ICFA Mini-Workshop on Slow Extraction 2019

Fermilab, Batavia

Spill Quality and Tune Ripple Cancellation at Ion-Beam Therapy Synchrotrons

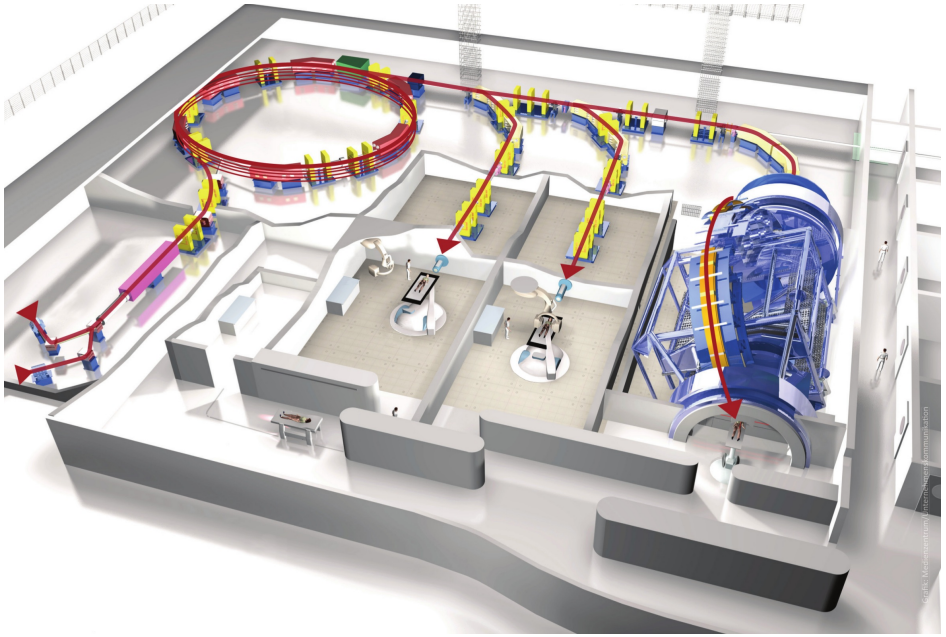
Claude Krantz

Marburg Ion-Beam Therapy Centre

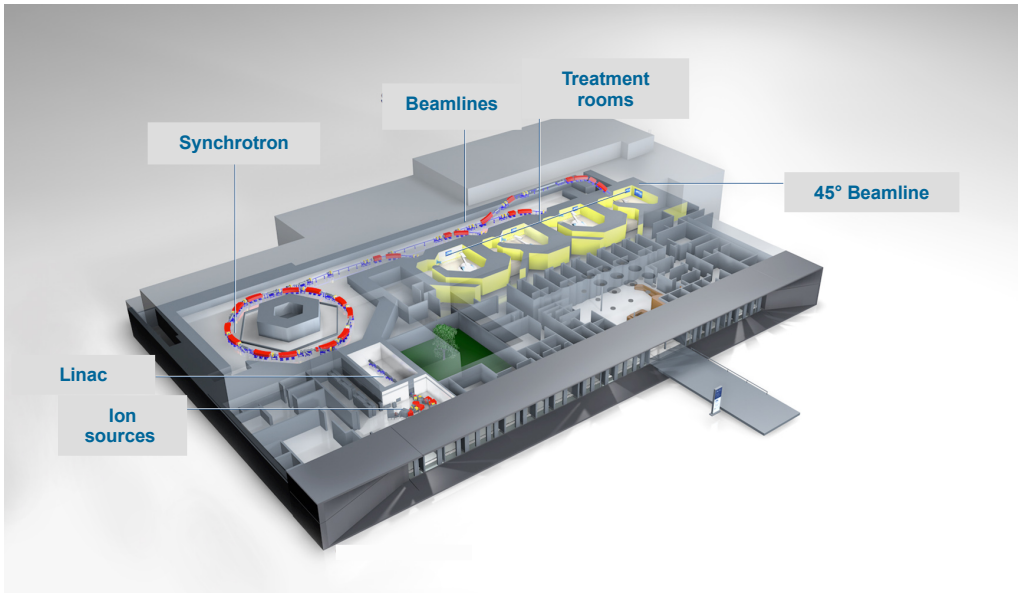
23 July 2019

Marburger Ionenstrahl-Therapiezentrum

Heidelberg (HIT) and Marburg (MIT) Ion-Beam Therapy Centres



klinikum.uni-heidelberg.de



http://www.mit-marburg.de

HIT and MIT are the only facilities for heavy-ion (p <u>and</u> $^{12}C^{6+}$) therapy in Germany.

HIT:

In clinical op. since Nov. 2009

Accelerator design by GSI,
based on GSI precursor experiments.

MIT:

In clinical op. since Oct. 2015

Linac: Identical to HIT machine.

Synchrotron + HEBT:
re-implementation by
Siemens HealthCare / Danfysik.

(*Identical machine is in op. at Shanghai Proton and Heavy Ion Centre*)

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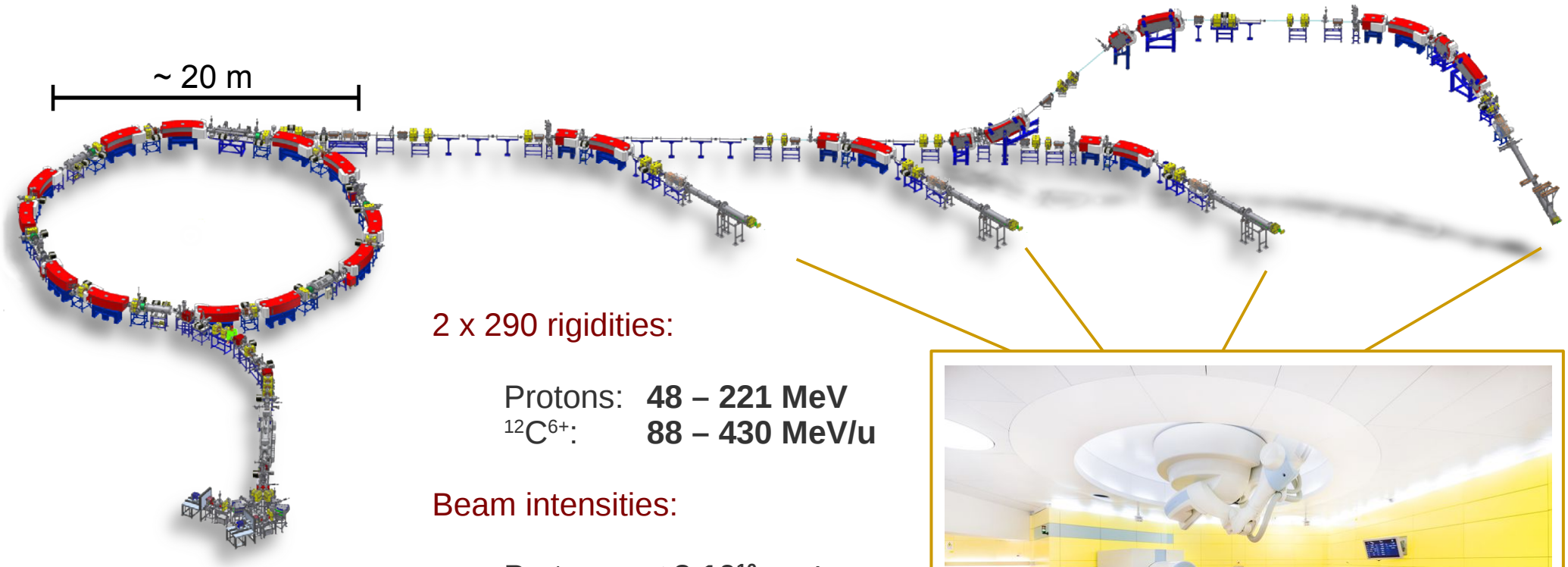
The MIT accelerator

Lazarev et al., Proc. of IPAC 2011
Scheeler et al. Proc. of IPAC 2016



2 x 290 rigidities:

Protons: **48 – 221 MeV**
$^{12}C^{6+}$: **88 – 430 MeV/u**

Beam intensities:

Protons: **≤ $3 \cdot 10^{10}$ parts.**
$^{12}C^{6+}$: **≤ $1 \cdot 10^{9}$ parts.**

per cycle

4 treatment rooms:

3 x hor., 1 x 45°

mit-marburg.de

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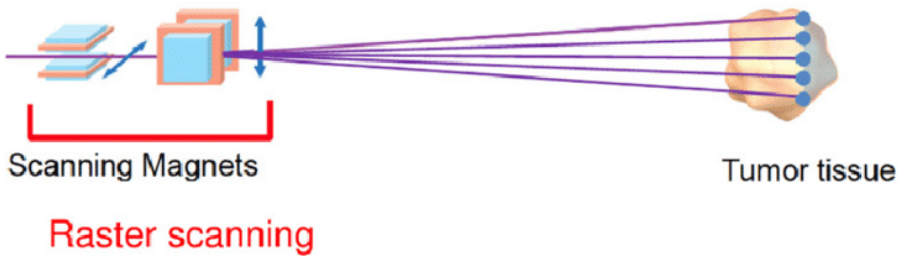
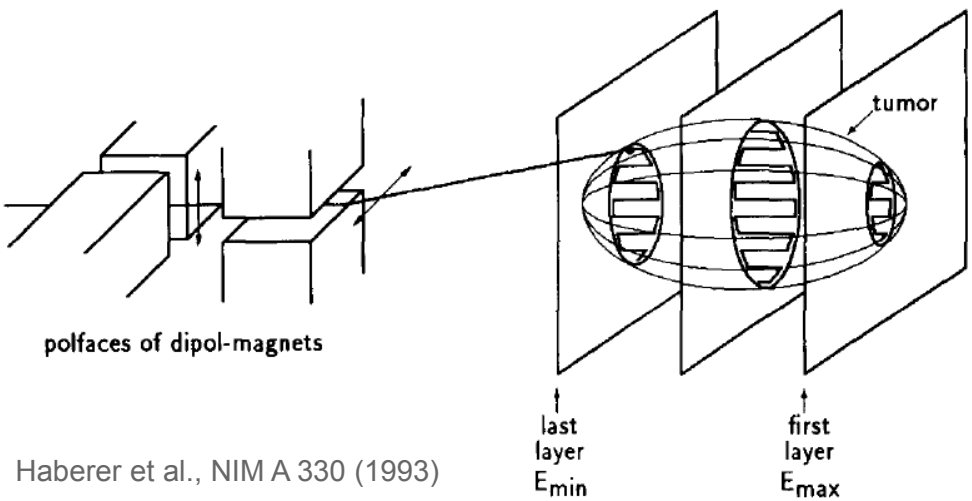
Pencil beam scanning method

Durante and Paganetti,
Rep. Prog. Phys. 79 (2016)





Haberer et al., NIM A 330 (1993)

1) Sequence of *pencil-beams* of defined range.

2) "Paint" each iso-energetic slice of the target using *scanning magnets*.

Optimum 3D tumour conformity of dose-distribution.

Requires a *high-quality* ion beam in pulses of **~ few seconds**

Stable pointing direction
… spot size
… **intensity**

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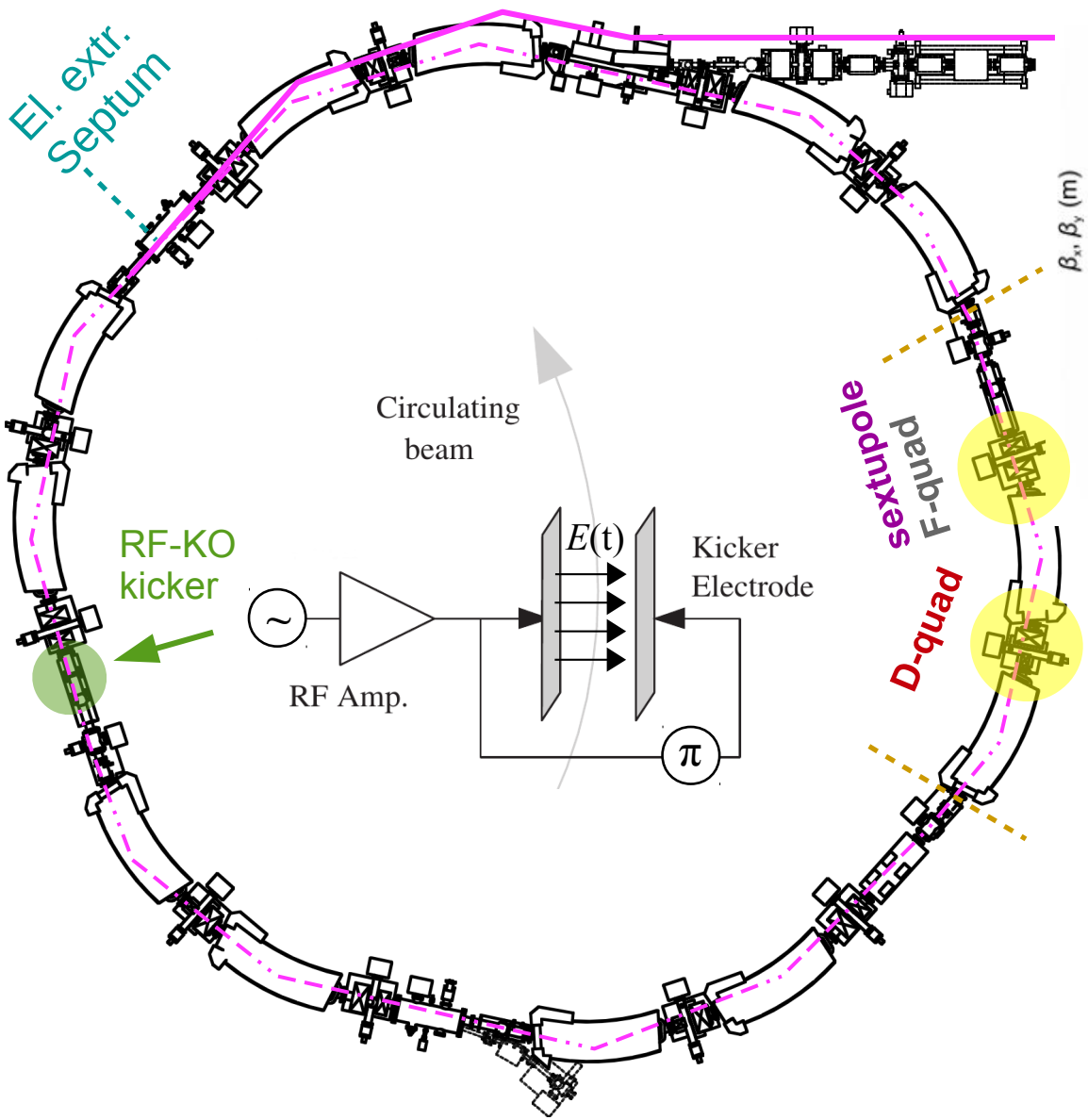
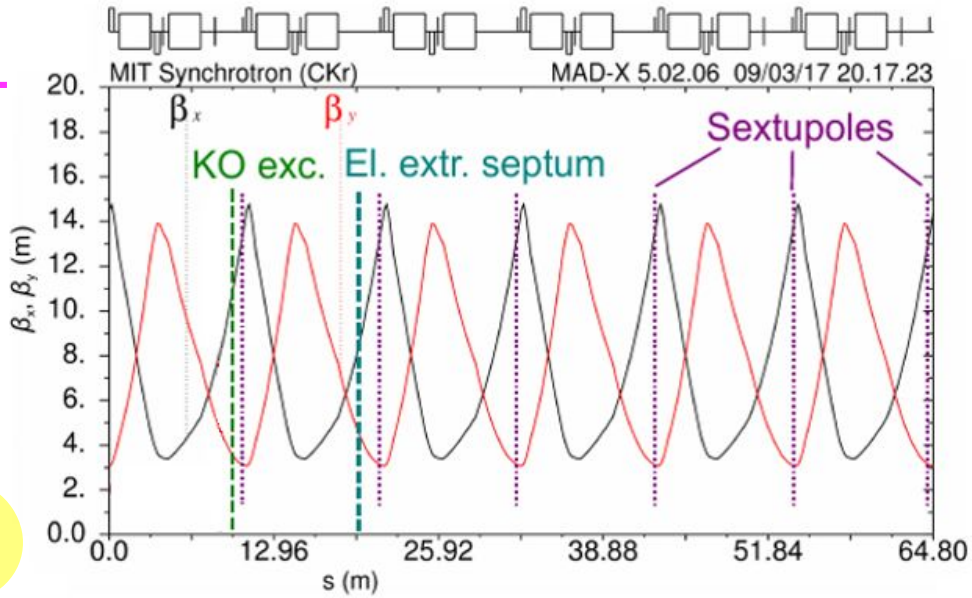
RF-KO system





← MIT synchrotron (65 m)

$B\rho_{max}$ ~ 6.6 Tm

Fixed optics during extraction

$Q_h \approx 1.69$, $\tilde{\xi}_h \approx -0.9$

RF-KO driven extraction via 5/3 resonance.

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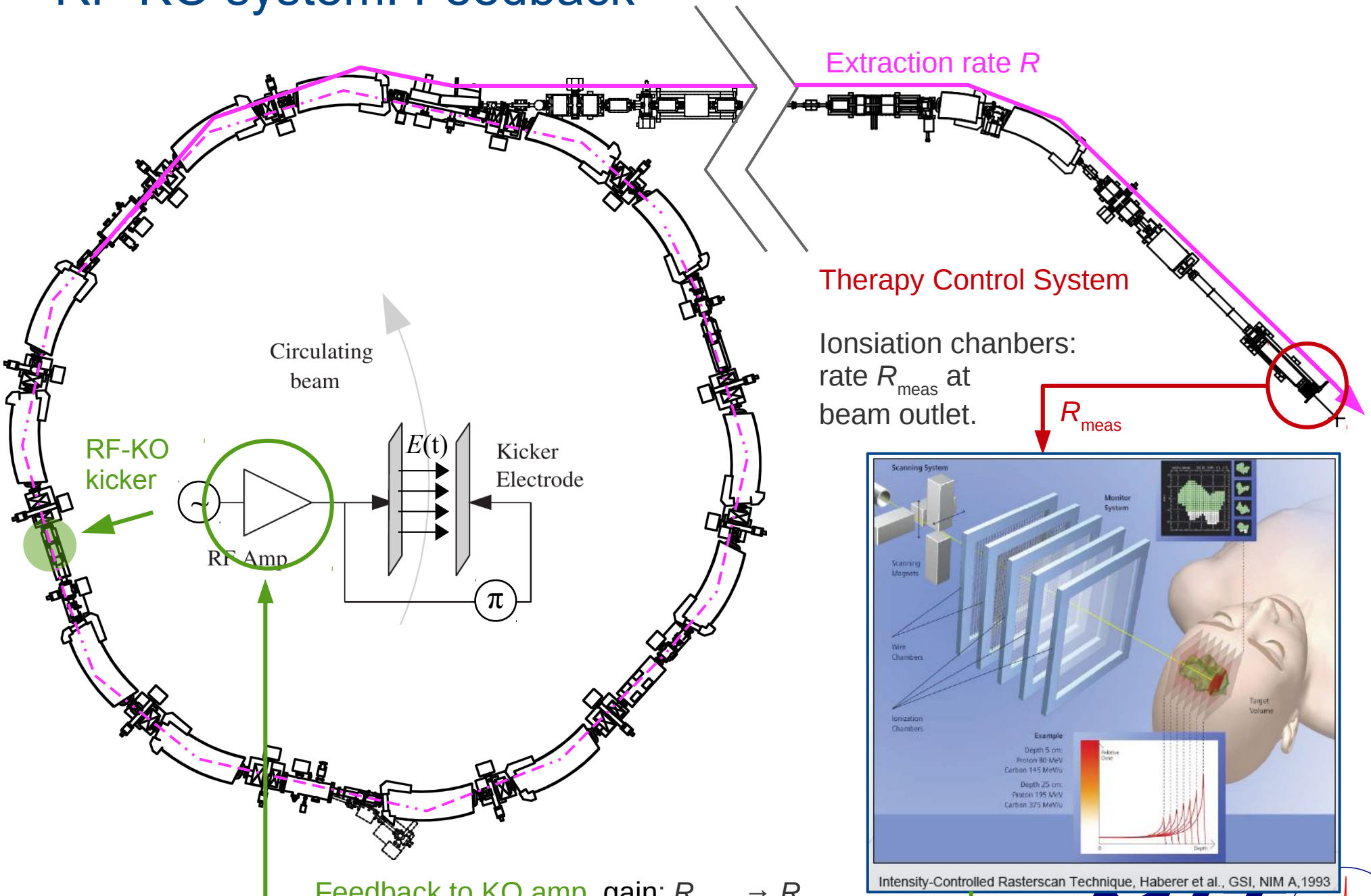
RF-KO system: Feedback



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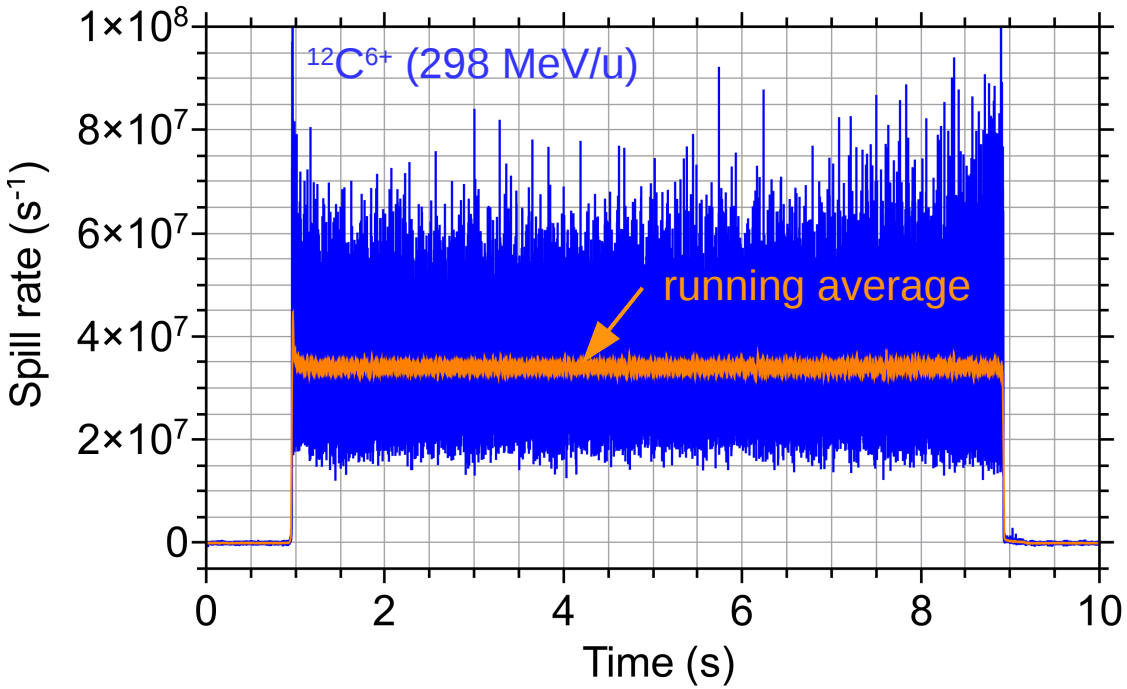
Spill quality

Spill contributed by MIT to the 2016 workshop:

C^{6+} (298 MeV/u), with DIC, 50 µs binning.



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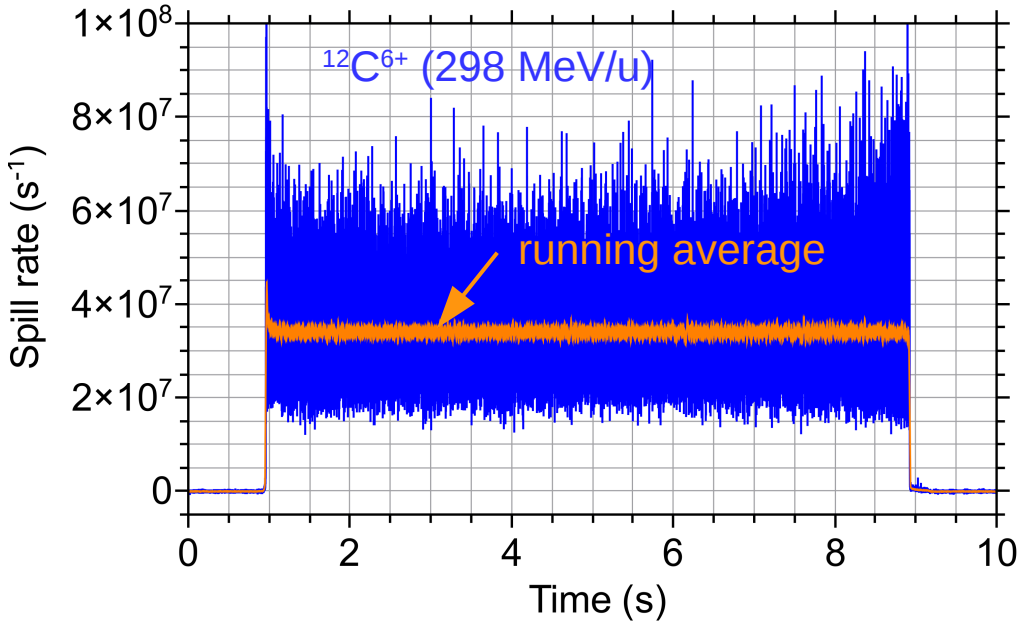
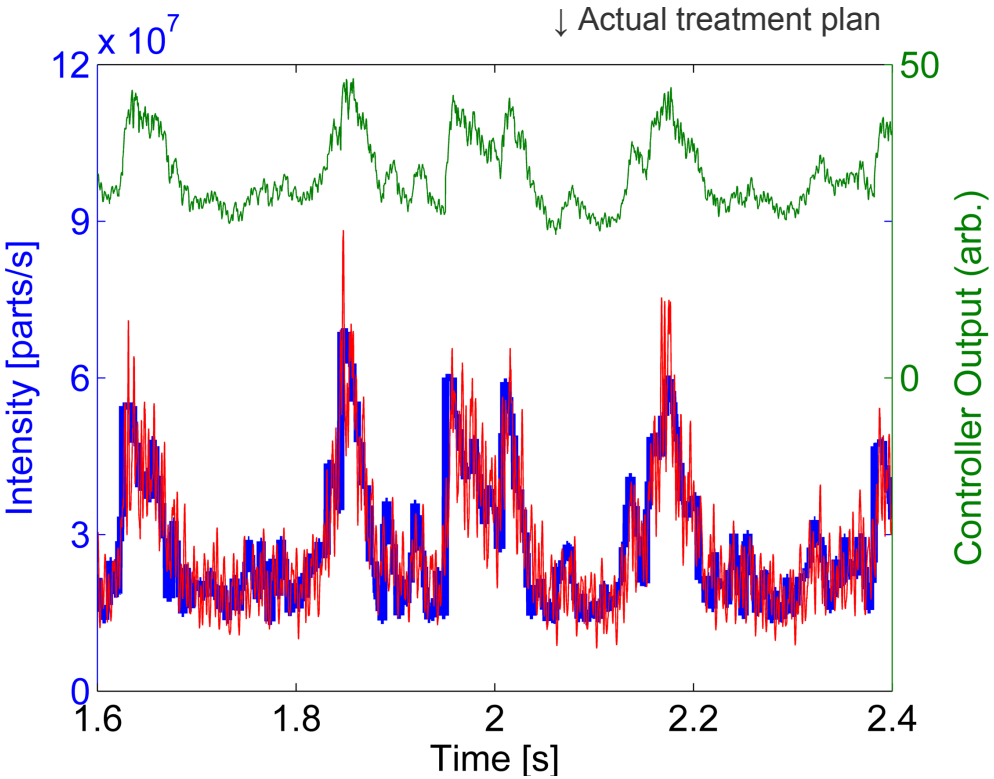
Spill quality



Spill **stabilisation** ...

… and spill **modulation!**

Beam response to RF-KO is fast.
Can *vary* the average spill rate
on ~ 10 ms time scale!



"Dynamic Intensity Control" (DIC)

See also: Schoemers, NIM A 795 (2015) 92–99

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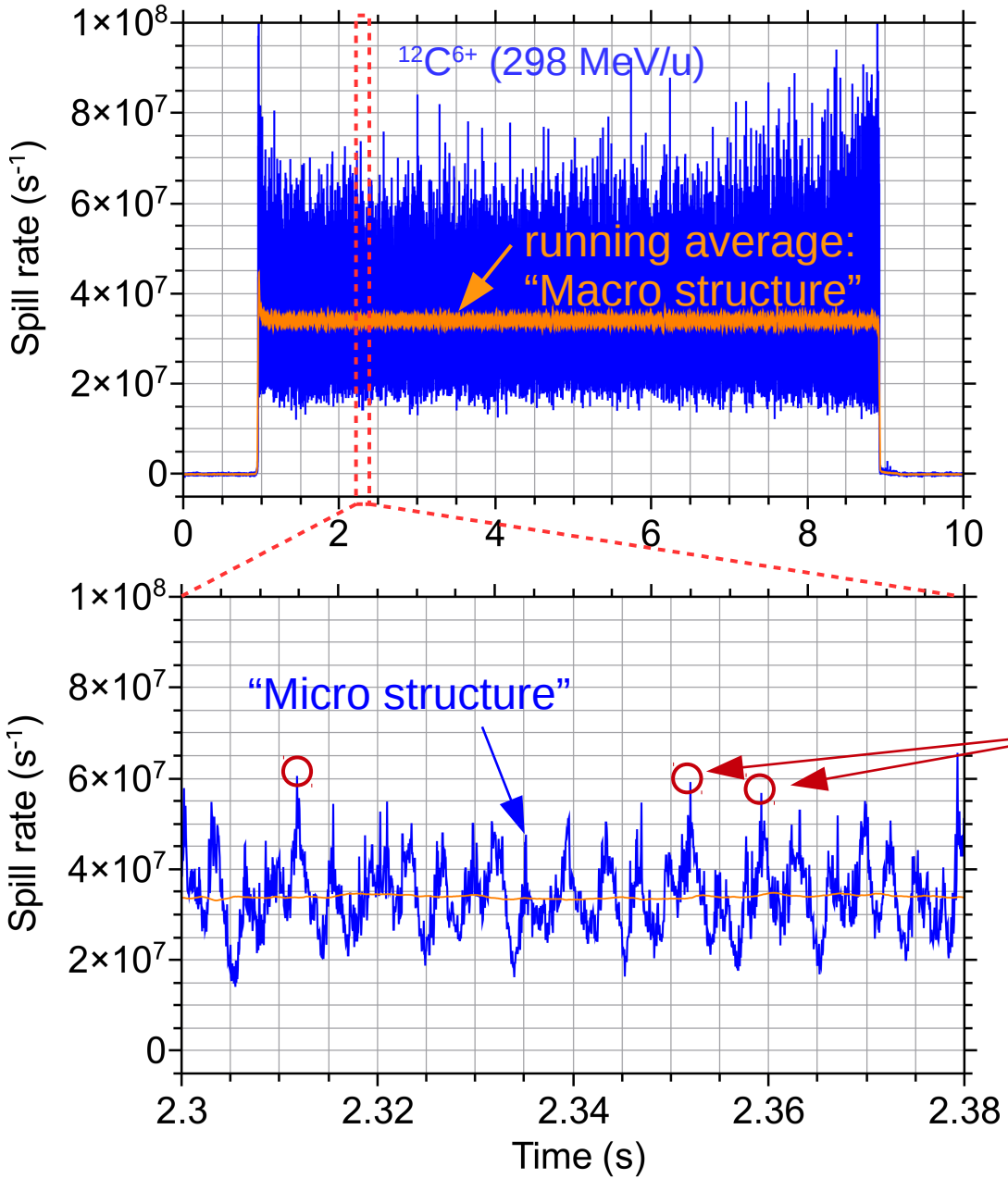
Spill quality



DIC feedback to RF-KO

→ provides very good **"macro structure"** (time scales down to ~ 10 ms),

→ on shorter times **"micro structure"** remains. (kHz ... MHz frequencies).

Note:
time resolution of IC detectors blurs structures below ~ 10 … 100 µs!

Spikes in extraction rate
→ can saturate ICs
→ automatic beam dumps

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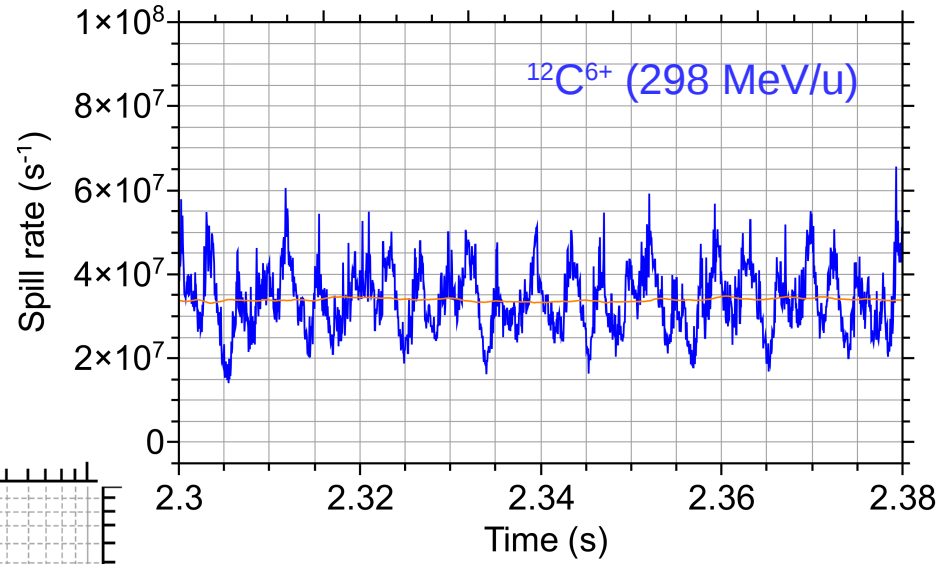
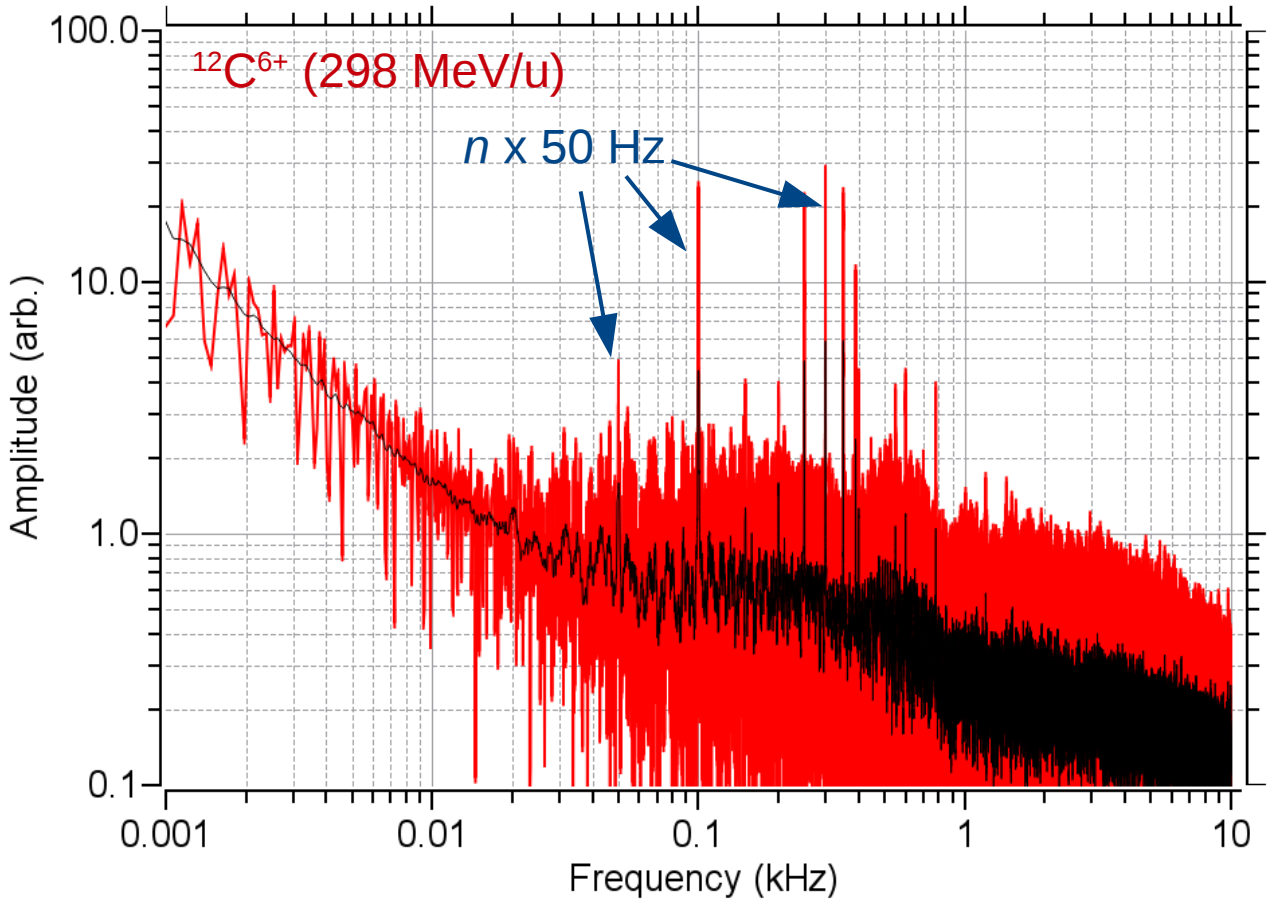
Spill quality



FFT



Micro-structure:

dominant *n* x 50 Hz (power-grid) lines.

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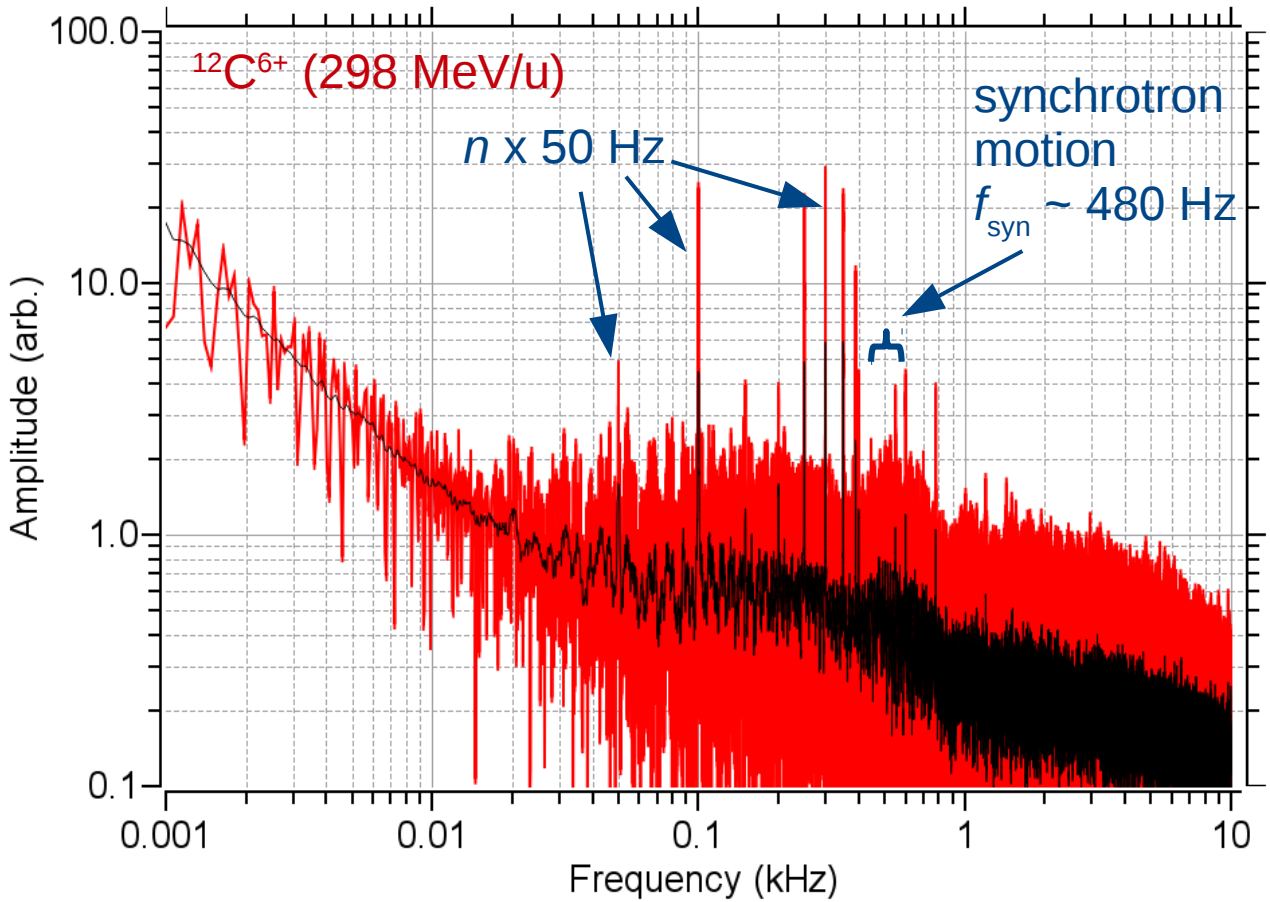
Spill quality



Spill optimisation techniques:

1) Extraction from bunched beam.

   → Sync. motion combined with chromaticity.

   → Faster sparatrix crossing.

   (Adopted from GSI)
   e.g. Sorge et al., Proc. IPAC 2018

2) "Matching" of RF-KO spectrum and particle tunes.

   → Excite high betatron amplitudes preferentially.

   → Faster sparatrix crossing.

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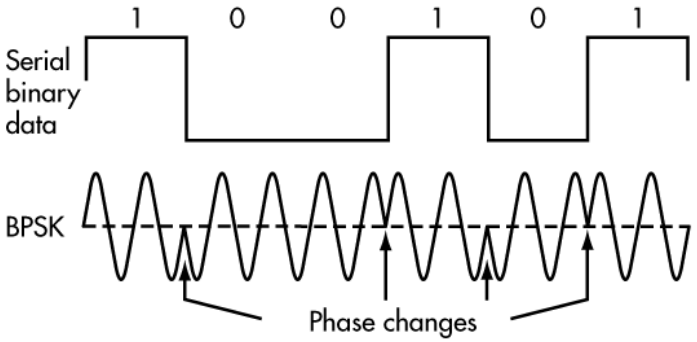
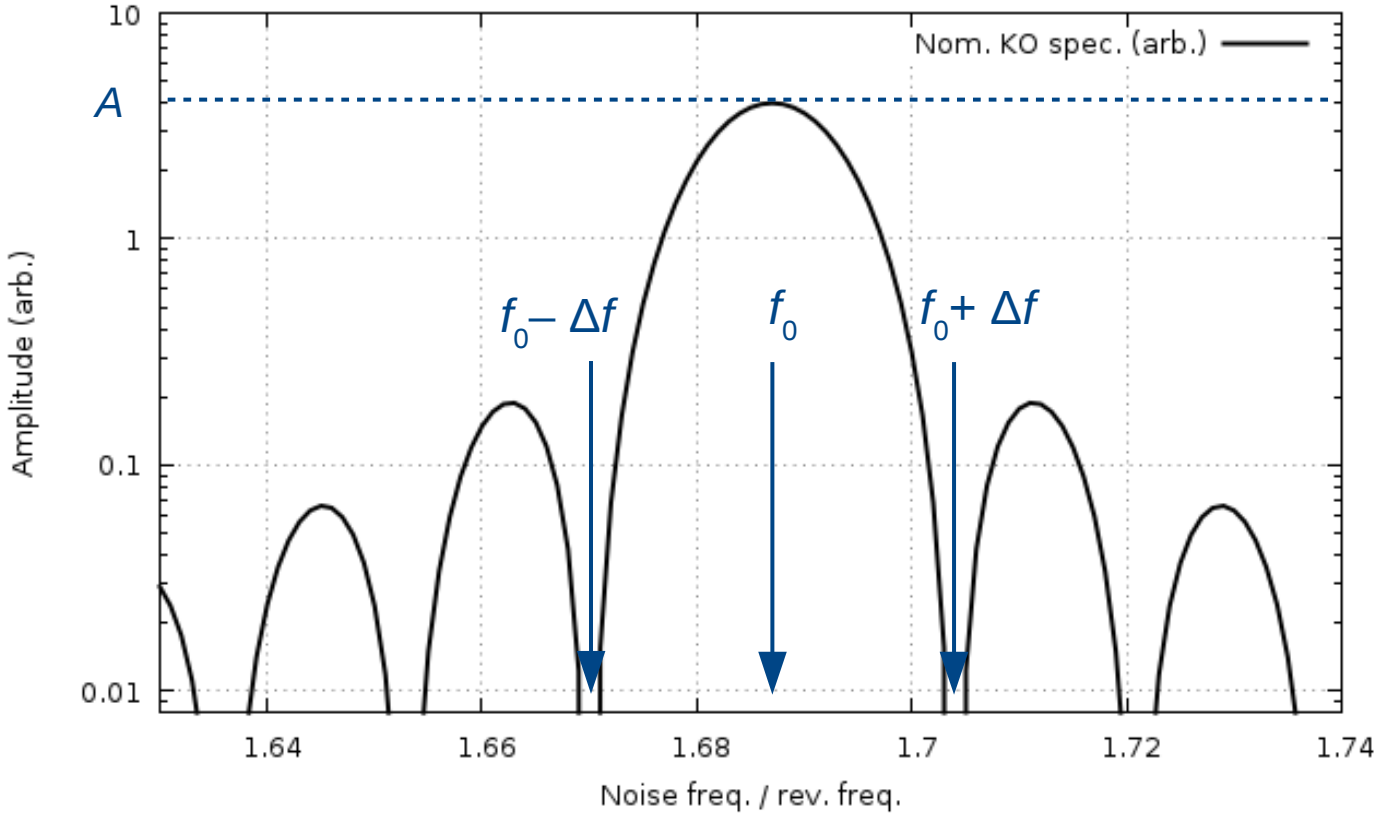
RF-KO Spectrum

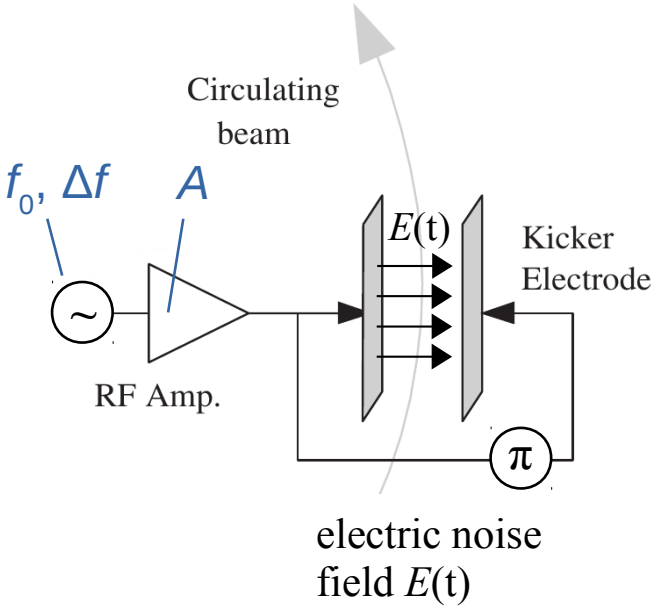
RF-KO spectrum is generated by **random phase-shift keying** (PSK).

3 parameters define the noise kicker spectrum:

- f_0: Main oscillator frequency
- Δf : Random PSK frequency
- A: Amplitude







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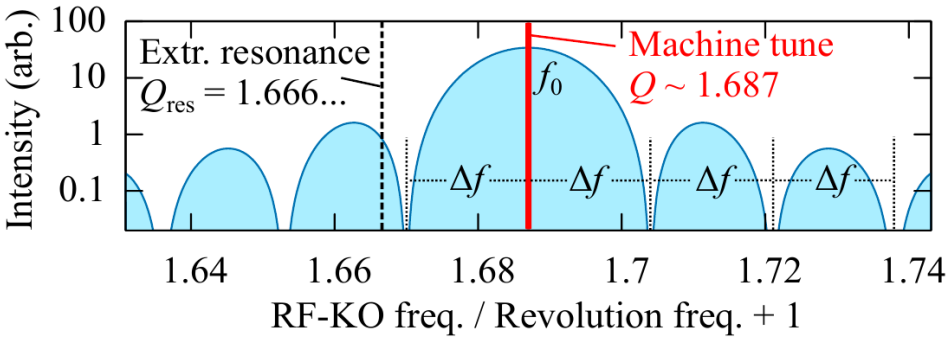
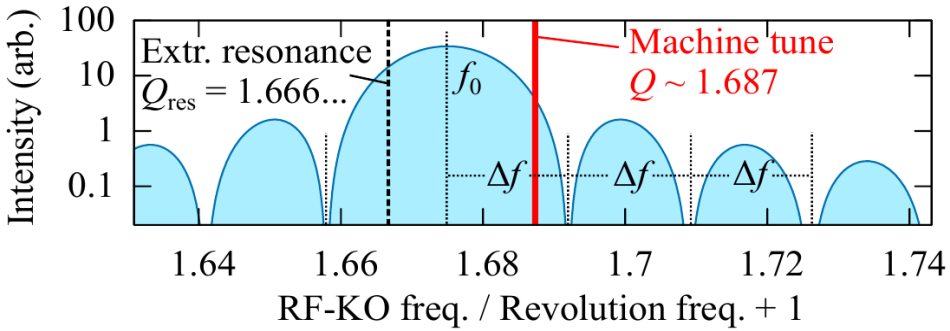
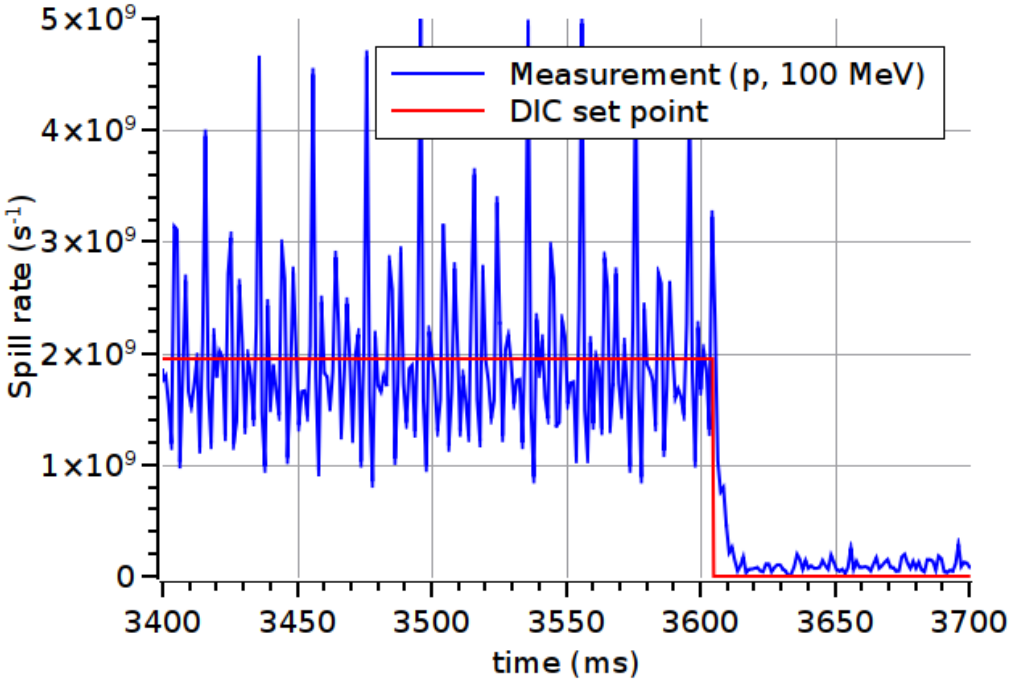
Micro structure: Effect of RF-KO spectrum

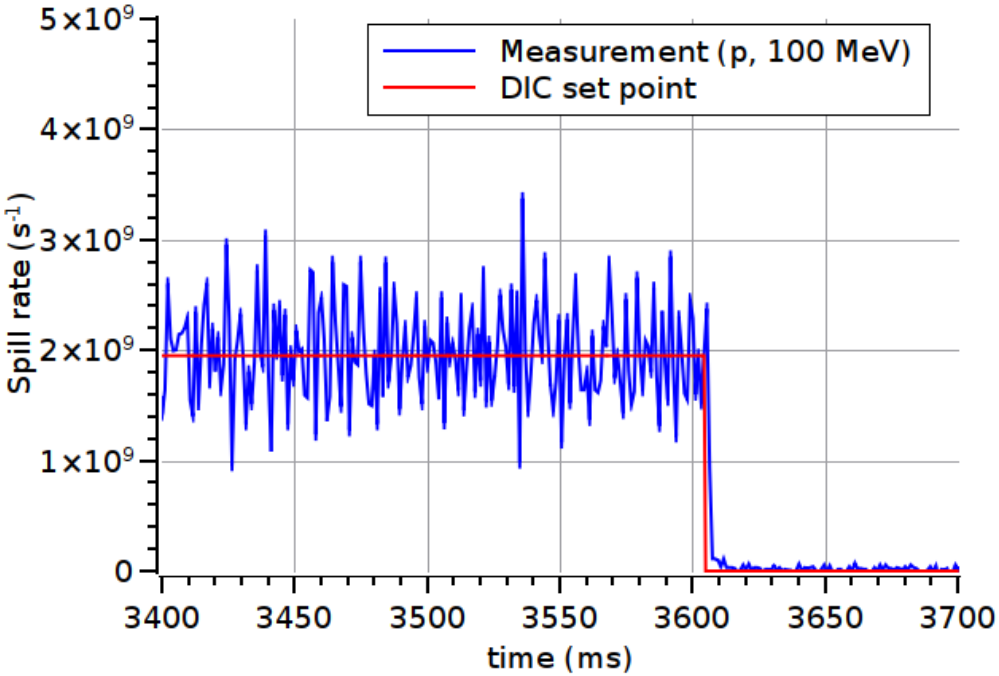
"Bad": RF-KO ~ Machine tune



"Good": RF-KO → Extraction res.







Krantz et al., Proc IPAC 2018

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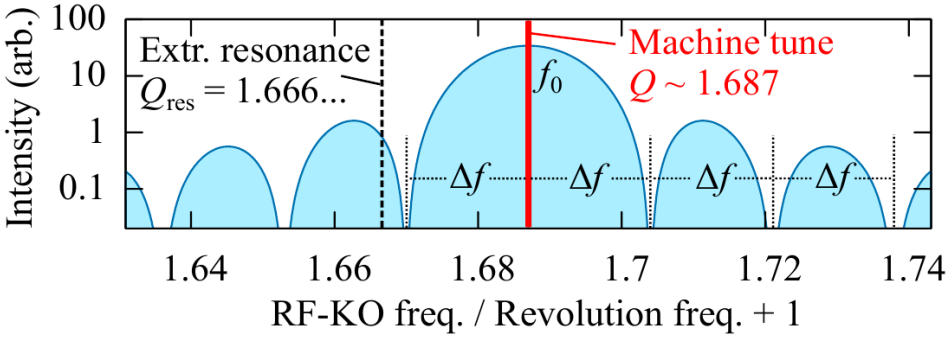

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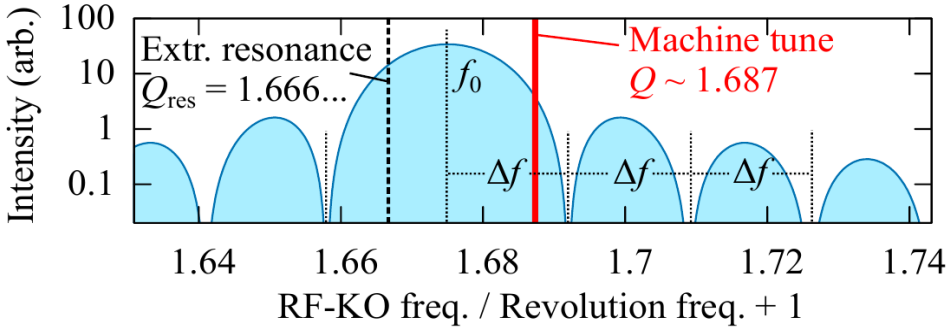

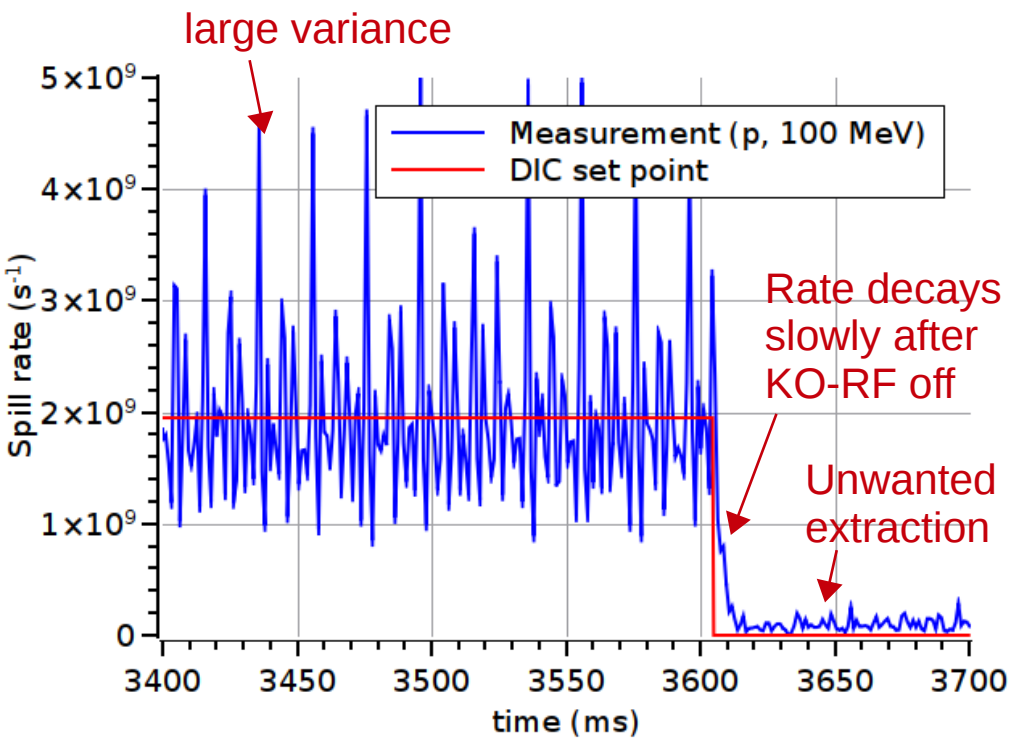

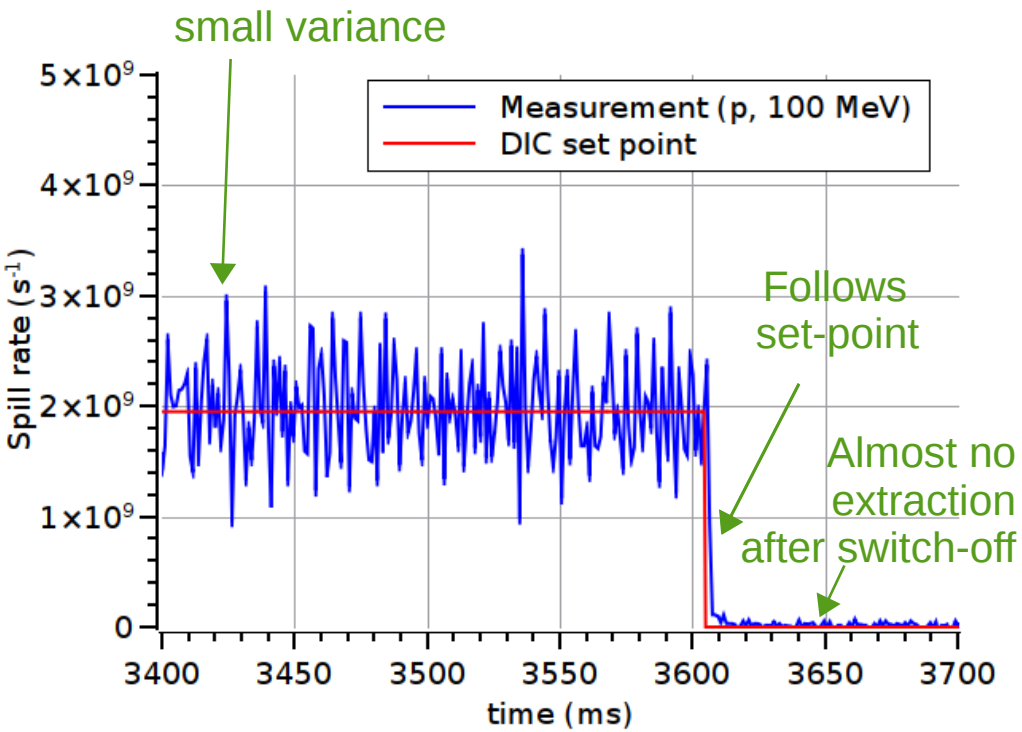

Krantz et al., Proc IPAC 2018

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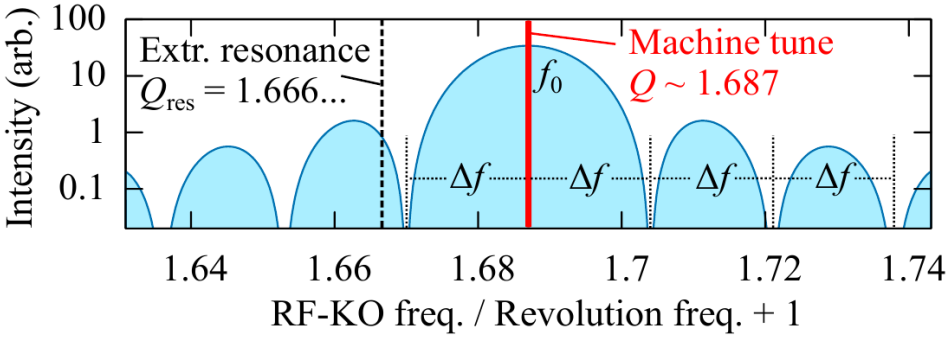

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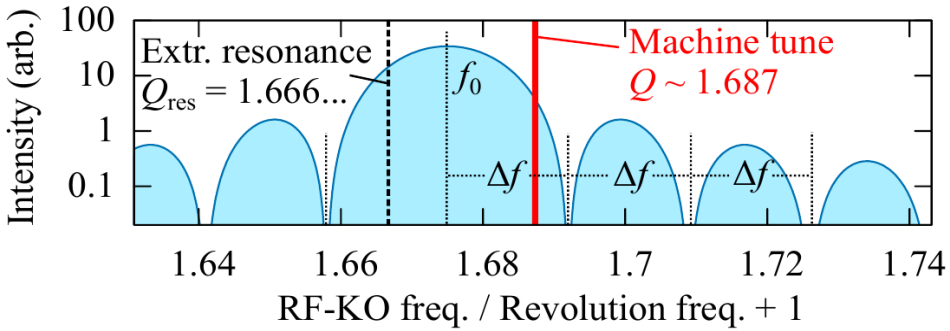
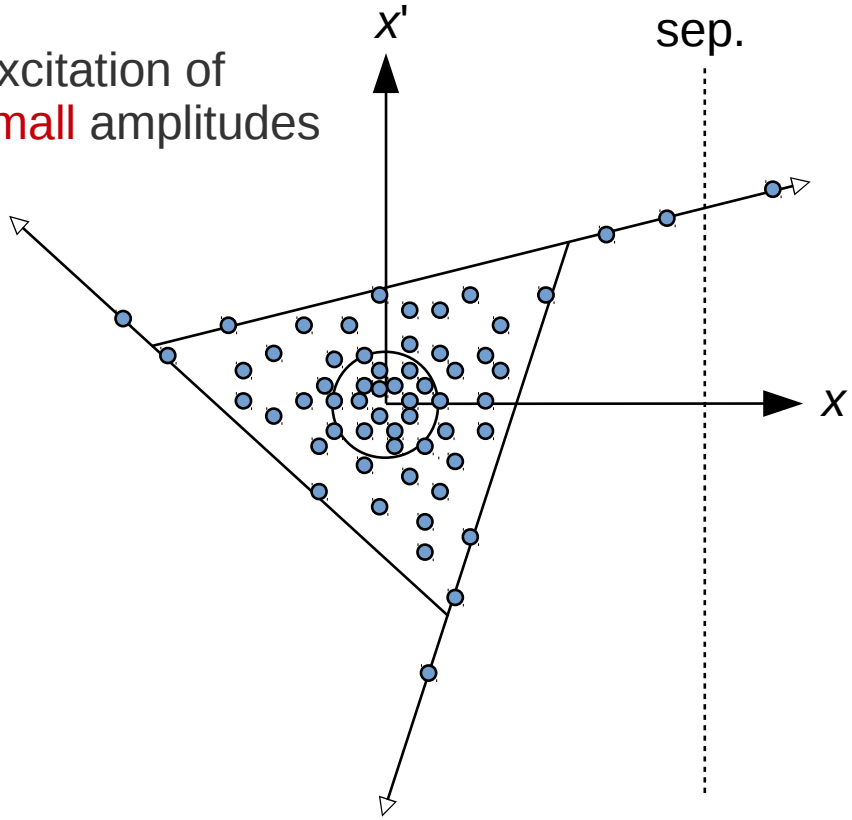
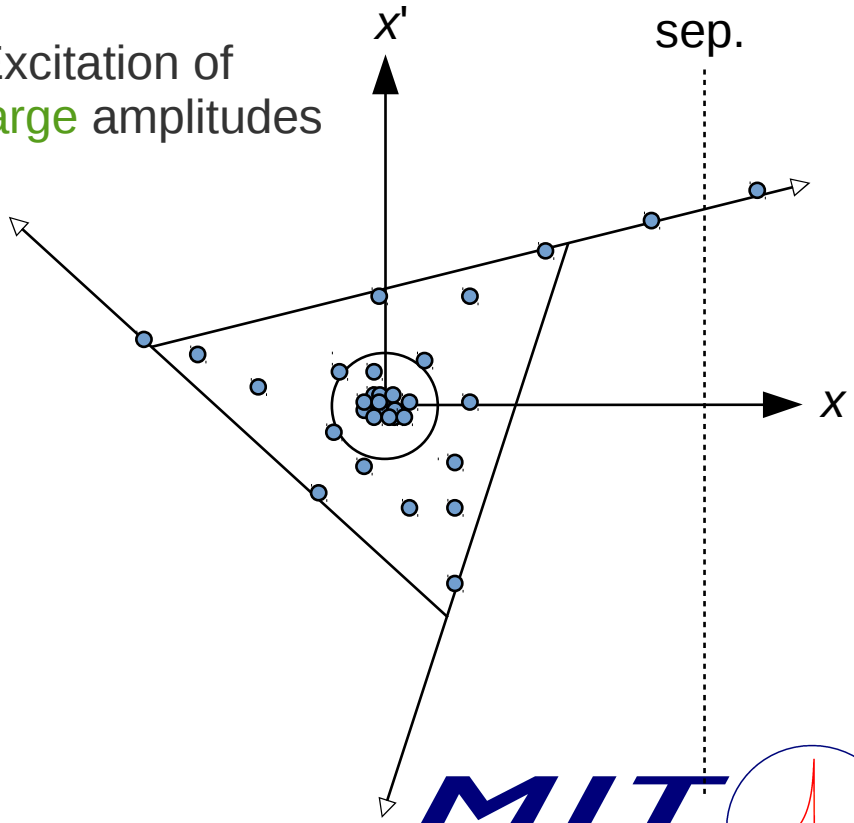


Excitation of small amplitudes



Excitation of large amplitudes



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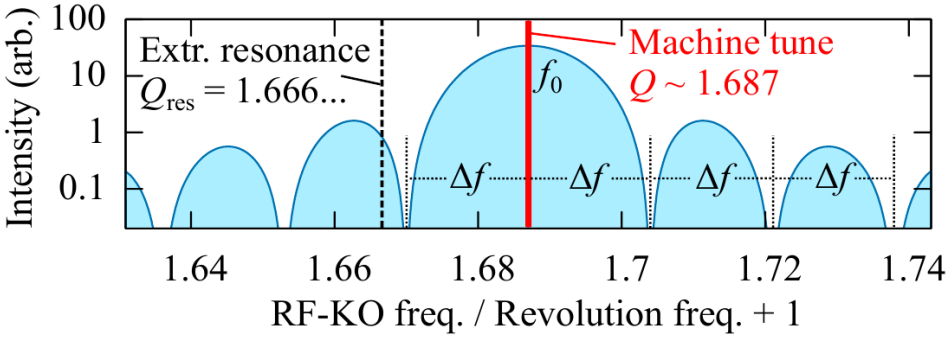
Micro structure: Effect of RF-KO spectrum

"Bad": RF-KO ~ Machine tune



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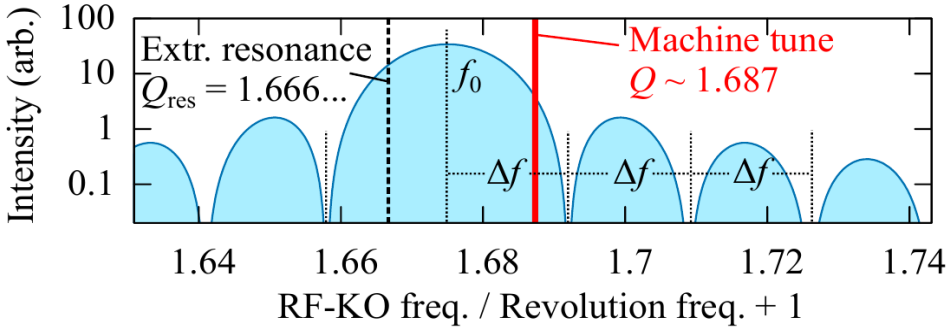
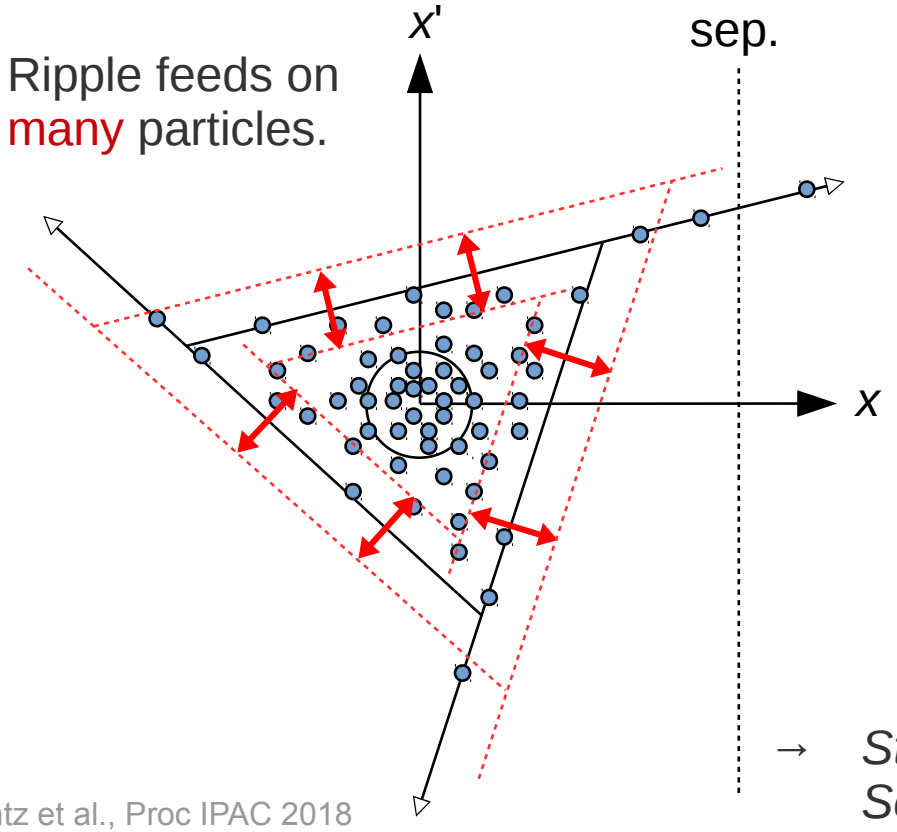
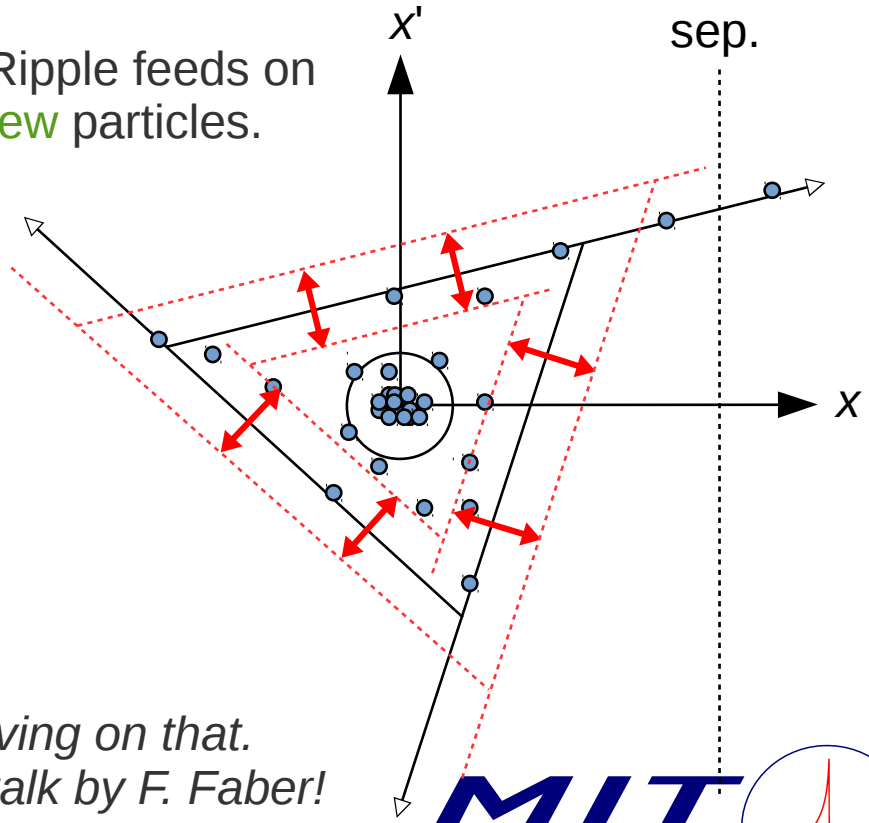


Ripple feeds on many particles.



Ripple feeds on few particles.



→ *Still improving on that.*
See next talk by F. Faber!

Krantz et al., Proc IPAC 2018

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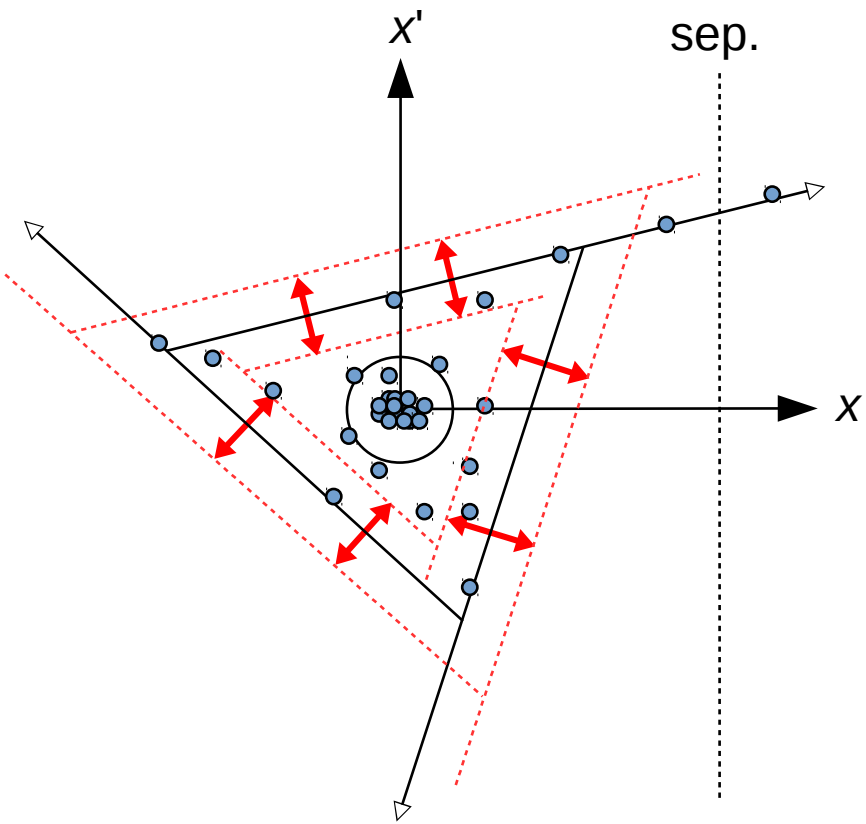
Micro structure: Ripple cancellation



Additional project since 2018:

Reduction of separatrix ripple

→ Stabilise machine tune via fast corrections of the quadrupole fields.

(“noise cancellation”)

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Ripple cancellation @ CNAO

Ripple compensation using an Air Core Quadrupole (ACQ) magnet has been demonstrated at the CNAO hadron therapy centre (Italy).

(cf. presentation by M. Pullia)

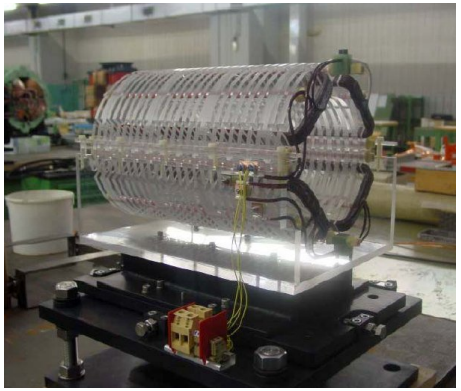
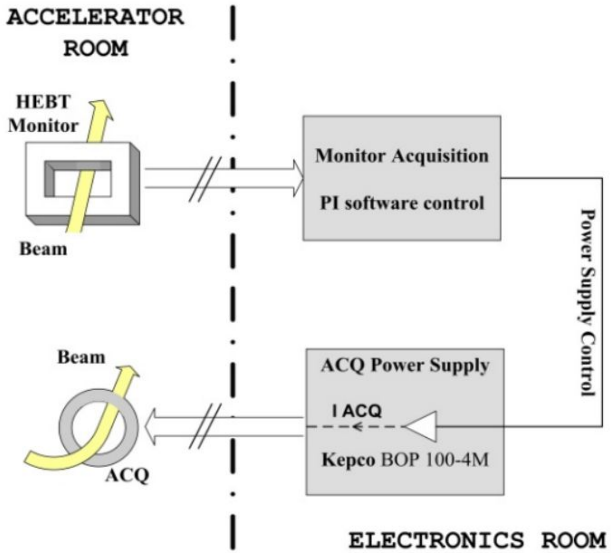
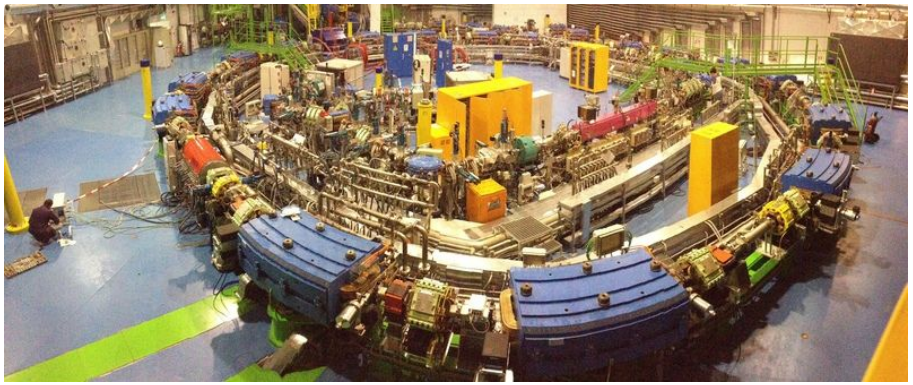
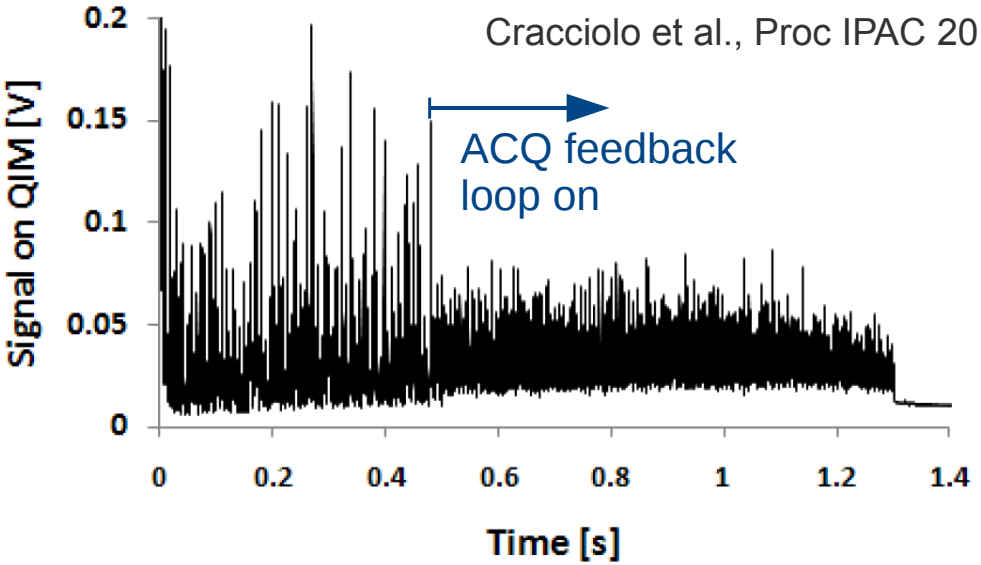


image: courtesy of M. Pullia





fondazionecnao.it



Cracciolo et al., Proc IPAC 2011

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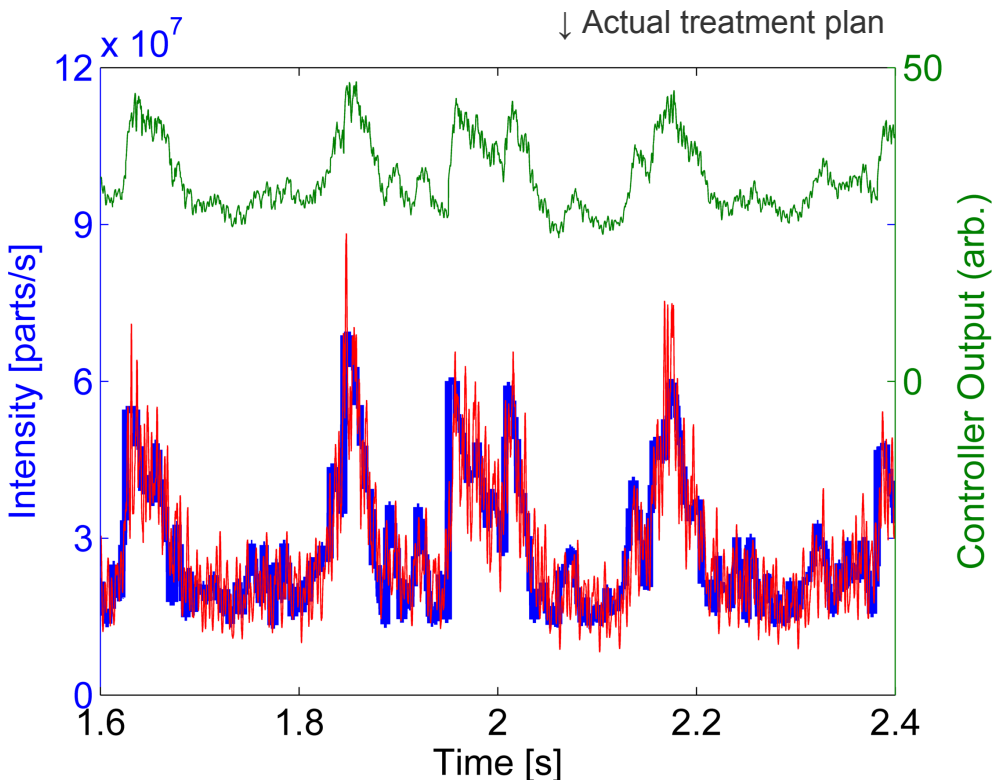
At MIT and HIT: Compatibility with DIC RF-KO required

DIC may *vary* the spill rate on the ~ 10 ms scale!

→ Possible ripple cancellation systems must be compatible with this wanted (but random) spill modulation!

A feedback loop could be prone to in-fighting with the DIC



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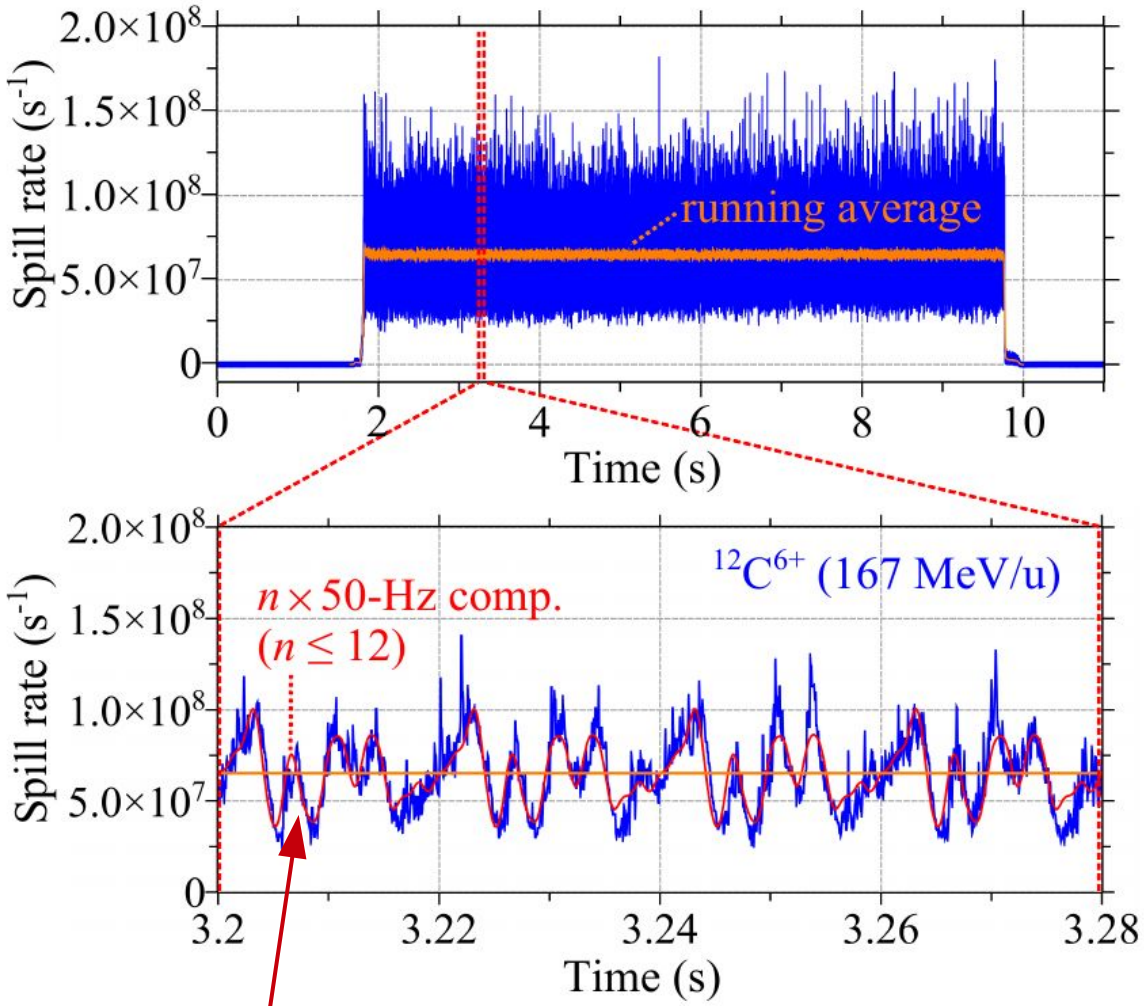
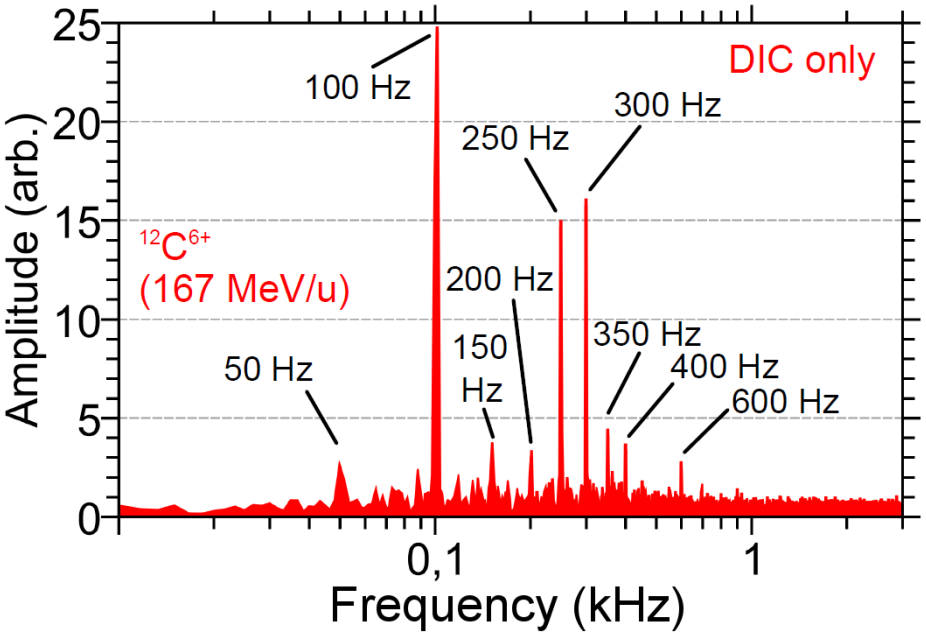
Cancellation of power-grid harmonics



Instead: Forward correction of power-grid harmonics (n x 50 Hz) …



Principle:
Use this function (inverted) as basis for the machine tune correction.
(And hope it is stable over time ...)

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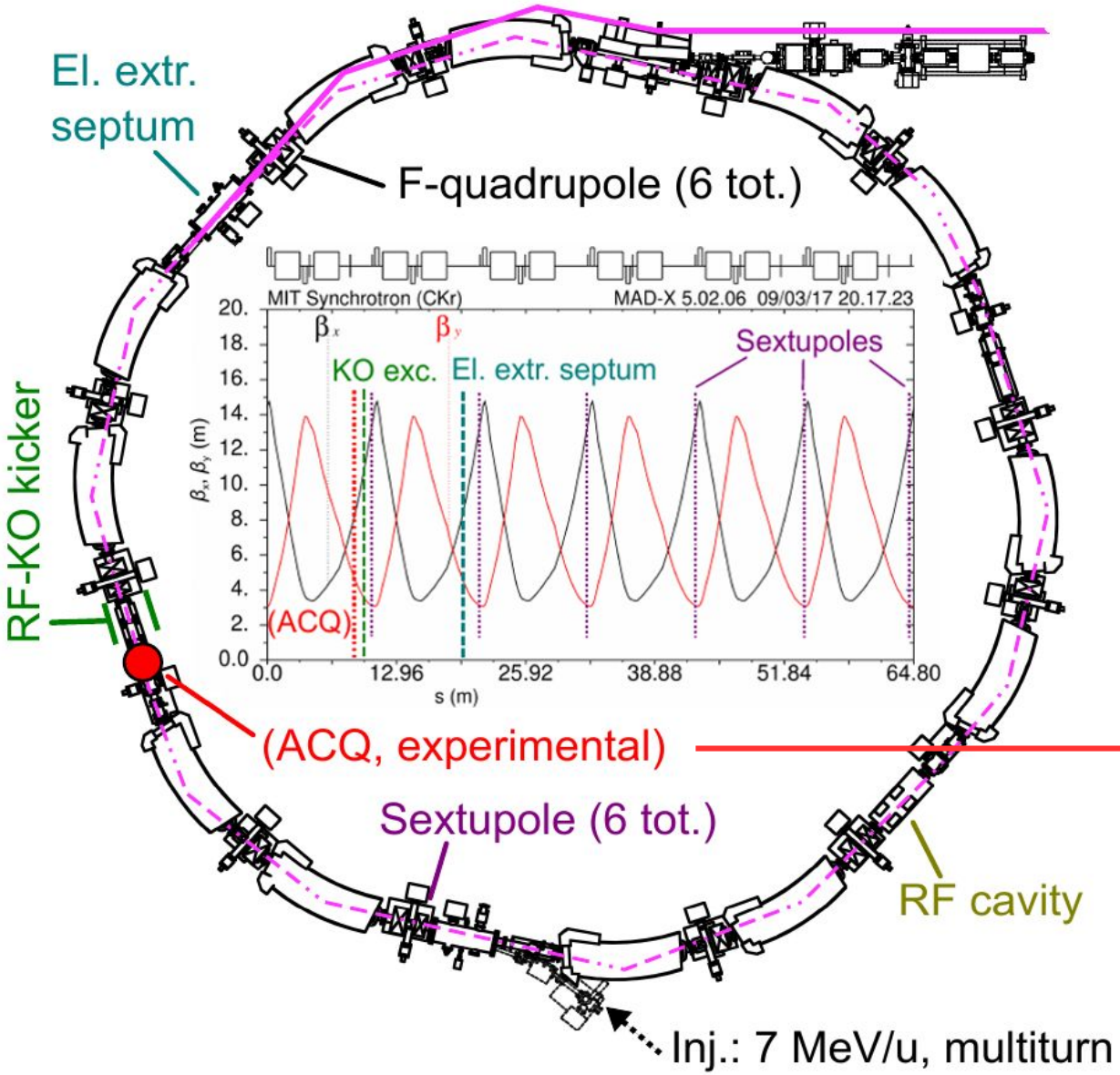
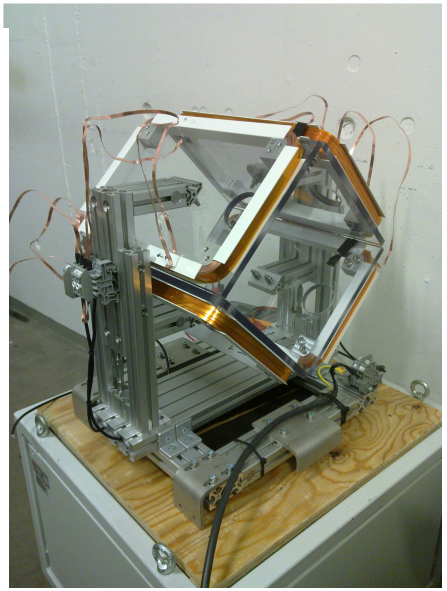
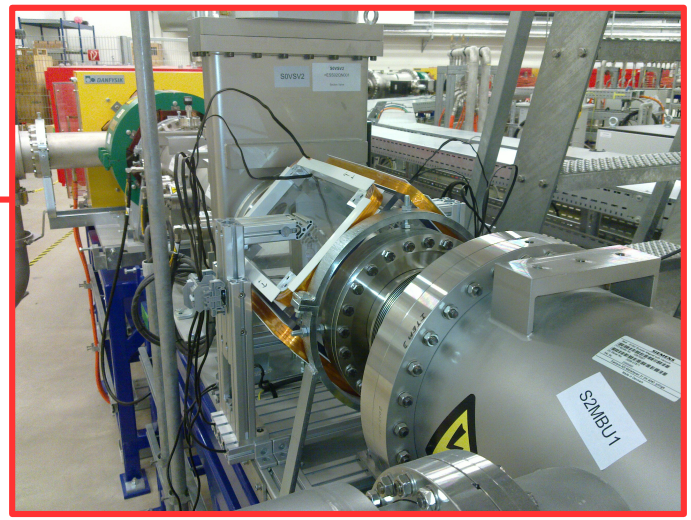
A simple Air-Core Quadrupole magnet: Use at MIT





Prototype ACQ built at MIT.

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



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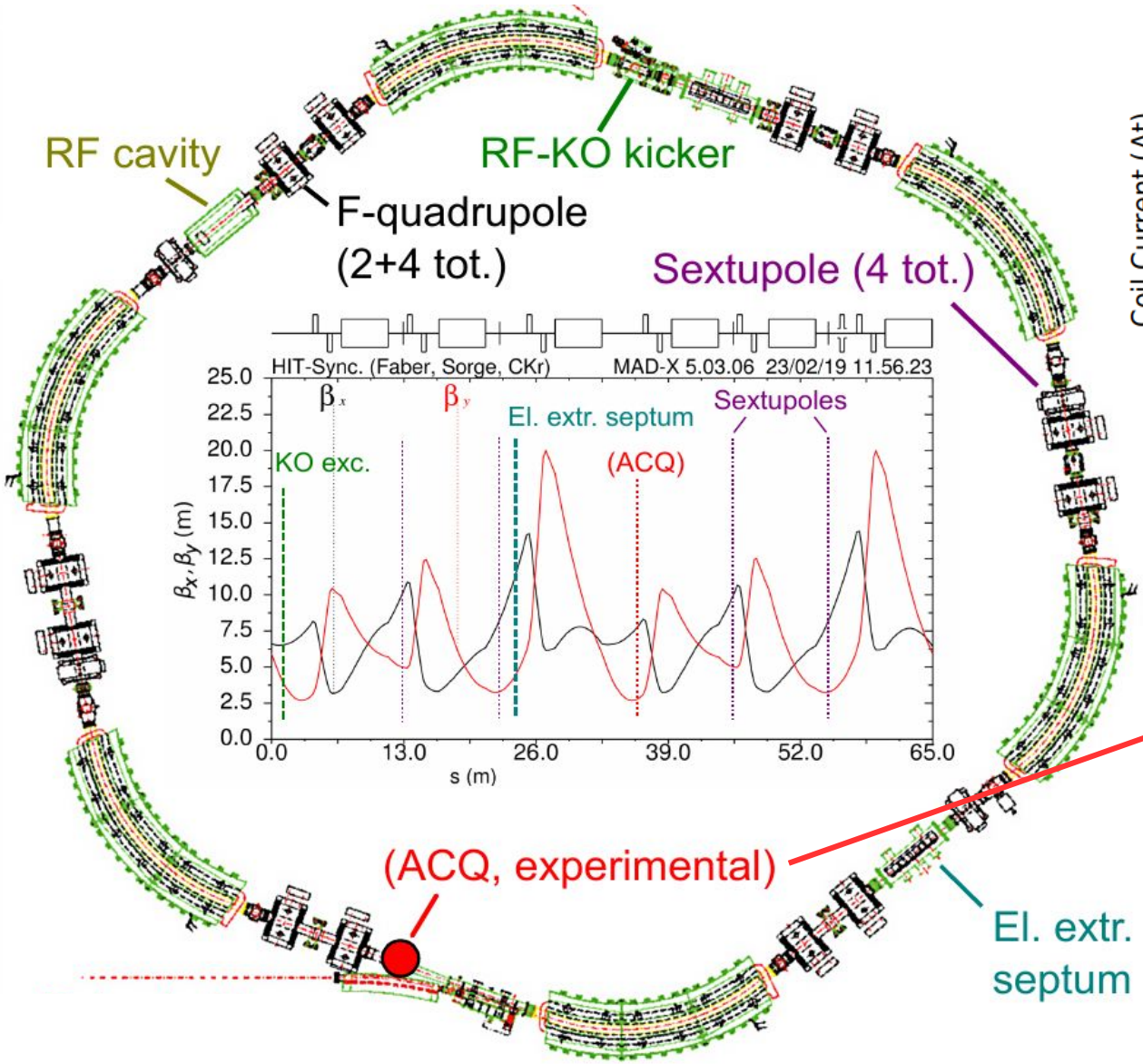
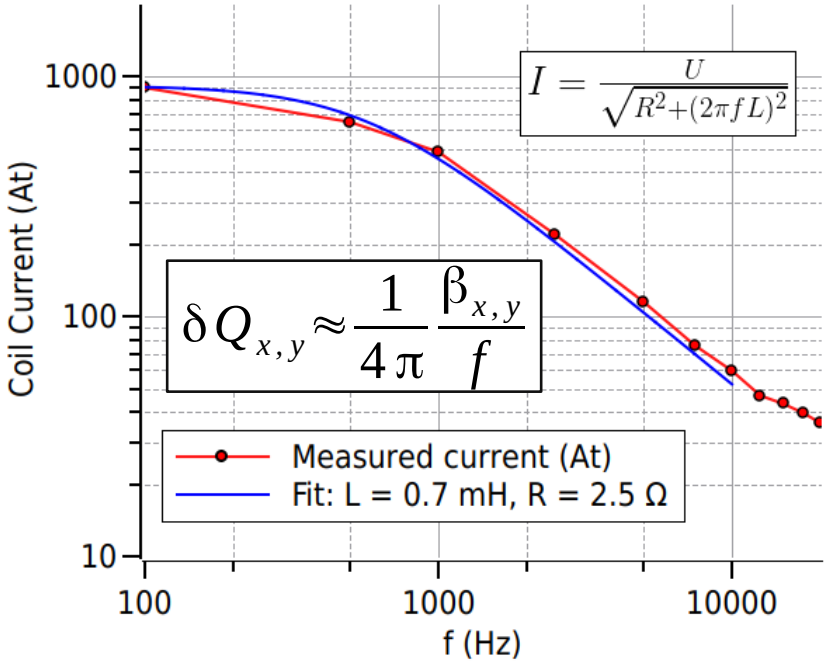
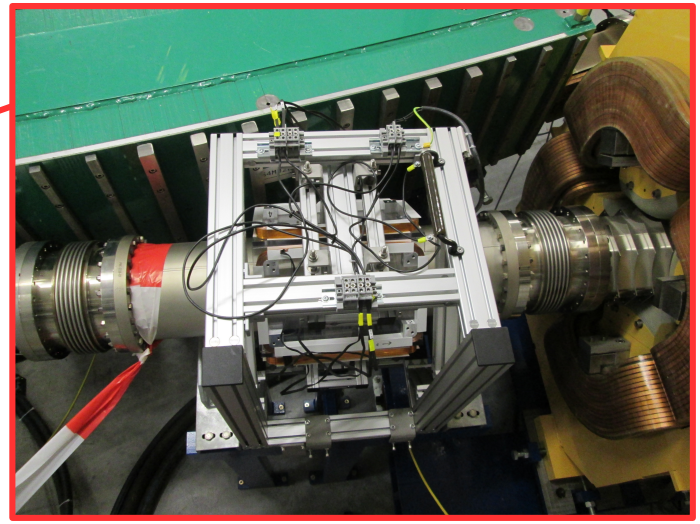
A simple Air-Core Quadrupole magnet: Use at HIT







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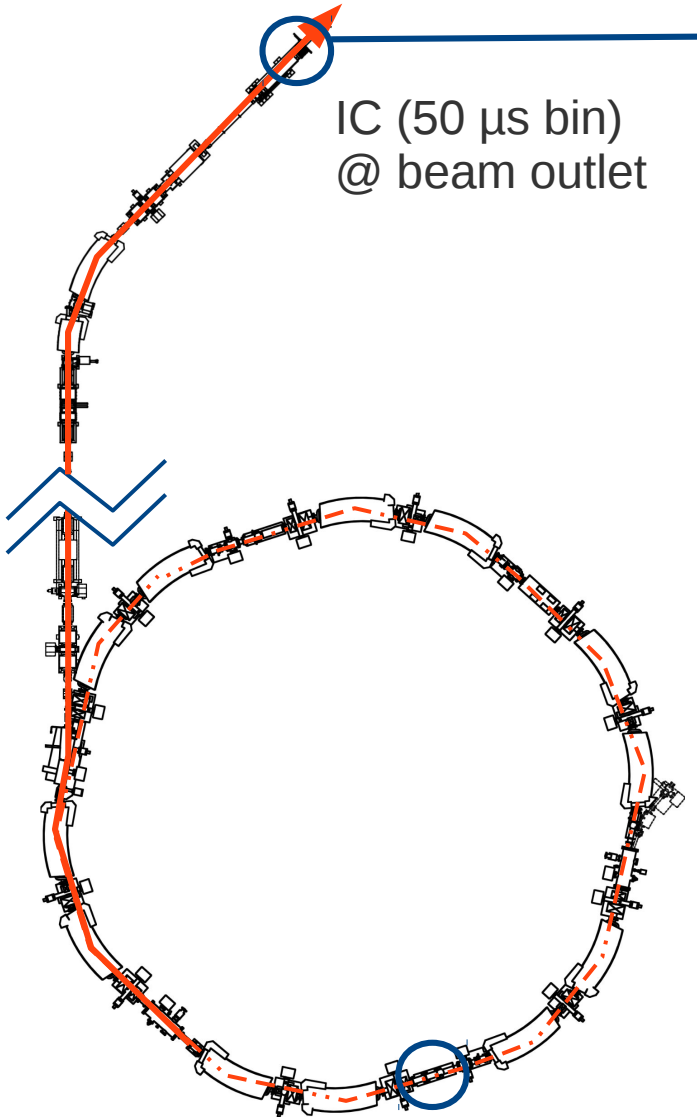
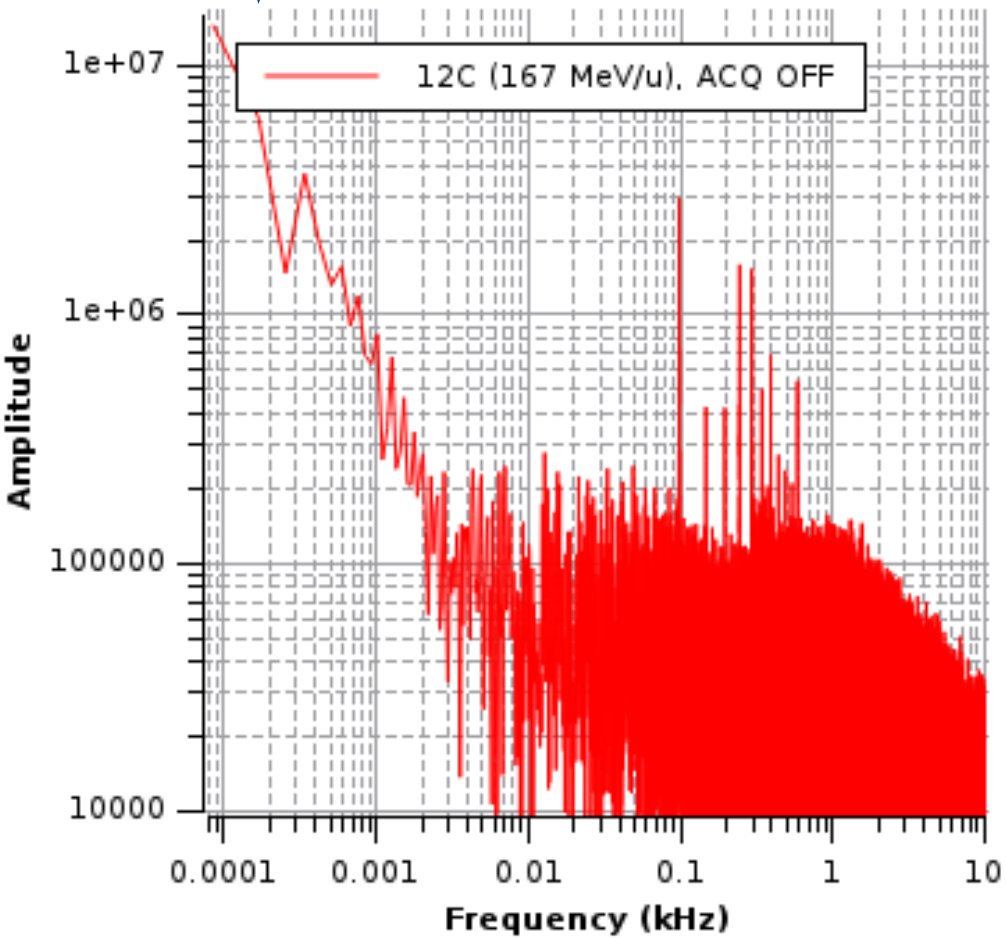
Beam Response to ACQ



FFT of spill (ACQ OFF)



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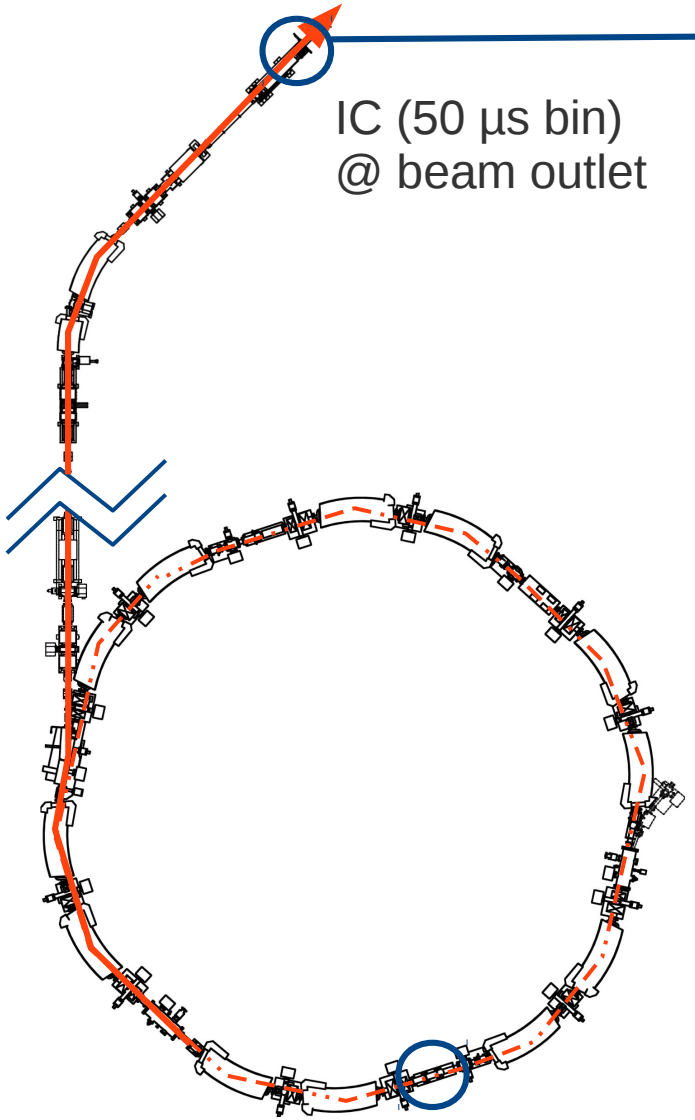
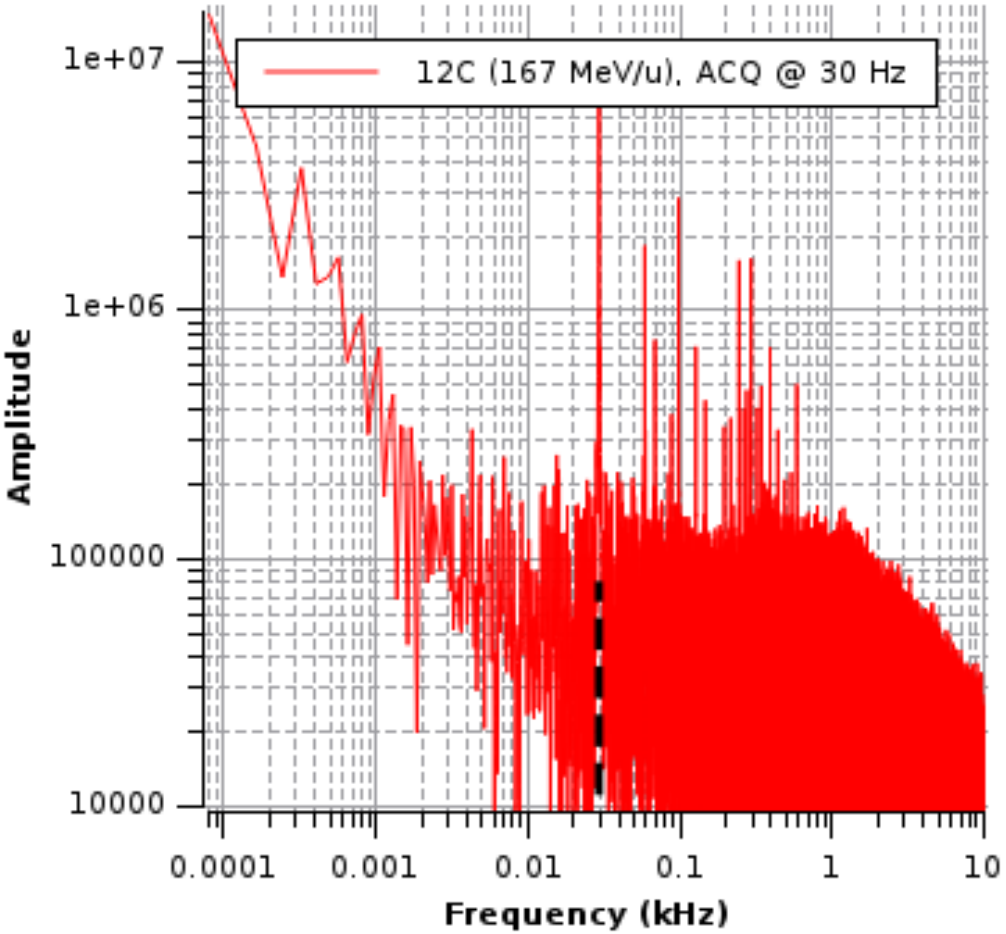
Beam Response to ACQ



FFT of spill (ACQ @ 30 Hz)



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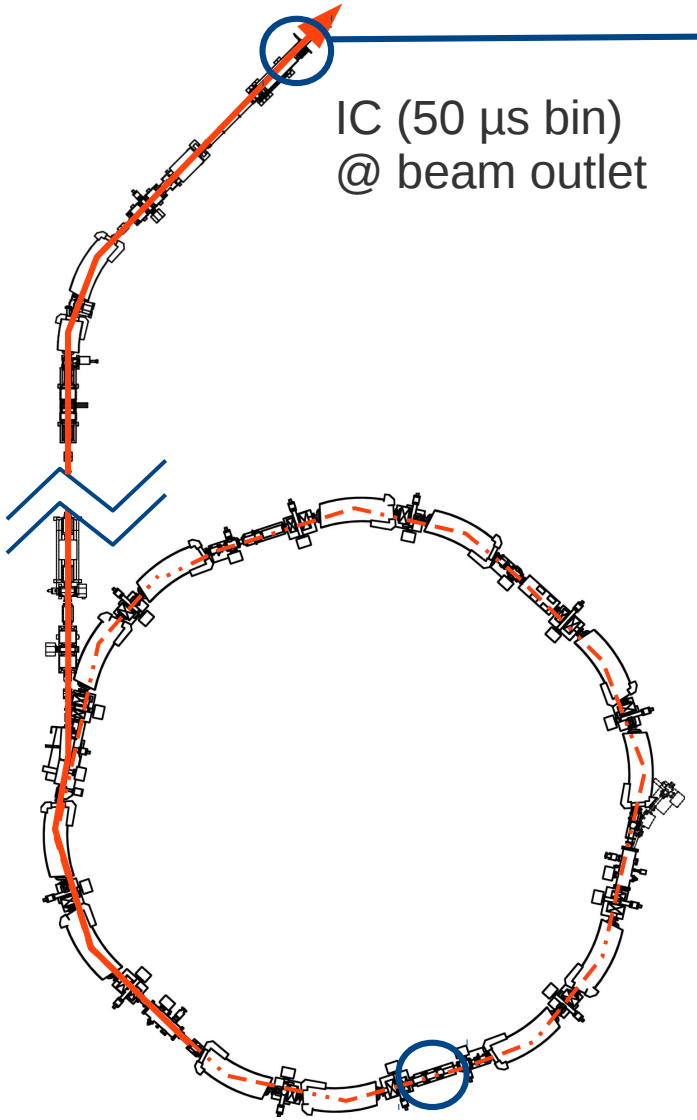
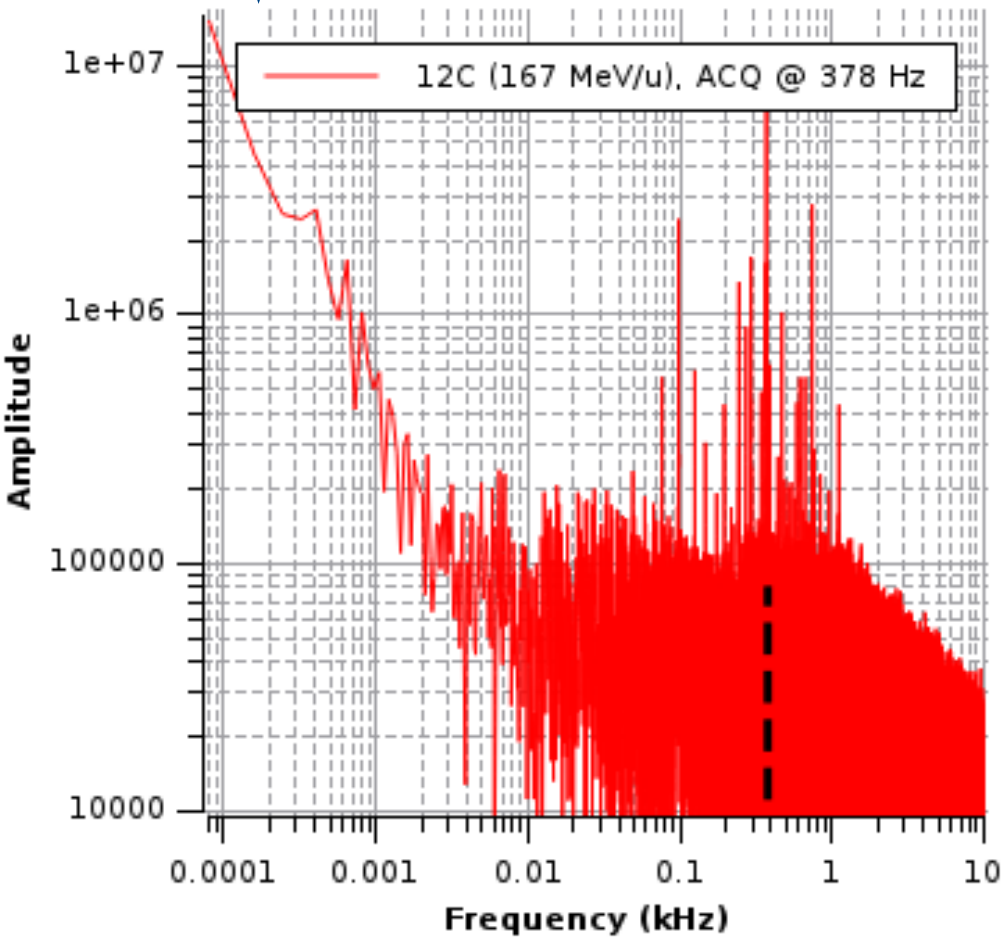
Beam Response to ACQ



FFT of spill (ACQ @ 378 Hz)



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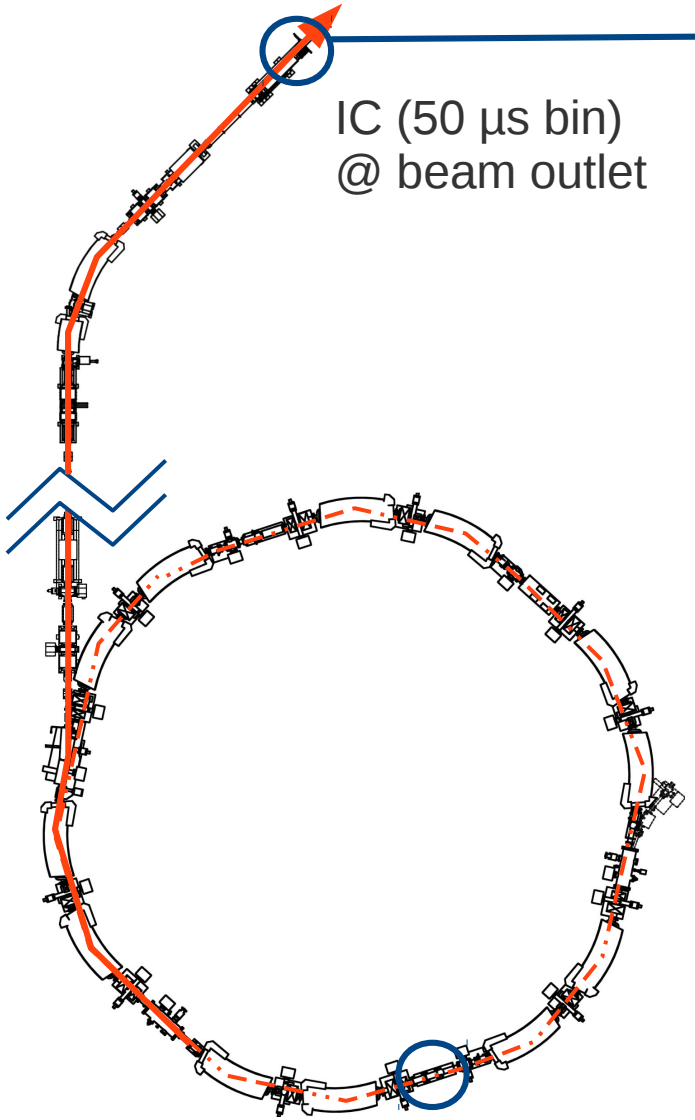
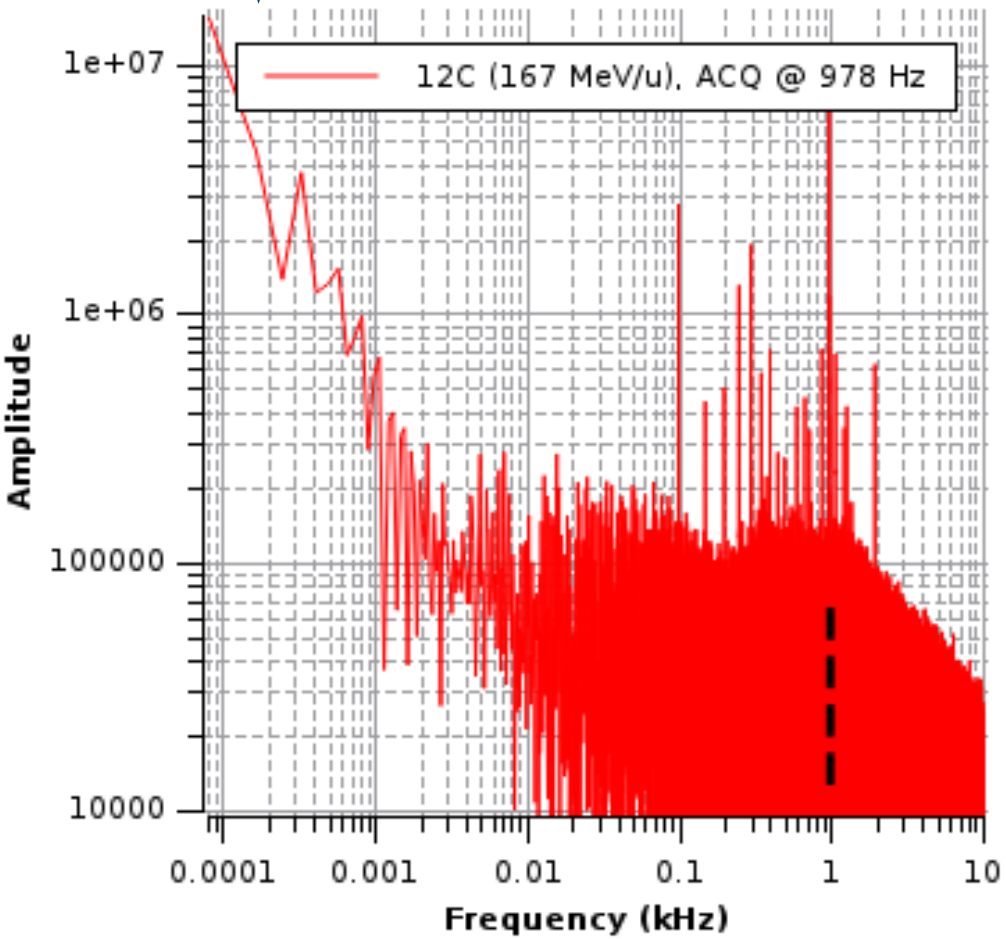
Beam Response to ACQ



FFT of spill (ACQ @ 978 Hz)



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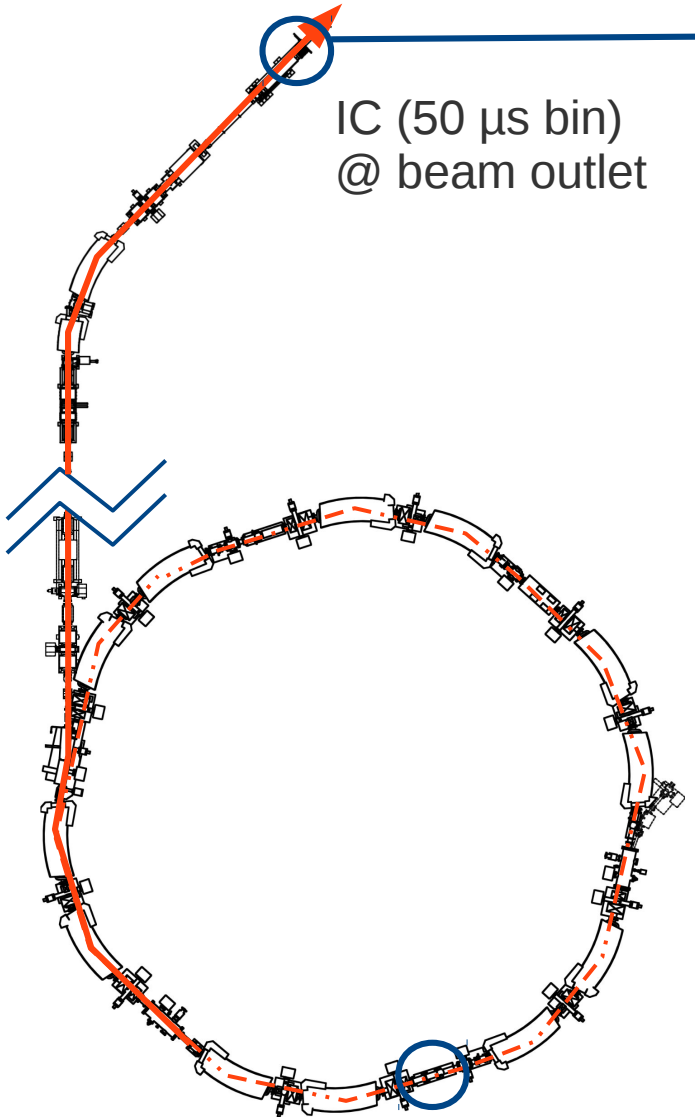
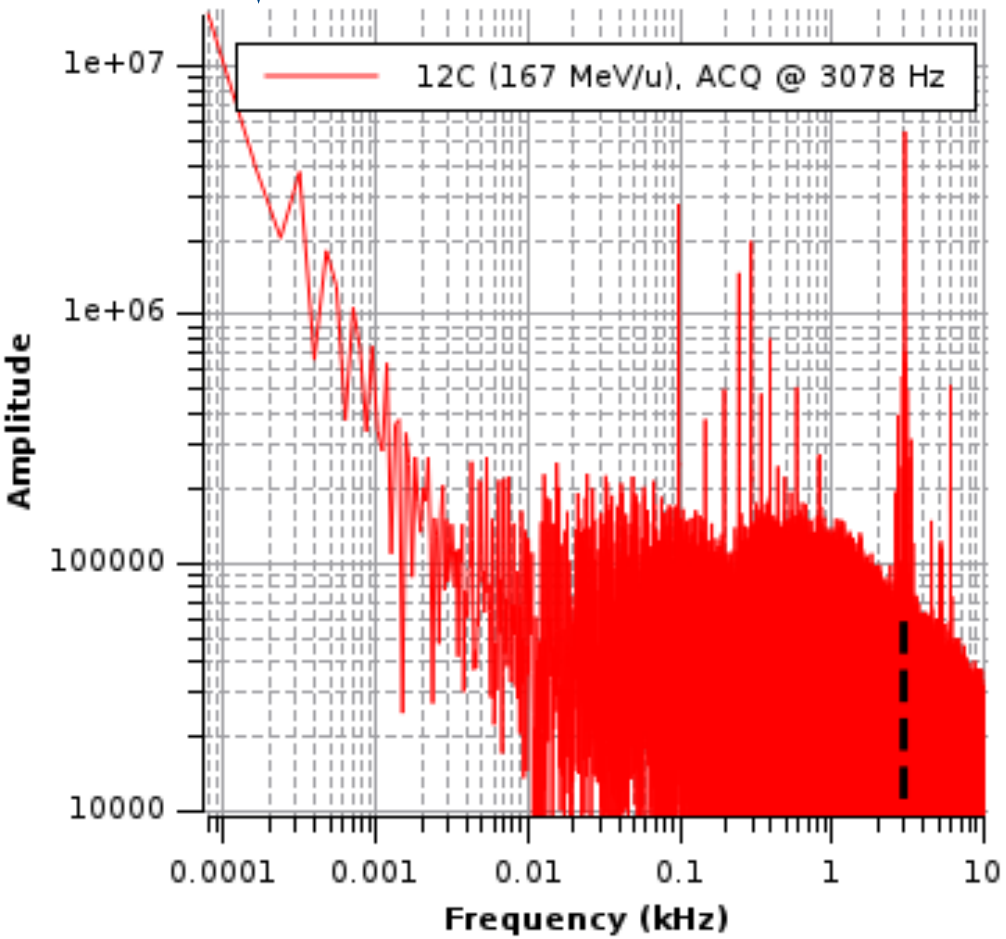
Beam Response to ACQ



FFT of spill (ACQ @ 3078 Hz)



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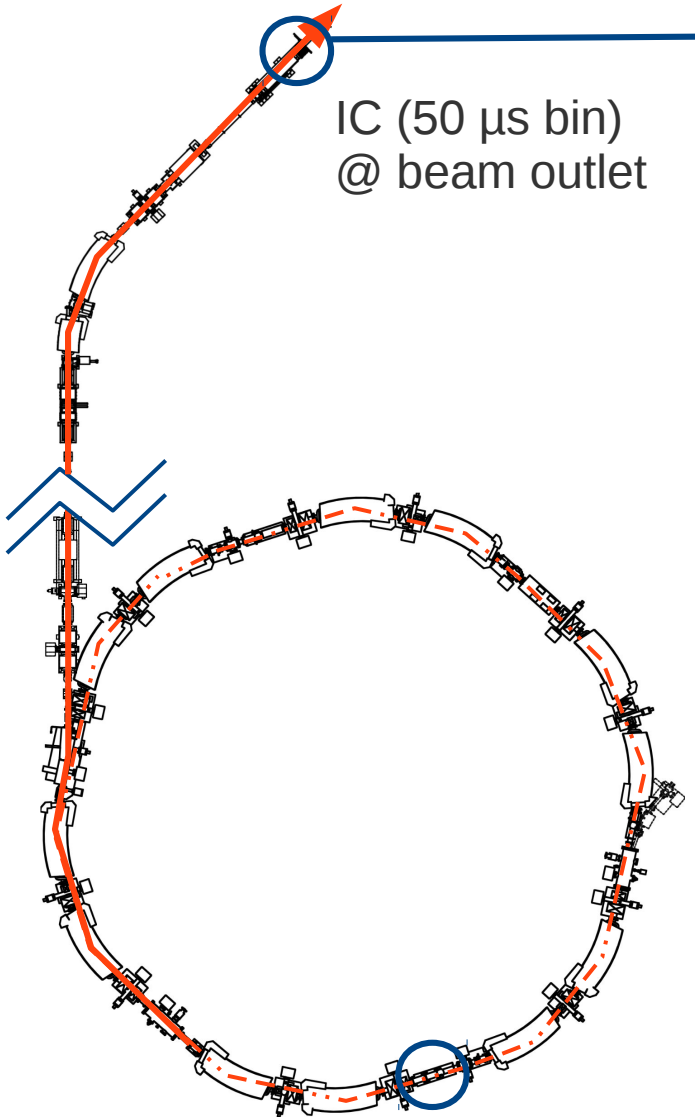
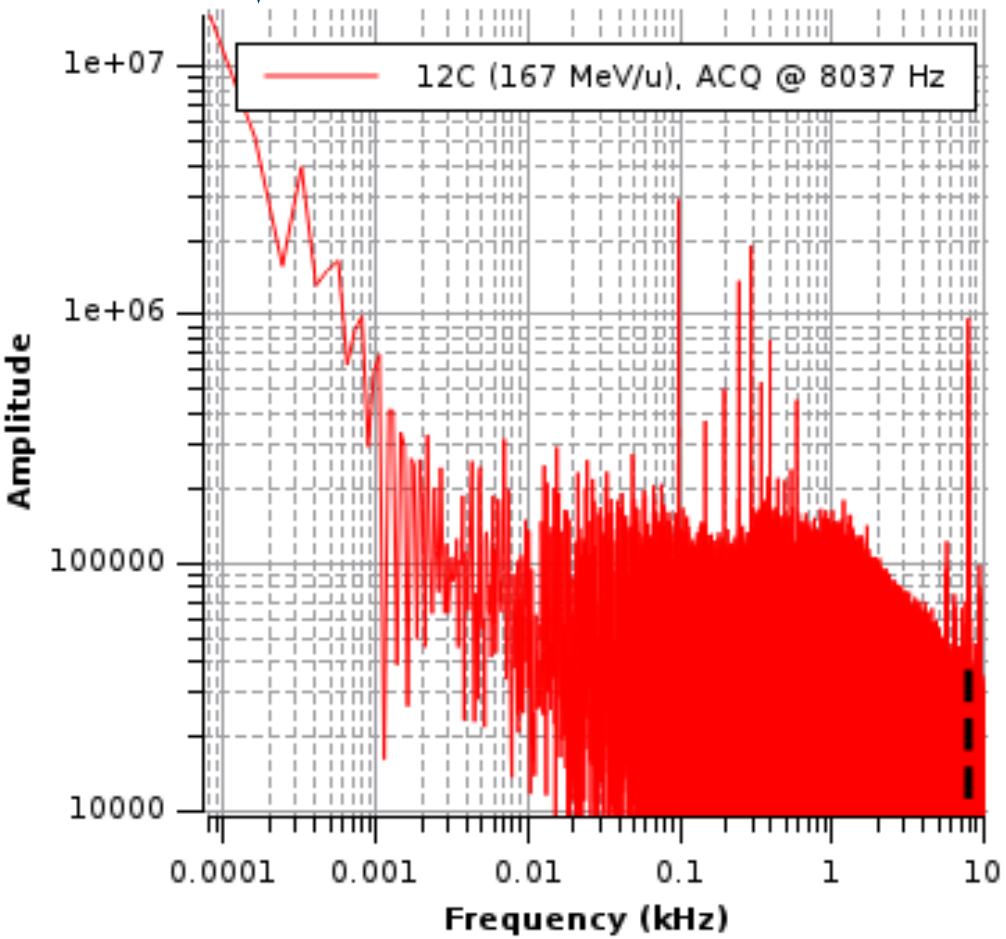
Beam Response to ACQ



FFT of spill (ACQ @ 8037 Hz)



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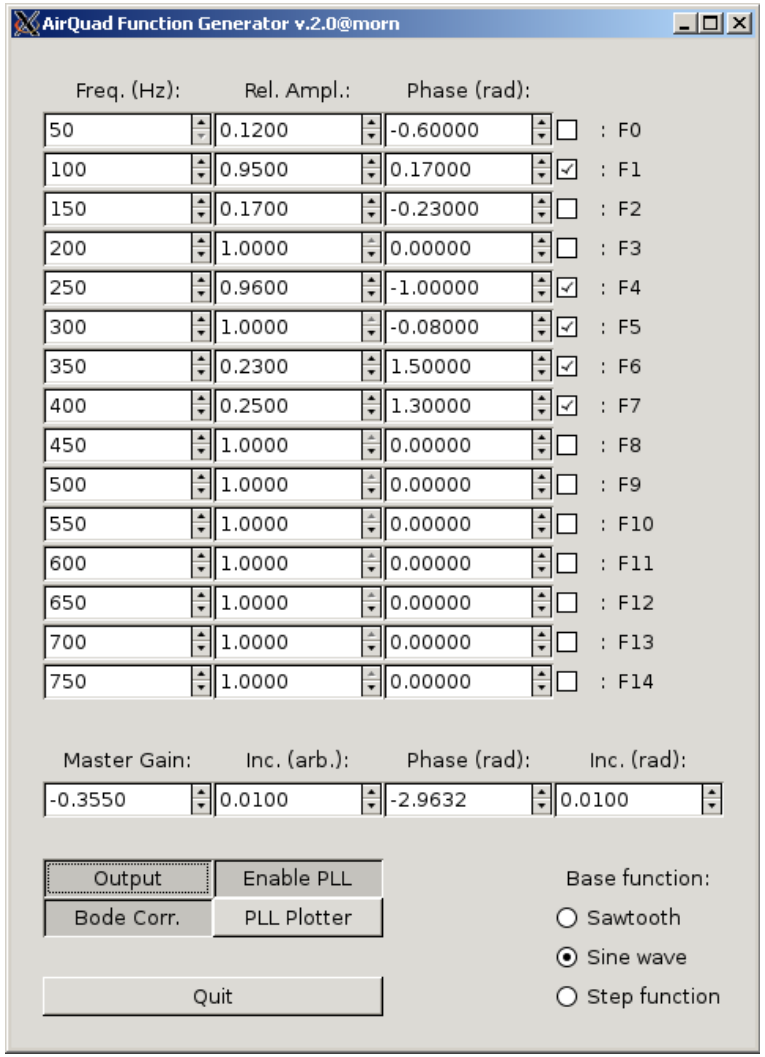
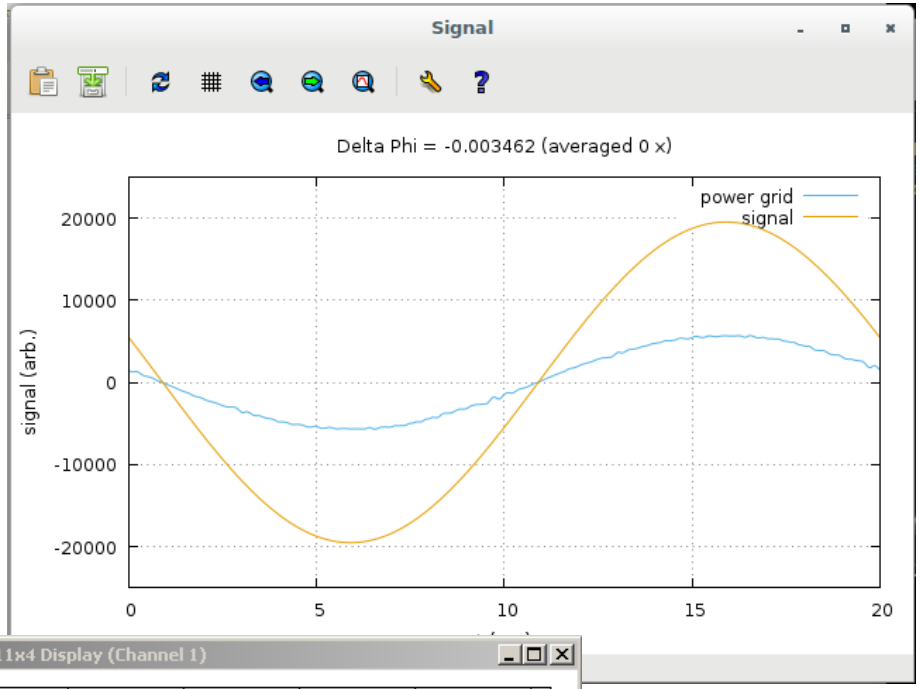
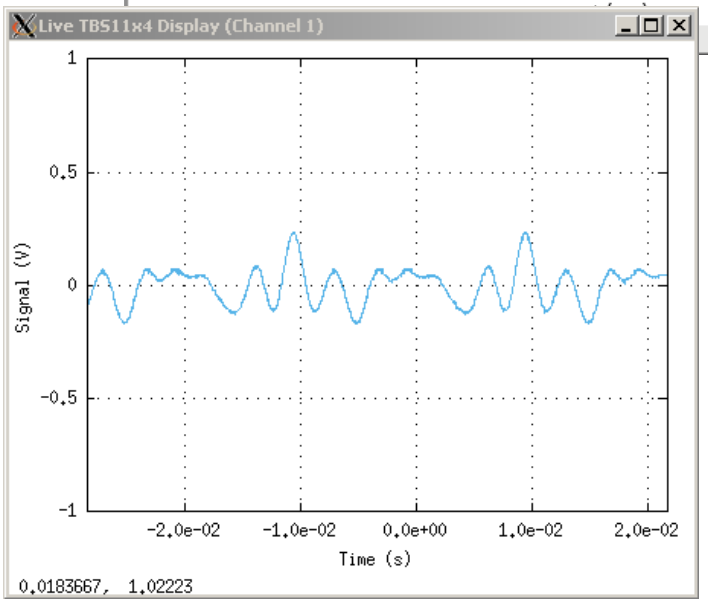
Cancellation of power-grid harmonics

Phase-locked
n x 50 Hz function generator.

Phase-locking of internal
„50-Hz“ clock to power-grid ref.
↓







← Arbitrary phase-locked sums of *n* x 50 Hz functions sent to ACQ amplifier.

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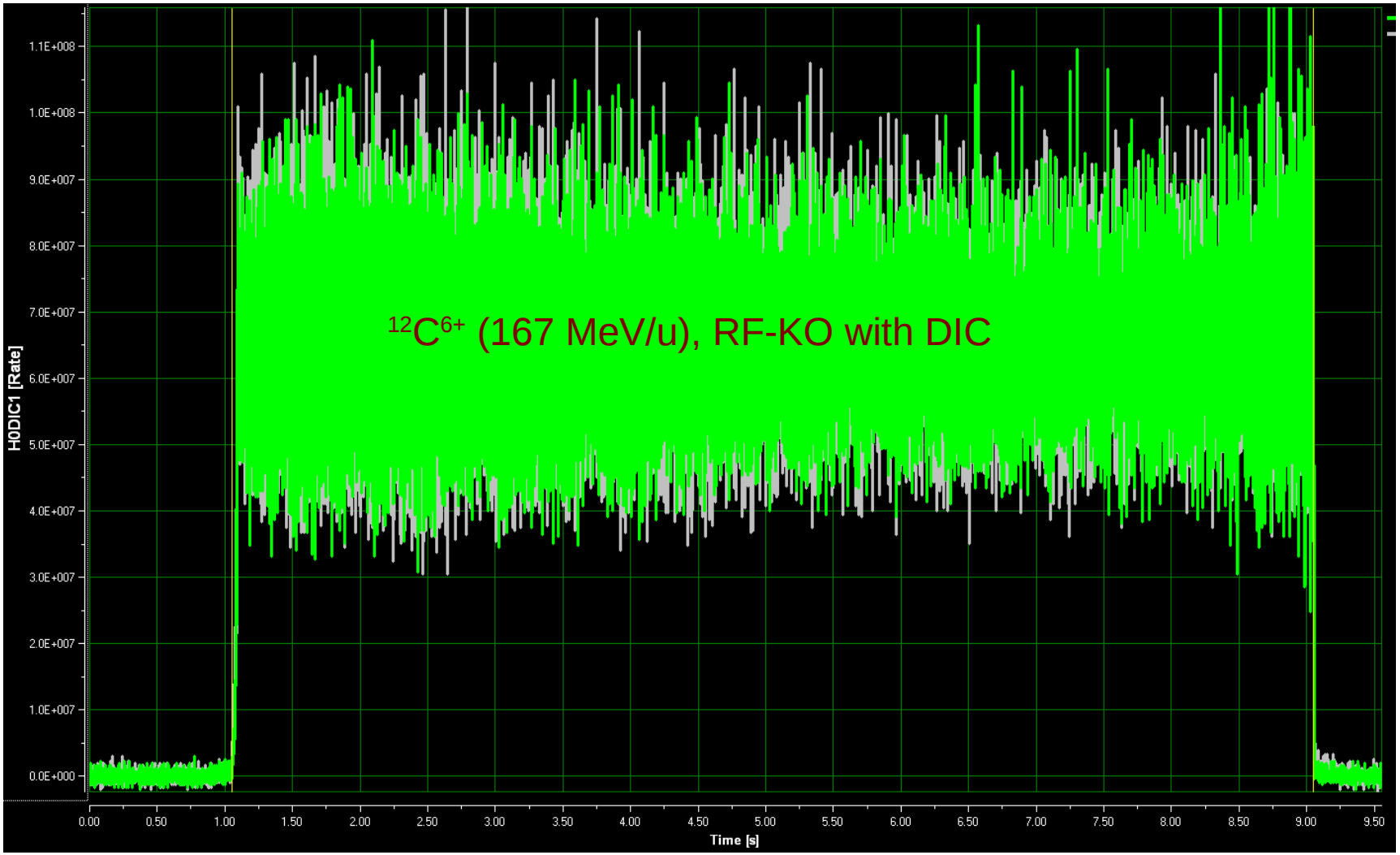
Does it work?

First tests (work in progress!)



Data: Ionisation chamber in extraction beam line.

MIT: $^{12}C^{6+}$ @ 167 MeV/u

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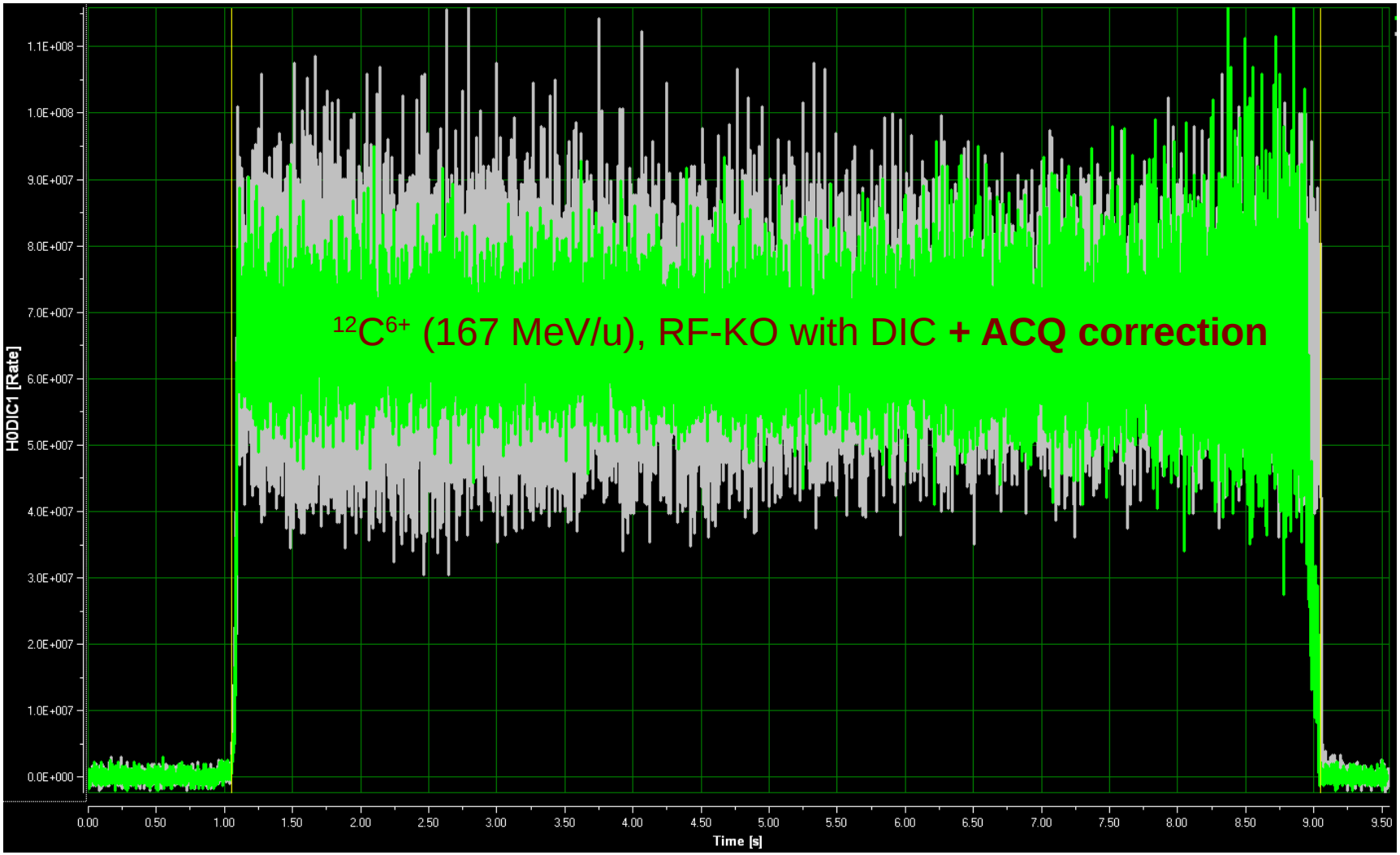
Does it work? … Yes!

First tests (work in progress!)



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Marburger Ionenstrahl-Therapiezentrum

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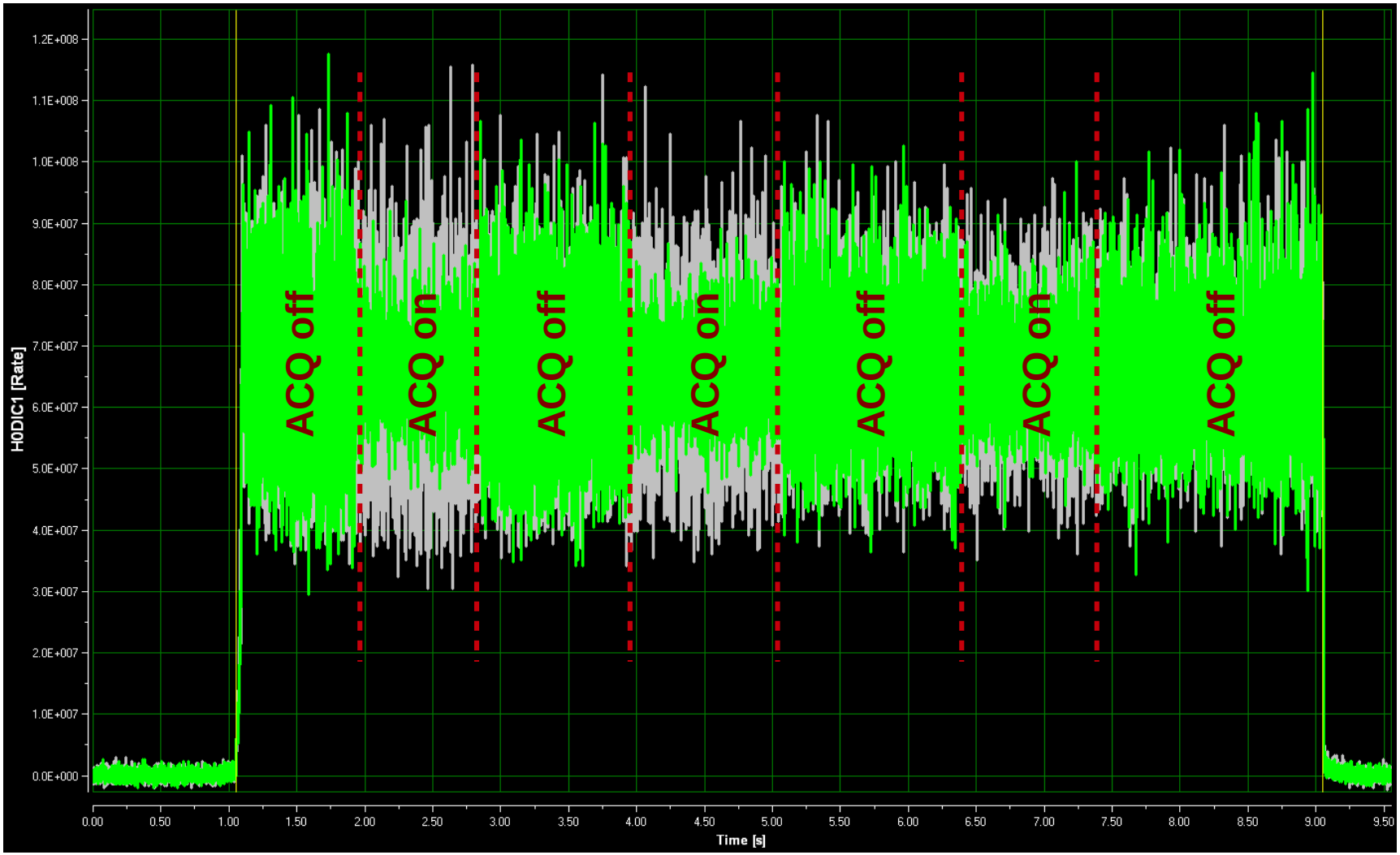

Data: Ionisation chamber in extraction beam line.

MIT: $^{12}C^{6+}$ @ 167 MeV/u

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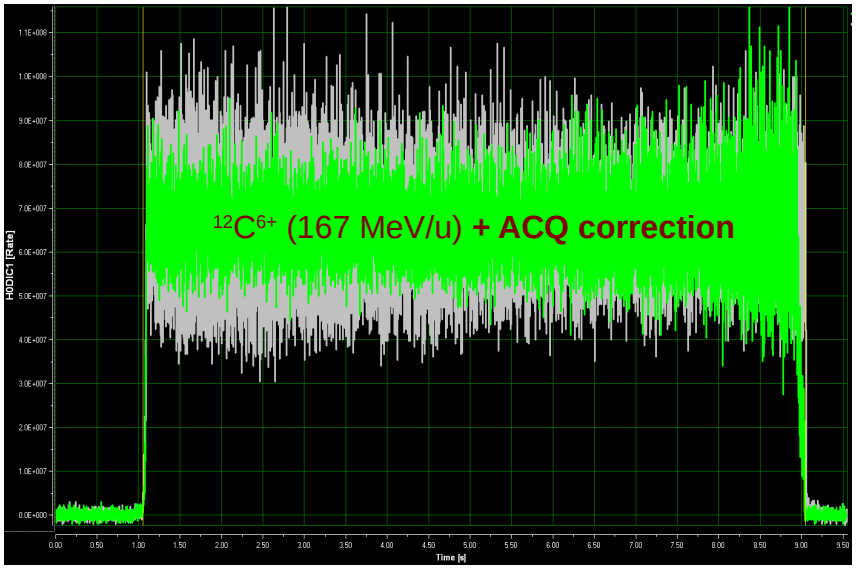
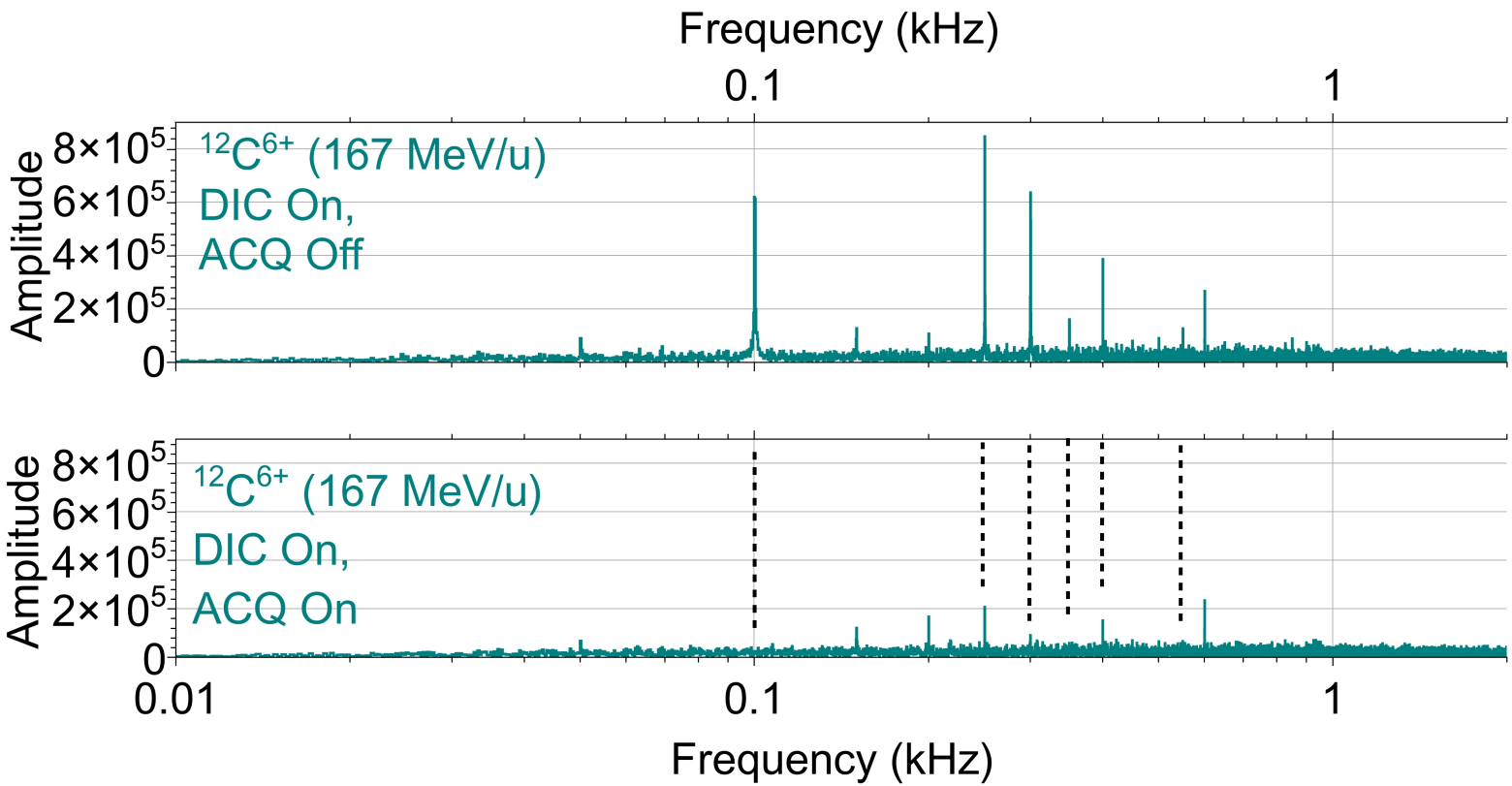
First results (@ MIT)

Up to now: Correction function is “hand-made”:

→ *Operator sets function generator while observing the spill FFT.*

Goal: Automatic learning routine populating a “library” of correction functions.





Corrections *seem* stable at least over ~ few days.

(Preliminary!)

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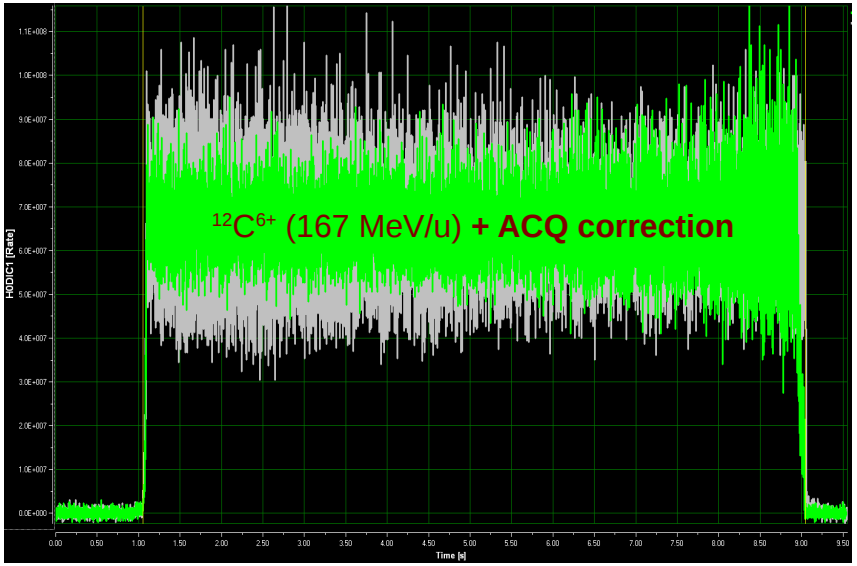
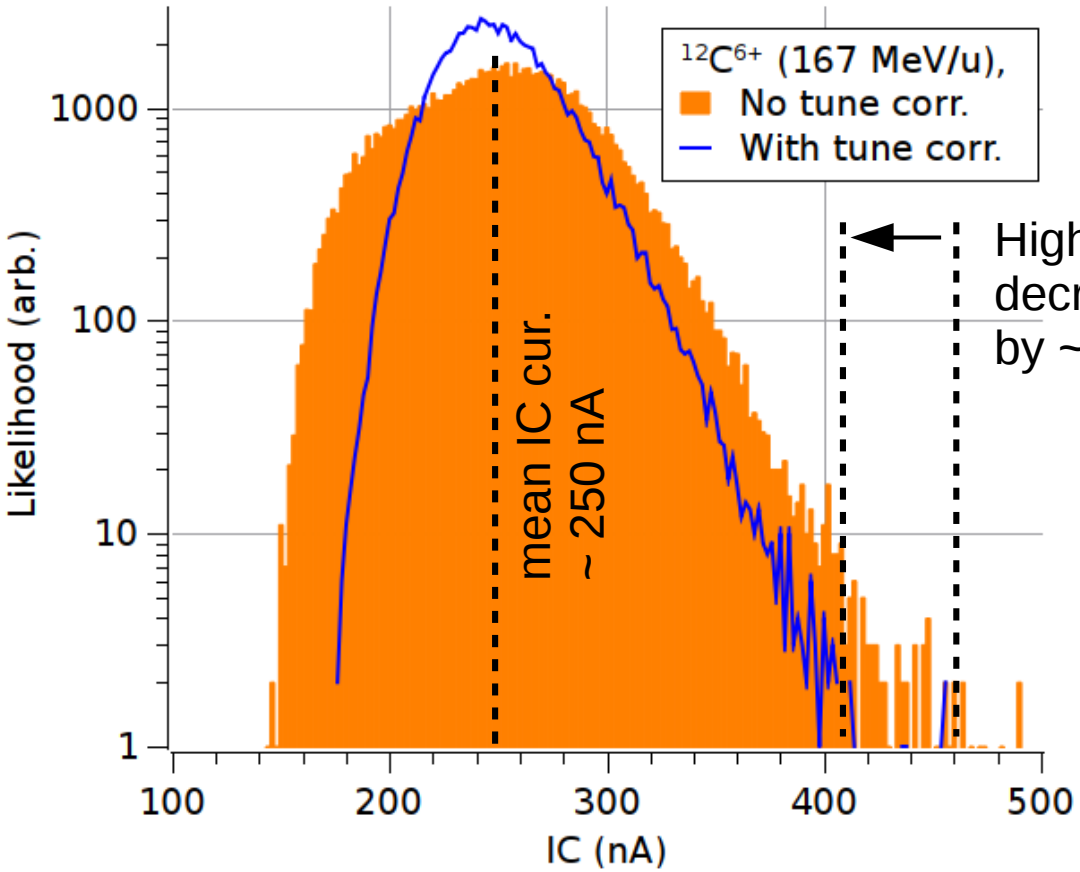
First results (@ MIT)



Histogram of IC measurements
(50 µs sampling)



High peaks decreased by ~ 50 nA

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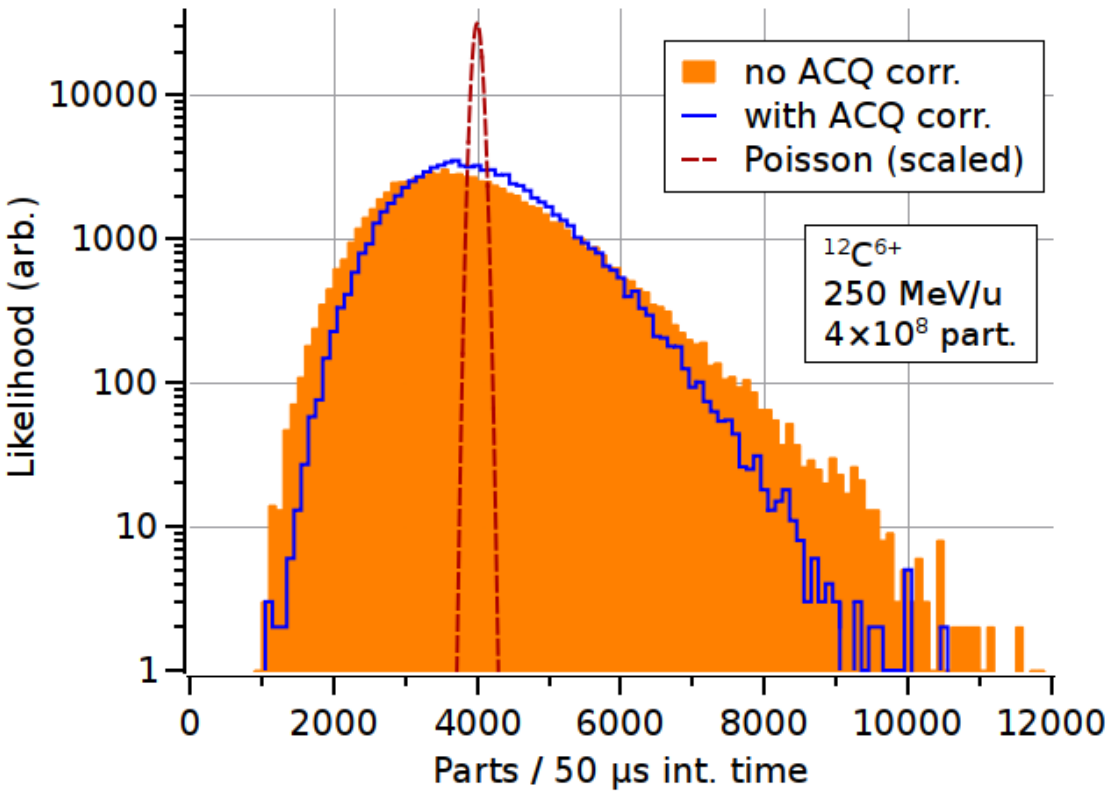
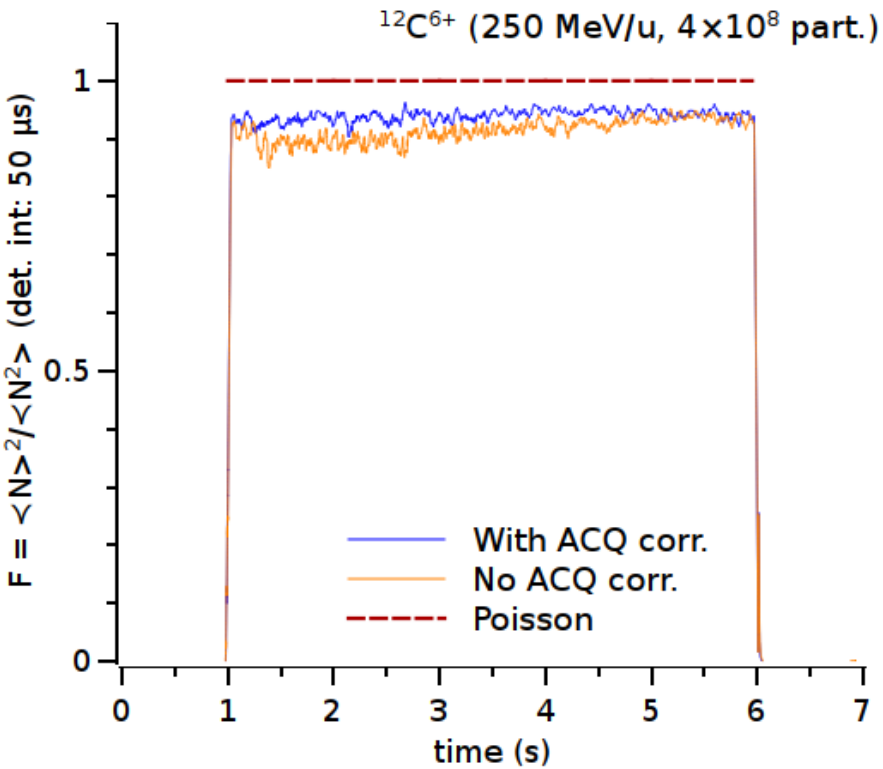
First results (@ HIT)



Duty-factor (GSI)

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

(Sorge et al., Proc. of IPAC 2018)



Overall:

Very similar results at the HIT and MIT synchrotrons.

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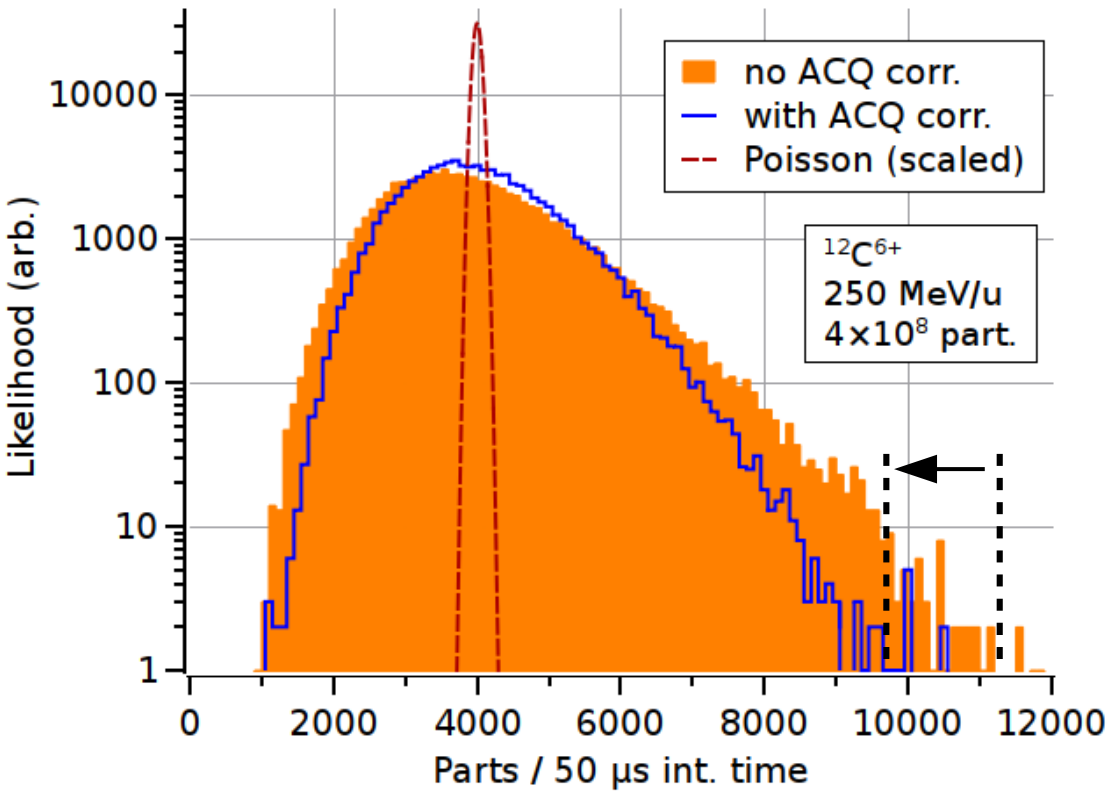
First results (@ HIT)



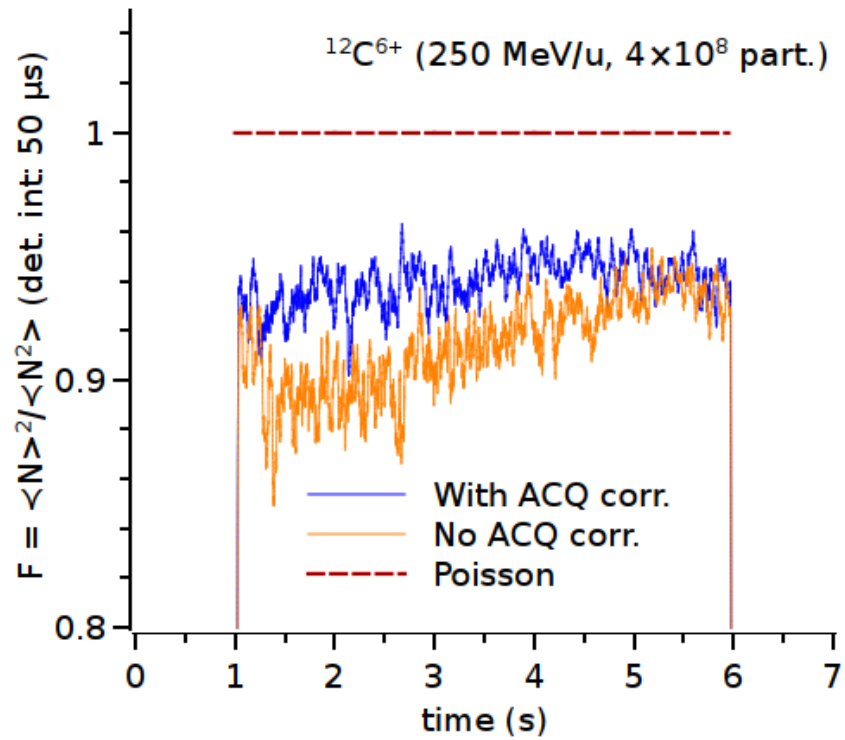
Duty factors all relatively close to 1 due to long detector integration (50 µs) and high rate.

Decrease of likelihood of high peaks is the most important aspect.

Duty-factor (GSI)

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

(Sorge et al., Proc. of IPAC 2018)



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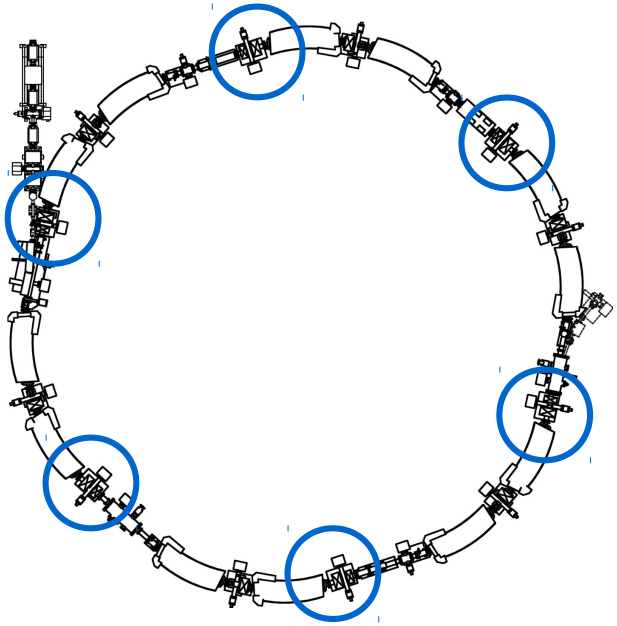
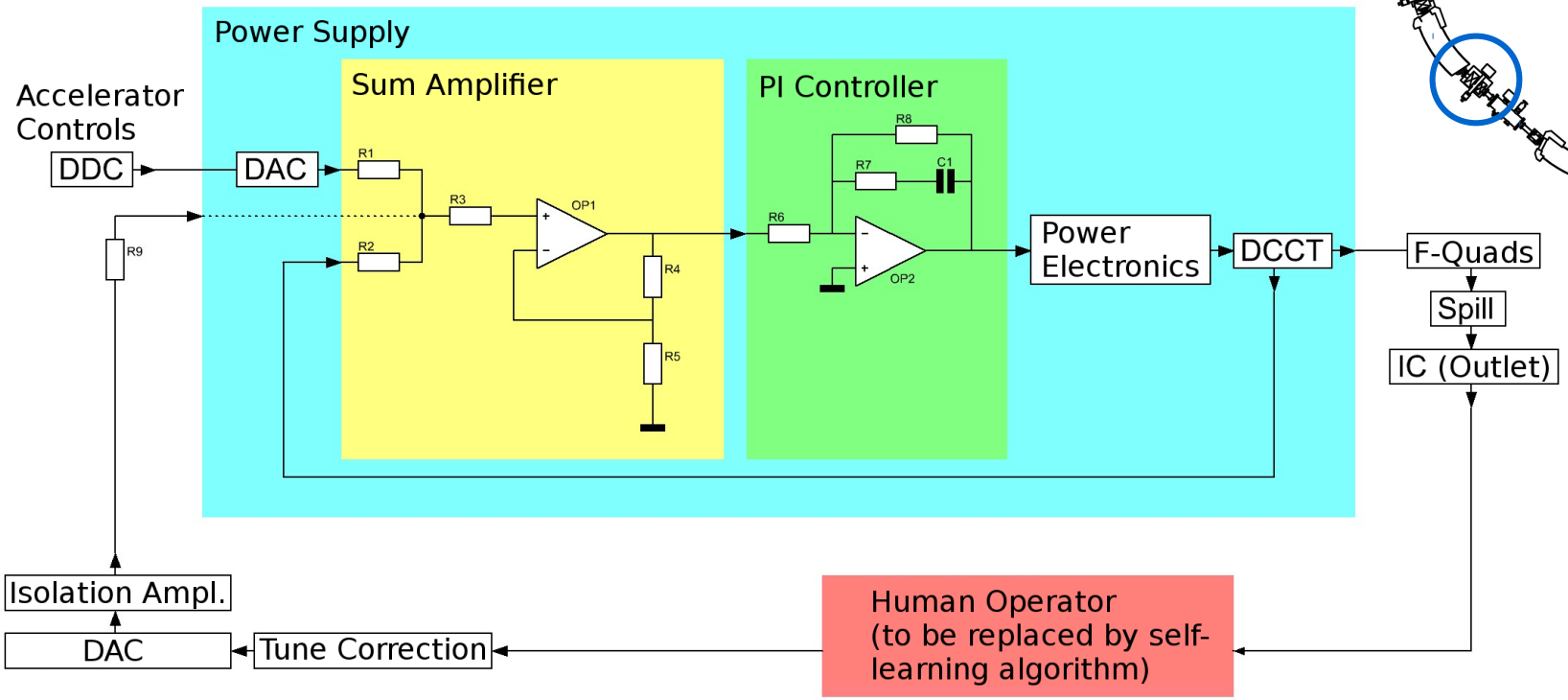
Outlook: Do we actually need the ACQ?

Idea: Apply tune ripple correction directly to F-quad family

→ Injection of forward correction into PS control loop (instead of ACQ)





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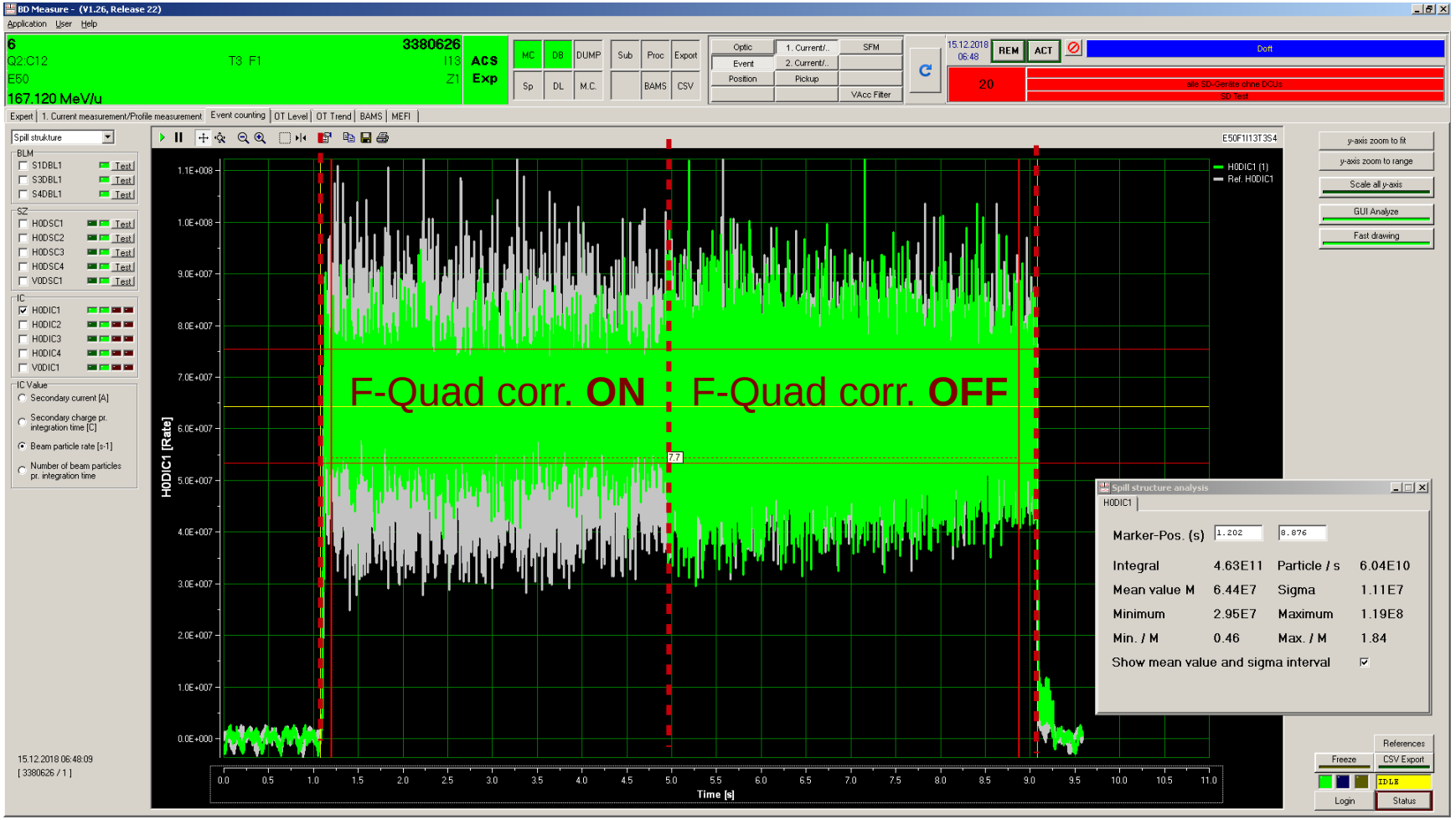
Outlook: Do we actually need the ACQ?

First tests: Cancellation by F-quads equally possible @ frequencies < 1 kHz ...



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Summary

Intensity-controlled RF-KO excitation, as used at HIT and MIT provides excellent spill structure.

Fast response of the beam to RF-KO is a key feature for the therapy application.

The effect of the **RF-KO spectrum** on the spill quality is significant.

Ripple cancellation by fast correction quadrupole fields seems promising.

Thank You for Your Attention.

MIT
Marburger Ionenstrahl-Therapiezentrum

HIT
Heidelberger Ionenstrahl-Therapiezentrum

U. Scheeler, T. Blumenstein,
C. K., M. Rothenburger,
A. Weber, M. Witt, Th. Haberer

R. Cee, F. Faber, E. Feldmeier,
M. Galonska, S. Scheloske,
C. Schömers, A. Peters,
Th. Haberer

RHÖN-KLINIKUM
AKTIENGESELLSCHAFT

UniversitätsKlinikum Heidelberg