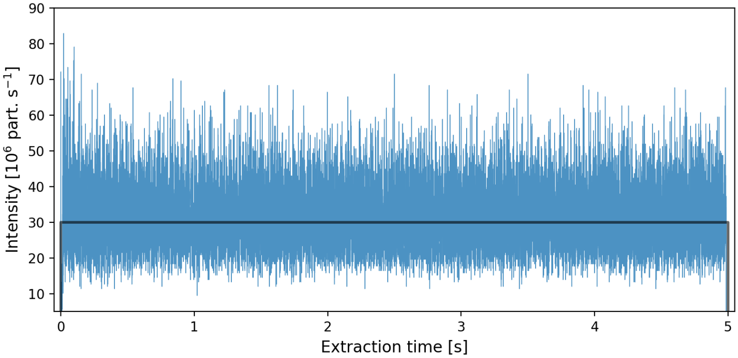


Figure: Typical spill at HIT.

Spill quality

$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

$$R = 94.5\%$$

Typical spill at HIT

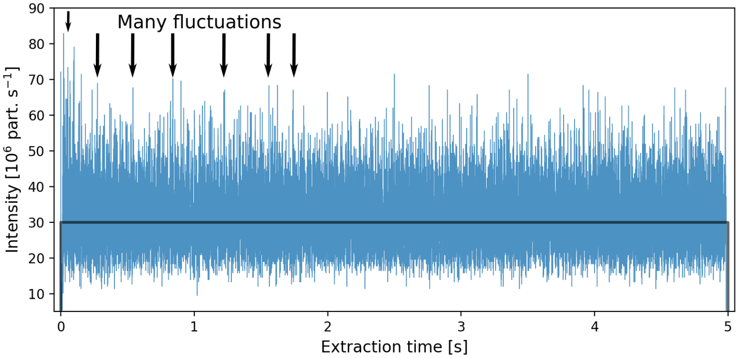


Figure: Typical spill at HIT.

Spill quality

$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

$$R = 94.5\%$$

Motivation

Questions

- Can we suppress the fluctuations?
- Can we improve the spill quality?

Motivation

- Faster dose delivery

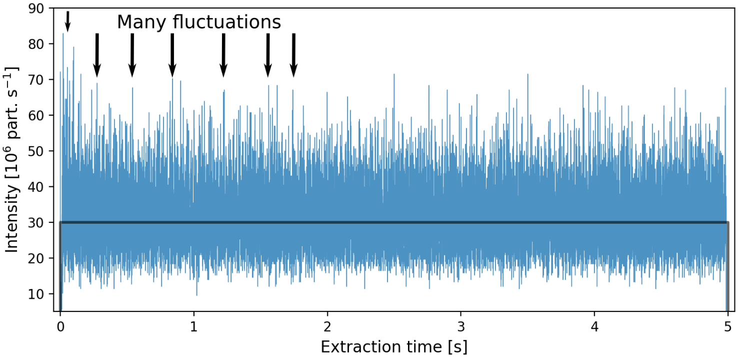
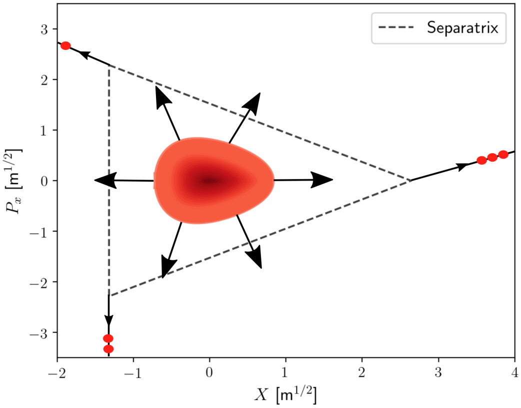


Figure: Typical spill at HIT.

Table of Contents

RF-KO slow extraction



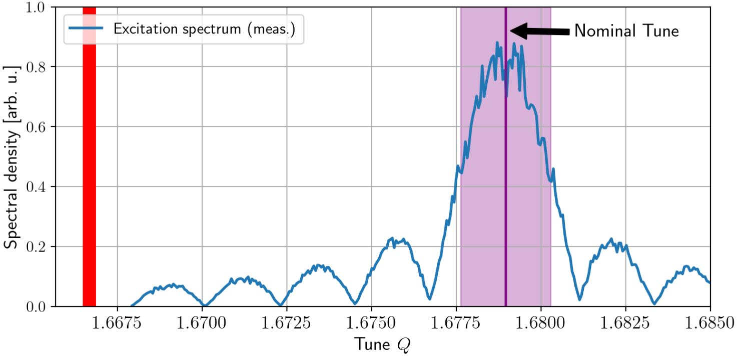
Betatron resonance

- Betatron frequency

$$f_\beta = (n \pm q) \cdot f_{\mathrm{rev}}$$

- Fixed linear ion-optics
- Fixed separatrix

Excitation spectrum at HIT



Betatron resonance

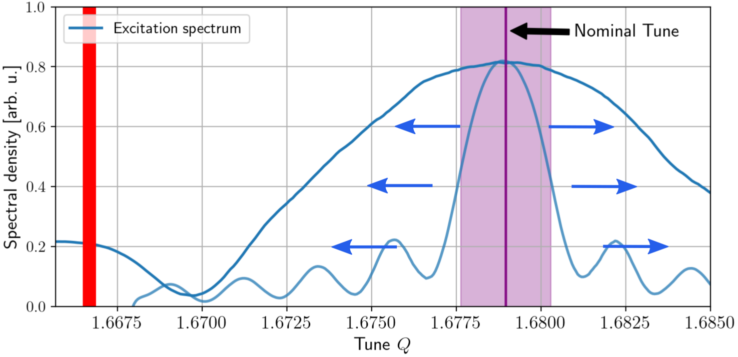
- Betatron frequency

$$f_\beta = (n \pm q) \cdot f_{rev}$$

- Chromatic tune spread

$$\frac{\Delta Q}{Q} = \xi \frac{\Delta p}{p}$$

Excitation spectrum at HIT



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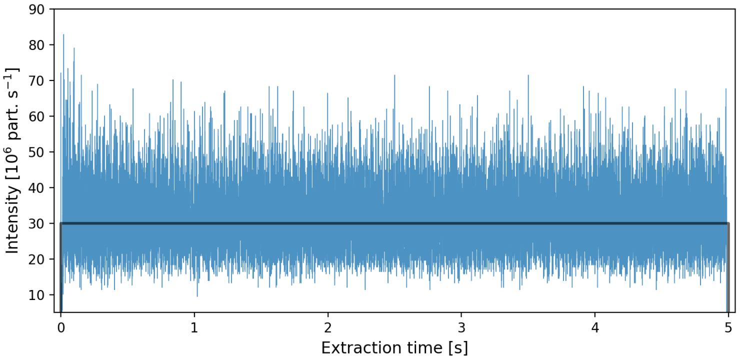
Typical spill at HIT



Spill quality

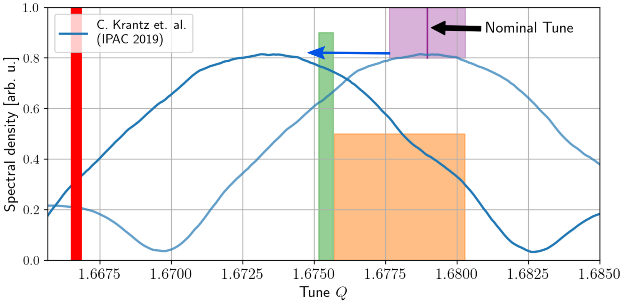
$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

$$R = 94.5\%$$

HIT's Approach

Questions

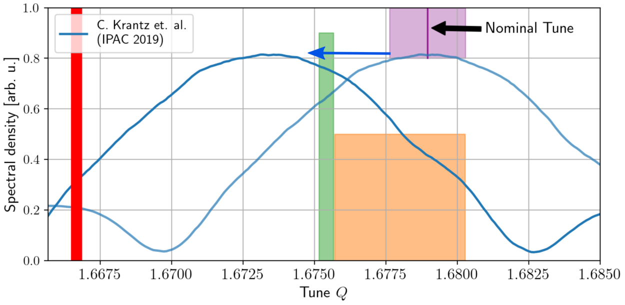
- Is it a good idea to use the tune distribution as reference for the excitation spectrum?
- Can we measure the tune distribution?
- Can we calculate the tune distribution?



HIT's Approach

Questions

- Is it a good idea to use the tune distribution as reference for the excitation spectrum? -> Probably
- Can we measure the tune distribution? -> Yes! (Indirectly)
- Can we calculate the tune distribution? -> Yes!



HIT's Approach

Questions

- Can we measure the tune distribution? -> Beam Transfer Function
- Can we calculate the tune distribution? -> Perturbation theory with Vlasov-Eq.

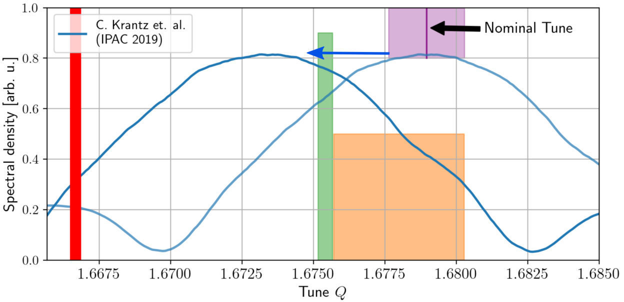
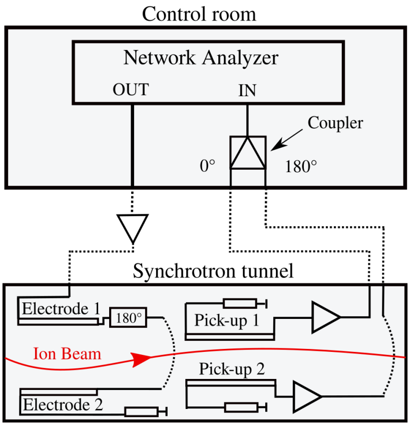
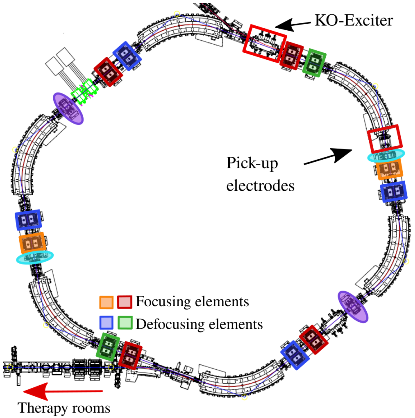


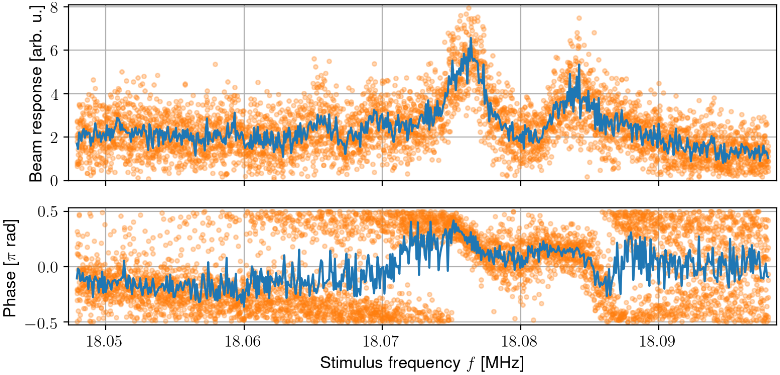
Table of Contents

BTF experimental setup





BTF Measurement



Carbon-ion

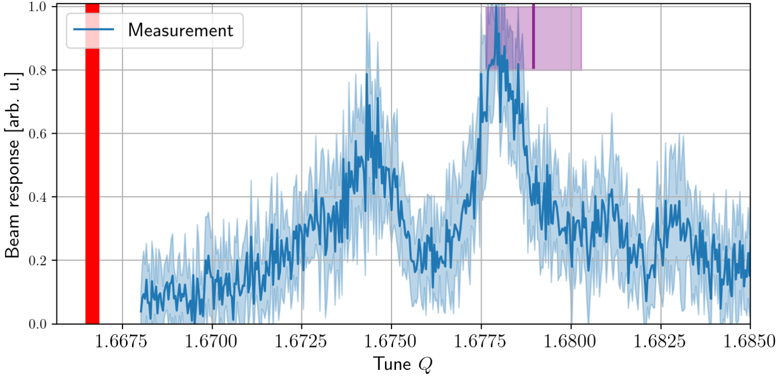
E_{kin} = 124.25 MeV/u

Extraction conditions

- Sextupoles at extraction conditions
- Coasting beam
- **Weak excitation**

Figure: BTF at extraction conditions at the lower 9th betatron band.
Orange: Raw data. Blue: Mean value.

BTF Measurement



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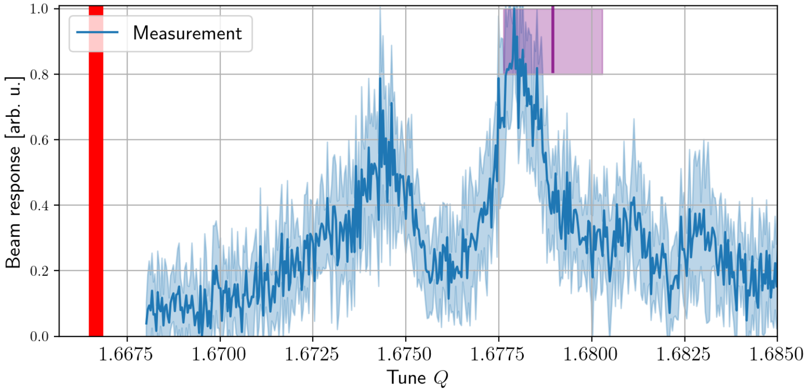
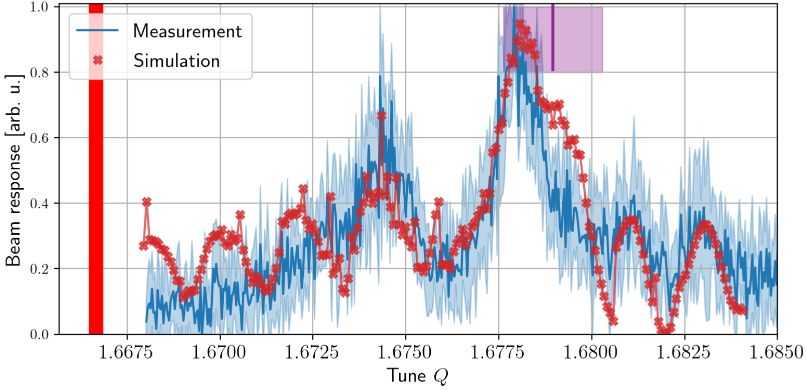
BTF Simulation



Simulation

- MADX tracking module
- $5 \cdot 10^4$ particles
- 2600 turns (~1ms)
- 200 tune steps
- Approx. 1TB of data
- 1 week of computing time

BTF Simulation and Measurement



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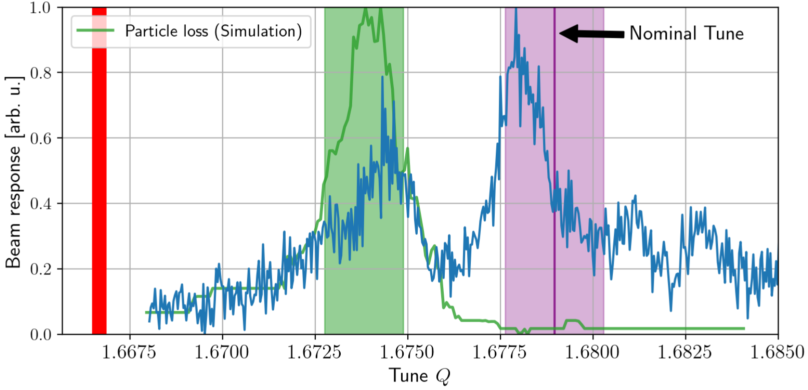
New excitation spectrum



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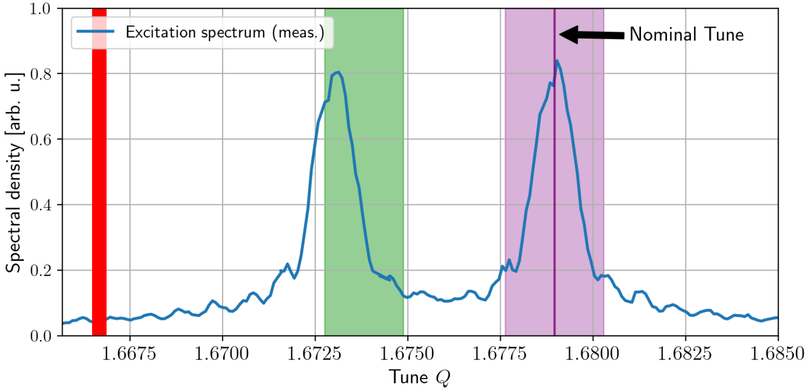


Excitation spectrum

- Two peaks
- Narrow bands (less than 5kHz)
- Central frequencies are $\sim$ 10kHz appart of each other

Spill with new excitation spectrum

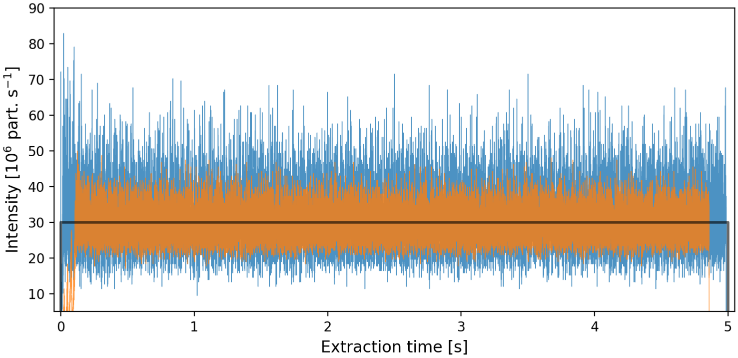


Figure: Spill with new excitation spectrum.

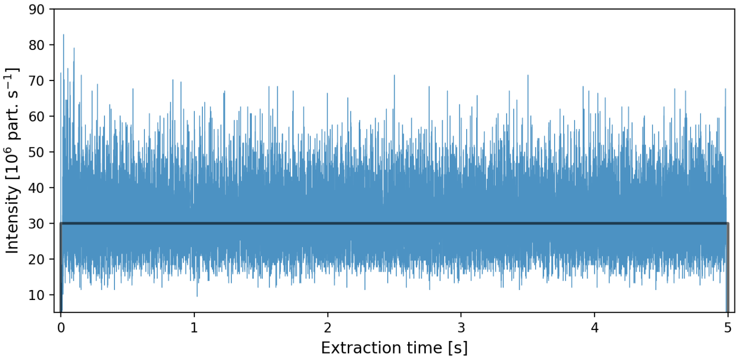
Spill quality

$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

$$R = 98.1\%$$

Table of Contents

Typical spill at HIT



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$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

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Spill with new excitation spectrum

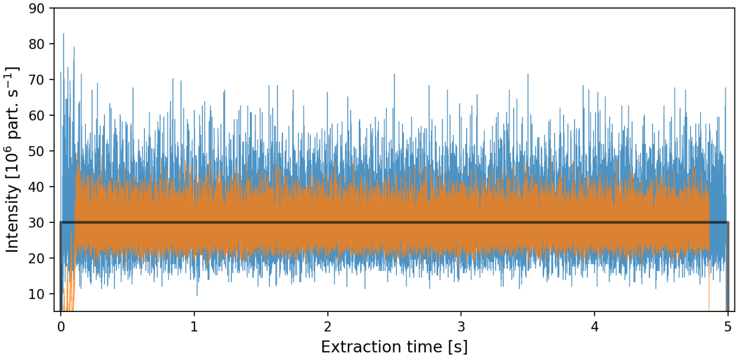

Figure: Spill with new excitation spectrum.

Spill quality

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Comparison of spill quality

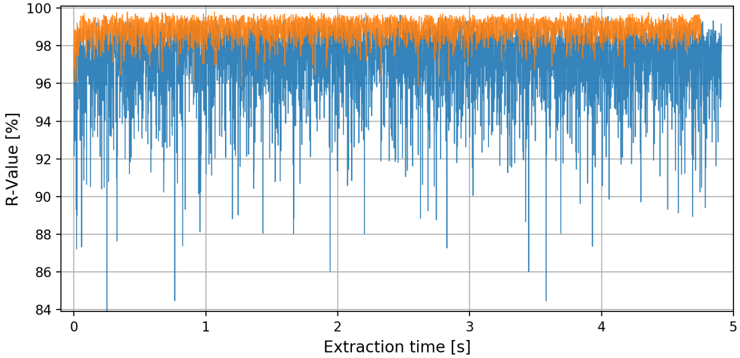


Figure: Spill quality through extraction in 1ms windows.

Spill quality

$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

Comparison of spill quality

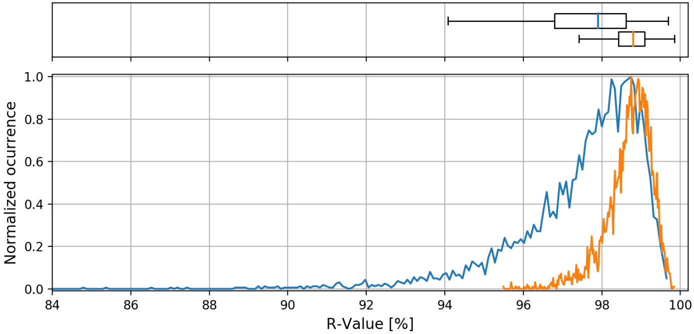
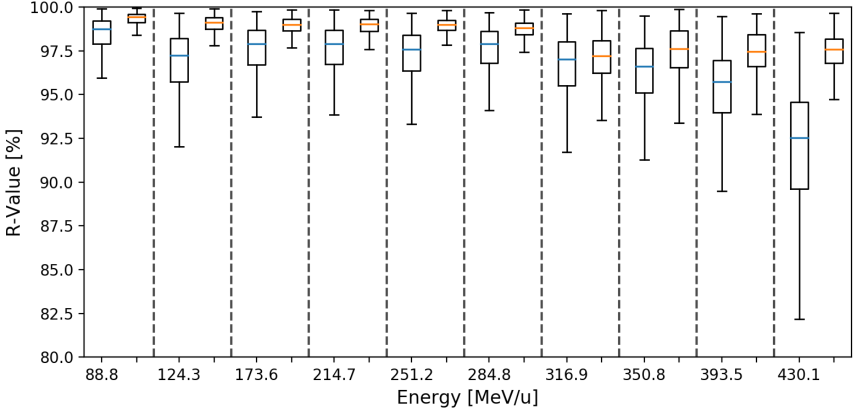


Figure: Histogram of R-Value over 5 s extraction.

Spill quality

$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

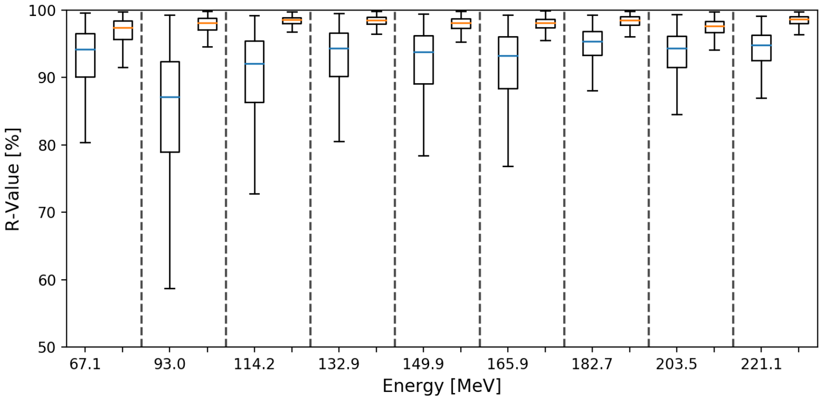
Improvement of spill quality: Carbon-ion



Spill quality

$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

Improvement of the spill-quality: Protons



Spill quality

$$R = \frac{\text{Mean}^2}{\text{Mean}^2 + \sigma^2}$$

Table of Contents

Summary

- Improvement of spill quality from $\sim$90% to $\sim$99%
- Improvement for all energies, ion species and intensity configurations
- Strong suppresion of fluctuations in the extracted particle yields
- Take the tune distribution as reference for the excitation signal
- Tune distribution is given by amplitude-detuning of the non-linear dynamics of the system

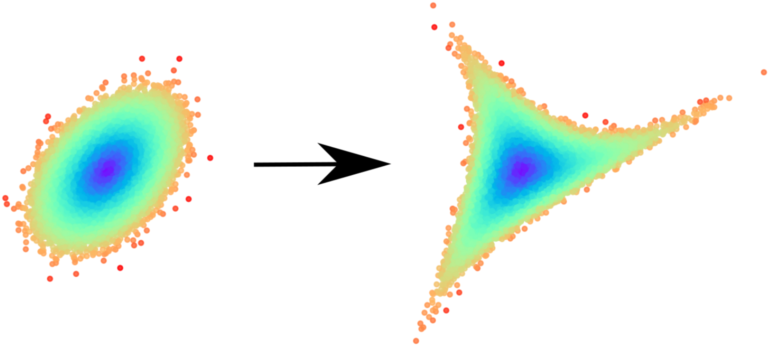
$$Q = \frac{1}{2\pi} \frac{\partial \mathcal{H}}{\partial J_x}$$

$$J_x : \text{Action} \propto \text{Amplitude in phase-space}$$

and the perturbed distribution in phase-space.

Phase-space

Thank you for your attention.



Extra-slides

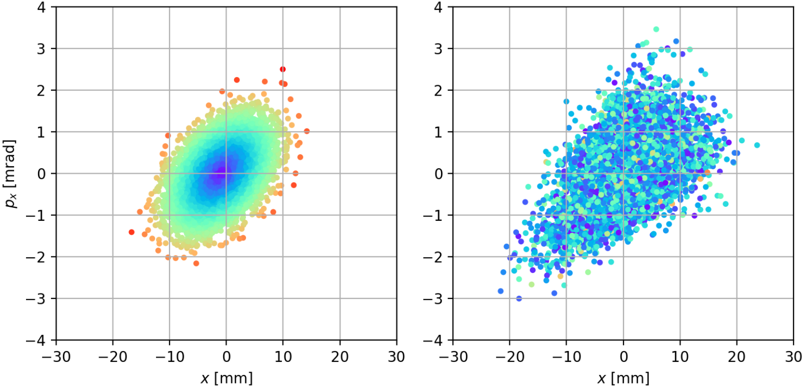
Schottky noise signals and BTF

With a coasting beam and no sextupoles:

Parameter	Design value	Measured value
Q_x	1.67895	$1.67952 \pm 5 \times 10^{-5}$
Q_y	1.755	$1.720 \pm 6 \times 10^{-3}$
η	0.47657	0.44 ± 0.02
ξ	-0.655	-0.72 ± 0.06
σ_δ	-	1.2×10^{-3} (FWHM)
ω_S	843.56 Hz	(810 ± 21) Hz

Table: Measured ion-optical parameters with a carbon ion beam C^{6+} with $E_{kin} = 125.25$ MeV/n.

BTF Simulation



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BTF Measurement

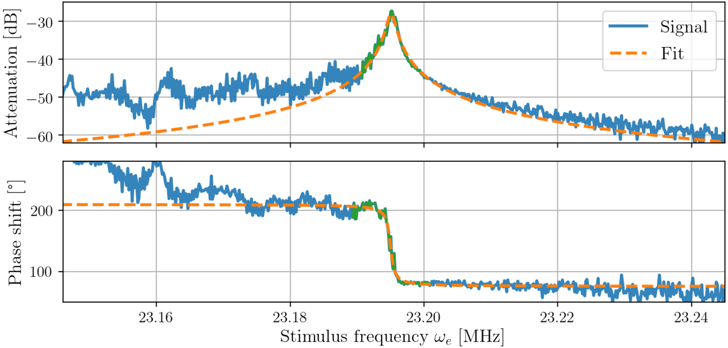


Figure: BTF of a C^{6+} coasting beam

Harmonic oscillator

$$A = \frac{f_0/m}{\sqrt{(\omega_0^2 - \omega_e^2)^2 + (\Lambda\omega_e)^2}}$$

$$\phi = \text{arccot}\left(\frac{\omega_0^2 - \omega_e^2}{\Lambda\omega_e}\right)$$

BTF Measurement

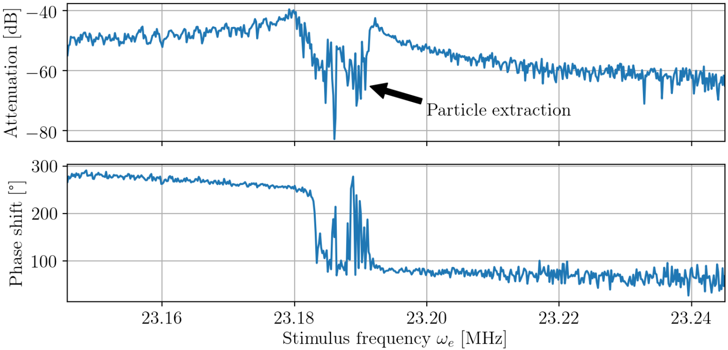
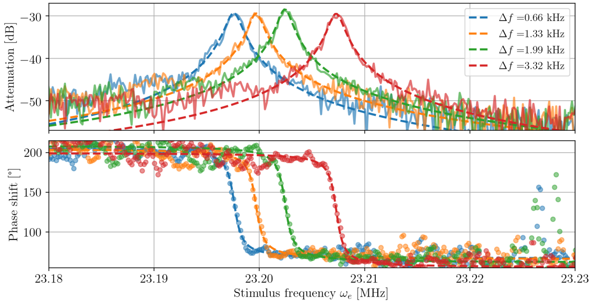


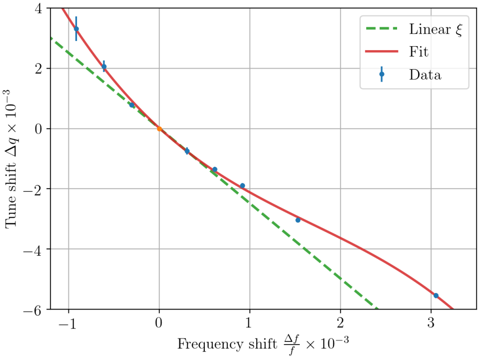
Figure: BTF with sextupolar fields

Extraction conditions

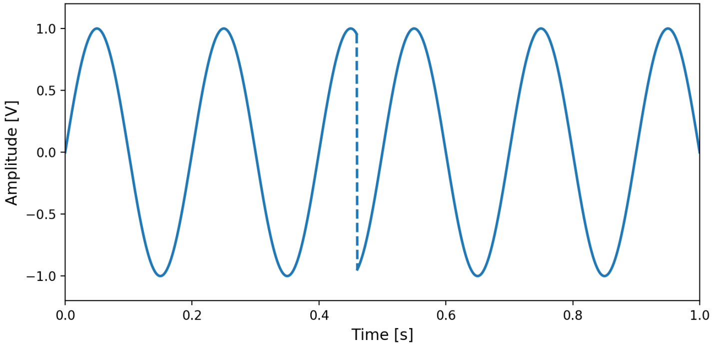
- Sextupoles at extraction conditions
- Coasting beam
- Same excitation as before

Chromaticity





Signal generation



Pseudo-Random BPSK

$$V(t) = V_0 \sin\left(2\pi f_0 + \phi_{\mathrm{BPSK}}\right)$$

$$\phi_{\mathrm{BPSK}} = \pi(n-1), \quad n = 0, 1$$

- ϕ_{BPSK} : Binary **Phase** Shift Keying