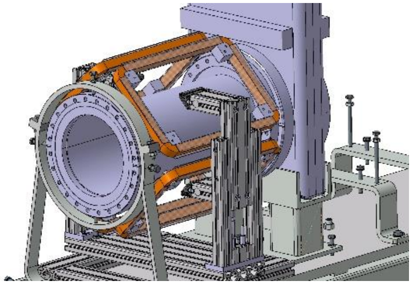
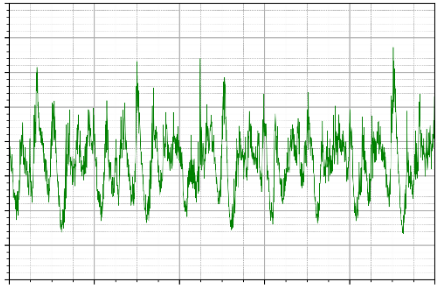
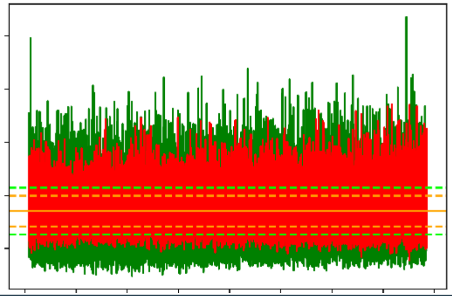
Air Core Quadrupole (ACQ) Project

Kick-off Meeting for I.Fast-REX

Andre Rojan

08 February 2021

MIT (Marburg, Germany)

The Experiment

- Spill ripple compensation by applying a time-dependent tune modulation
- The tune modulation is achieved using the ACQ and a “handmade“ static signal

- Investigation was performed in order to answer the questions:
  - How many compensation signals are required to improve the spill over the whole energy range?
  - How long can a fixed compensation signal be used /

    does the effect of the compensation signal change over time?

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Extraction System at MIT

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Development & Experimental Setup

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Results of the Experiment ($^{12}C^{6+}$)

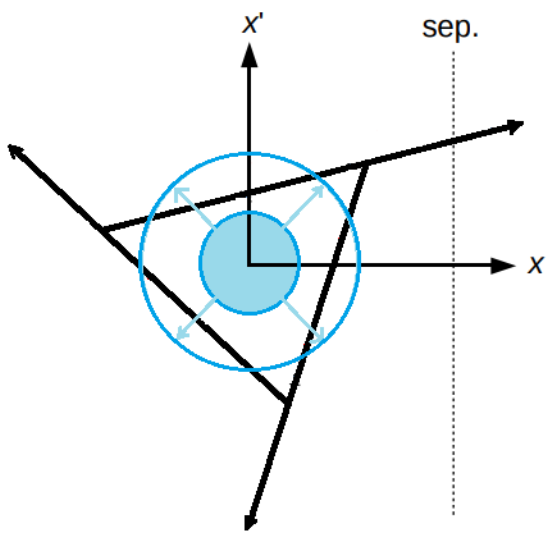
FFT of the Energy Range

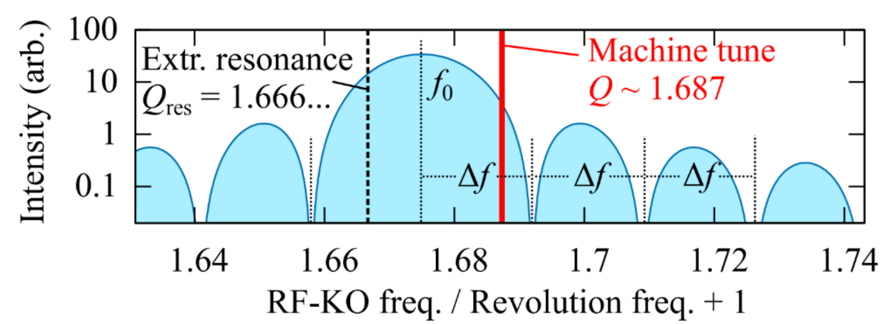
Ripple Suppression over Time

Extraction System at MIT
RF KO-Extraction

RF knockout amplitude selection (amplitude growth)

Particles leave the stable triangle due to the resonant excitation of a KO-Exciter

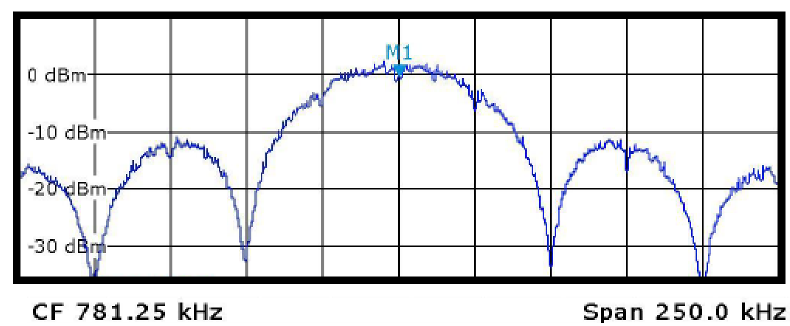




[Krantz et al., Proc. of IPAC 2018]

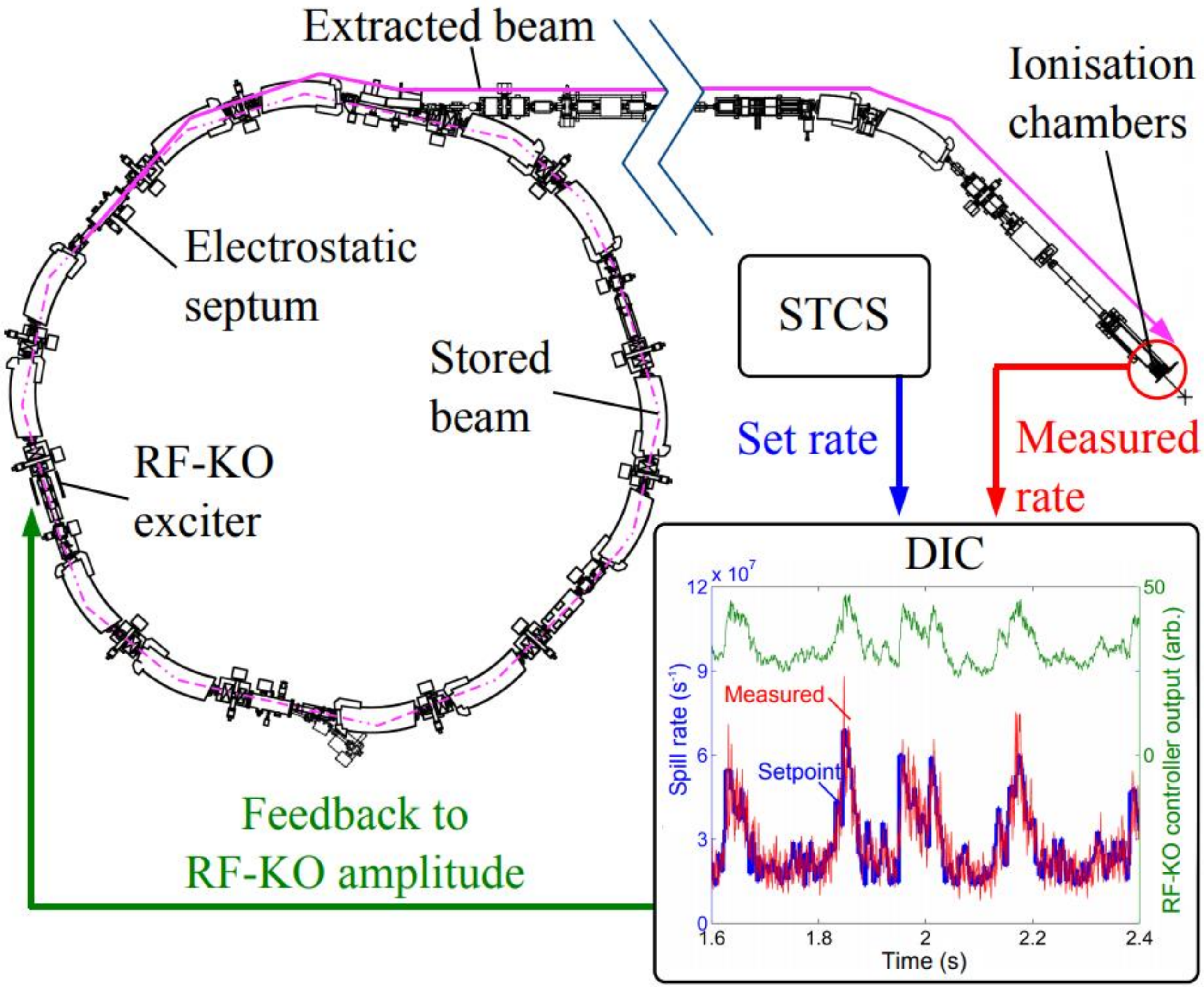
Static machine tune during extraction.
Main frequency f_0 between Q and Q_{res}.

The KO RF spectrum is generated by random phase shift keying (PSK).



Typical KO signal on a spectrum analyzer

Extraction System at MIT
Extraction System

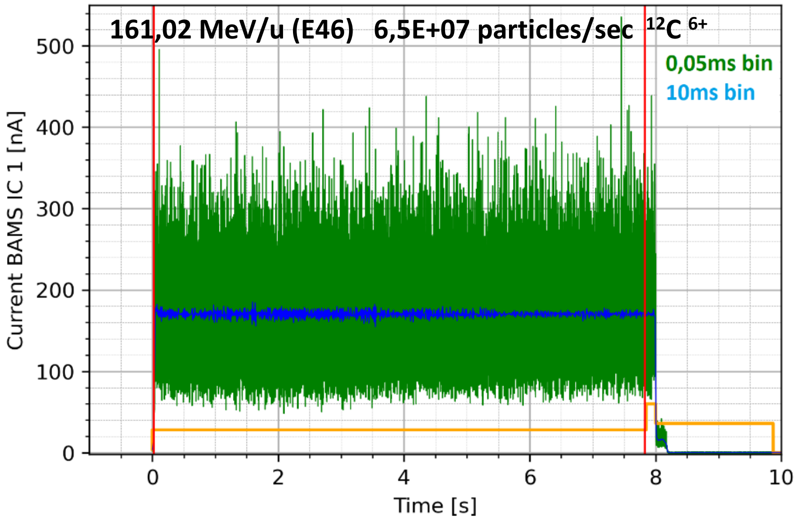


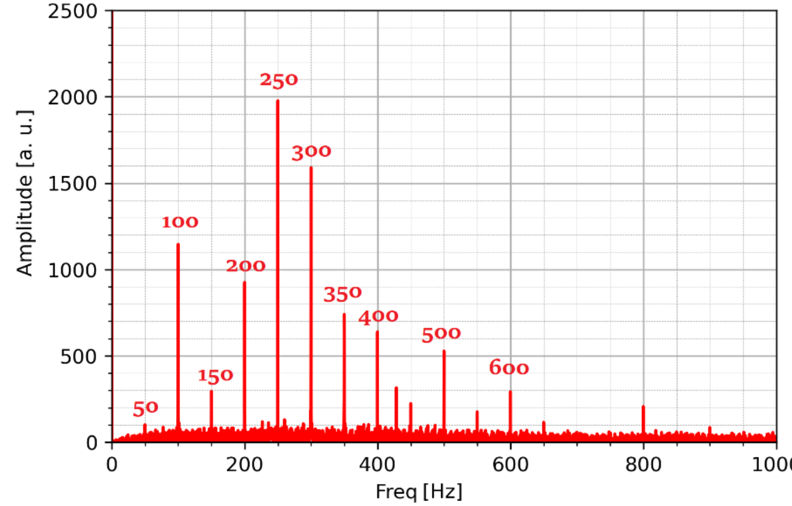
[Krantz et al., Proc. of IPAC 2018]

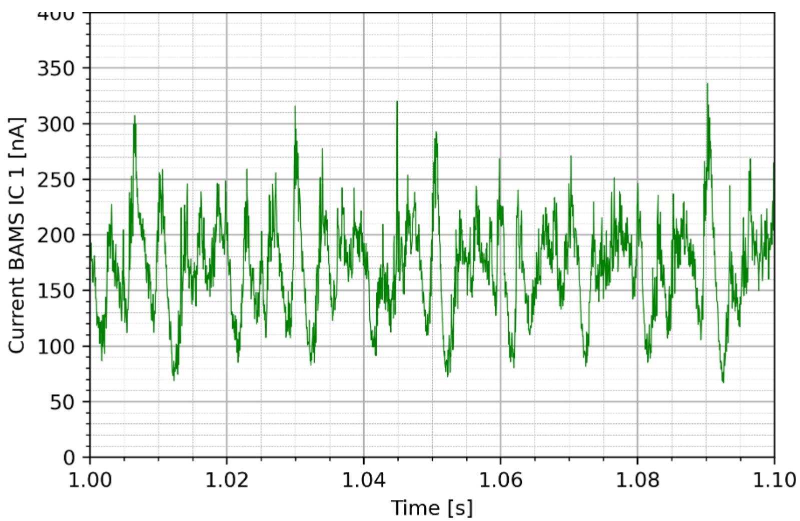
Extraction System at MIT

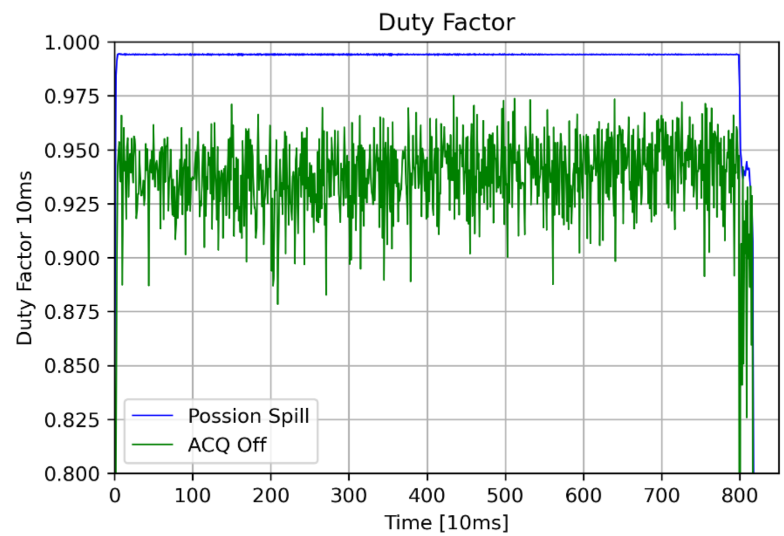
Spill without Ripple Kompensation

MIT Marburger Ionenstrahl-Therapiezentrum









[Singh et al., J. Phys.: Conf. Ser. 1067 (2018) 072002]

$$F = \frac{\langle N \rangle^2}{\langle N^2 \rangle} = \frac{\mu^2}{\mu^2 + \sigma^2}$$

Concept of the ACQ
Basic Idea – Tune Shift

History of the Project

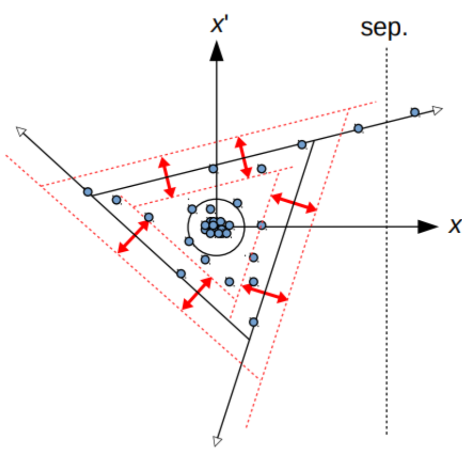
2016 Proposal of ripple compensation using an ACQ at MIT
(inspired by efforts at CNAO, see [Caracciolo et al. Proc. of IPAC 2011])

2017 The ACQ is developed in cooperation between HIT and MIT

2018 First demonstration of ACQ ripple compensation at HIT and MIT
[Krantz et al., Proc. of IPAC 2018]

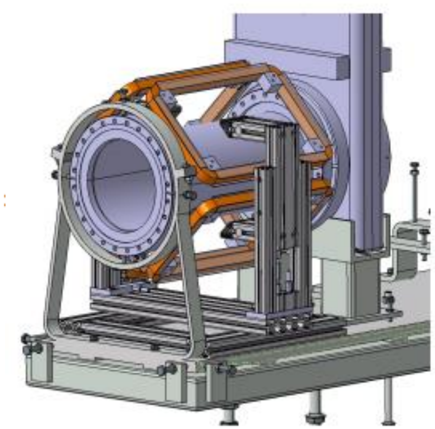
2020 Continuation of the project at MIT

Basic Idea:
Counteract the wobbling separatrix by introducing an additional magnetic field which affects the machine tune



$$A = \frac{48\sqrt{3}\pi^2}{S^2}(\delta Q)^2$$

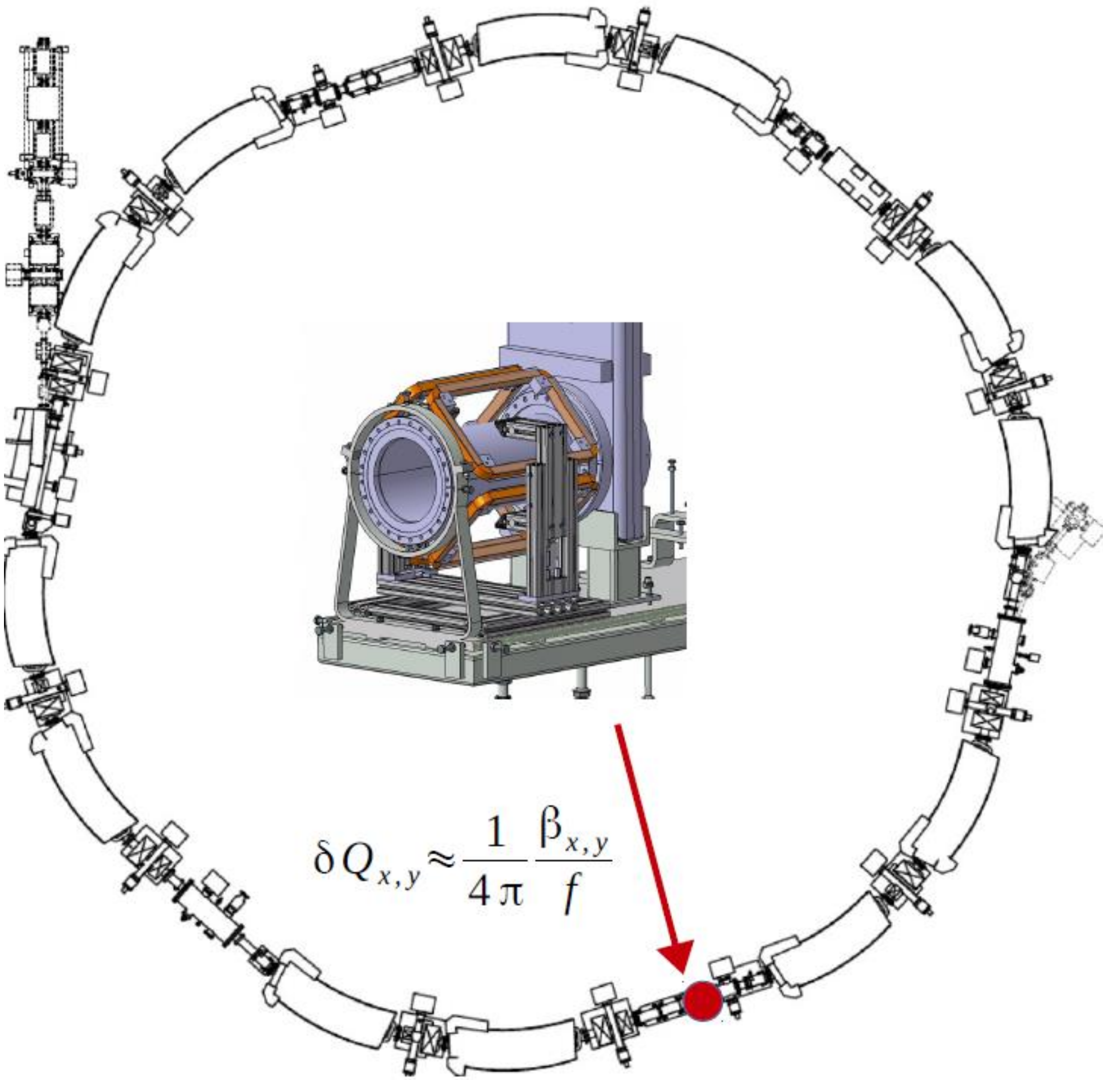
$$\delta Q_{x,y} \approx \frac{1}{4\pi}\frac{\beta_{x,y}}{f}$$



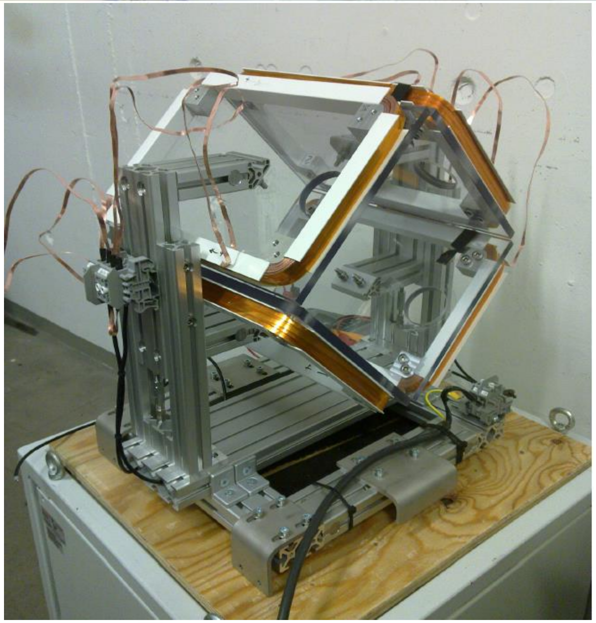
Picures: Courtesy of C. Krantz
(3rd Slow Extraction Workshop, Batavia, 2019)

Concept of the ACQ

Experimental Setup - Positioning of the ACQ



$$\delta Q_{x,y} \approx \frac{1}{4\pi} \frac{\beta_{x,y}}{f}$$



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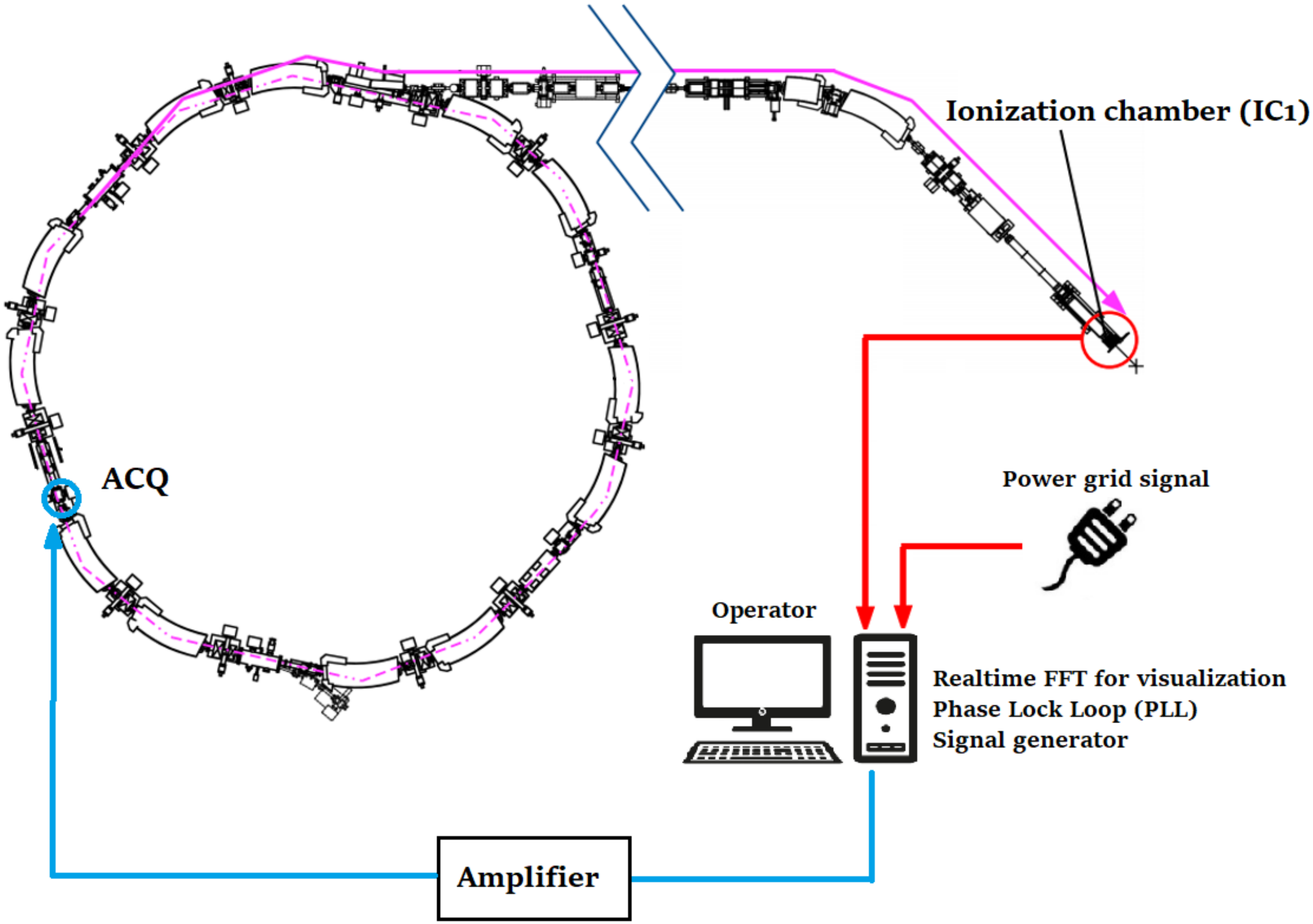
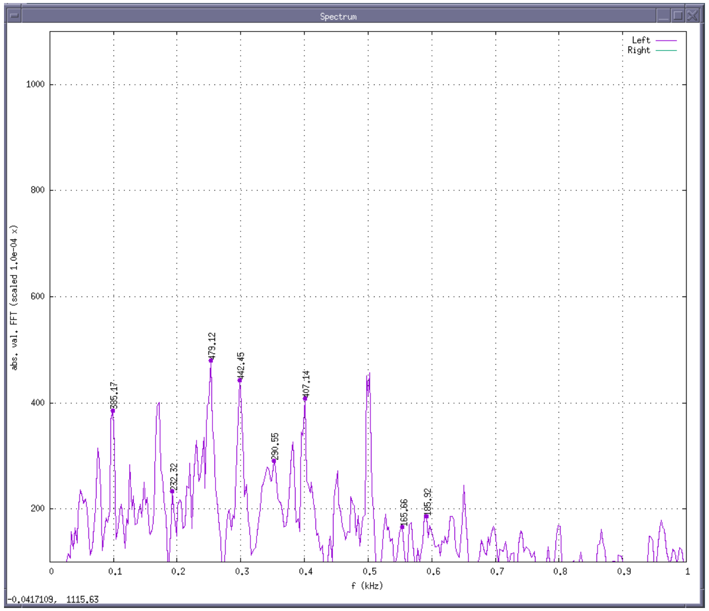
Concept of the ACQ
Experimental Setup

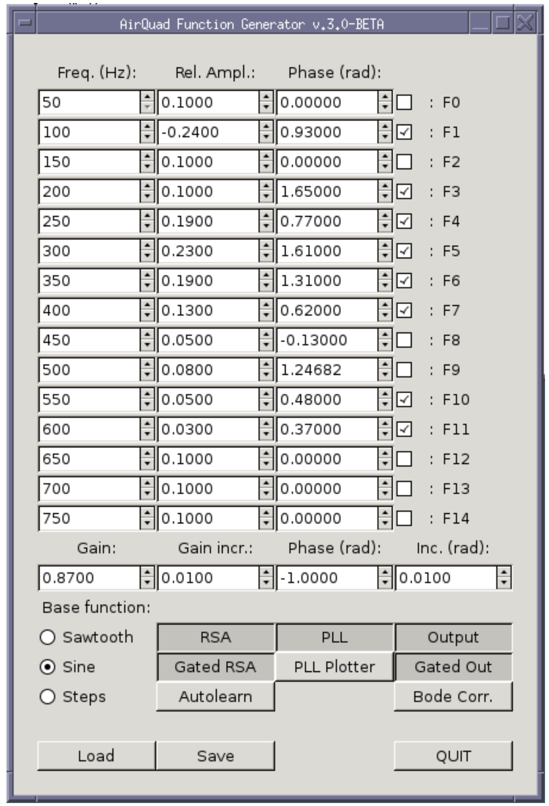


Concept of the ACQ

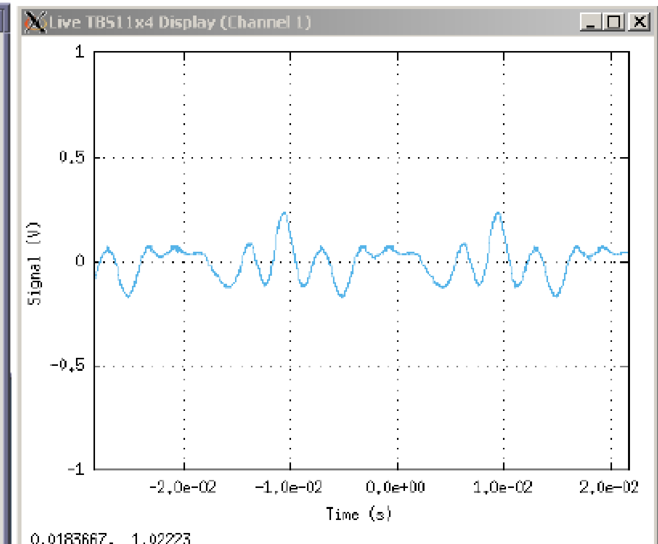
Creating a Compensation Signal



Realtime Spectrum Analyser
(Online FFT of spill)



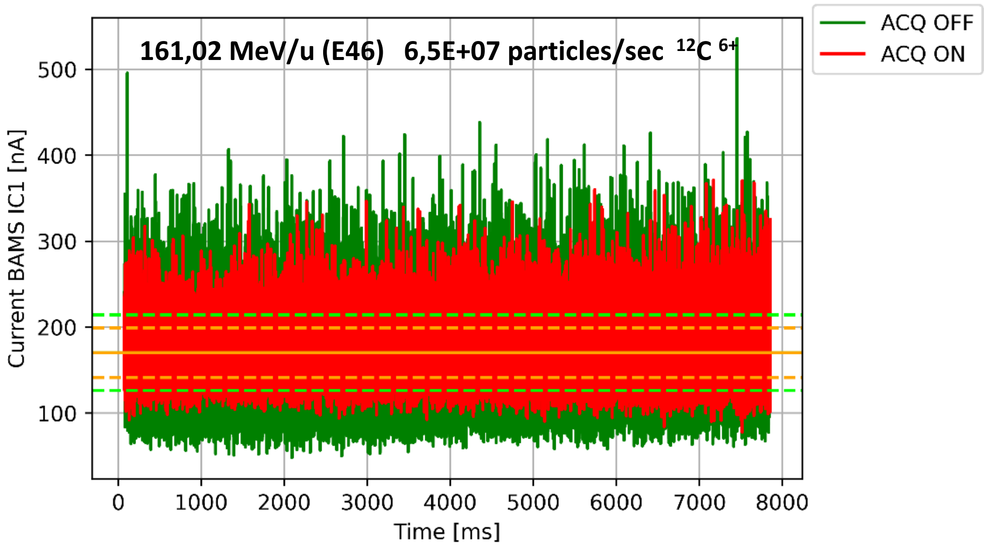
Signal generator GUI
(arbitrary mixing of power-grid harmonics)

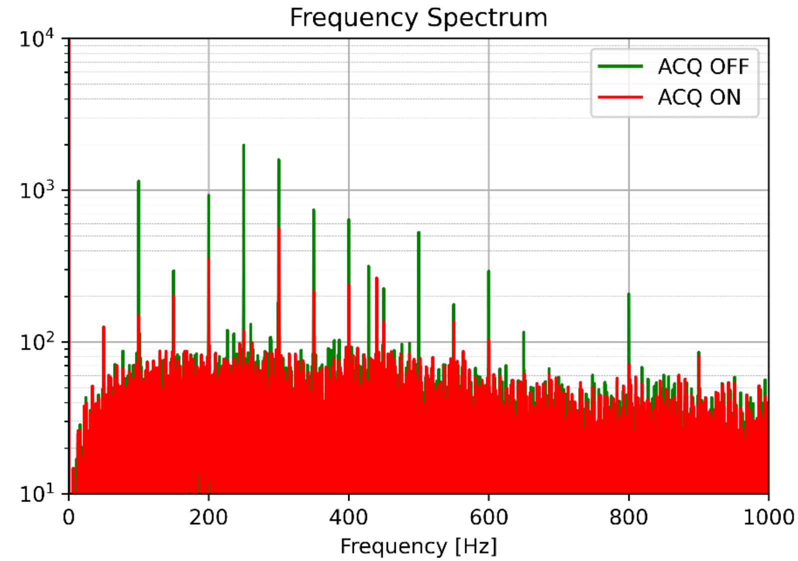


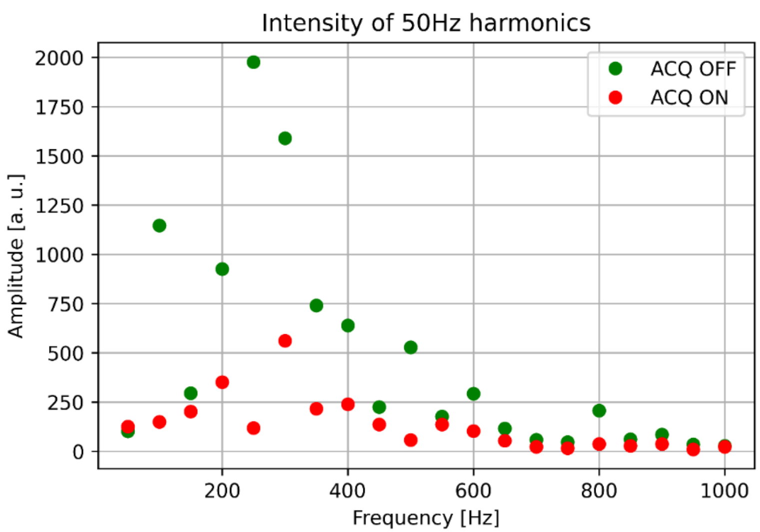
Output signal to ACQ
(phase-locked to mains)

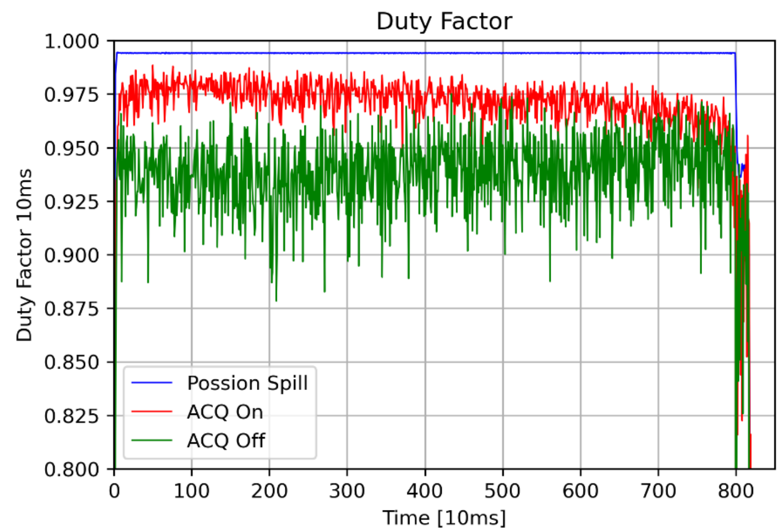
Concept of the ACQ

Effect on the Spill





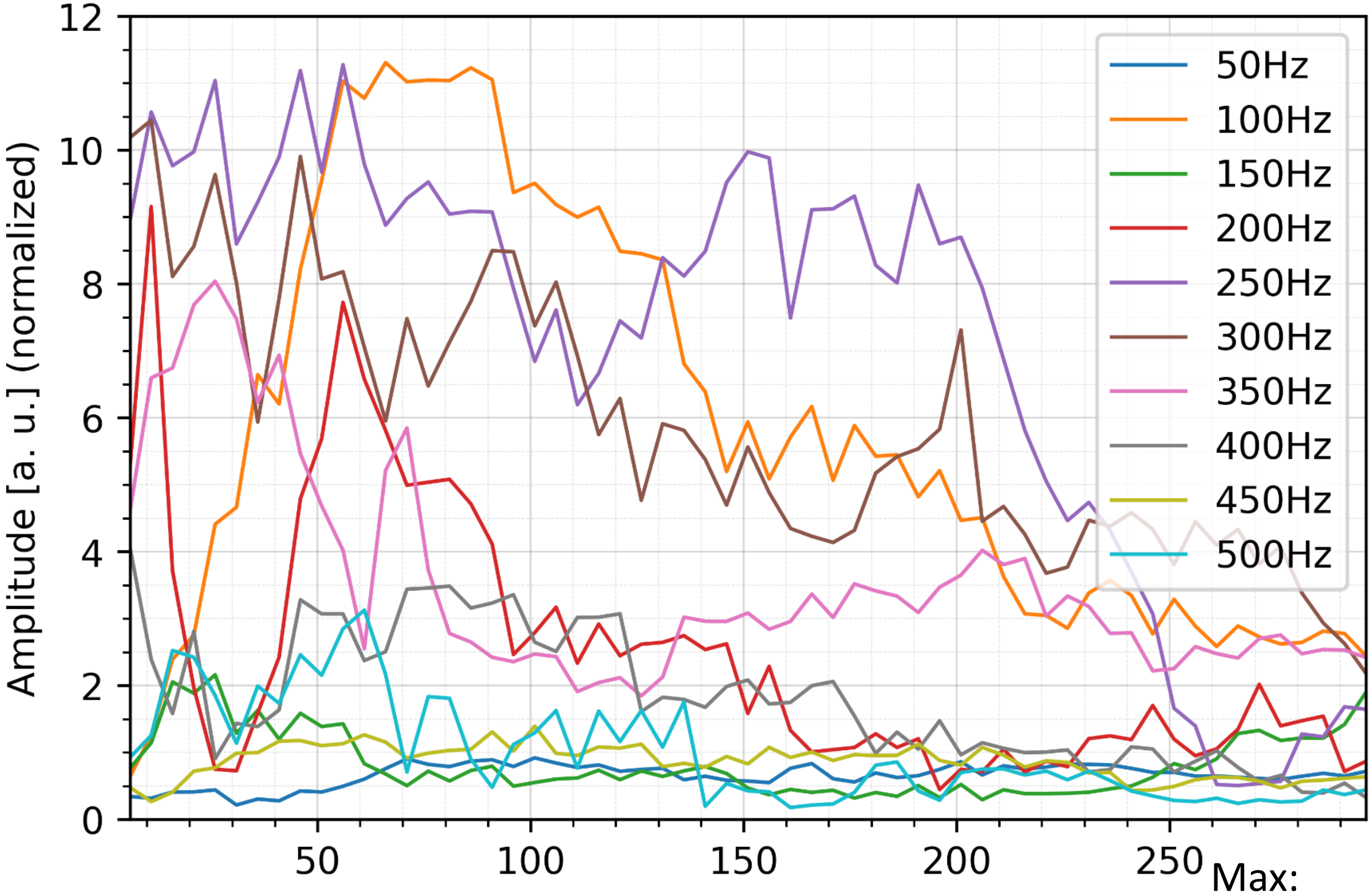




[Singh et al., J. Phys.: Conf. Ser. 1067 (2018) 072002]

$$F=\frac{\langle N\rangle^2}{\langle N^2\rangle}=\frac{\mu^2}{\mu^2+\sigma^2}$$

Results of the Experiment
FFT of the Energy Range (Uncompensated)



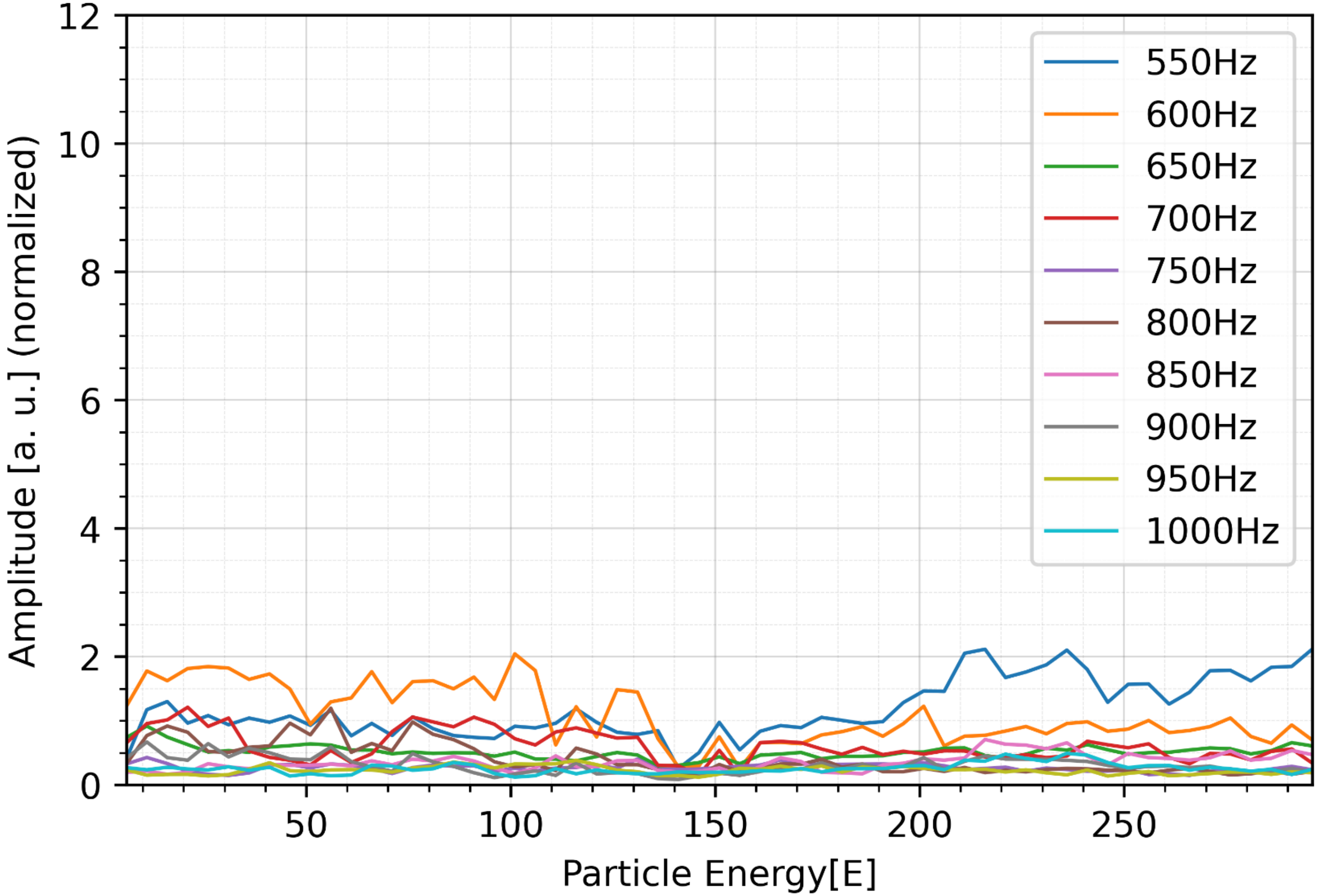
Min:
86,22 MeV/u (E6)

Max:
430,12 MeV/u (E296)

Dominant Frequencies: 100Hz,200Hz,250Hz,300Hz,350Hz,400Hz

Results of the Experiment

FFT of the Energy Range (Uncompensated)



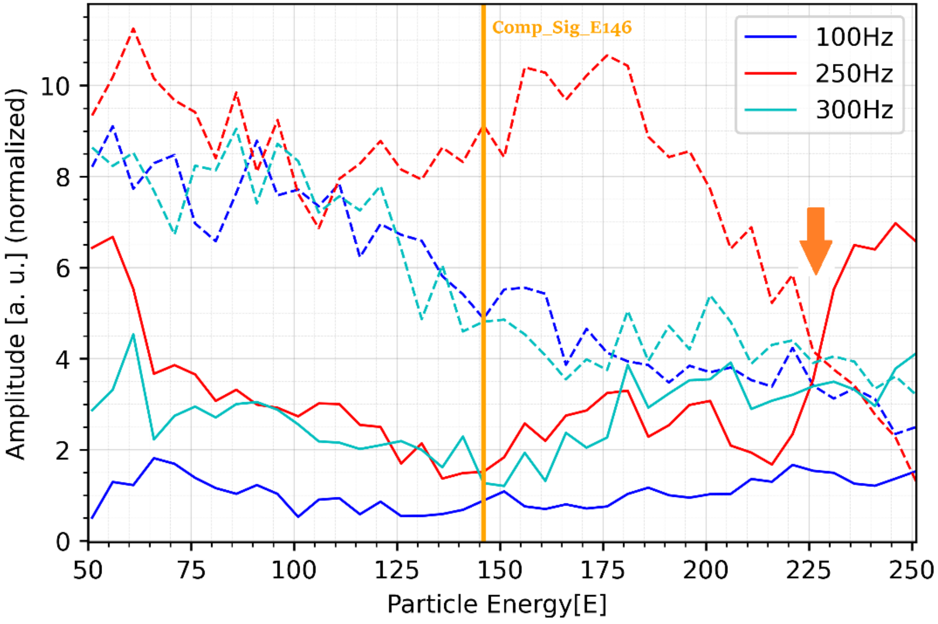
Frequencies > 500 Hz are less dominant

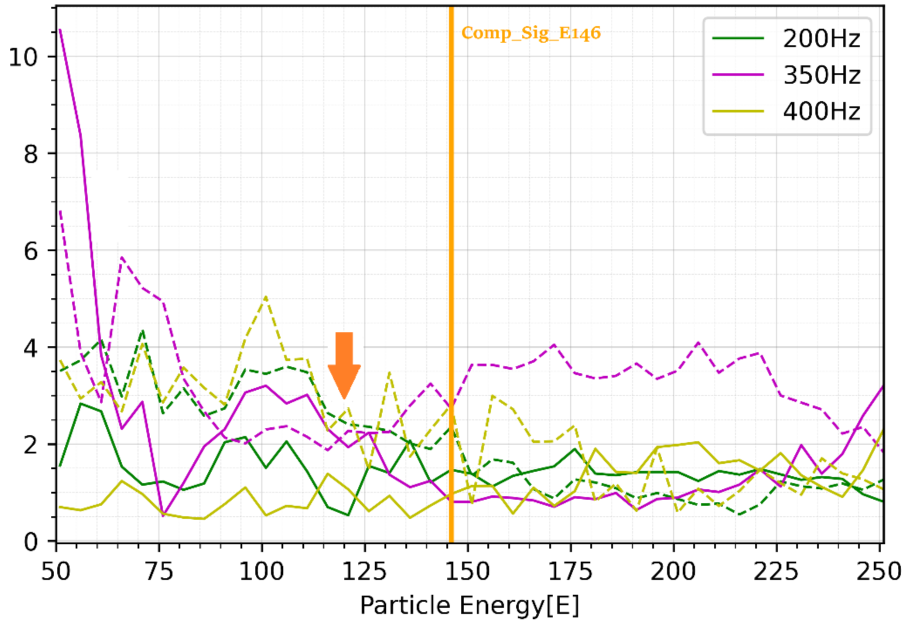
Results of the Experiment

Effect on Neighboring Energies

Compensation function optimized for the energy state E146

The function was applied on neighboring energies (step size 5E)



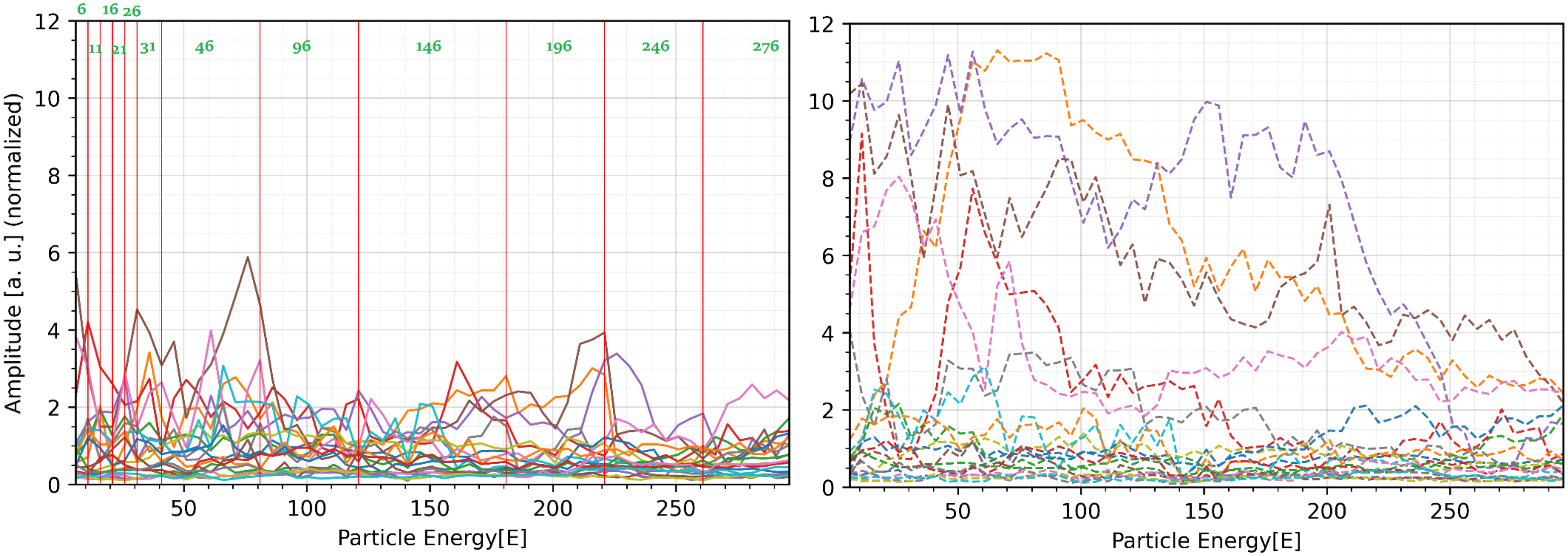


⇒ The compensation function suppresses dominant frequencies in a energy range (121,221)

⇒ Outside this energy range frequencies can be enhanced (250Hz for example)

Results of the Experiment
Compensation for the whole Energy range

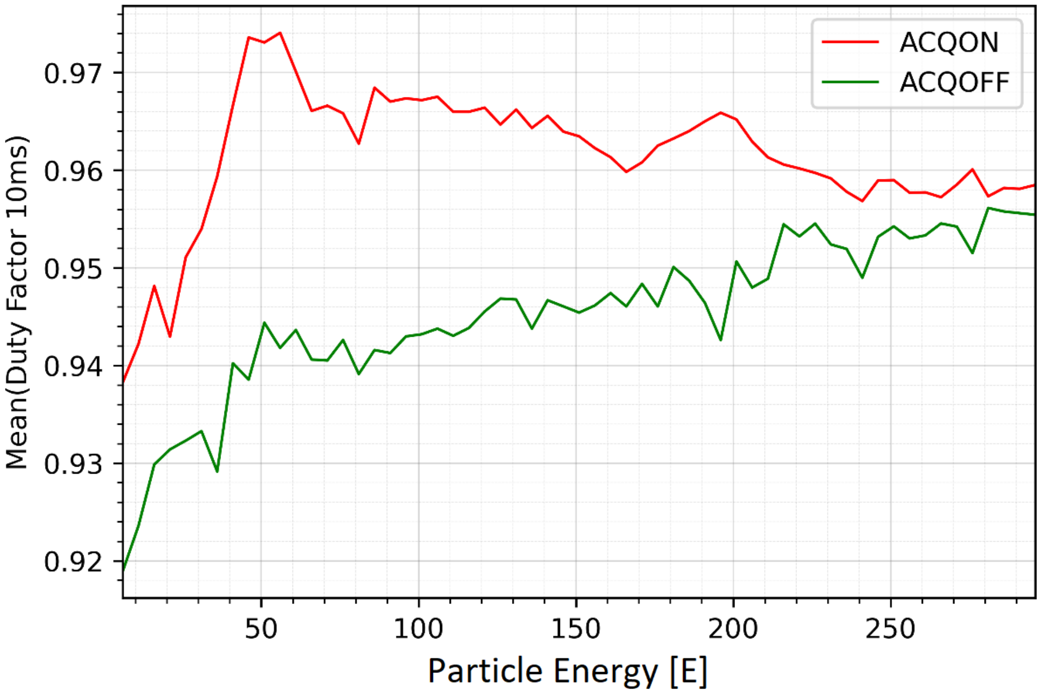
A set of compensation functions was created in order to suppress 50hz harmonics for the whole energy range.
The compensation functions are optimized for the energy states:
[6,11,16,21,26,31,46,96,146,196,246,276]



⇒ It is more challenging to optimize functions at low energies < E 51
⇒ More compensation functions are required
⇒ At high energies (>E 246) 50Hz harmonics are less dominant

Results of the Experiment

Compensation for the whole Energy range

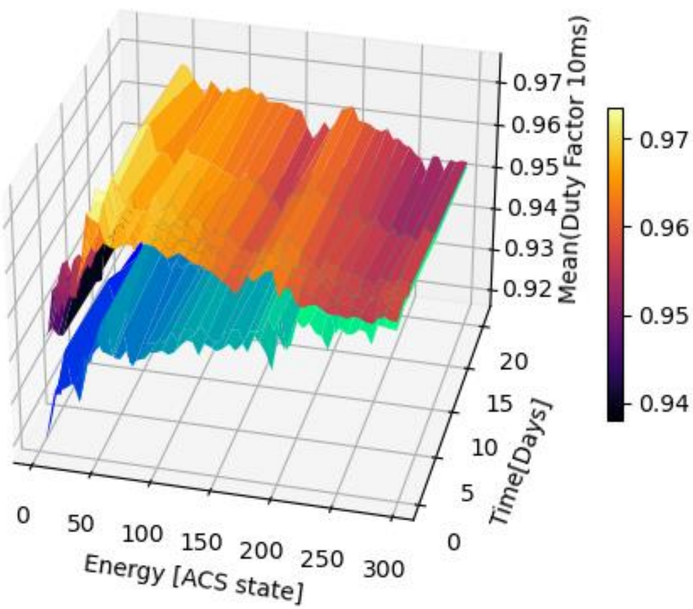


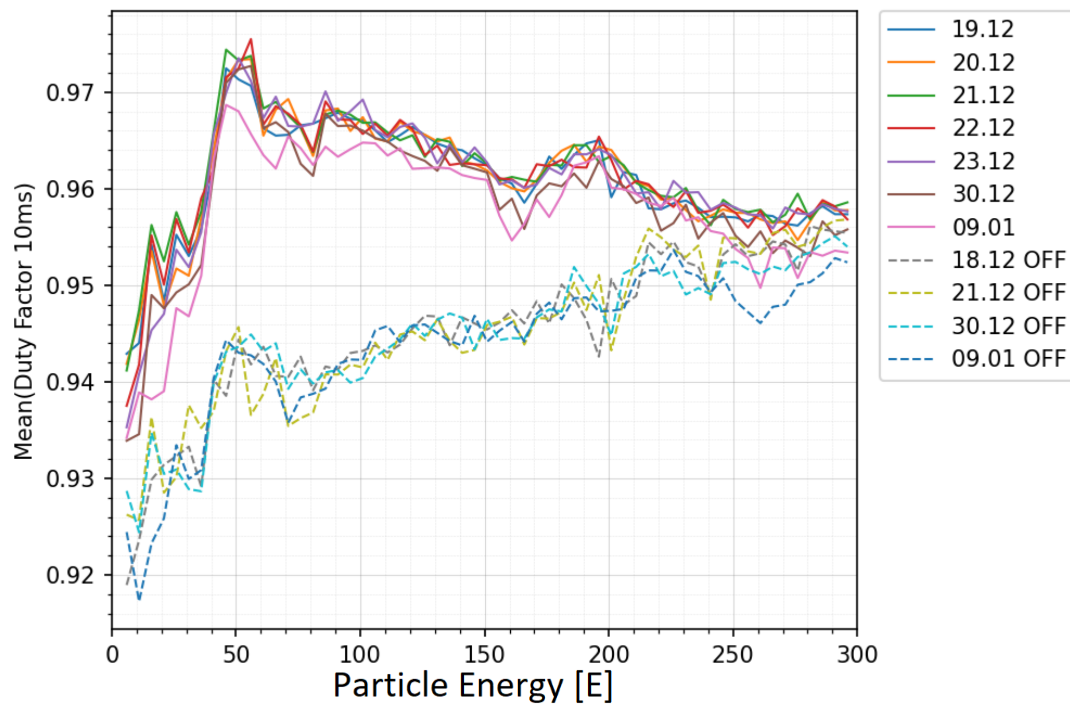
⇒ The compensation function set improves the spill quality for all energies

⇒ How does the compensated spill quality change over time?

Results of the Experiment
Compensation for the whole Energy range

Interactive 3D plot in Jupyter Notebook





Summary

- Spill ripple compensation was performed for the whole $^{12}C^{6+}$ energy range
- An examination over 21 days has shown that the spill quality (duty factor) decreases slightly over time
- The duty factor was always greater for activated ripple compensation (using the introduced compensation function set)

- More compensation functions are required for low energies
- High energies are difficult to optimize due to the already good spill quality

- Further Investigation
  - same examination for protons
  - optimizing the number and energy range of compensation functions
  - Automatic (re-)optmisation of compensation signals

Marburger Ionenstrahl-Therapiezentrum

Thanks for your attention.