# Slow Extraction at the Marburg Ion-Beam Therapy Synchrotron

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Marburger Ionenstrahl-Therapiezentrum

GSI Accelerator Seminar

25 April 2019

# Overview

1) The Marburg Ion-Beam Therapy Centre (MIT)

2) RF-KO slow extraction at MIT

3) Tune ripple compensation (ongoing ...)

# The Marburg Ion-Beam Therapy Centre

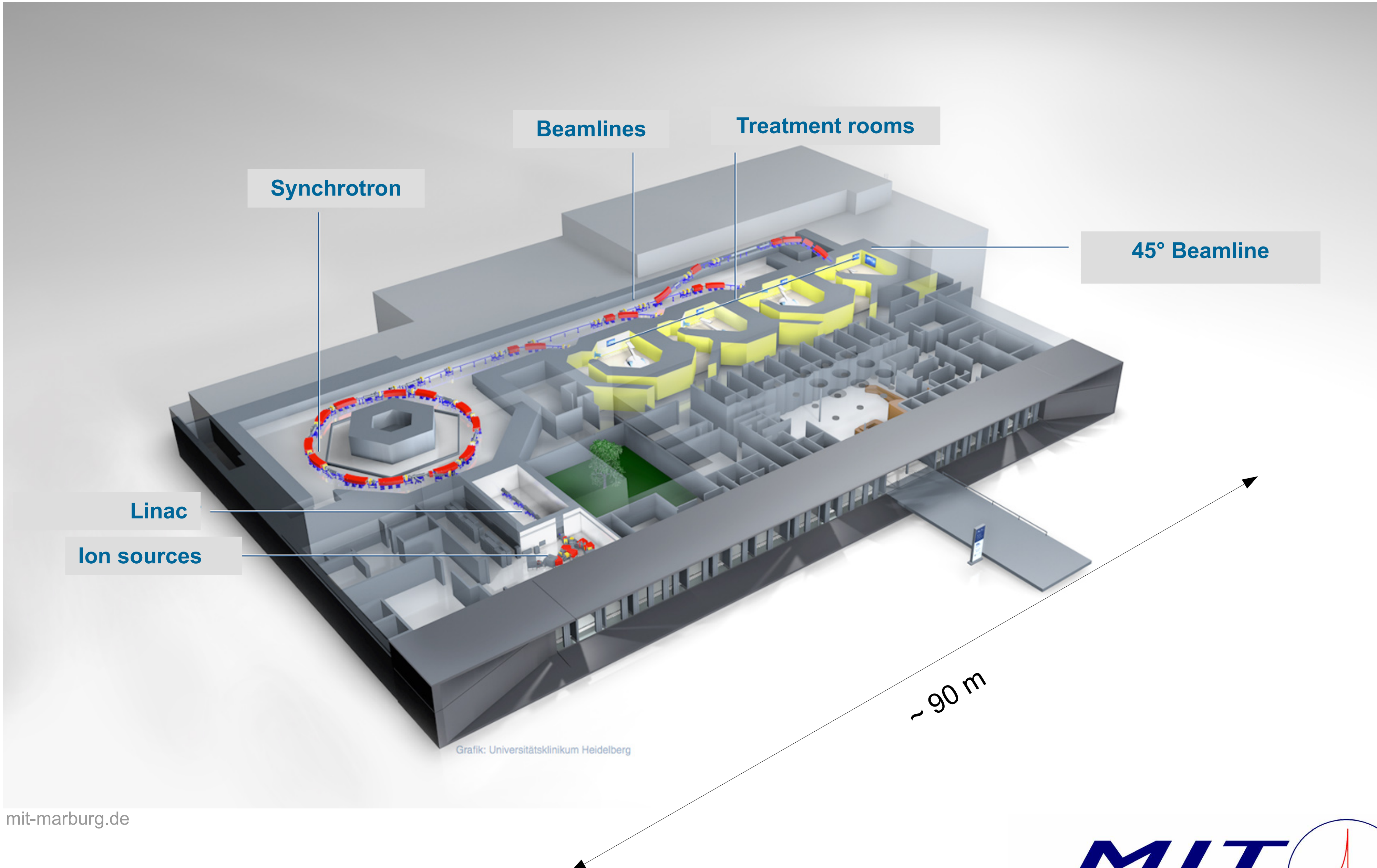
move36-marburg.de

hammeskrause.de

maps.google.com

MIT
Marburger Ionenstrahl-Therapiezentrum

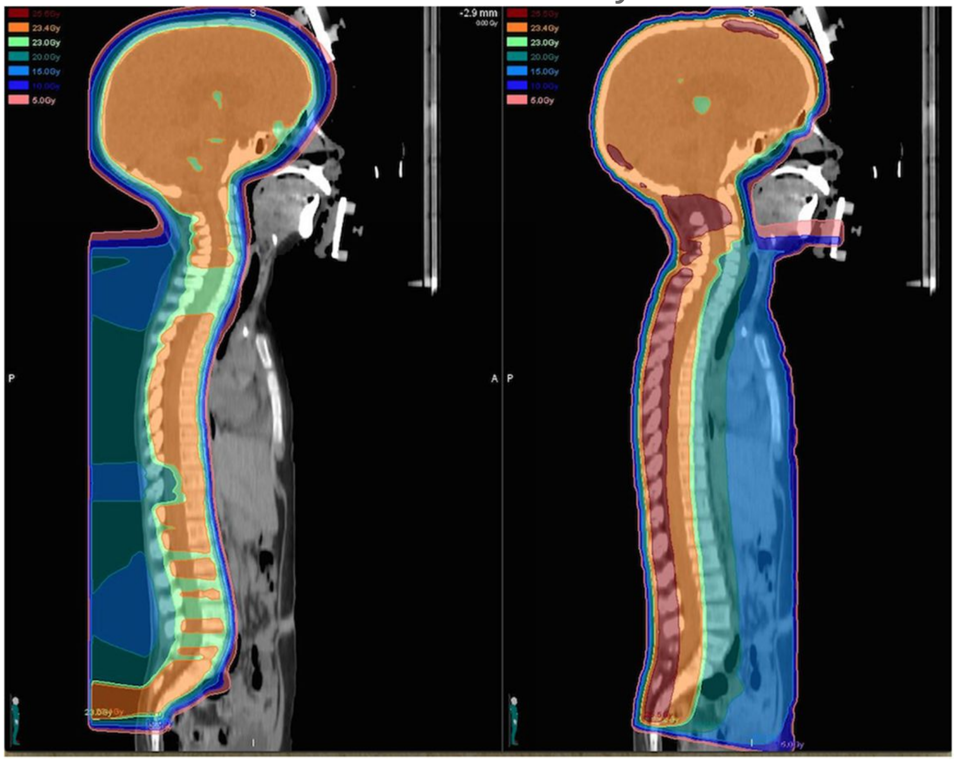
# The Marburg Ion-Beam Therapy Centre



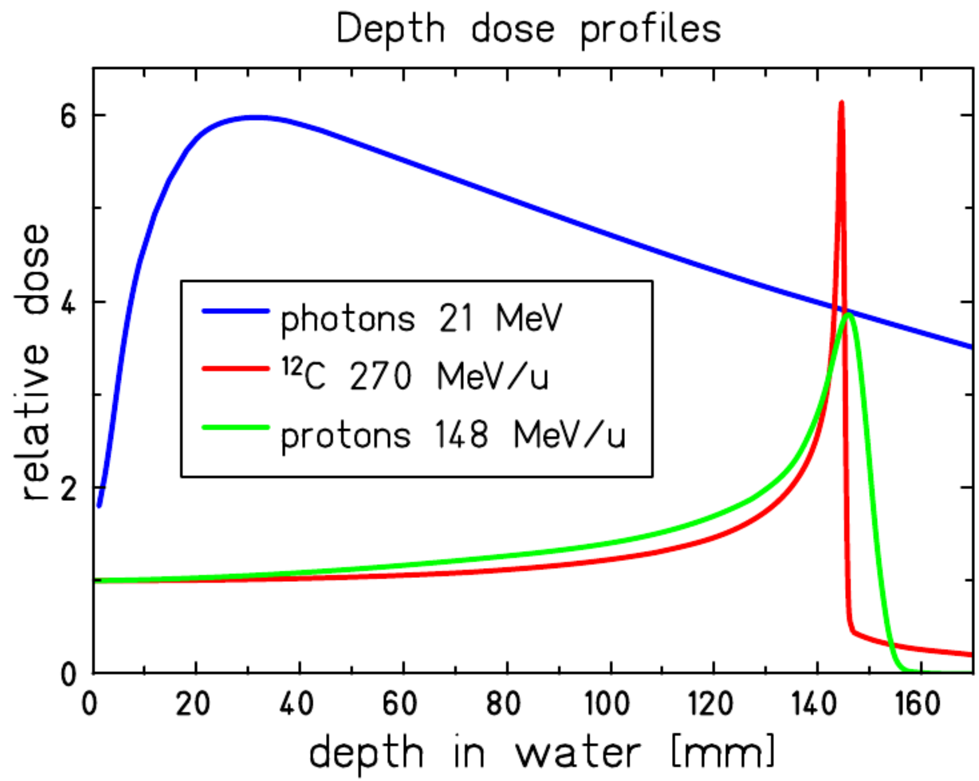

mit-marburg.de

# Radiation therapy with ion beams

Ions X-Rays



Eaton et al., Front. Oncol. 5 (2015) 261




Krämer & Durante, Eur. Phys. J. D 60 (2010)

High-energy X-rays:
Depth dose deposition defined by *attenuation* and *surface escape*.

Ion beam:
Range defined by starting energy ("*Bragg peak*").

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{Z^2 e^4 n_e}{4\pi\varepsilon_0 m v^2} \cdot \frac{1}{2} \ln\left(\frac{2mv^2}{I}\right)$$

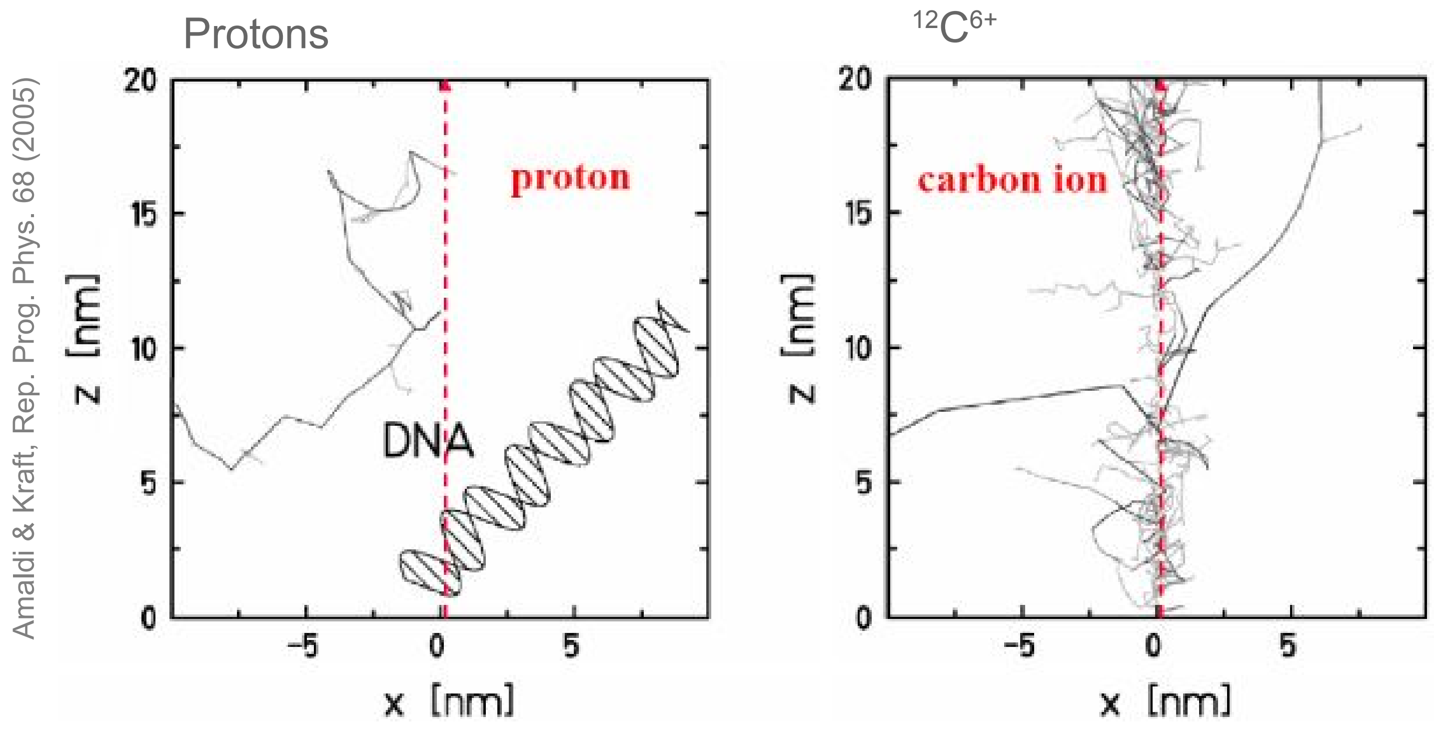
# Radiation therapy with ion beams

*Bethe formula* :

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{Z^2 e^4 n_e}{4\pi\varepsilon_0 m v^2} \cdot \frac{1}{2} \ln\left(\frac{2mv^2}{I}\right)$$

$\rightarrow \mathrm{d}E/\mathrm{d}x \sim Z^2$

Stopping force rises strongly with projectile nuclear charge!




Heavier ions ($^{12}C^{6+}$) have higher "*biological effectiveness*".

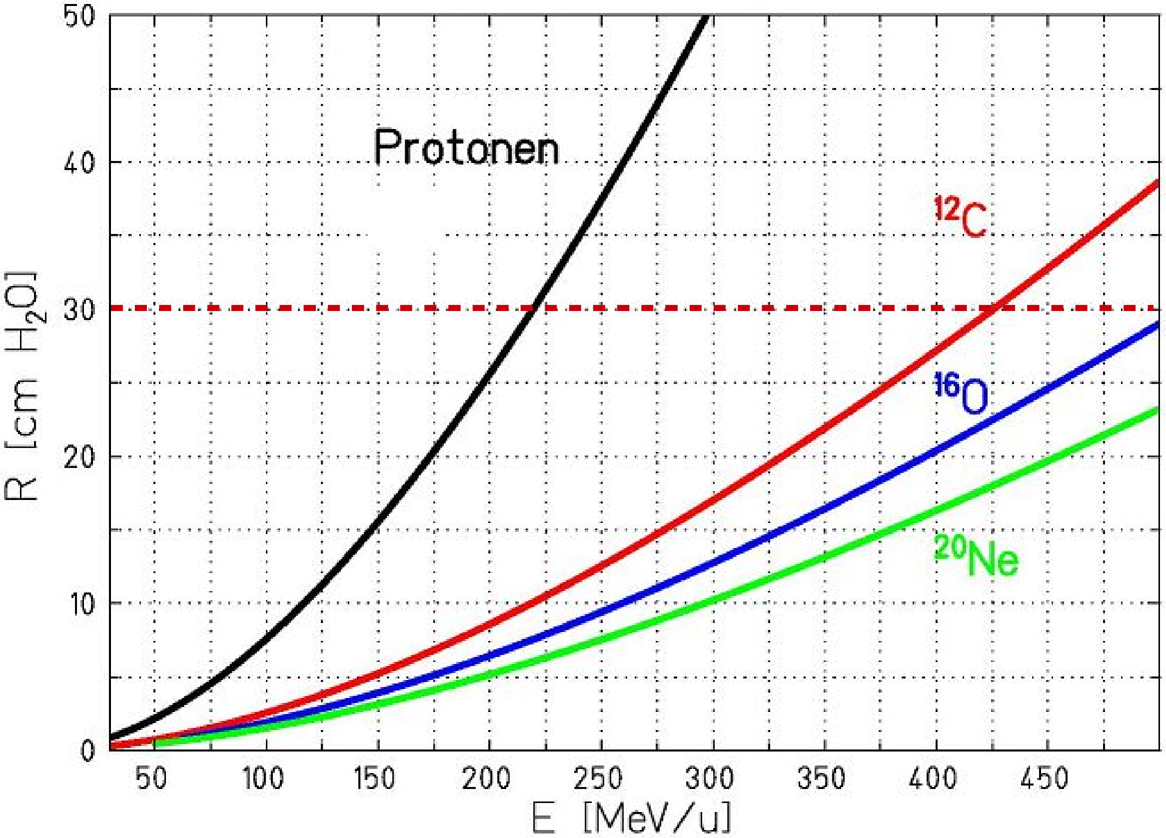
# Radiation therapy with ion beams

## Particle energy:

Standard maximum irradiation depth ~ 30 cm.

| | | |
|---|---|---|
| ~ | **220 MeV** | for p |
| | **430 MeV/u** | for $^{12}C^{6+}$ |

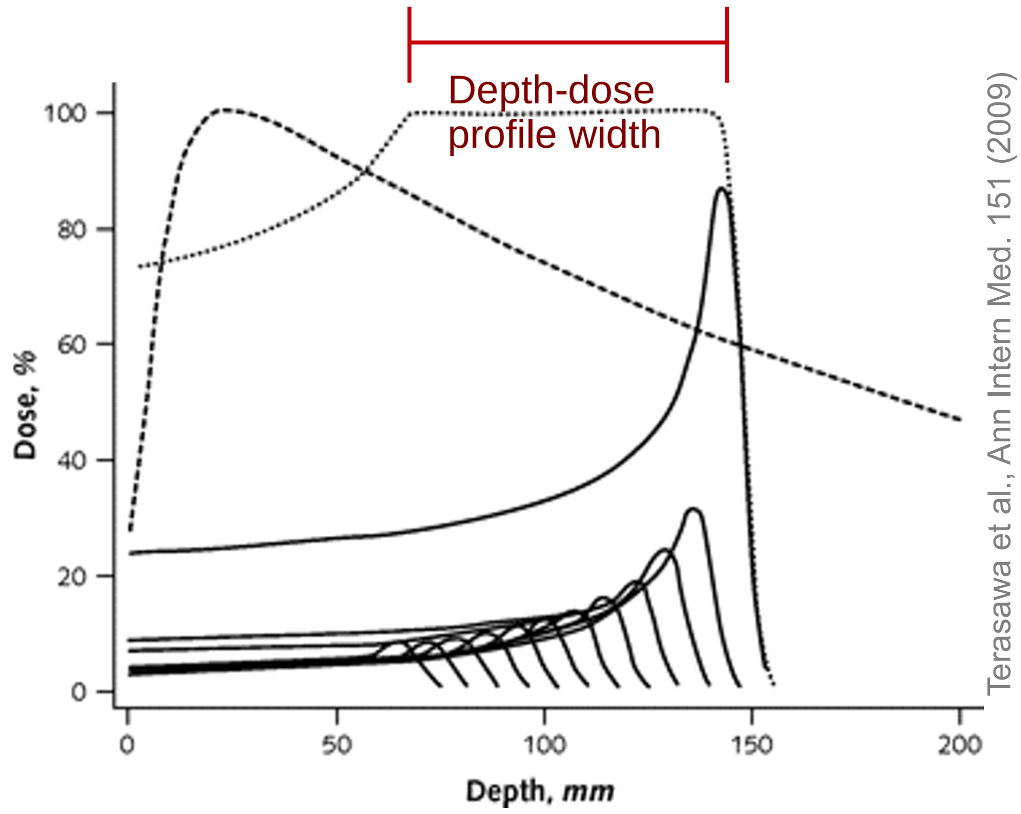
| | | |
|---|---|---|
| ~ | 2.3 Tm | for p |
| | 6.6 Tm | for $^{12}C^{6+}$ |



# Dose delivery: Longitudinal distribution

Match depth-profile of target by *stacking* of several beams of different energies.

**Remark:**
Requires a dense *spectrum of energies* from the accelerator.



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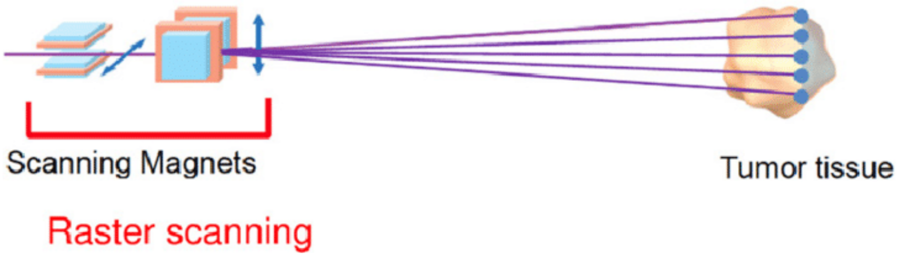
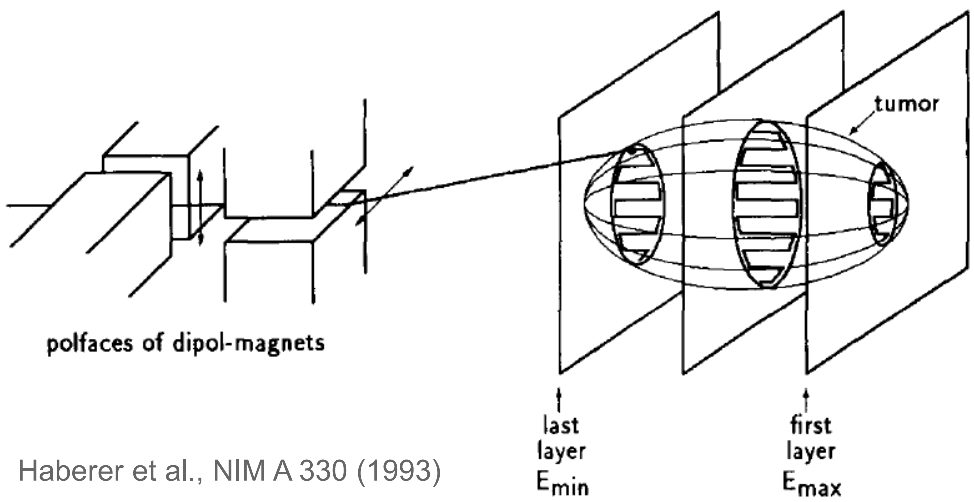
# Dose delivery: Lateral distribution

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




Haberer et al., NIM A 330 (1993)

State-of-the-art: Raster scanning

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

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

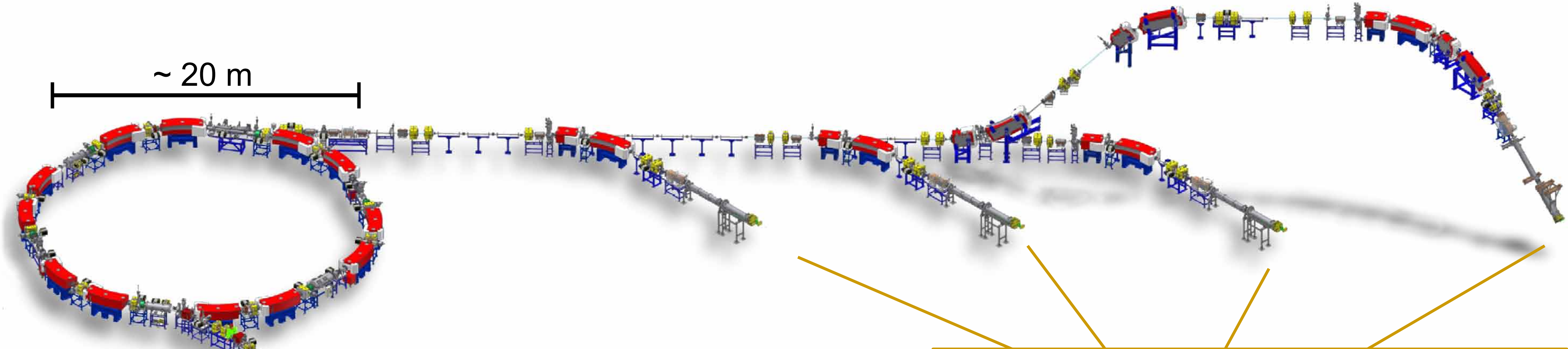
Optimum 3D tumour conformity of dose-distribution.

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

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

# 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**

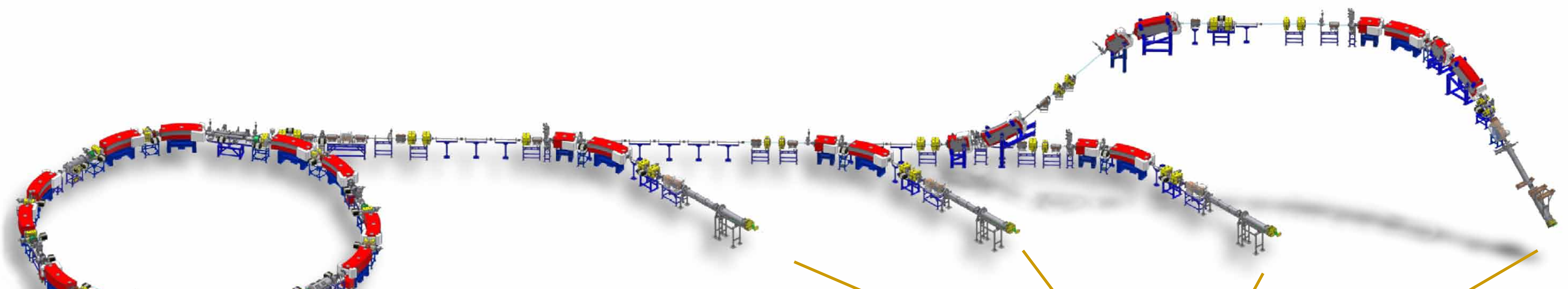
**Beam intensities:**

Protons: **$4 \cdot 10^{8}$ – $2 \cdot 10^{10}$ parts.**
$^{12}C^{6+}$: **$10^{7}$ – $8 \cdot 10^{8}$ parts.**

per cycle

mit-marburg.de

# The MIT Accelerator

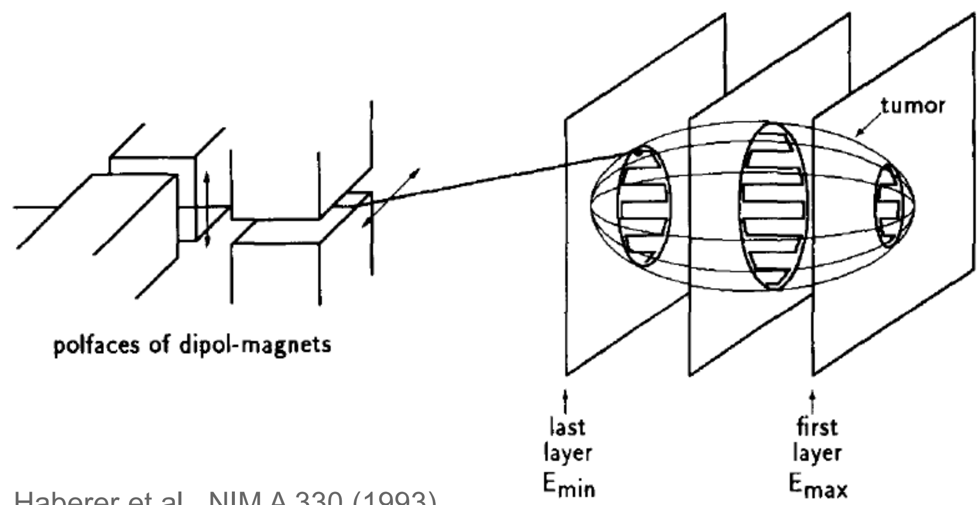


4 treatment rooms:

3 x horizontal,

1 x 45°-vertical.

Pencil-beam scanning dose delivery systems.




Haberer et al., NIM A 330 (1993)



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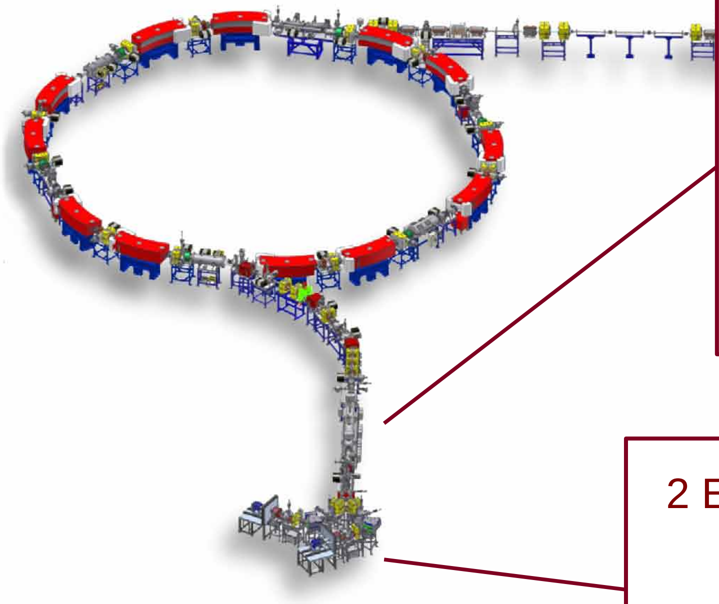
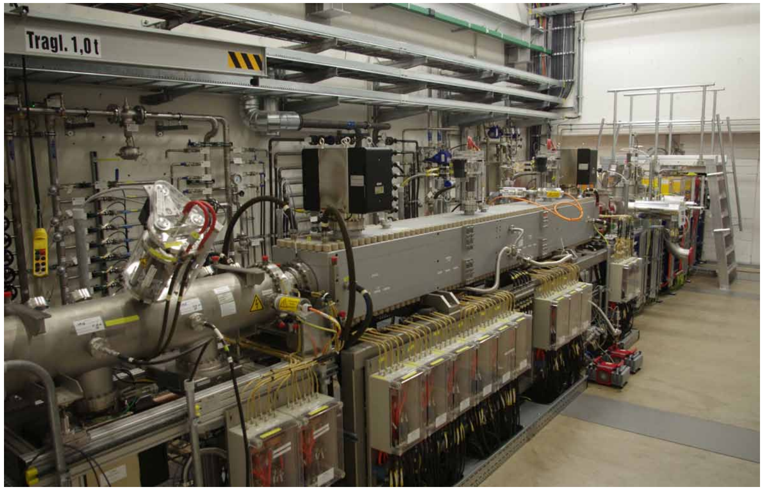
# The MIT Accelerator



Linear accelerator

RFQ (400 keV/u)
+
IH structure (7 MeV/u)

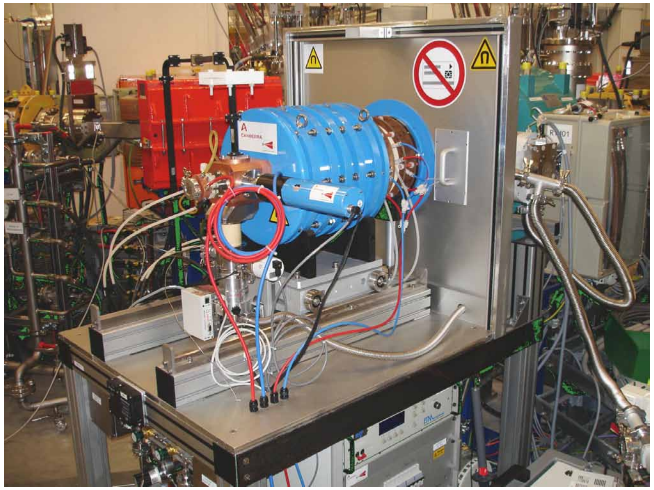
then stripping to
p and $C^{6+}$



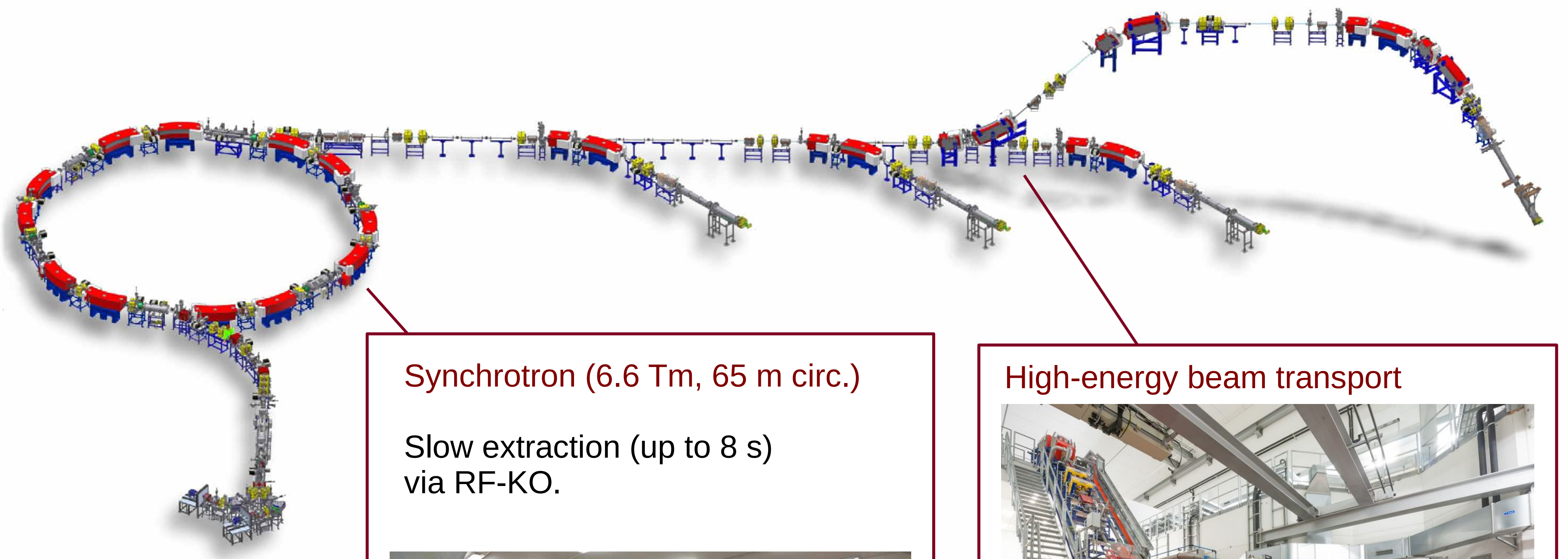

2 ECR ion sources

(Supernanogan)

$H_3^+$ : ~700 µA
$C^{4+}$ : ~140 µA



# The MIT Accelerator



Synchrotron (6.6 Tm, 65 m circ.)

Slow extraction (up to 8 s)
via RF-KO.

Møller et al., Proc. of PAC 2007

High-energy beam transport

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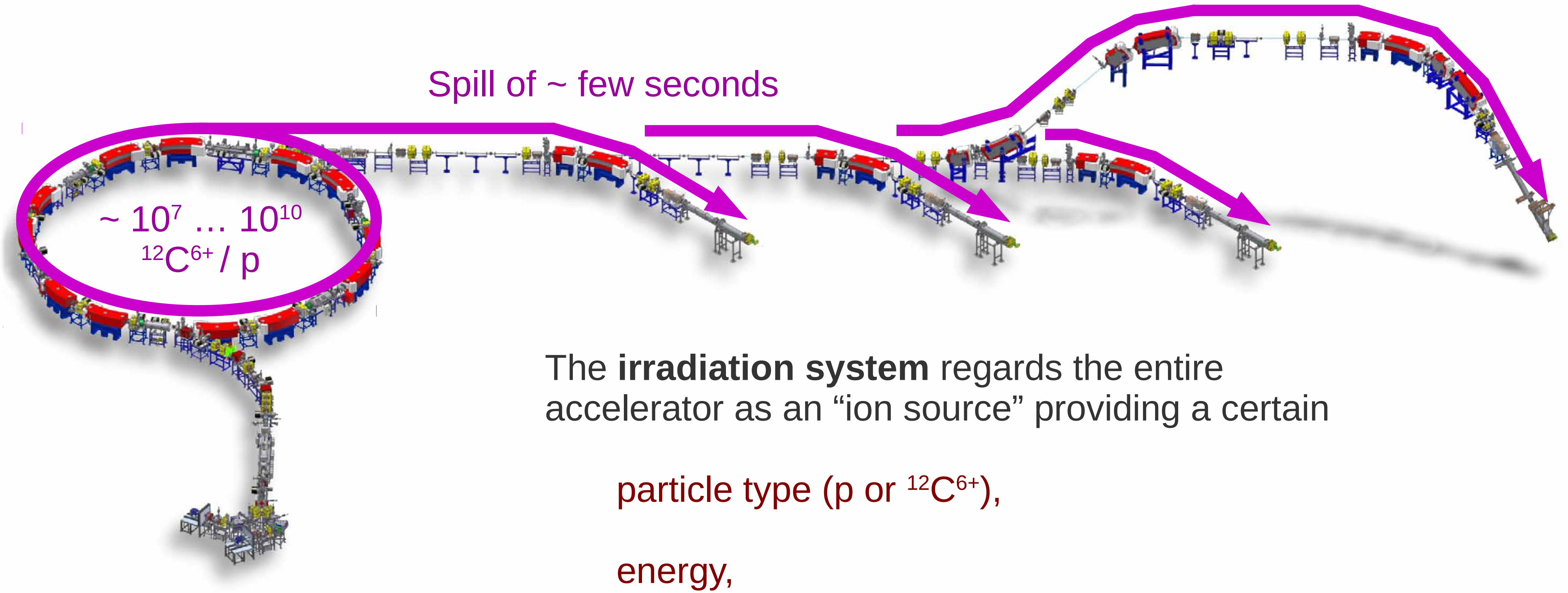
# Slow Extraction




The **irradiation system** regards the entire accelerator as an "ion source" providing a certain

particle type (p or $^{12}C^{6+}$),

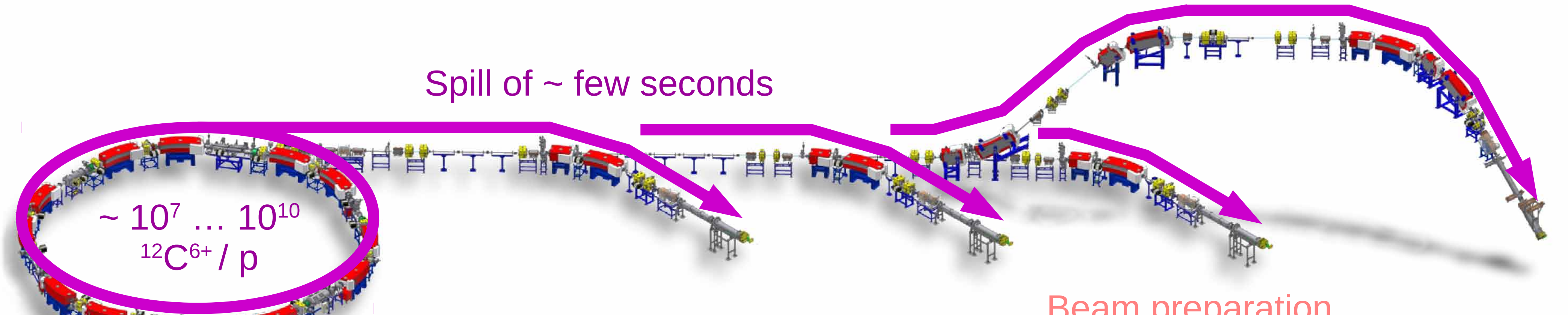
energy,

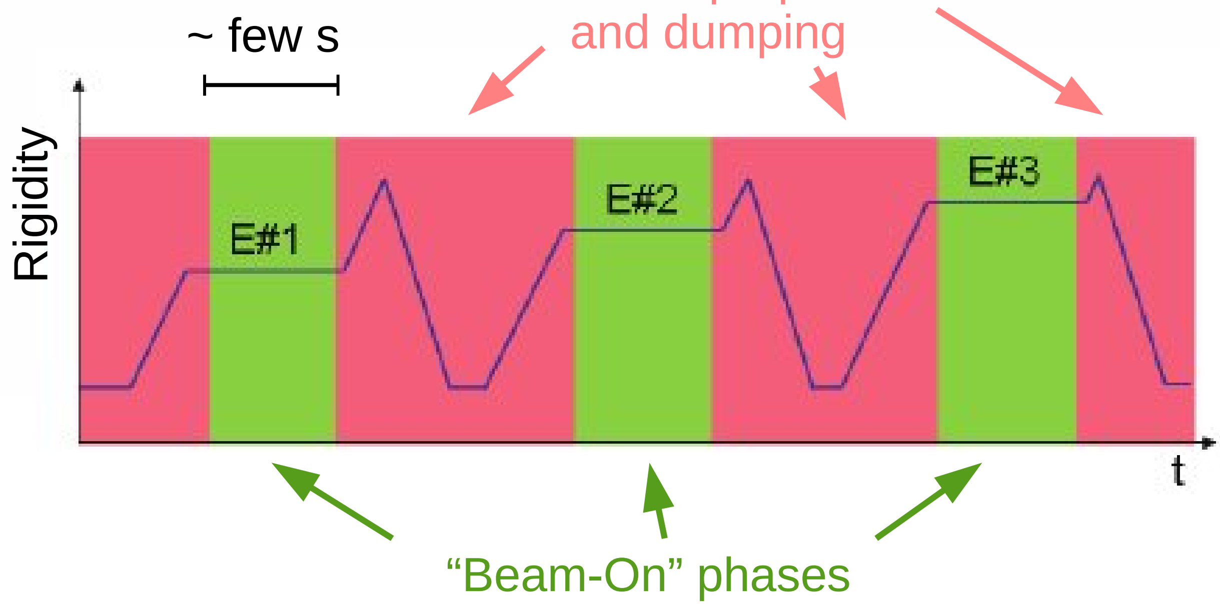
spot size, and

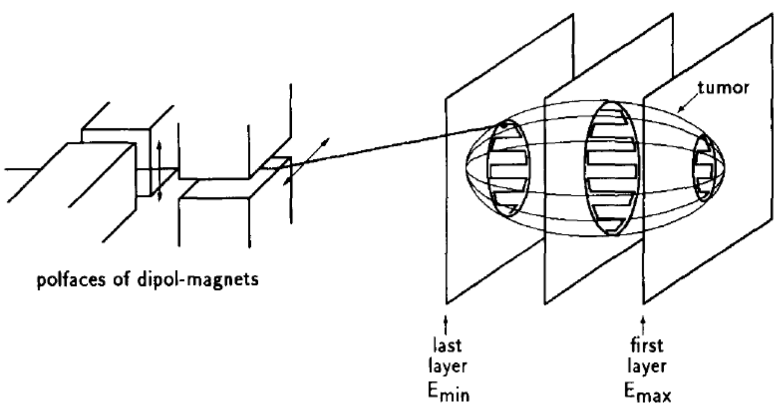
intensity (particles/s)

on command.

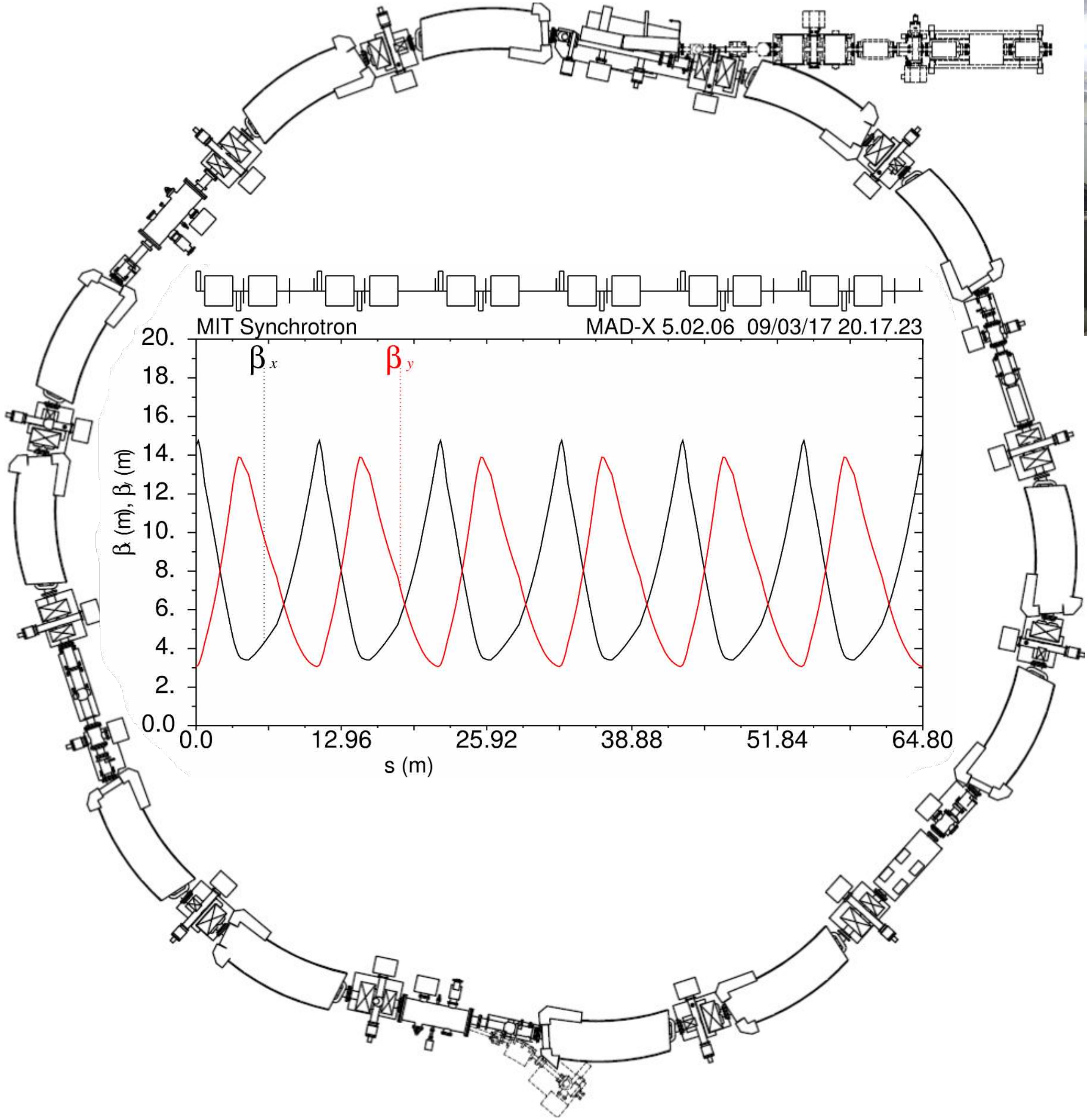
# Slow Extraction



# Slow extraction




**Synchrotron**:

65 m circumference

0.5 … 6.6 Tm

6 Sectors: ...-S-F-M-D-M-O-…
(2 quad families)

Tune at flattop: $Q_h$ ~ 1.69

→ Slow extraction via 2/3 (sextupole) resonance



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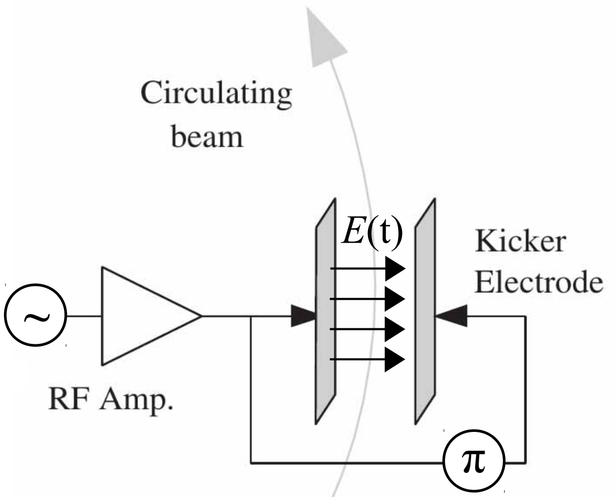
# Slow extraction

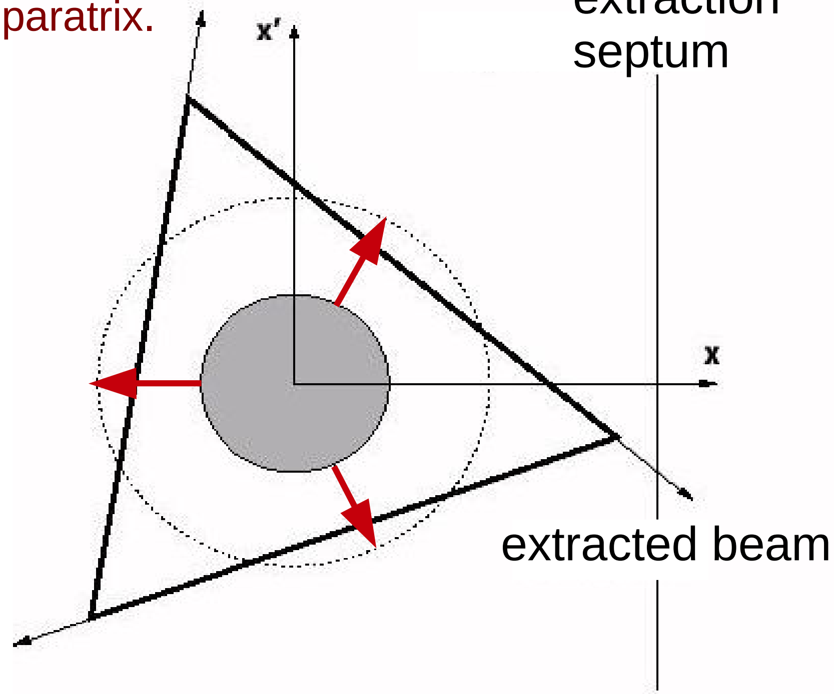
## (Transverse) RF-Knock-Out method:

### Excite horizontal betatron motion

Horizontal RF-kicker electrode
~ in sync with horizontal particle tune.



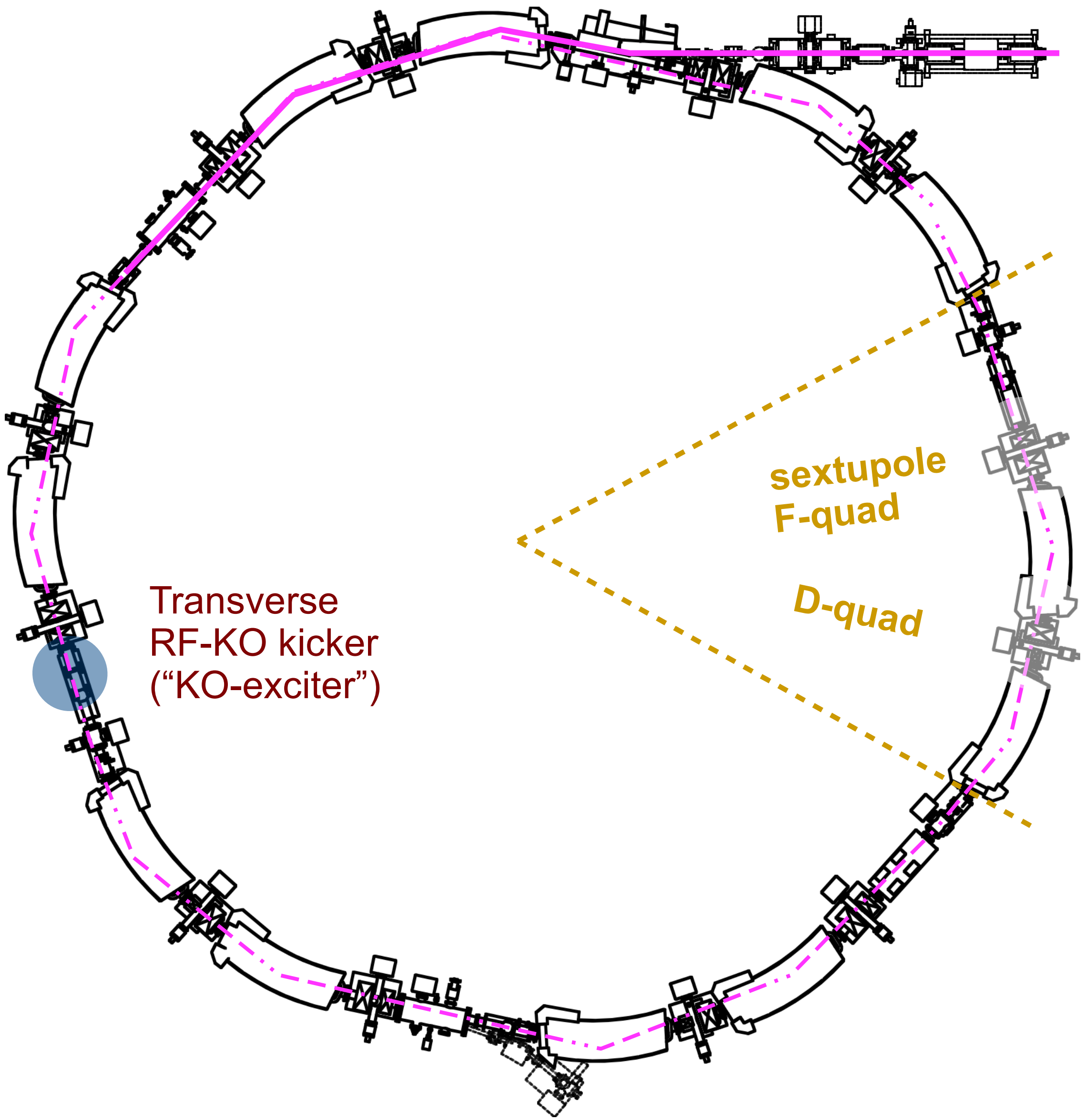

particle emittance ***grows*** towards separatrix.



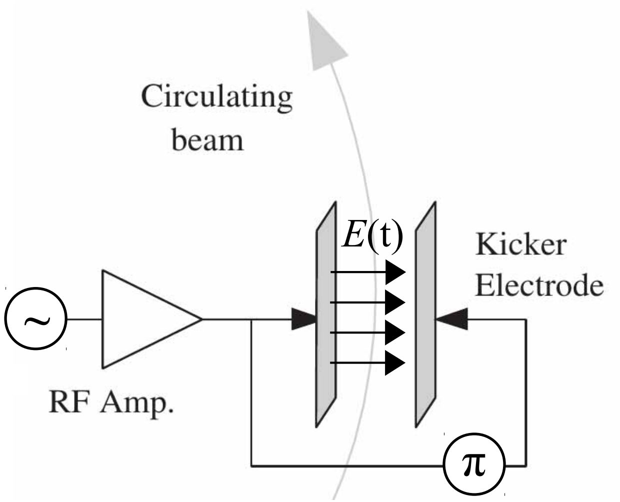

Albrecht, PhD, 1996

Used e.g. at the MIT, HIT, and HIMAC therapy synchrotrons.

# Slow extraction

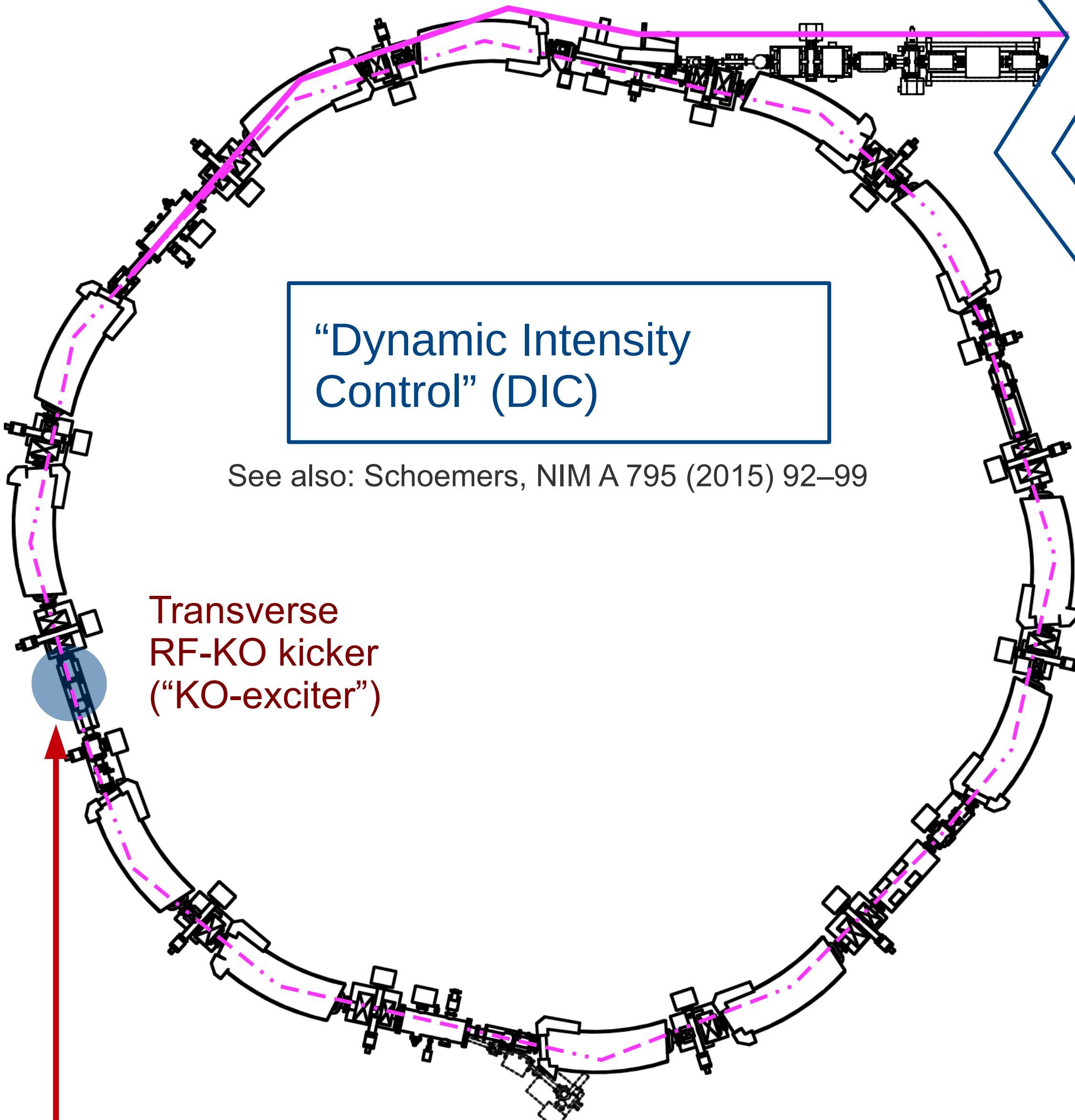


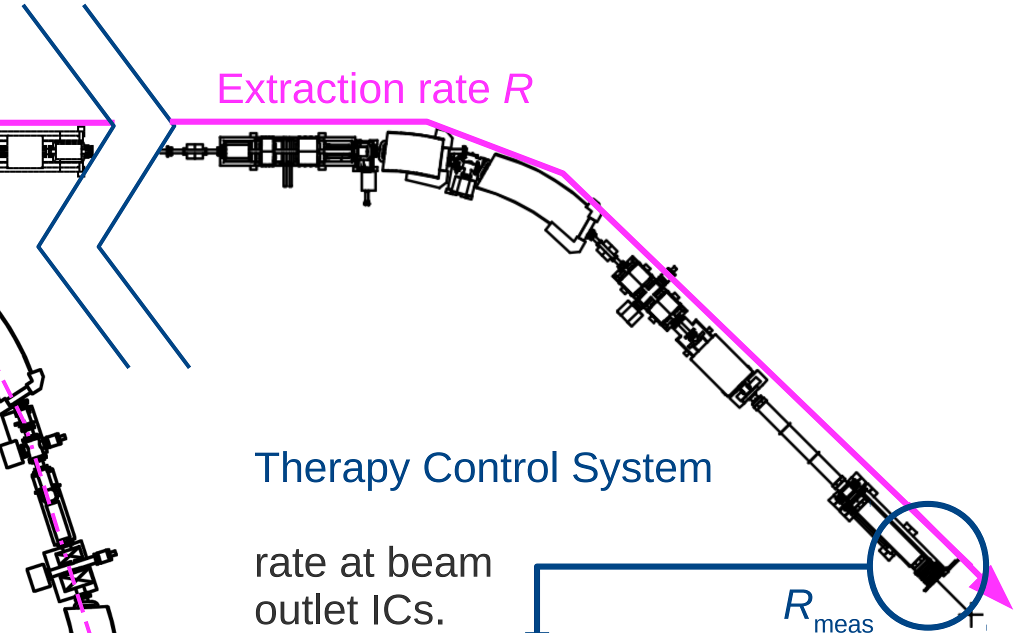

Fixed optics during extraction ($Q_h$ ~ 1.69).




RF-KO-exciter is a fast element!

# Slow extraction





Extraction rate $R$

"Dynamic Intensity Control" (DIC)

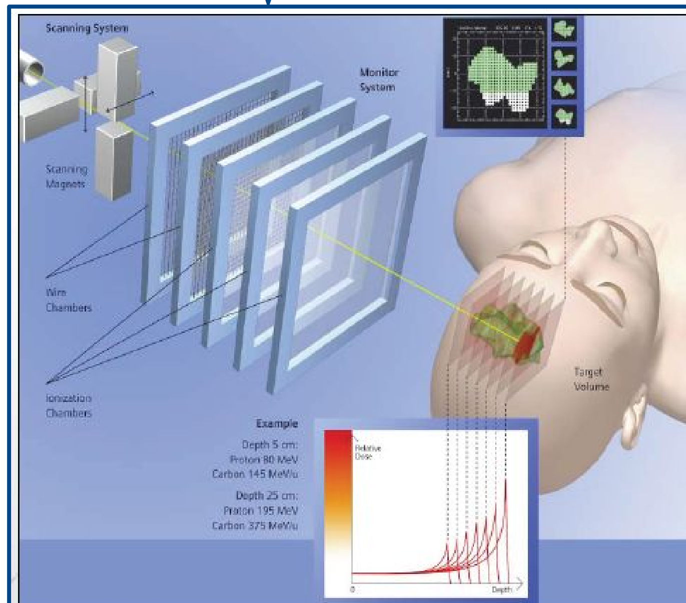
See also: Schoemers, NIM A 795 (2015) 92–99

Transverse RF-KO kicker ("KO-exciter")

Therapy Control System

rate at beam outlet ICs.

$R_{meas}$

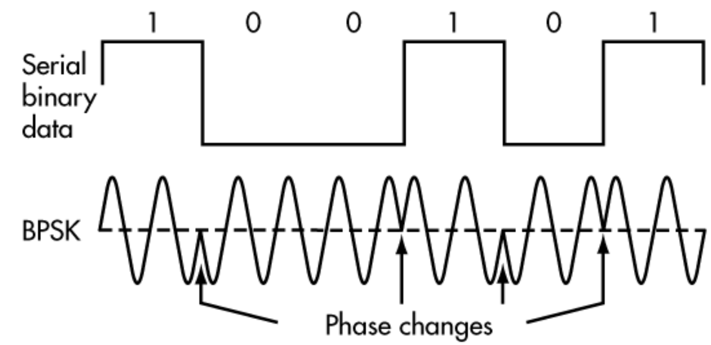



Intensity-Controlled Rasterscan Technique, Haberer et al., GSI, NIM A,1993

Feedback to KO amplifier power such that $R_{meas} \rightarrow R_{set}$

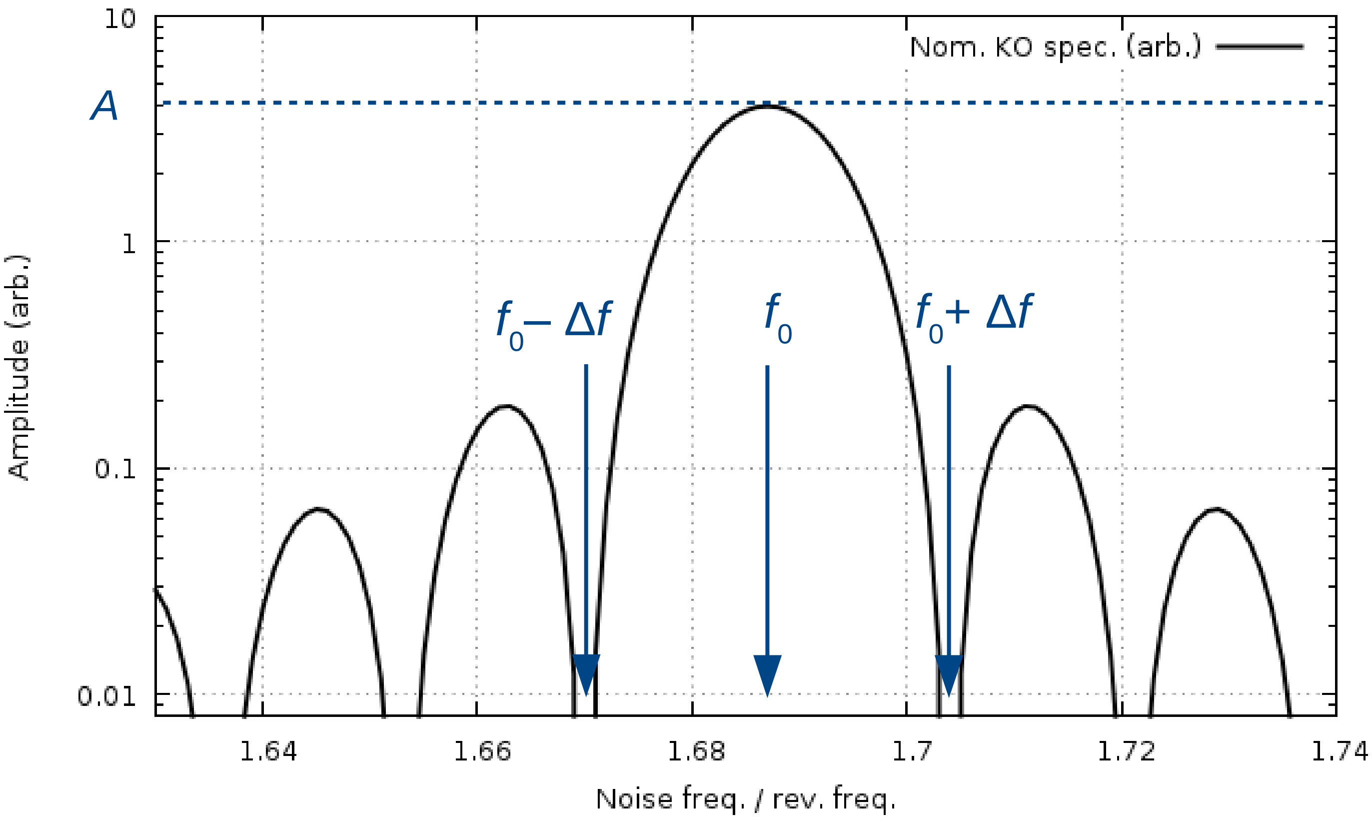
# RF-KO Spectrum (I)

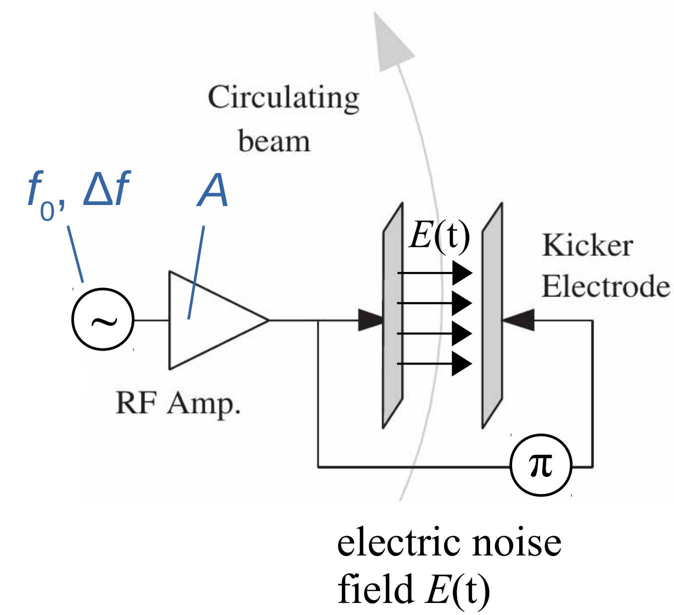
RF-KO spectrum is generated by **random phase-shift keying** (PSK).




3 parameters define the noise kicker spectrum:

- $A$: Amplitude
- $f_0$: Main oscillator frequency
- $\Delta f$ : Random PSK frequency

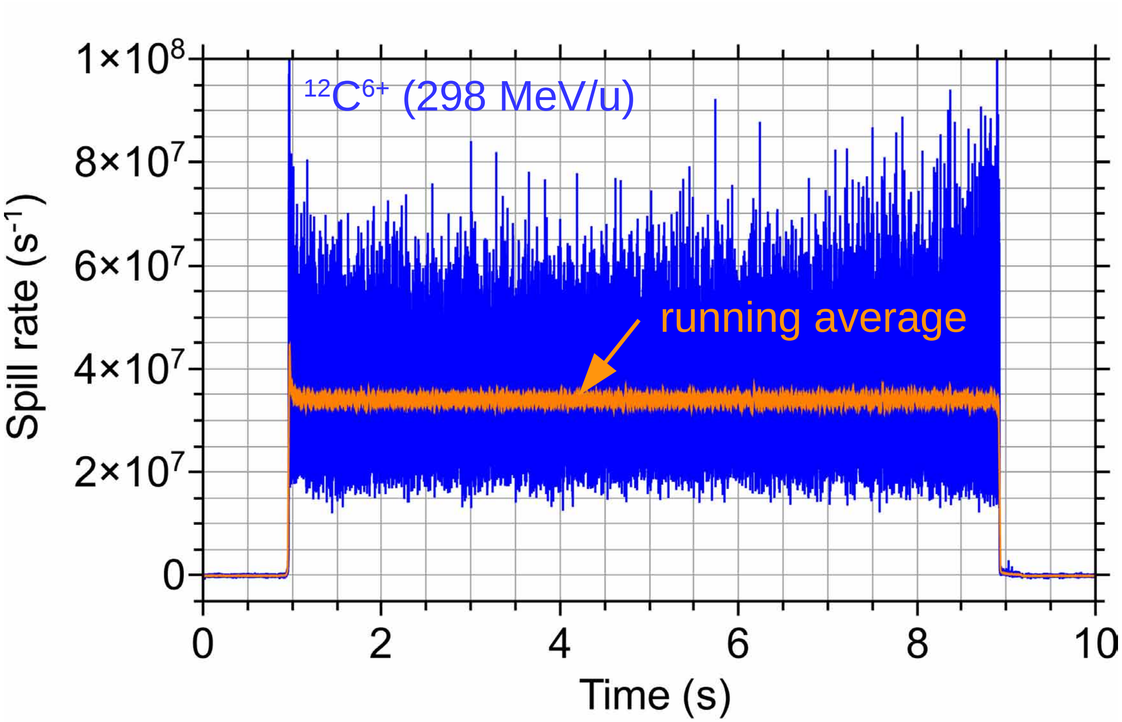


# Spill quality

Spill contributed by MIT to the 2016 “Slow Extraction Workshop”:

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





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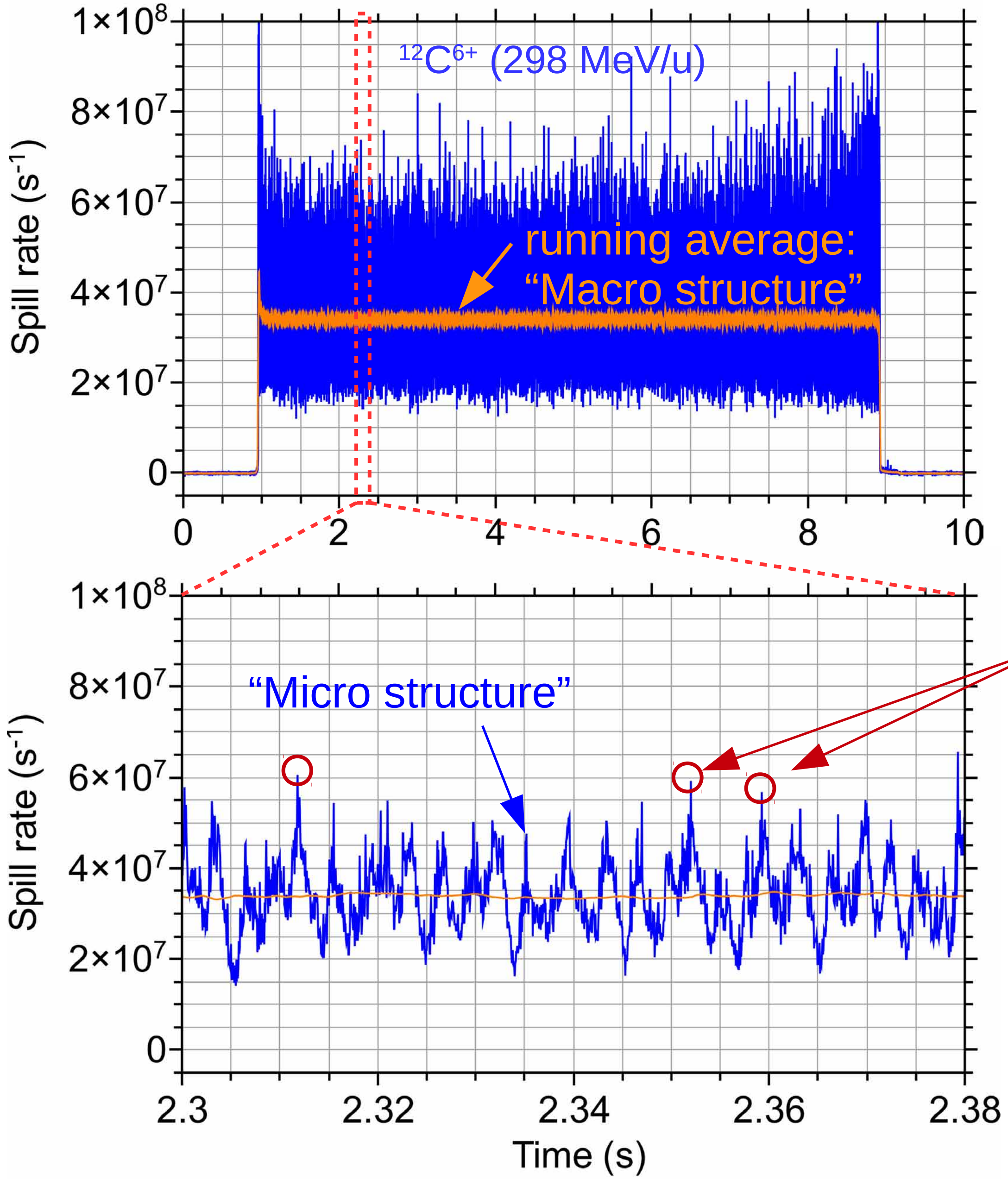
# Spill quality: "Micro"- and "Macro"-structure




RF-KO extraction combined with DIC

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

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

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

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



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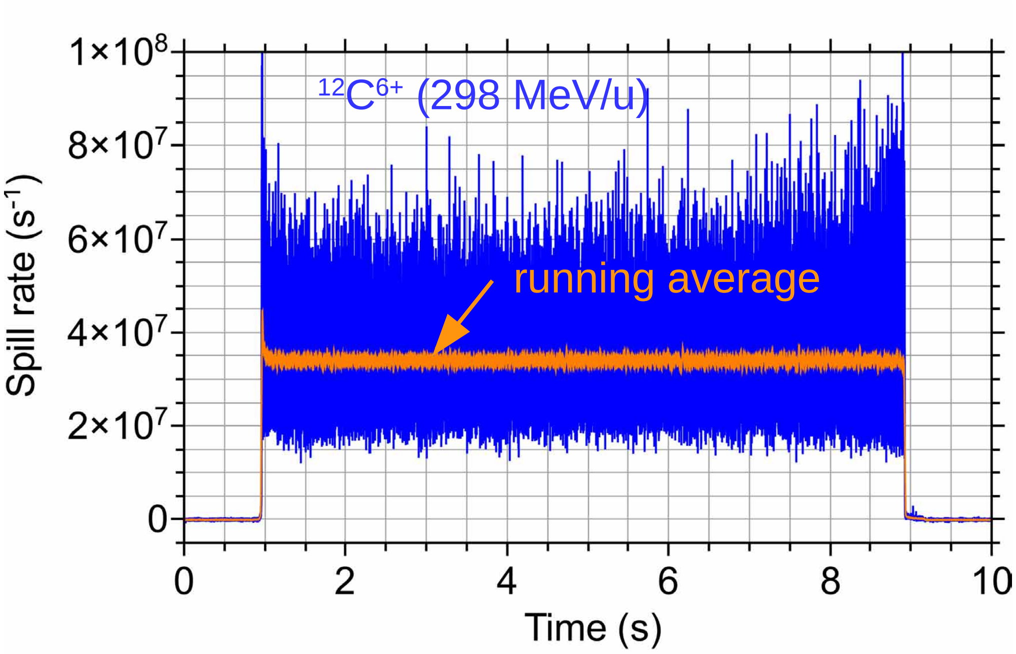
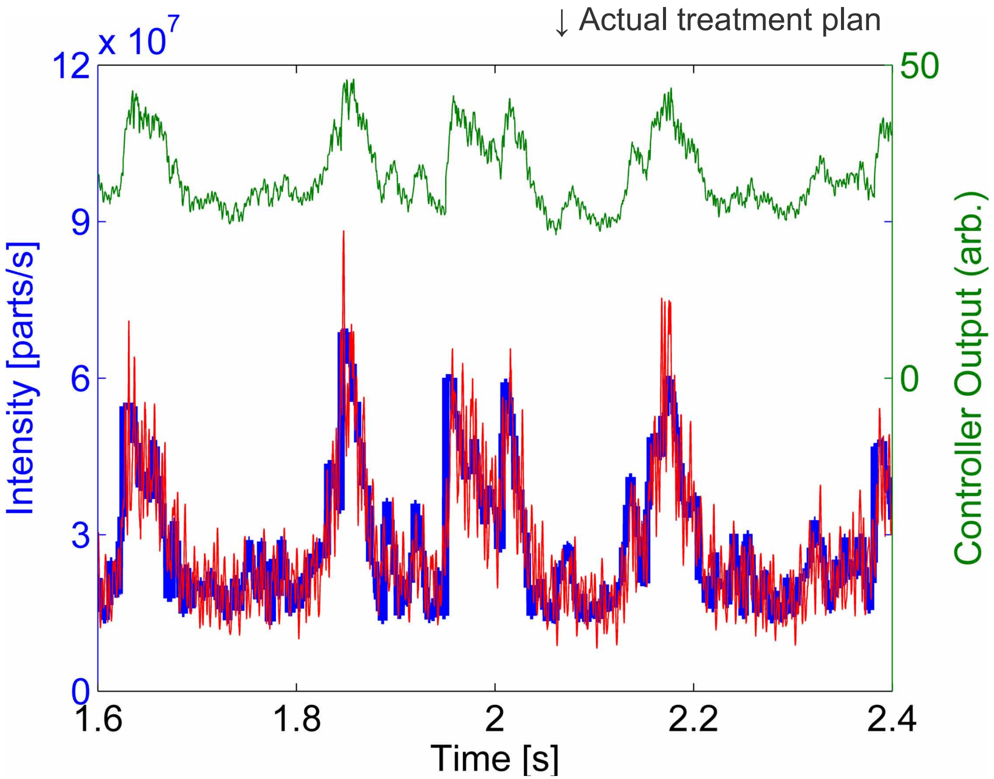
# Macro structure with DIC




From spill **stabilisation** ...

… to spill **modulation**.



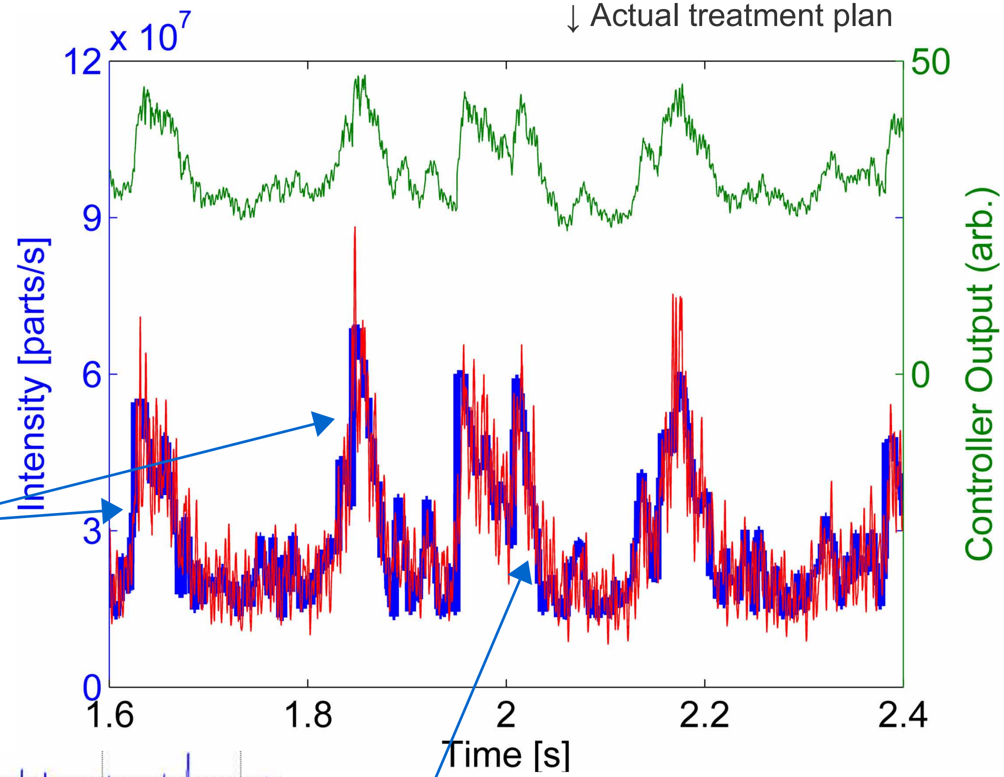

DIC can *vary* the spill rate on the ~ 10 ms scale.

# Macro structure with DIC

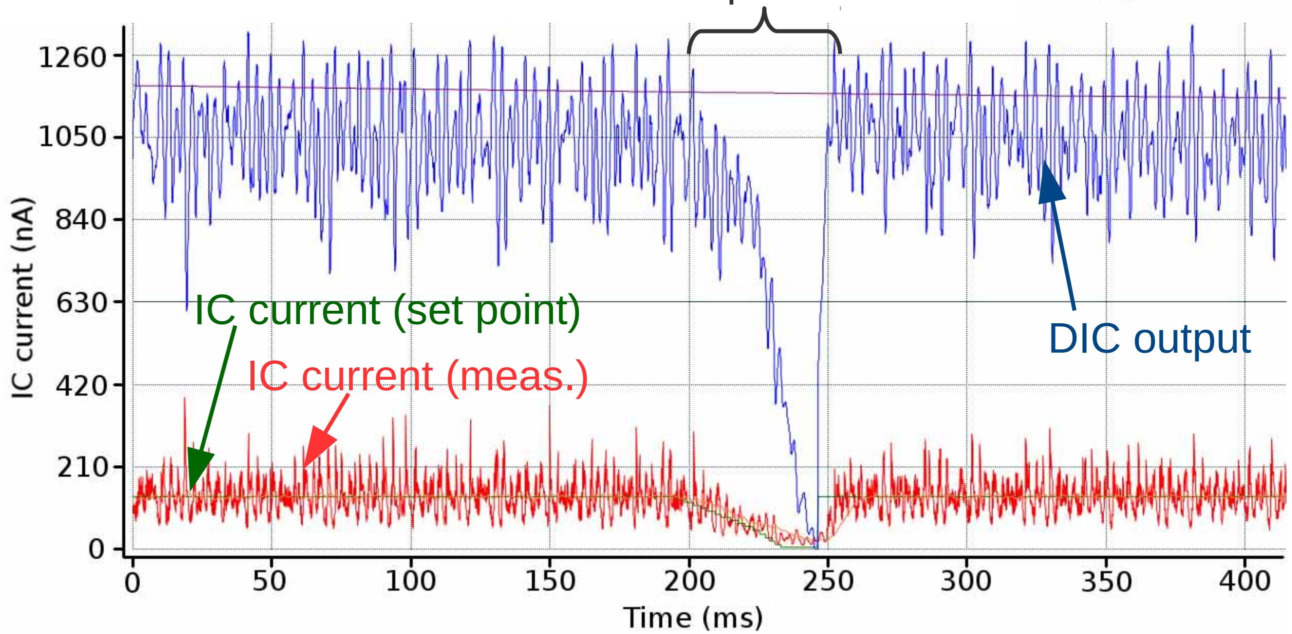
Irradiation plans may include jumps in the extraction rate by up 33 x (in both directions!).

*Ramping-up* the extraction rate is relatively easy ...

↓ Actual treatment plan




ramp-down




More challenging:

Fast (~ 10 ms) ramps from high to low intensity.

← Benchmark plan to test ramping-down behaviour of extraction rate.

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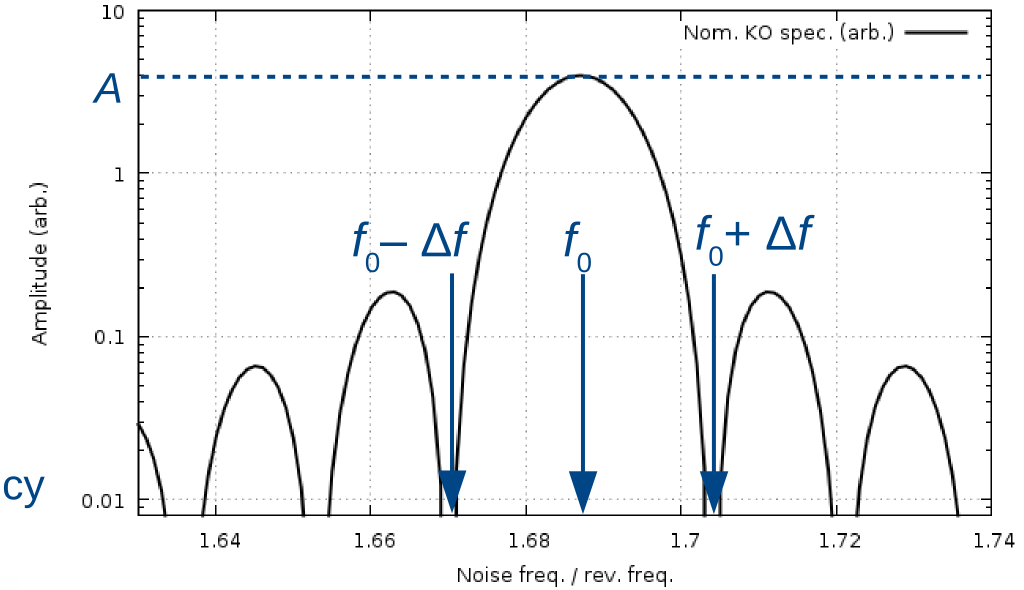
# RF-KO-Spectrum (II)



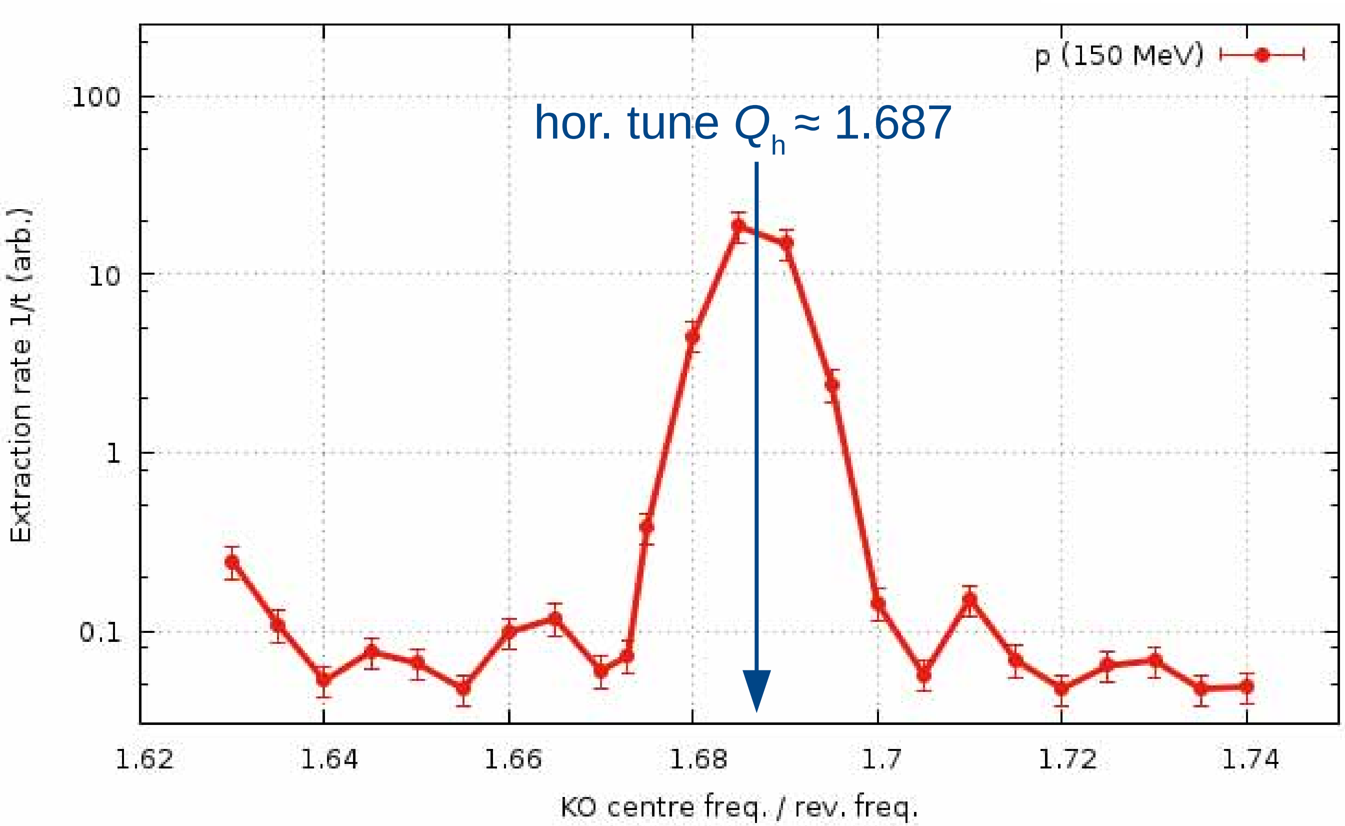

Controlled @ runtime via DIC

Part of machine setup

*A*: Amplitude

$f_0$: Main sine frequency

$\Delta f$ : Random PSK frequency




Possible optimisation strategy for $f_0$ :

Highest extraction rate:

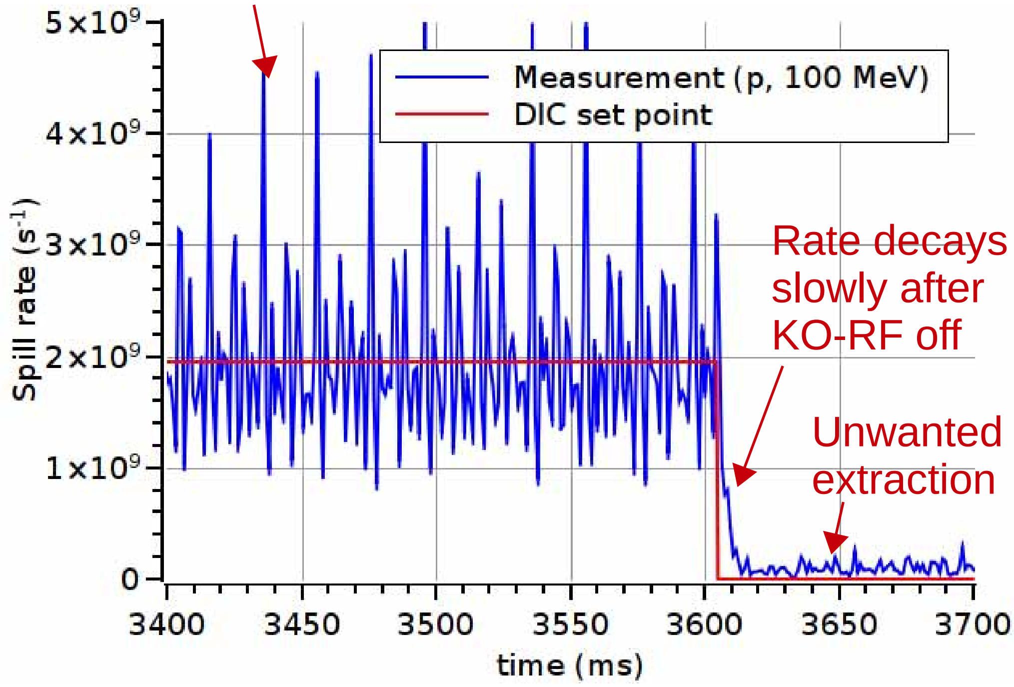
→ $f_0 / f_{rev} = Q_h$ [ 1 ]

**But:** is this really the "best" extraction setting?

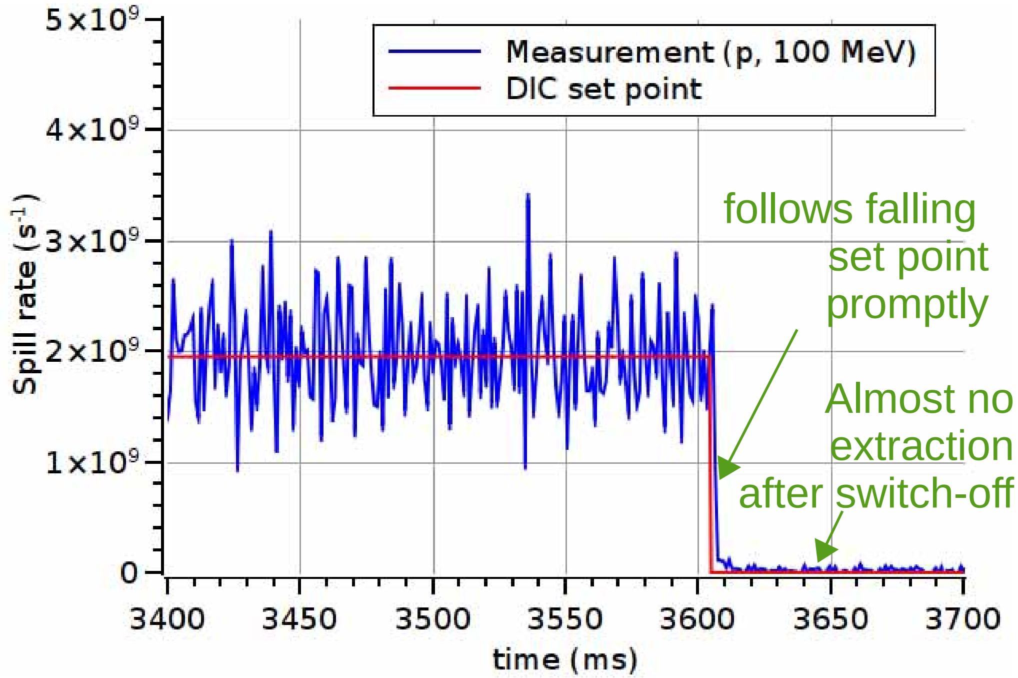
# Macro structure: Optimal response to DIC

**"Bad"** machine setting

Bad micro structure
(more on that later ...)

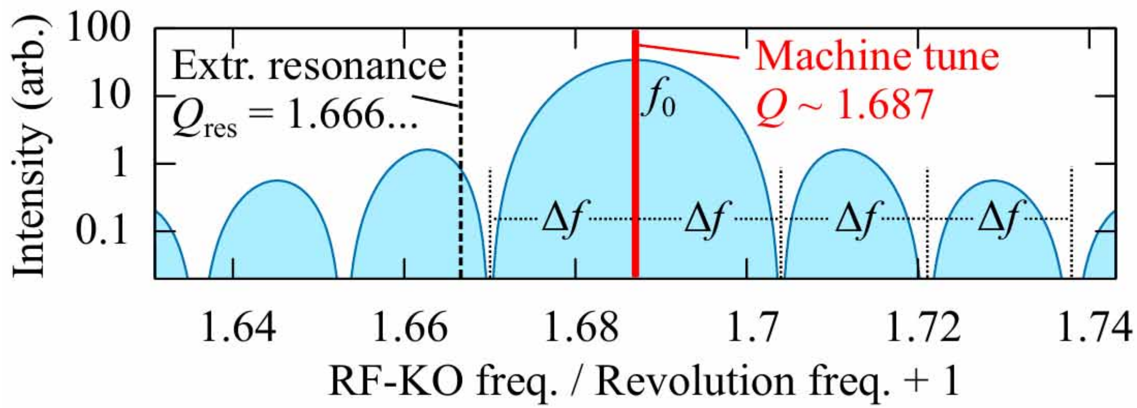



**"Good"** machine setting

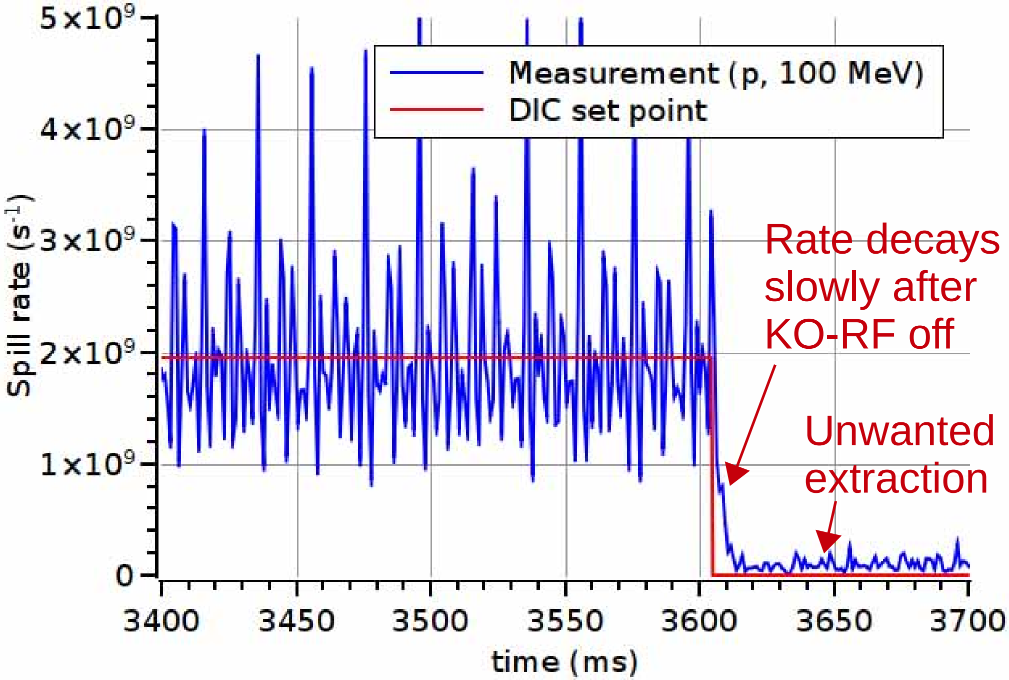



Only difference: RF-KO exciter spectrum

# Macro structure: Optimal response to DIC

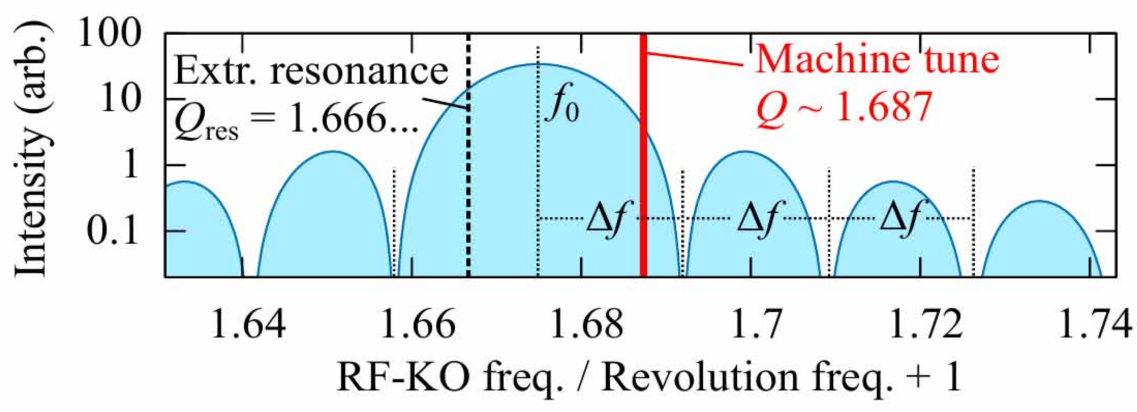



KO-RF spectrum aligned with **machine tune** (highest max. extr. rate) ...

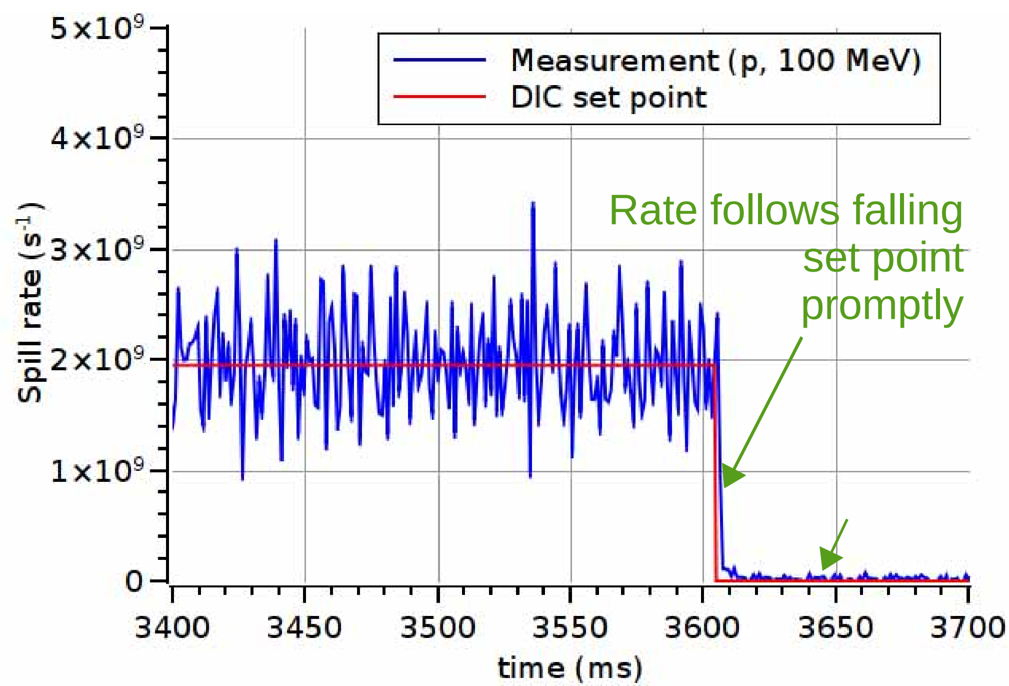



… results in **"bad"** ramp-down behaviour!

# Macro structure: Optimal response to DIC

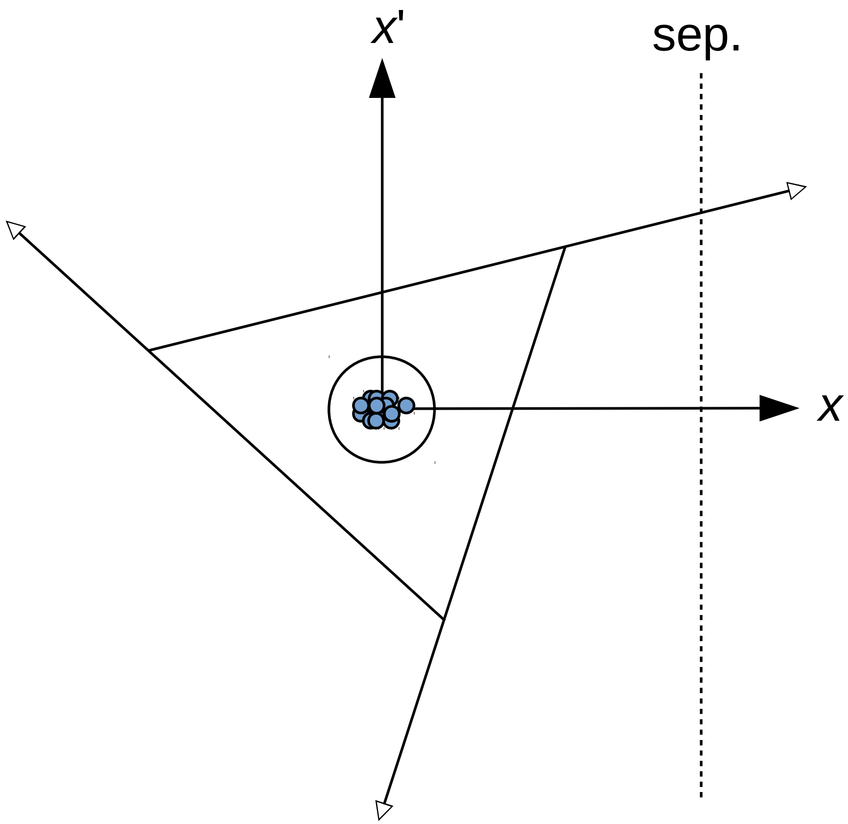



KO-RF spectrum shifted towards **sext. resonance** ...




… **"good"** ramp-down behaviour!

# Macro structure: Optimal response to DIC

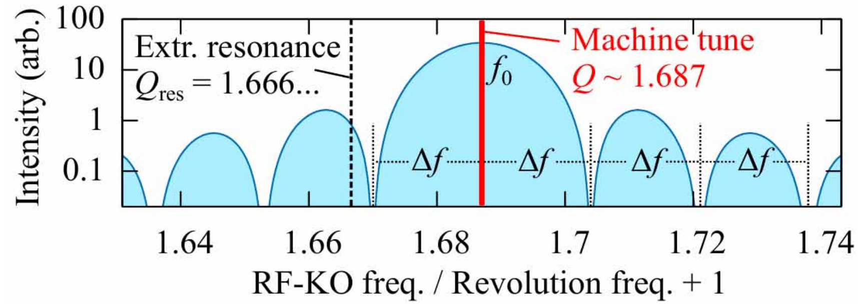


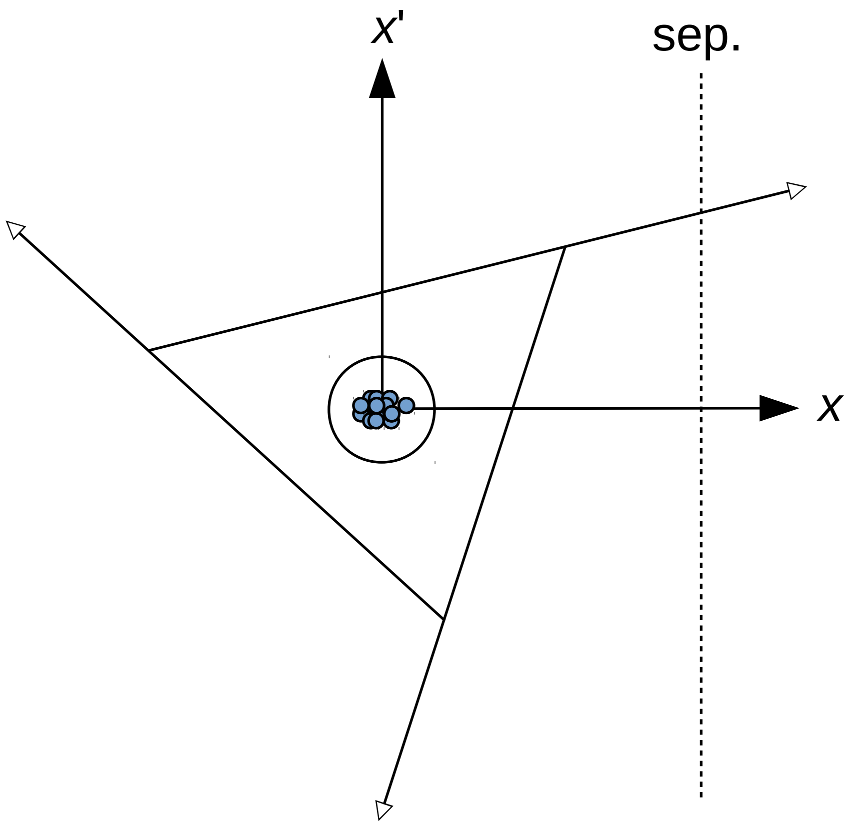

**Explanation?**

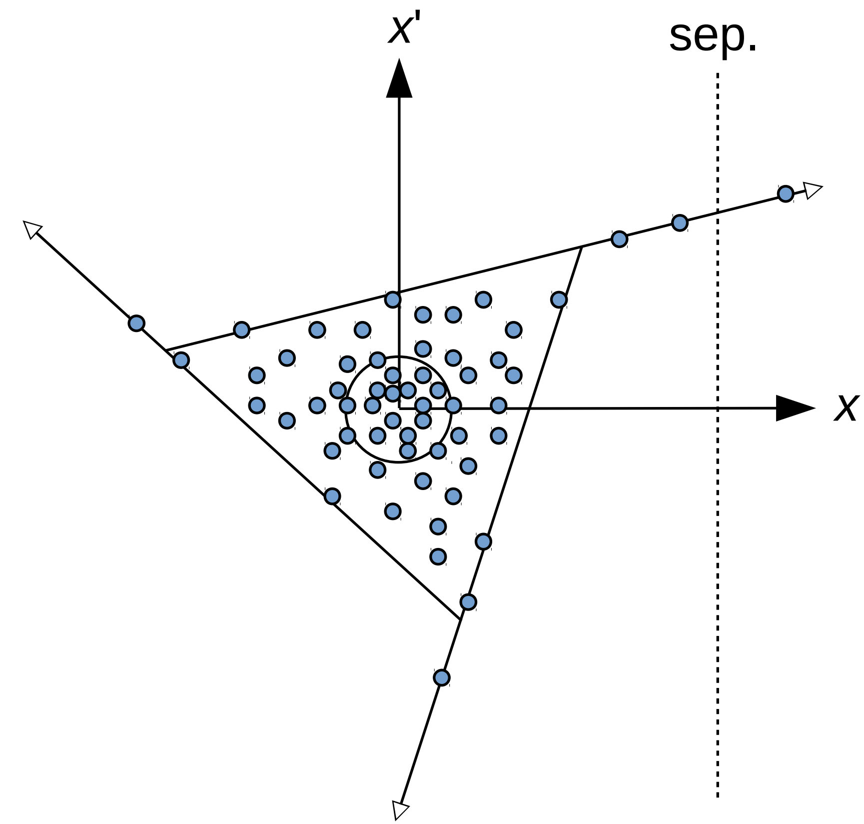
Before RF-KO:

(Relatively) low-emittance beam

# Macro structure: Optimal response to DIC



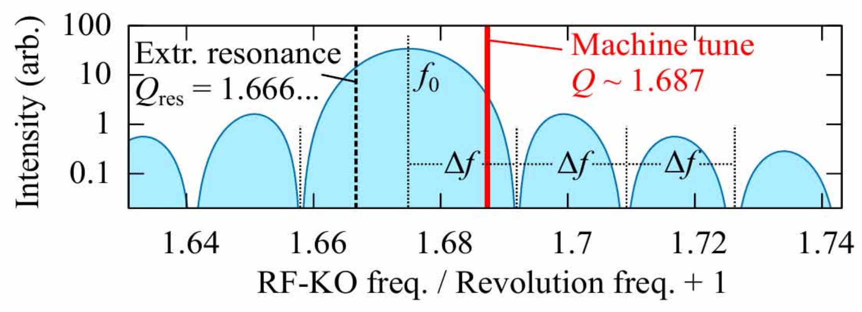



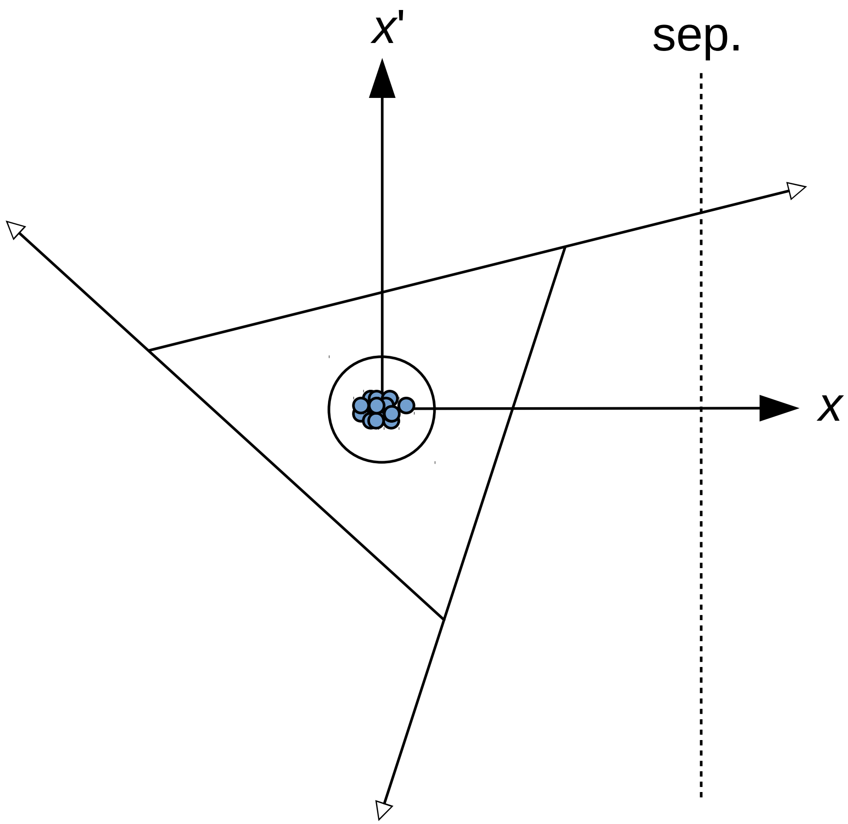



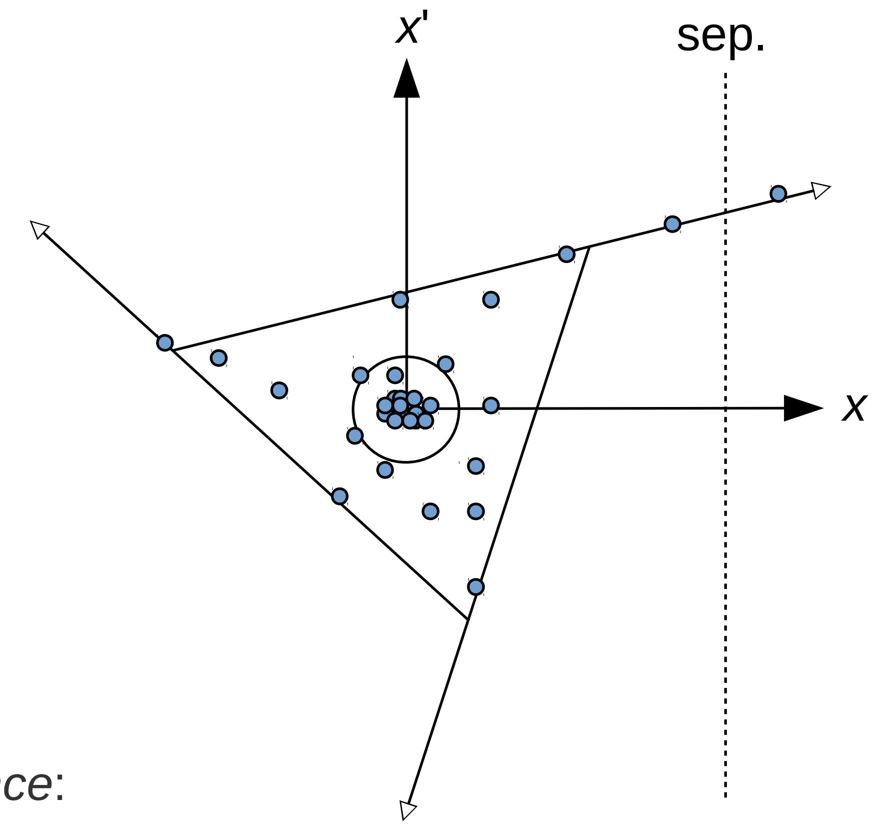

RF-KO spectrum centred on *machine tune*:

→ RF-KO excites **low amplitudes** preferentially.

# Macro structure: Optimal response to DIC



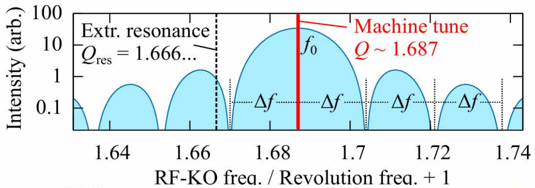




RF-KO spectrum shifted towards *extraction resonance*:

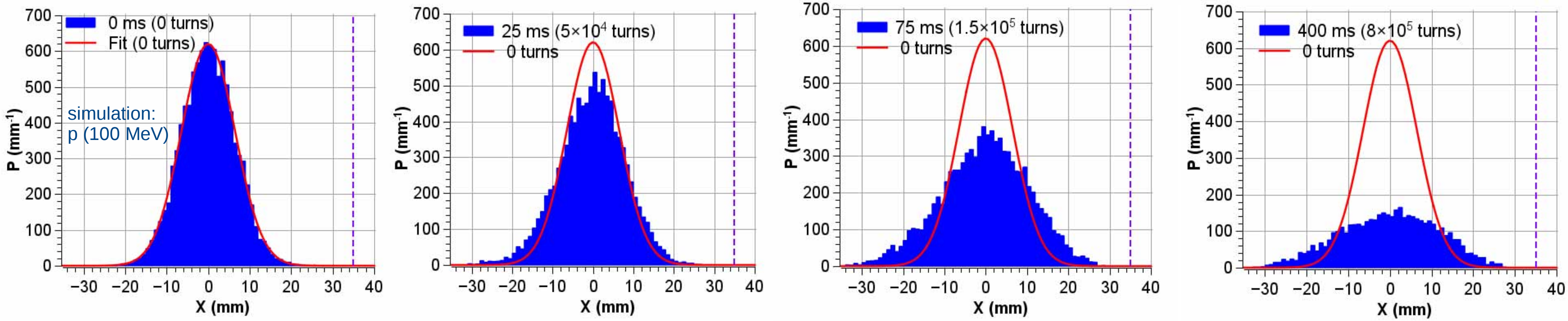
→ RF-KO excites **large amplitudes** preferentially.

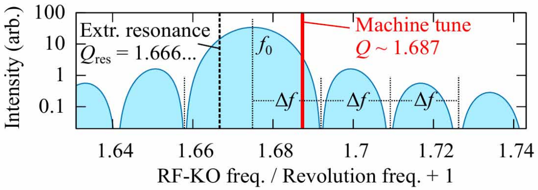
# Macro structure: Optimal response to DIC




## Tracking simulation 1: RF-KO @ machine tune – **"Bad"** setting

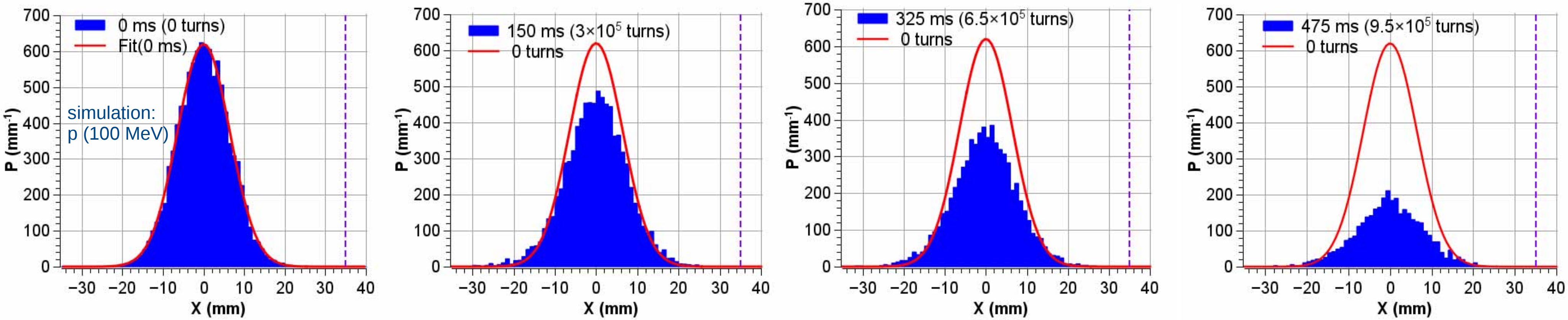
Beam core is excited preferentially, large unstable halo.




## Tracking simulation 2: RF-KO @ extr. res. – **"Good"** setting

Particles in halo are rapidly extracted, beam core "keeps shape".

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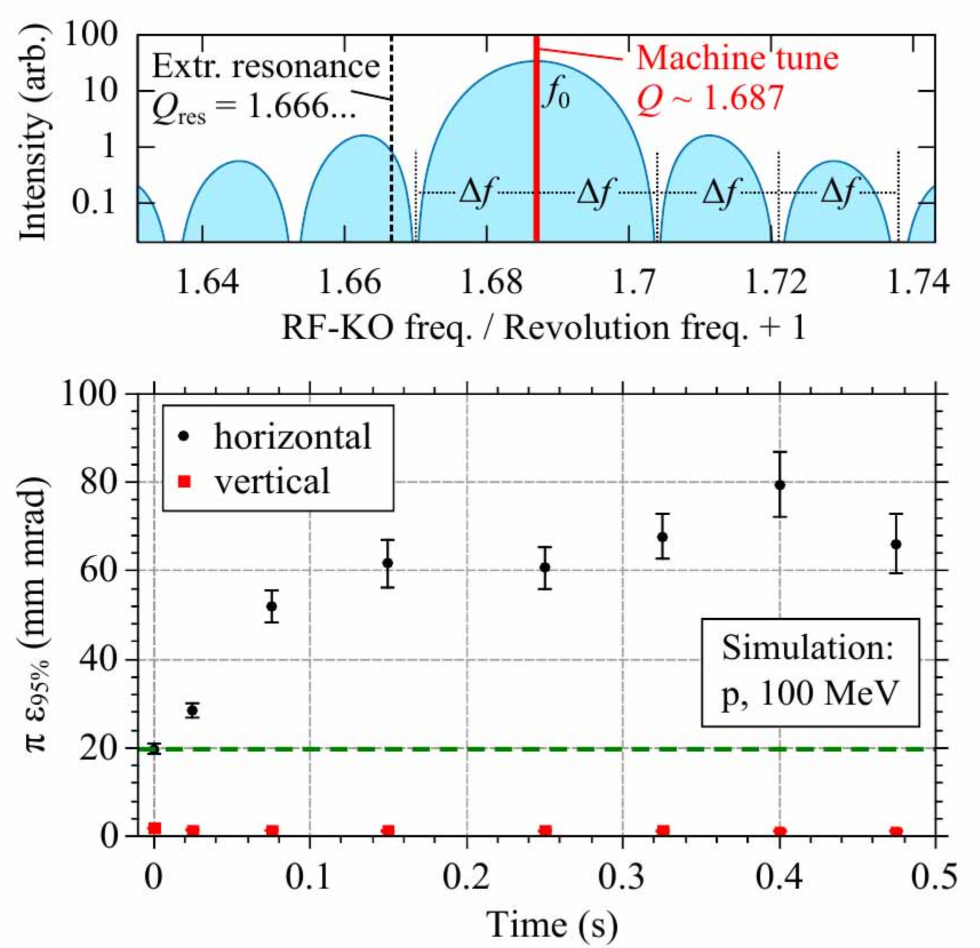
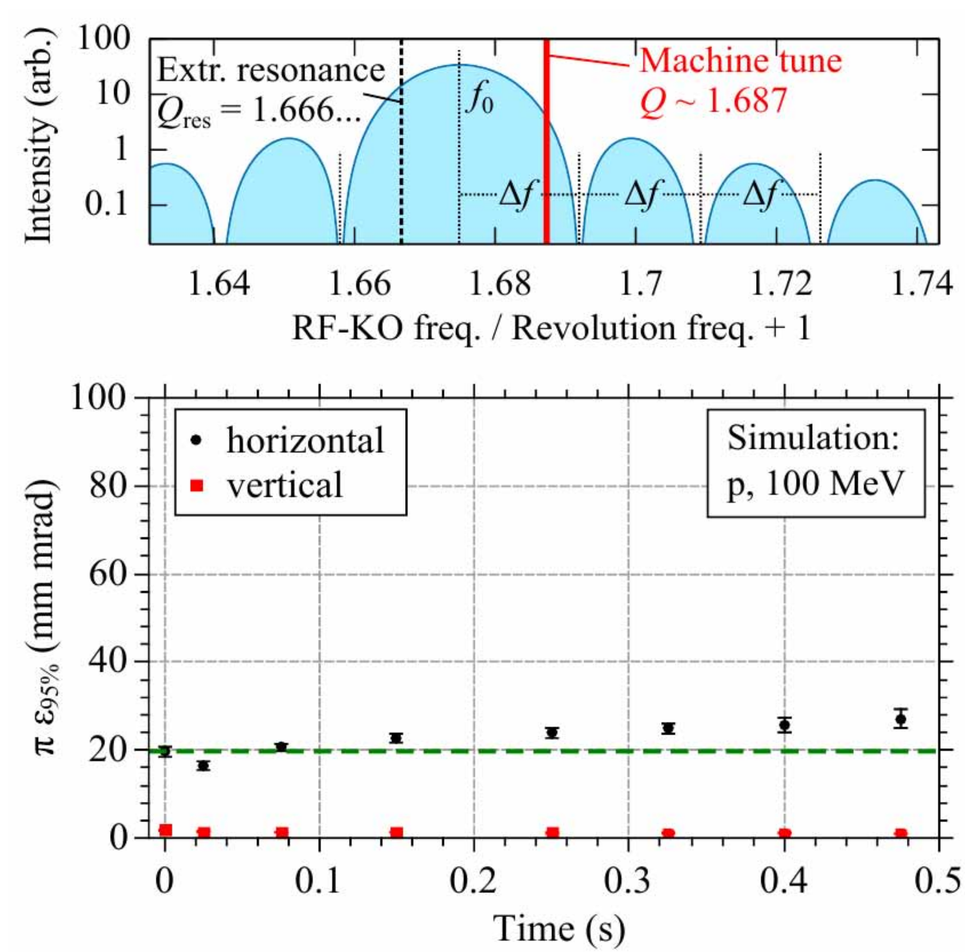
# Macro structure: Optimal response to DIC

RK-KO @ machine tune
→ Strong hor. emittance growth (simulation).




RF-KO @ extr. resonance
→ Weak hor. emittance growth (simulation).




Krantz, Proc. of IPAC 2018, pp. 1084

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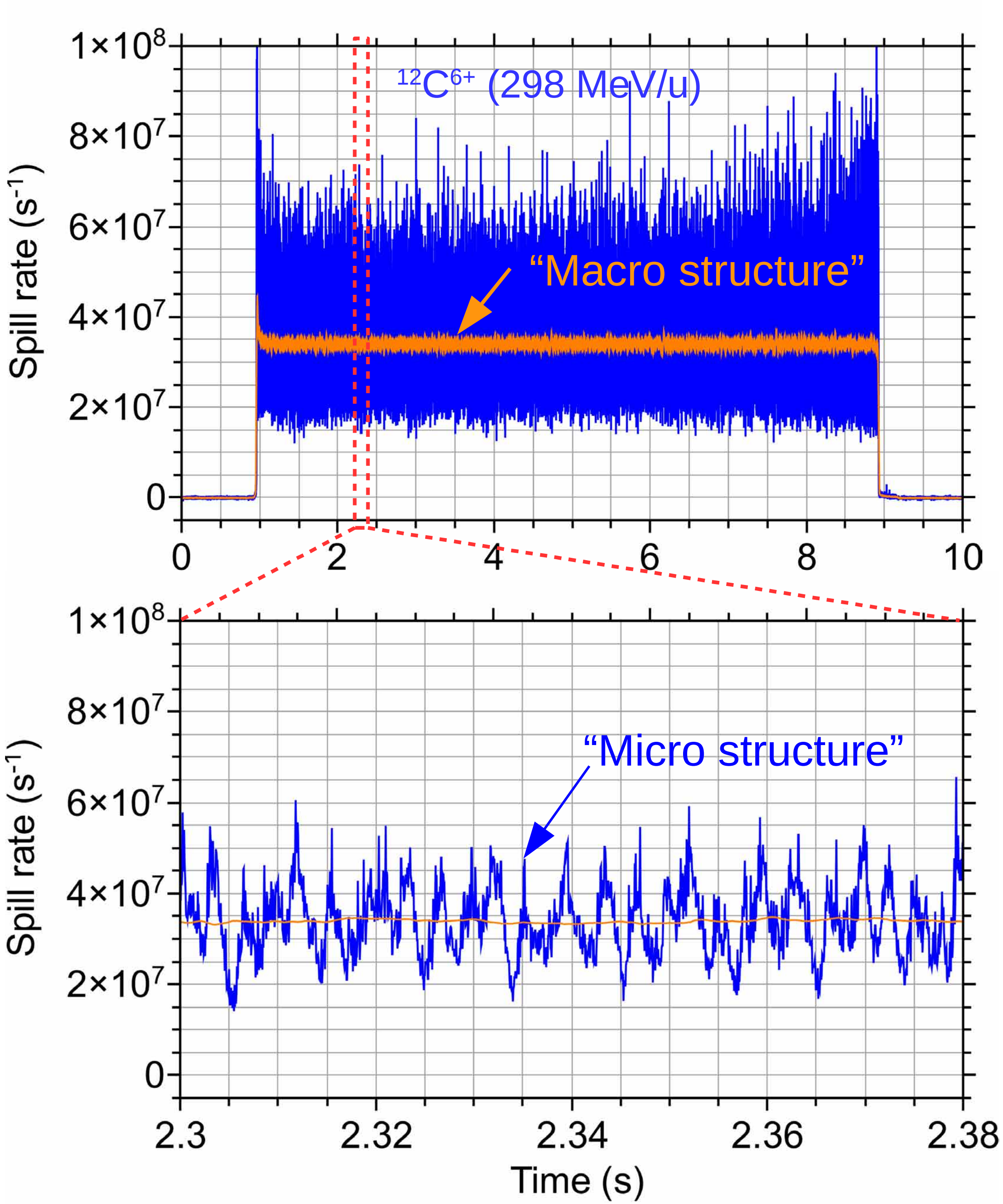
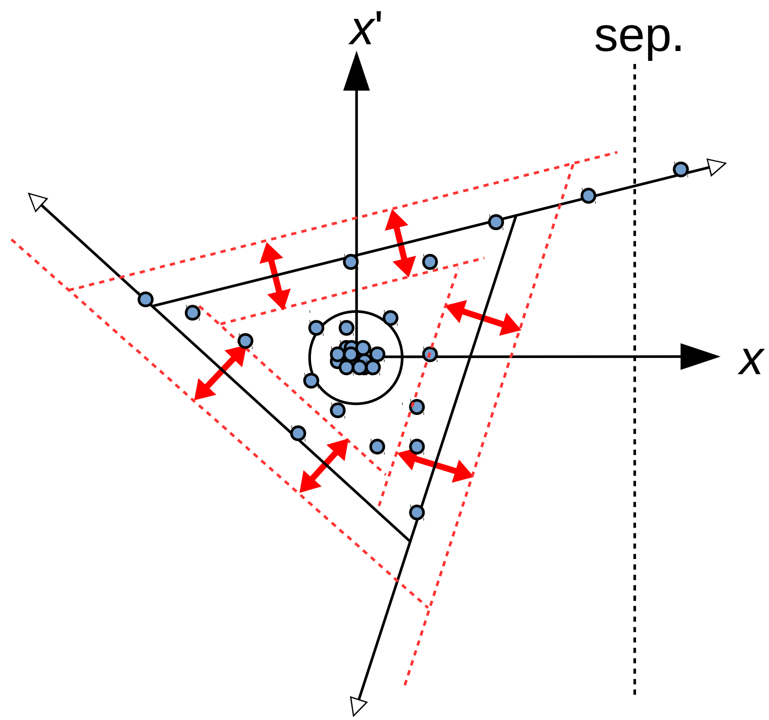
# “Micro” structure

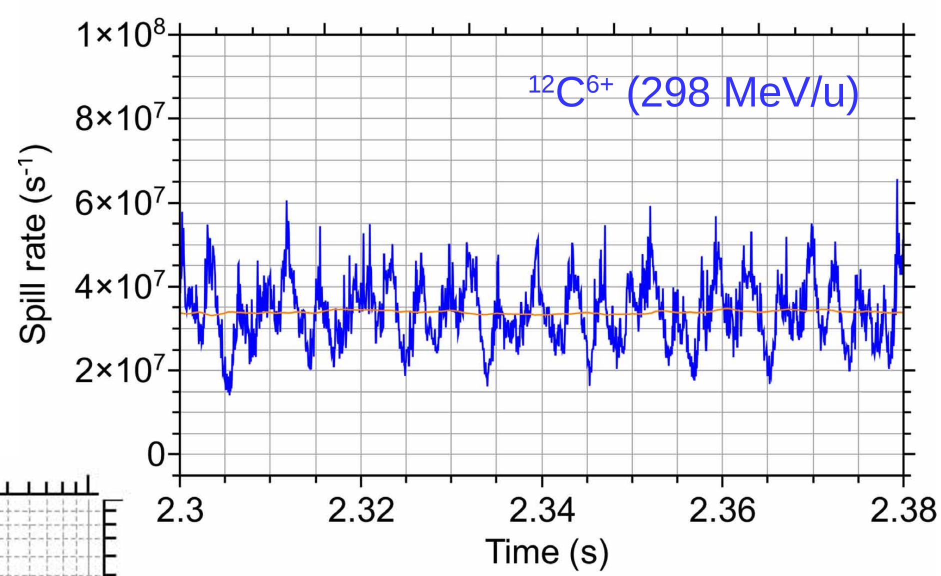


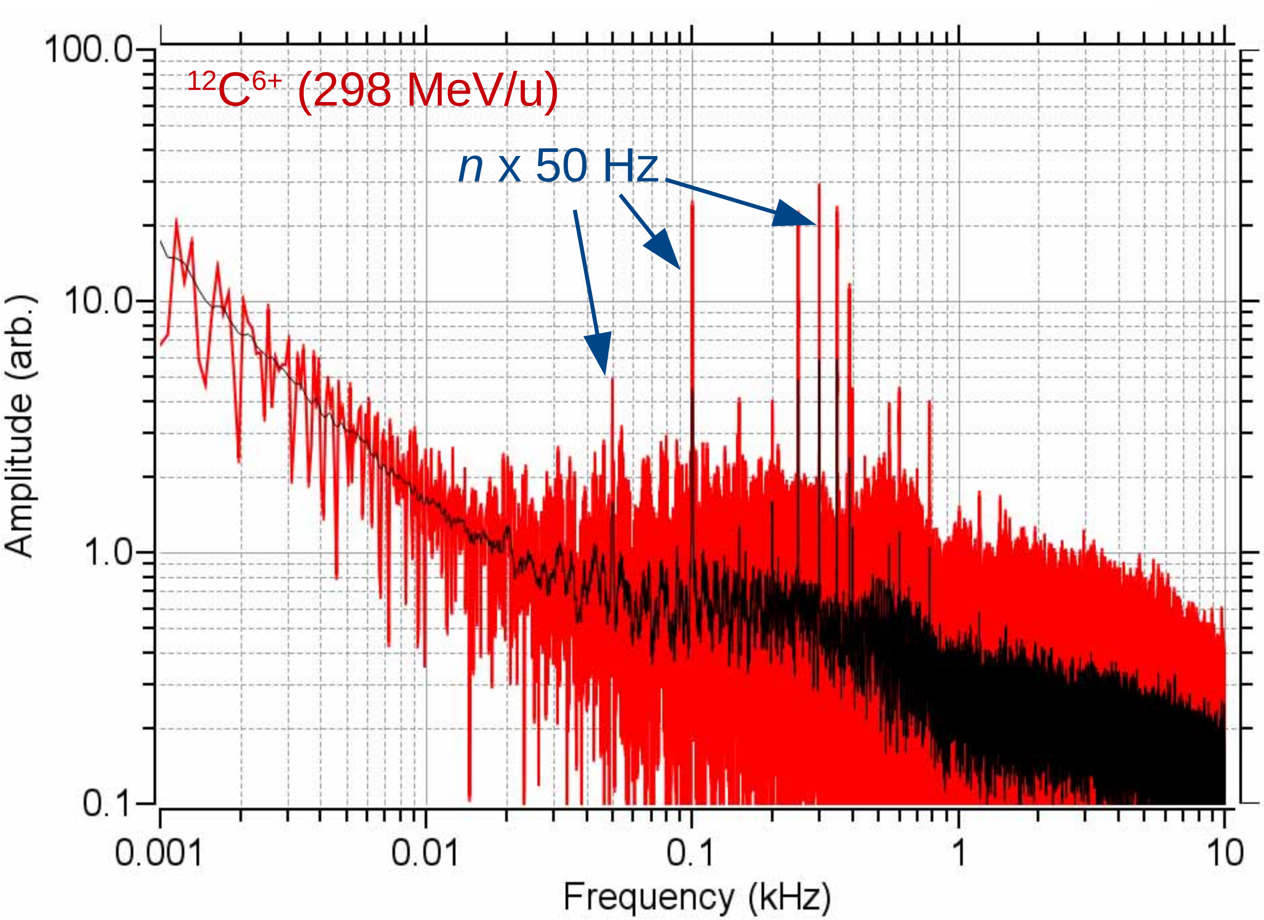

Main suspect: **Power supply ripple**

→ Hor. tune ripple
→ “Pulsing” of separatrix

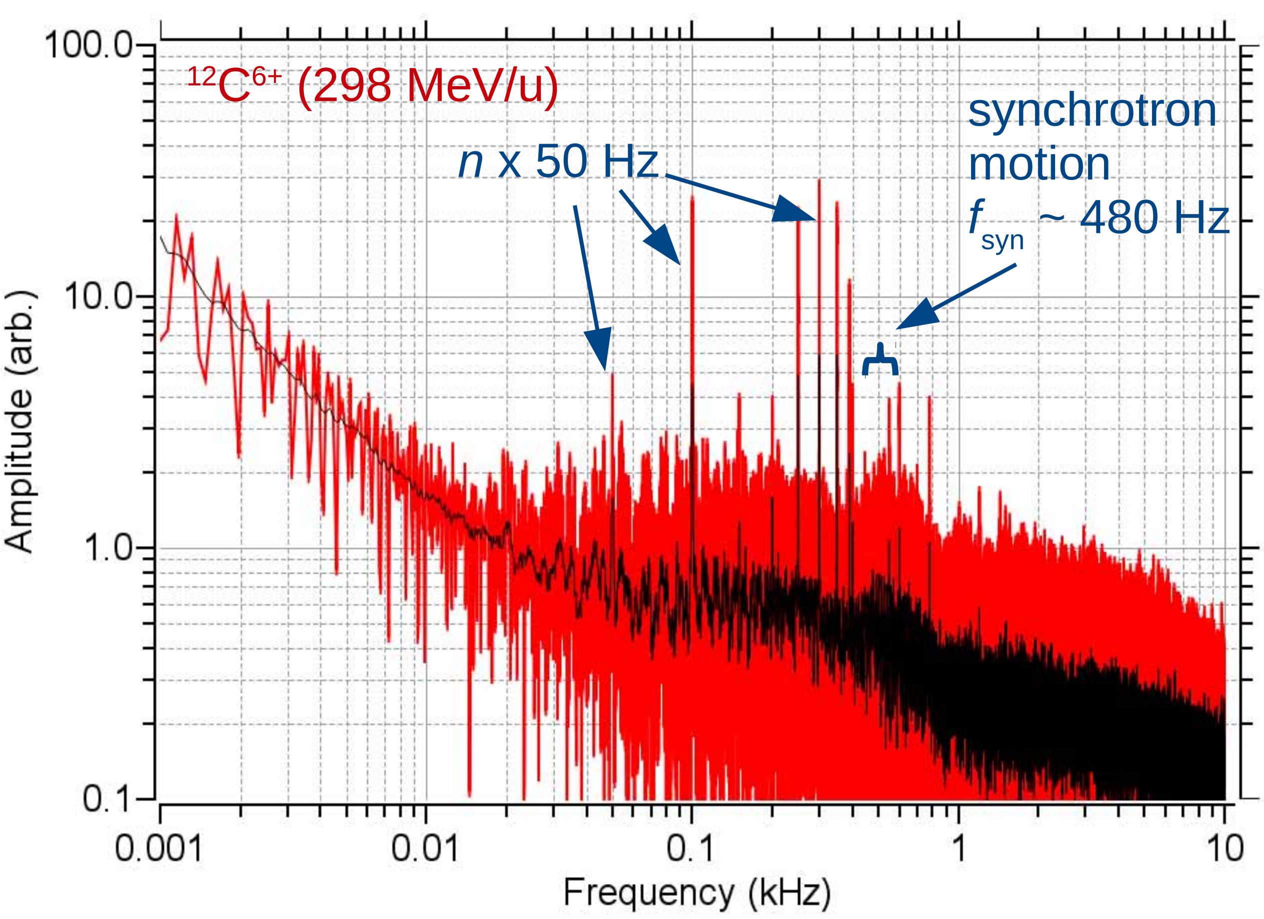
# Micro structure




FFT



# Micro structure




Extraction from bunched beam.

(Adopted from
GSI and HIT)

→ Better > kHz-scale microstructure.

e.g. Sorge et al., Proc. IPAC 2018



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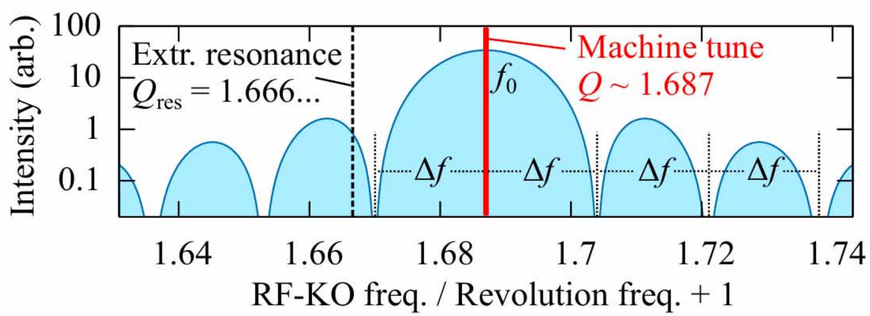
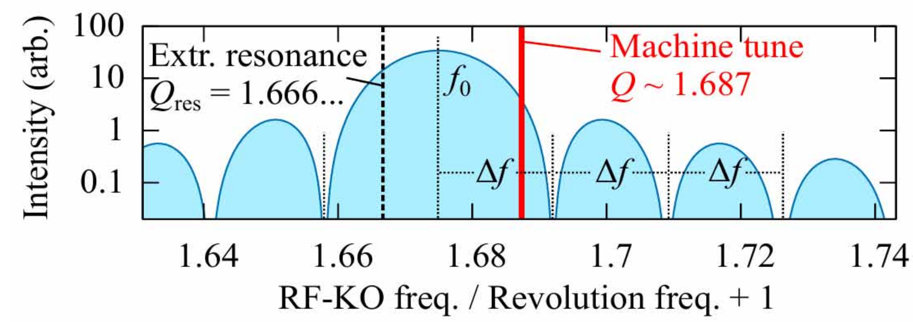
# Micro structure: Effect of RF-KO spectrum

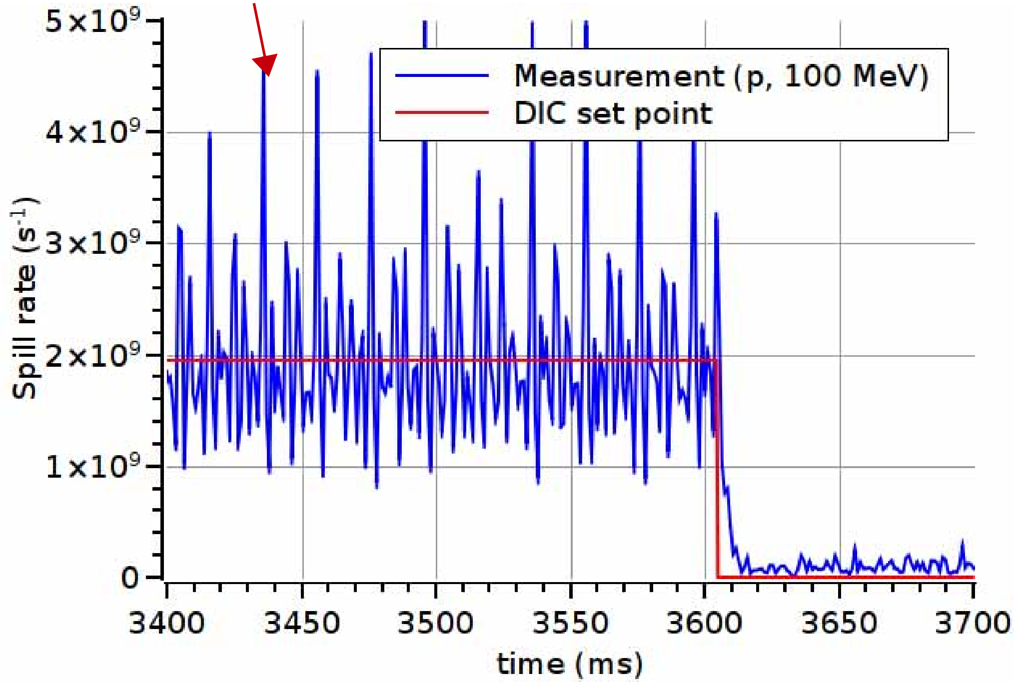
**"Bad"** RF-KO setting

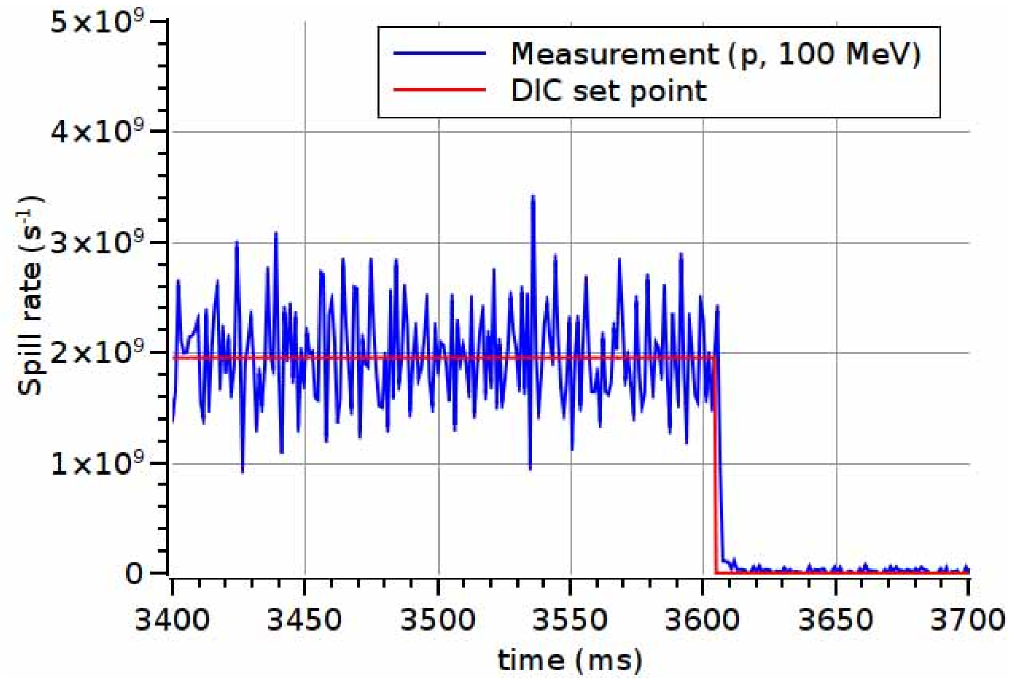



**"Good"** RF-KO setting




Bad micro structure

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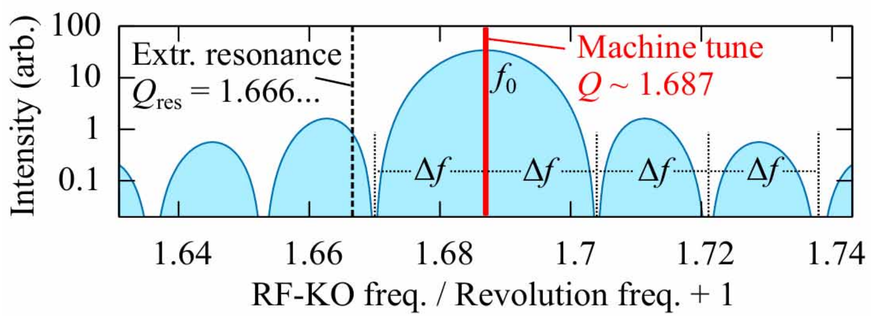
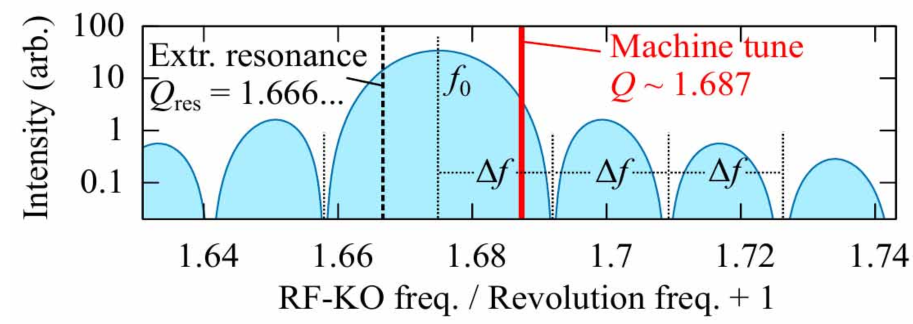
# Micro structure: Effect of RF-KO spectrum

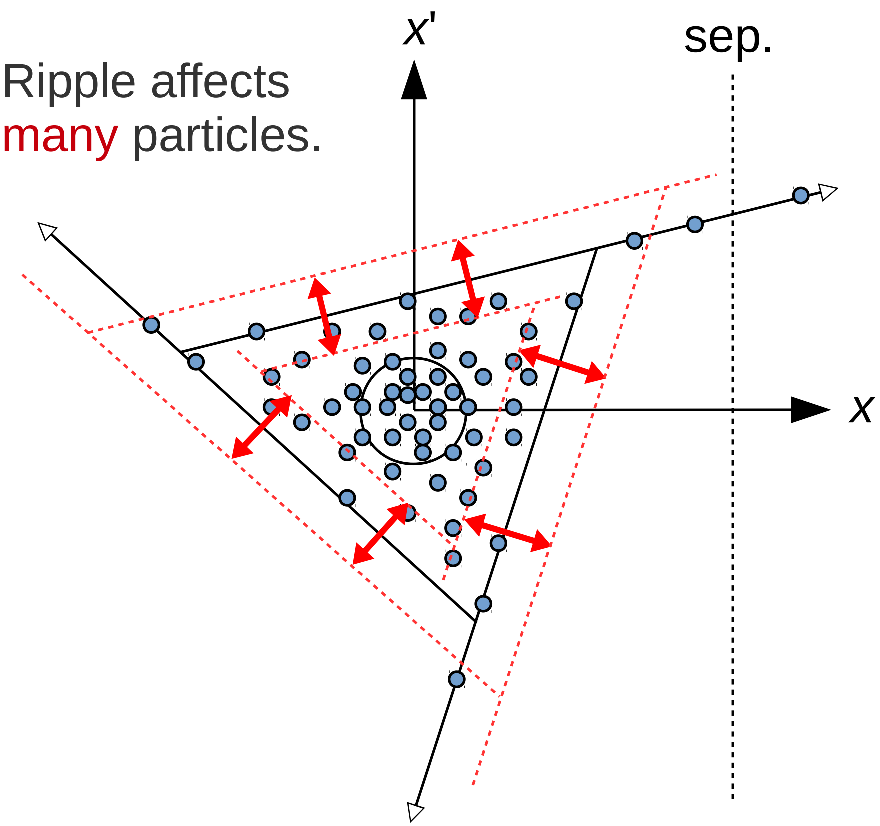
**Bad** setting



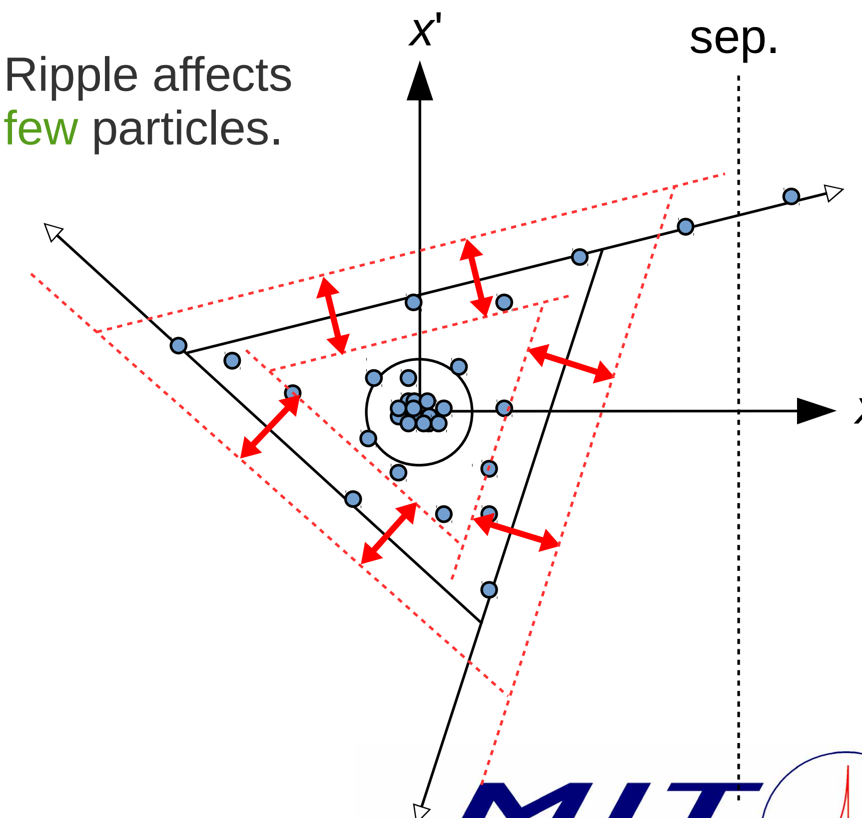

**Good** setting




Ripple affects
many particles.

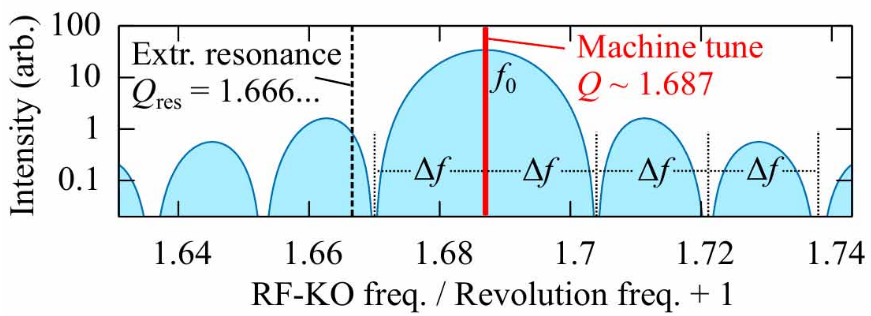



Ripple affects
few particles.

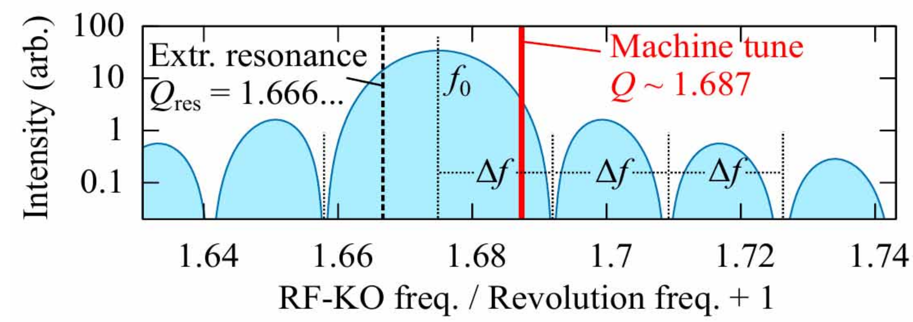


# Micro structure: Effect of RF-KO spectrum

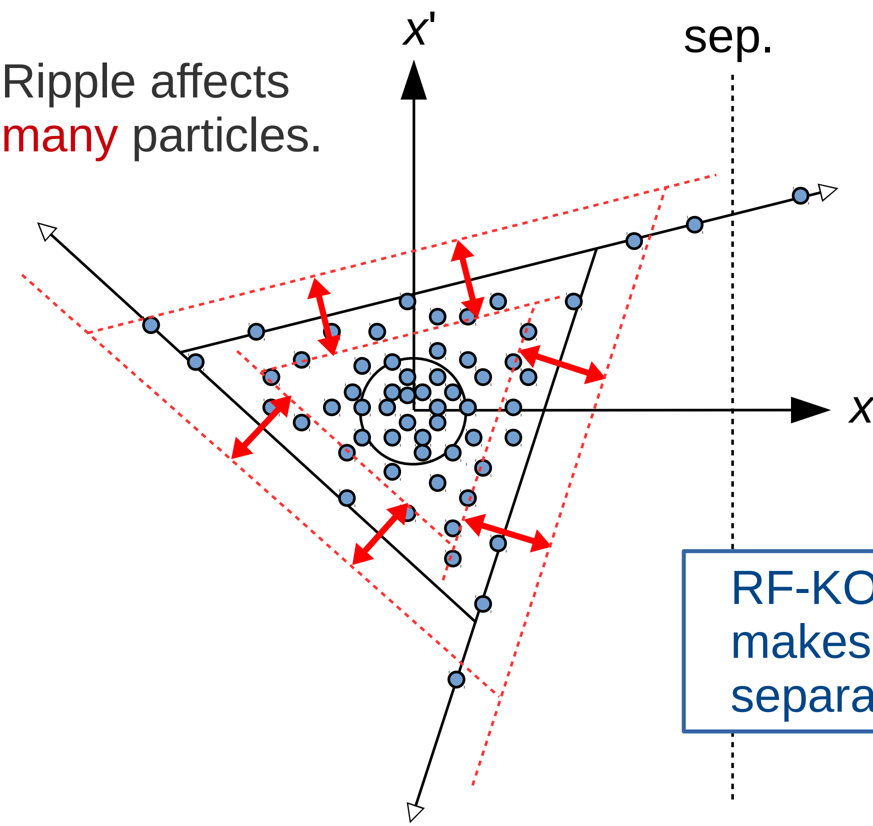
**Bad** setting



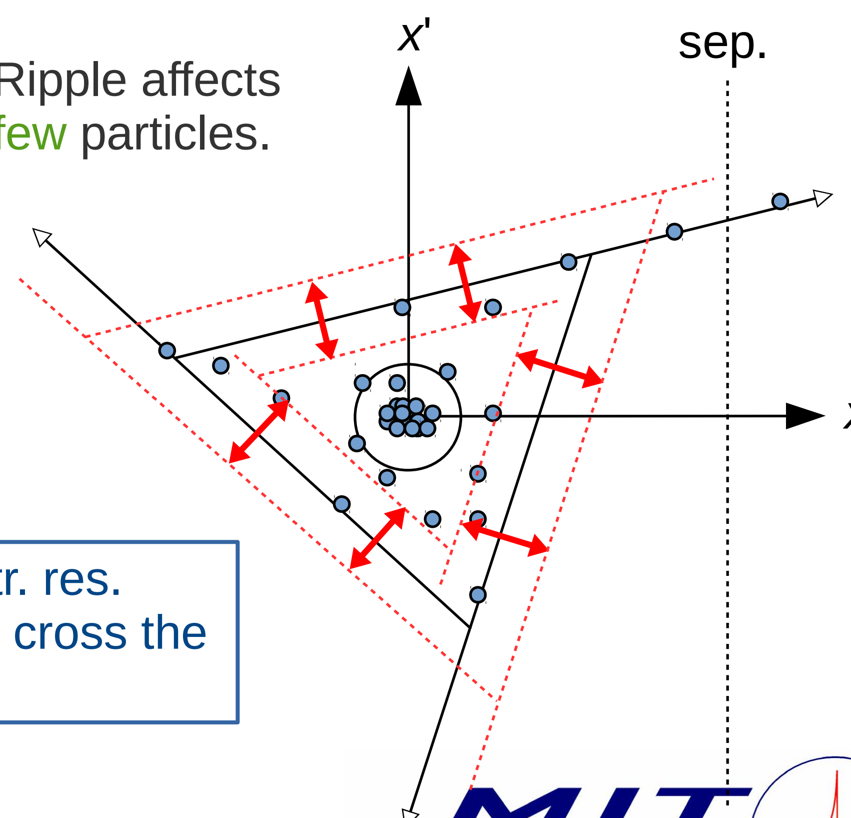

**Good** setting




Ripple affects many particles.




Ripple affects few particles.




RF-KO near extr. res. makes particles cross the separatrix **fast**!

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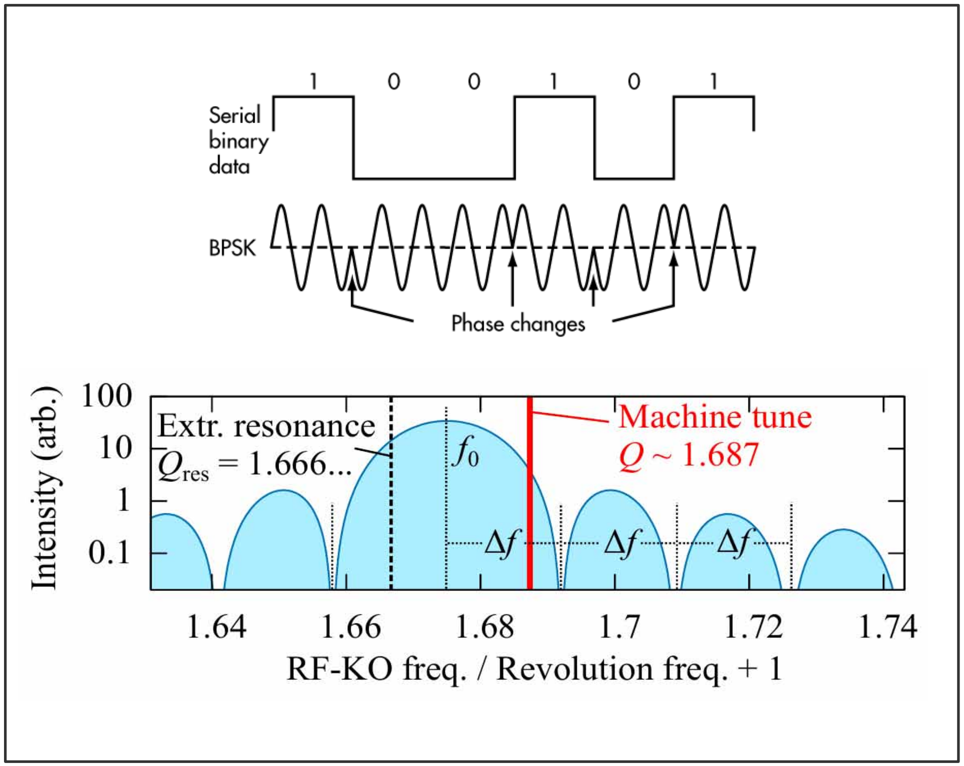
# Micro structure: Effect of RF-KO spectrum

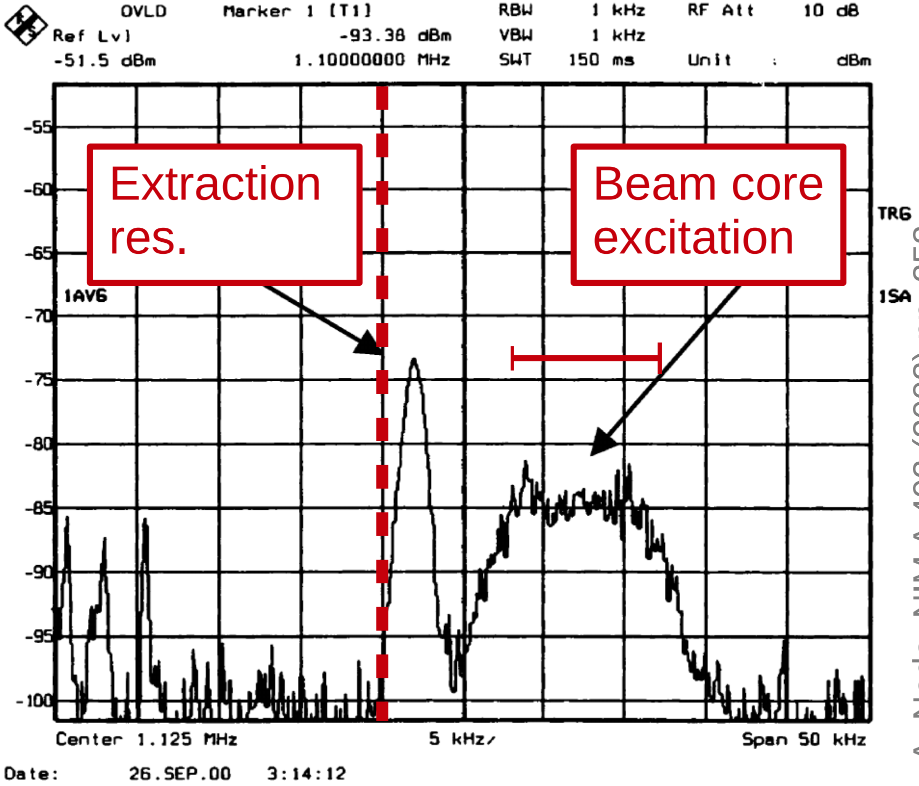
**Note:** One can probably improve further using more elaborate RF-KO spectra!

Random phase-shift spectrum
(e.g. MIT, HIT, GSI)




?

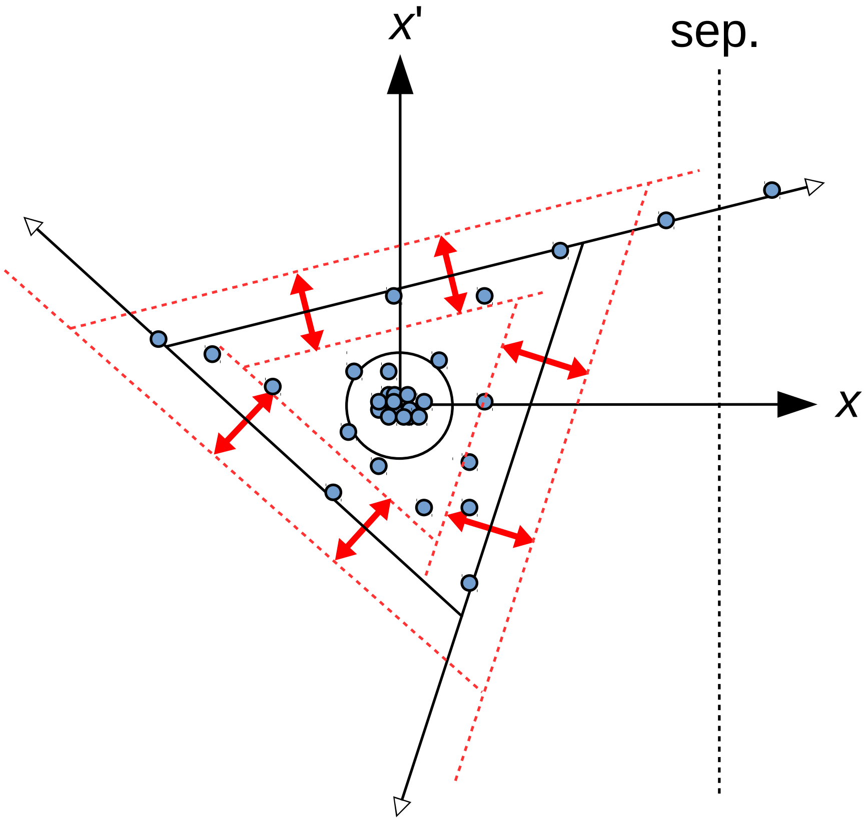
"Dual-function" RF-KO spectrum
at HIMAC (NIRS):




A. Noda, NIM A 492 (2002) pp. 253

See also: F. Faber (PhD, TU DA/HIT), in prep.

# Micro structure: Ripple compensation?




How to get rid of the separatrix ripple?

1) Get better power supplies.

Expensive!
People have tried …

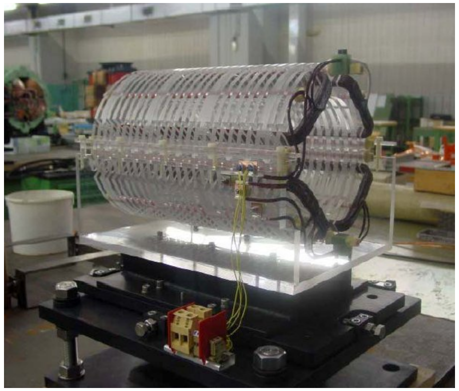
2) Active tune correction:

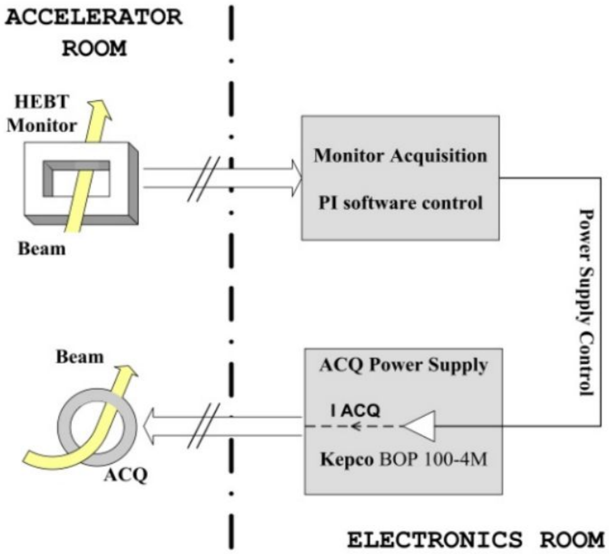
Use measured spill signal to stabilise the tune via **fast corrections of the quadrupole fields**.

("noise cancellation")

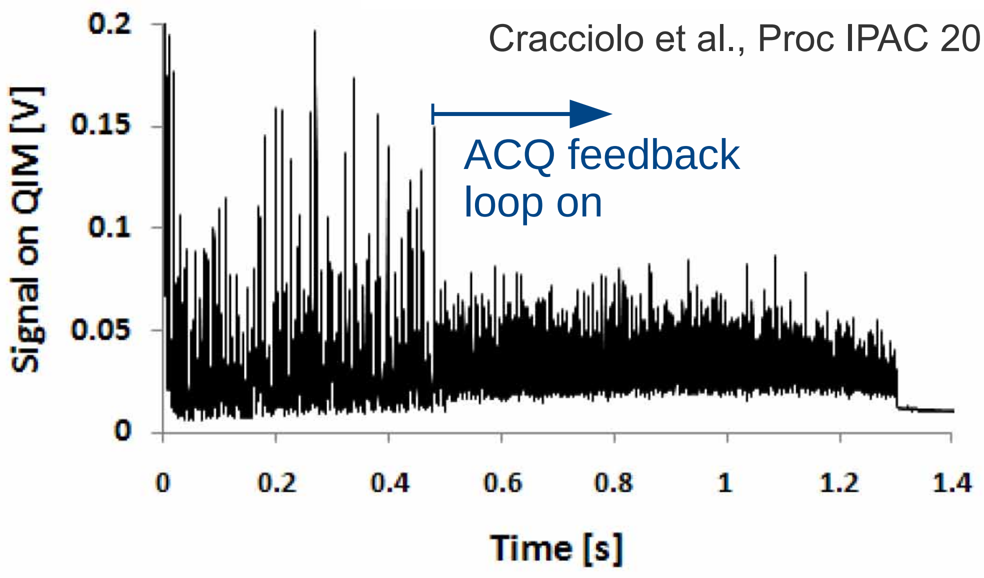
# Ripple compensation @ CNAO

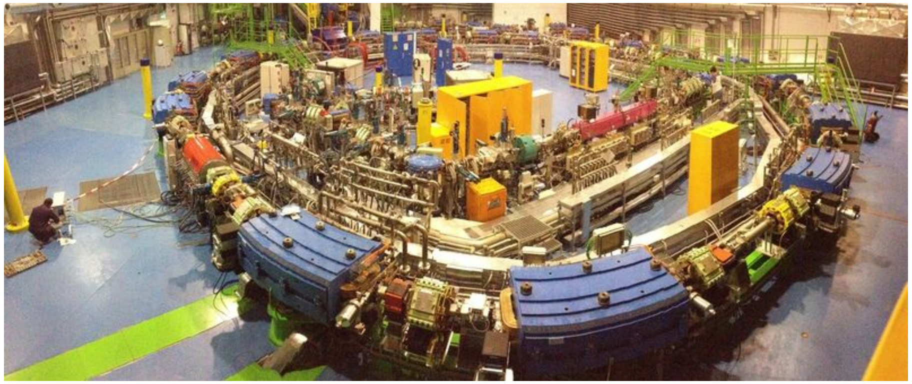
Compensation system using an Air Core Quadrupole (ACQ) magnet is used in production at the CNAO hadron therapy centre (Italy).






Cracciolo et al., Proc IPAC 2011



fondazionecnao.it

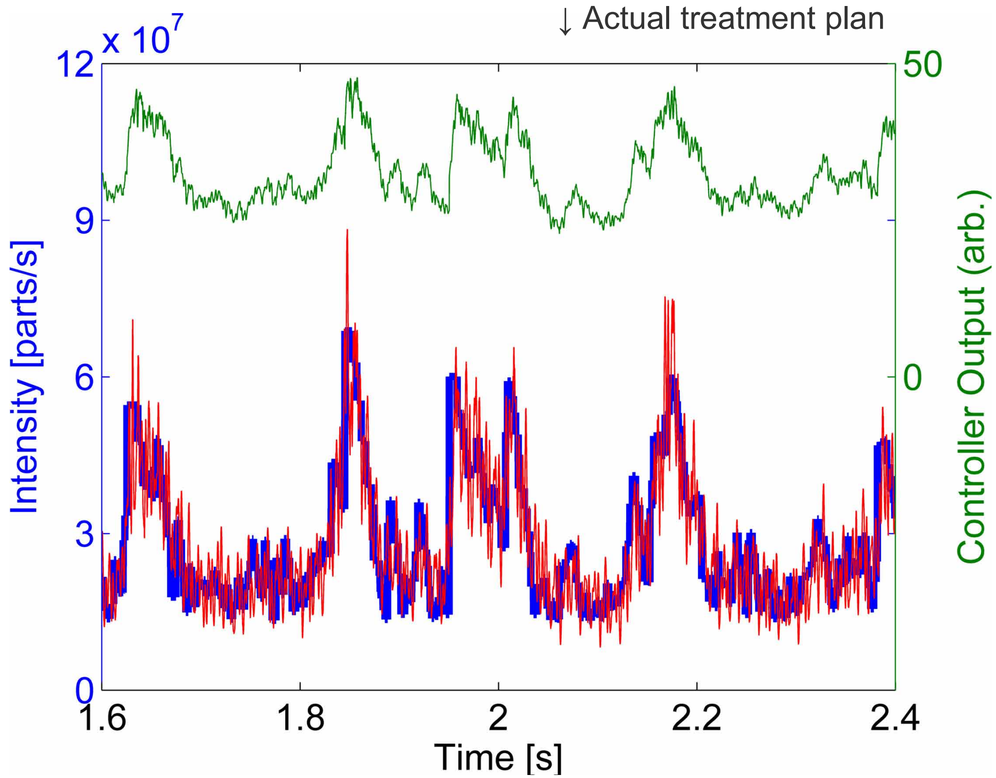
# Additional problem a MIT (and HIT)

Seen earlier:

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



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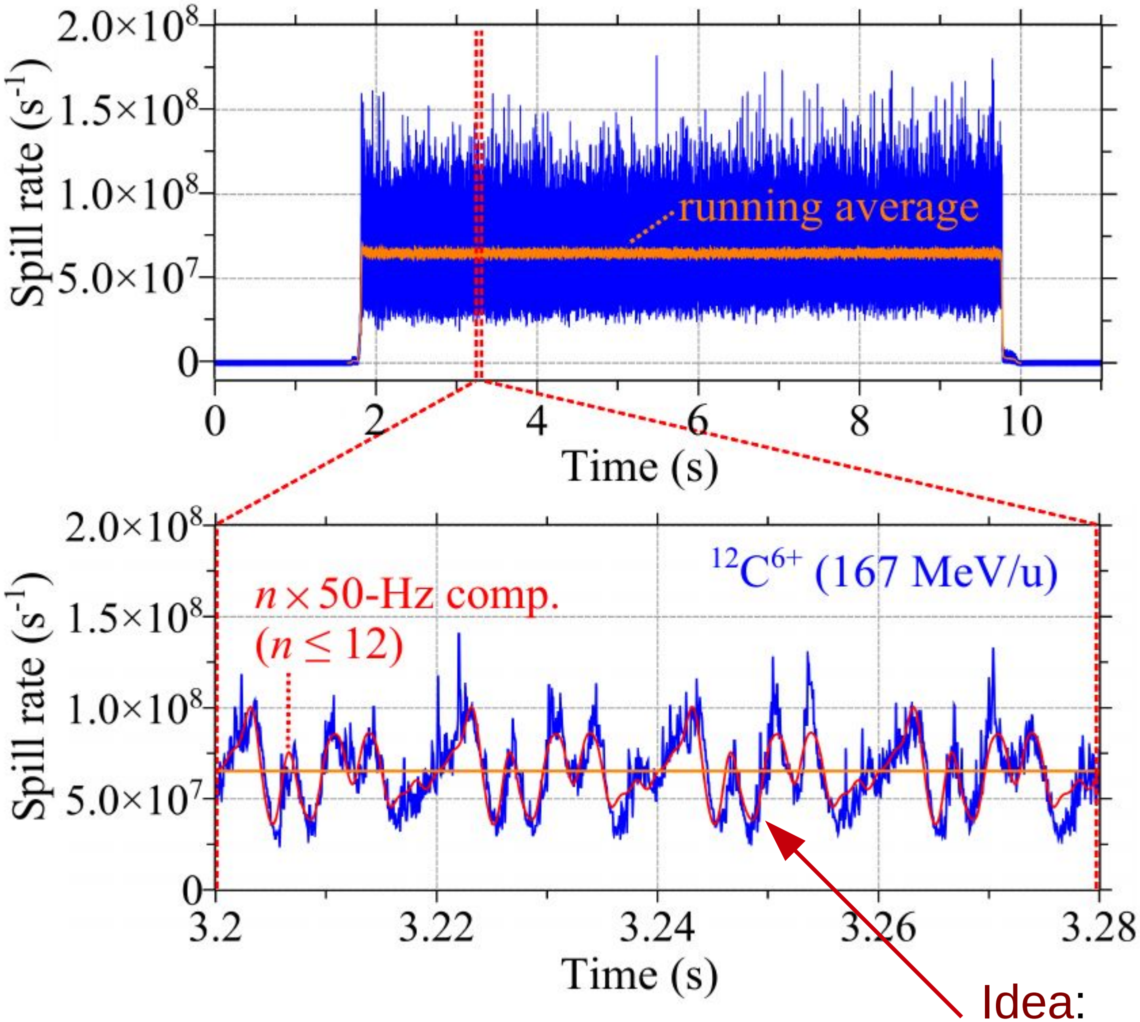
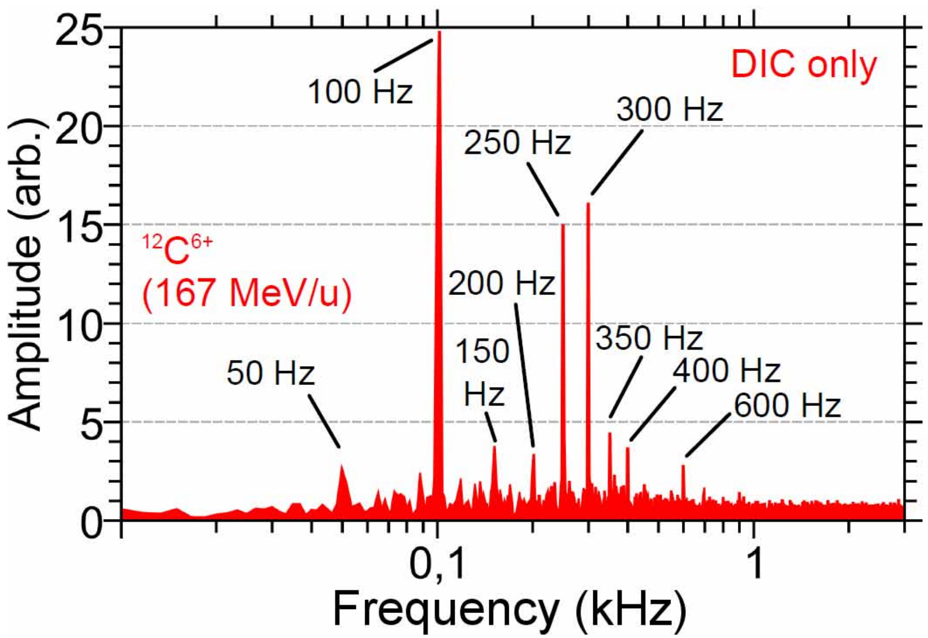
# Ripple compensation: Power-grid harmonics



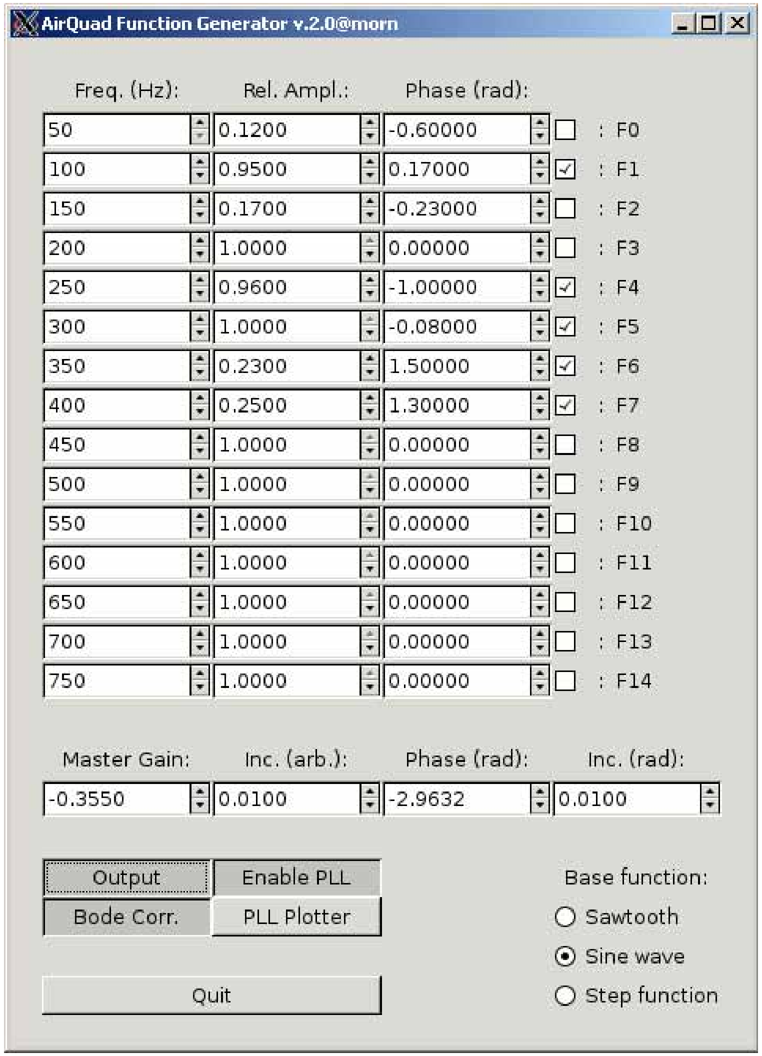

kHz-scale microstructure is dominated by (< 1 kHz) power-grid harmonics …

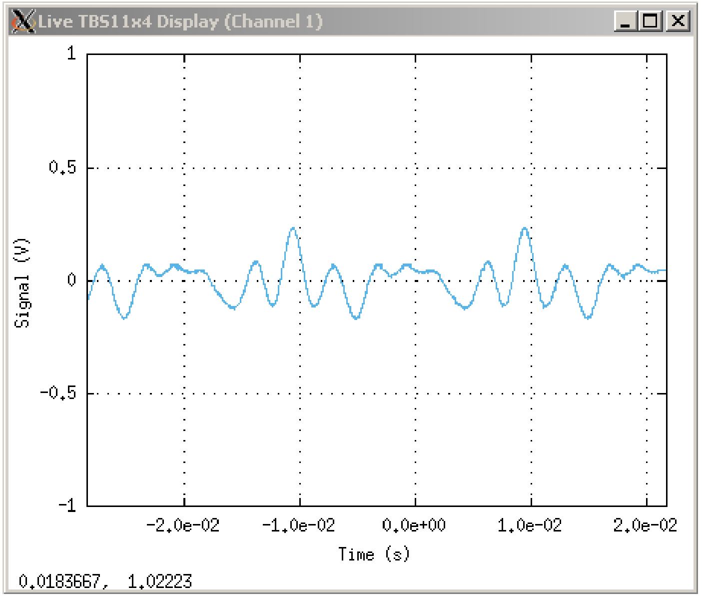



Idea:
Use this function (inverted) as forward-correction for the machine tune!

# Ripple compensation: Power-grid harmonics

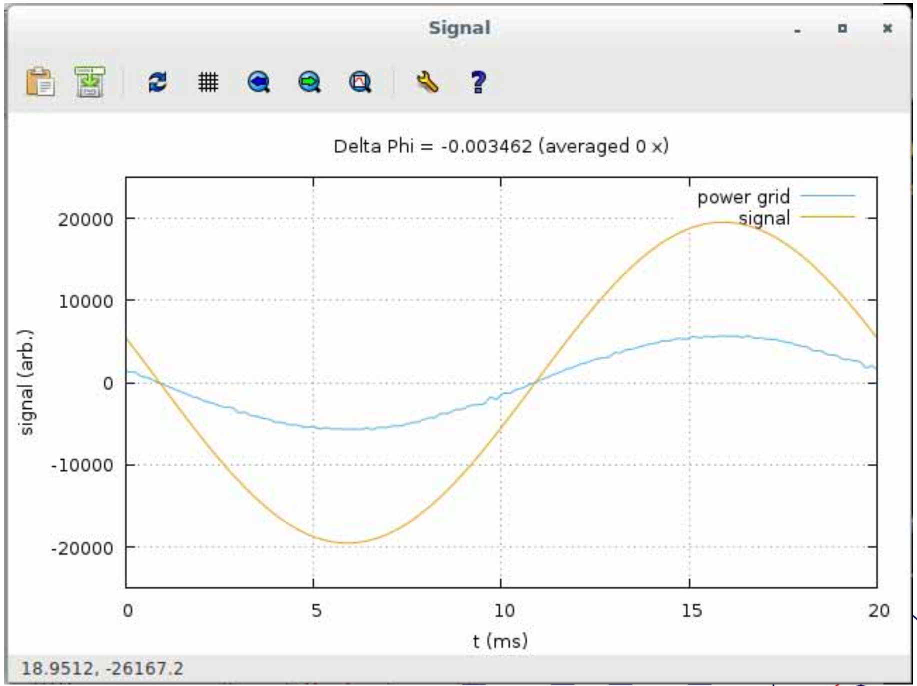
Pitfall: Power-grid frequency
is actually not very stable …
→ Need **phase-locked function generator.**



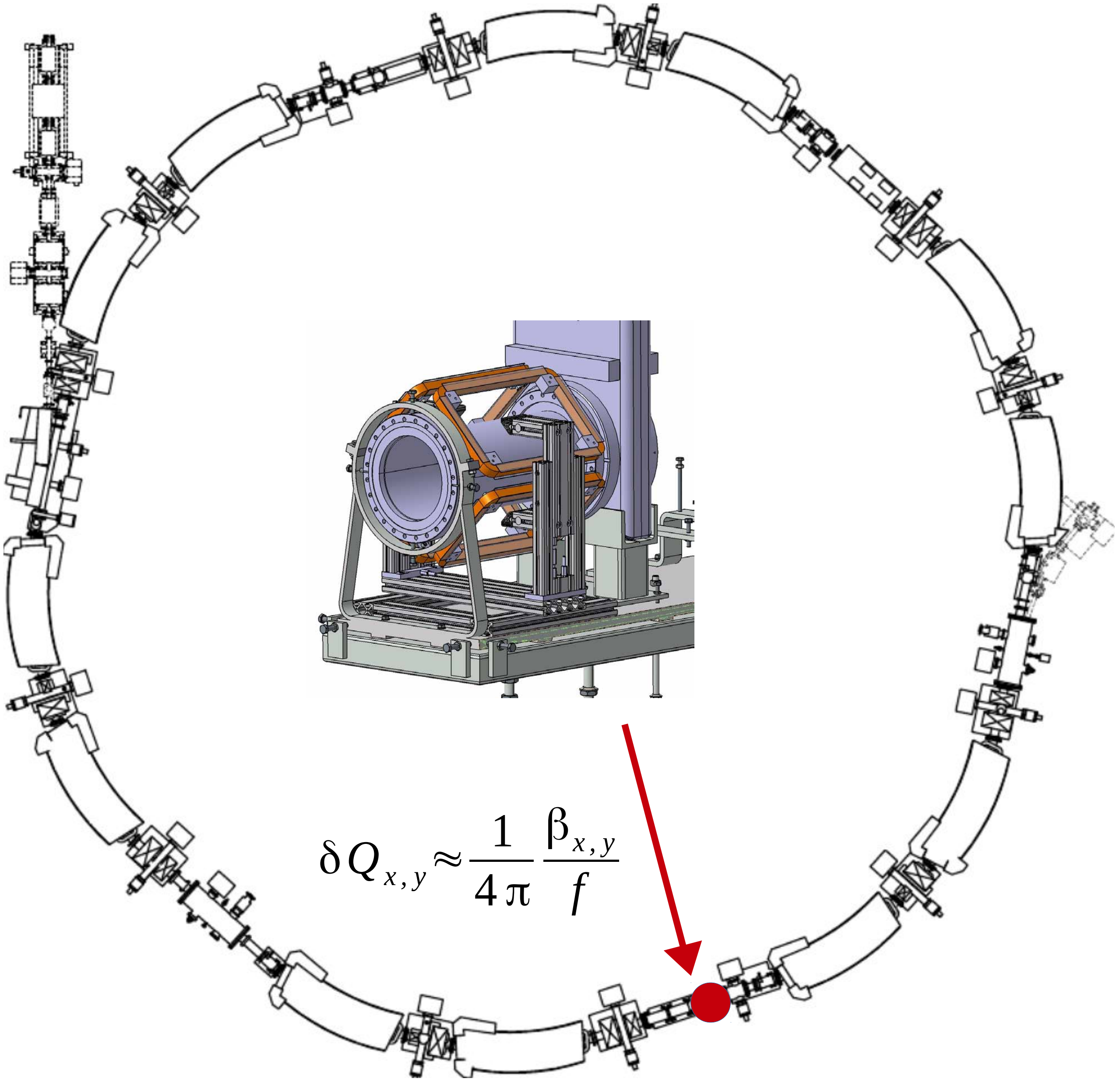




← ACQ signal

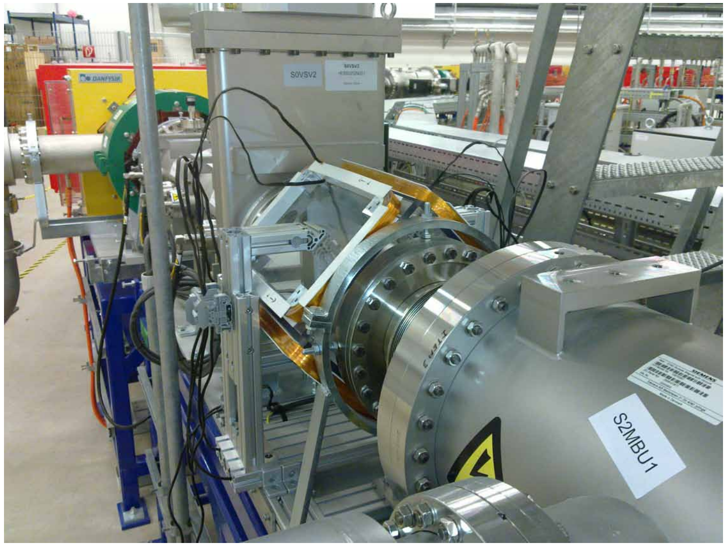
Continuous phase-locking of internal „50-Hz“ clock to power-grid ref.
↓

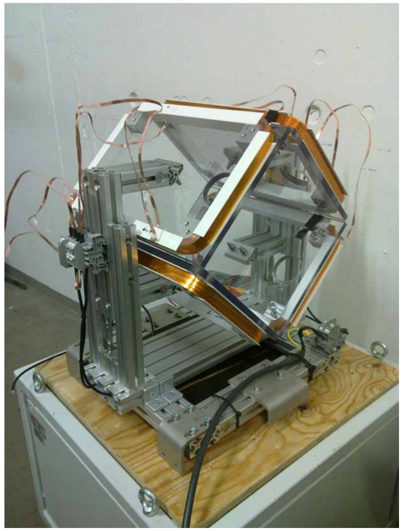


# A simple Air-Core Quadrupole magnet



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



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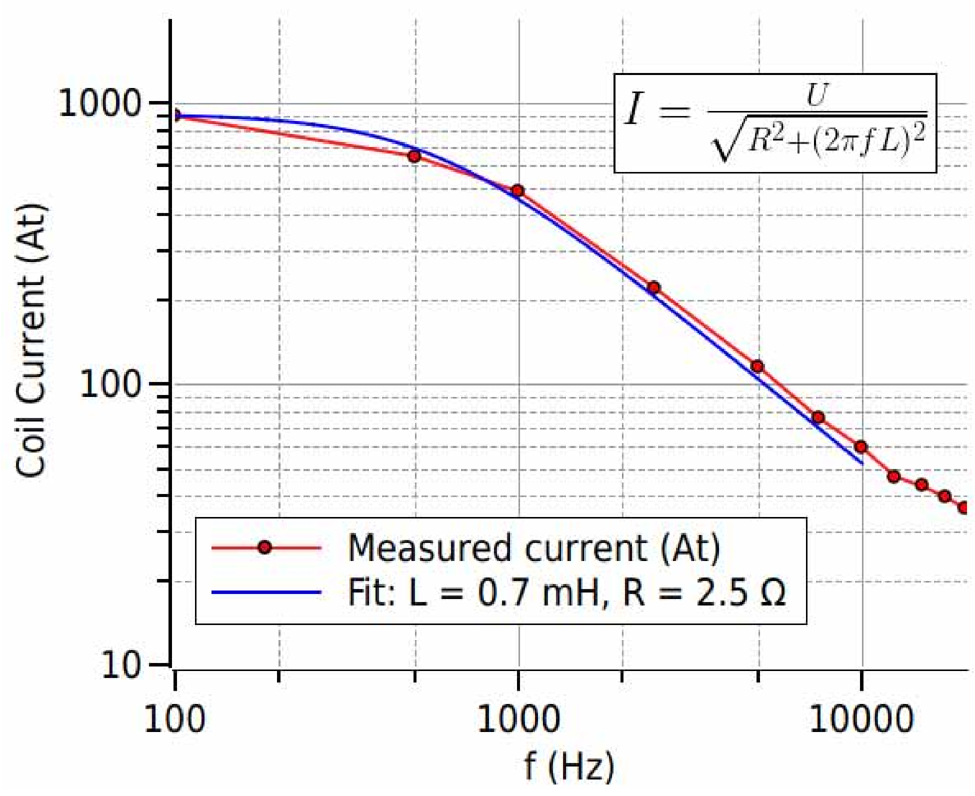
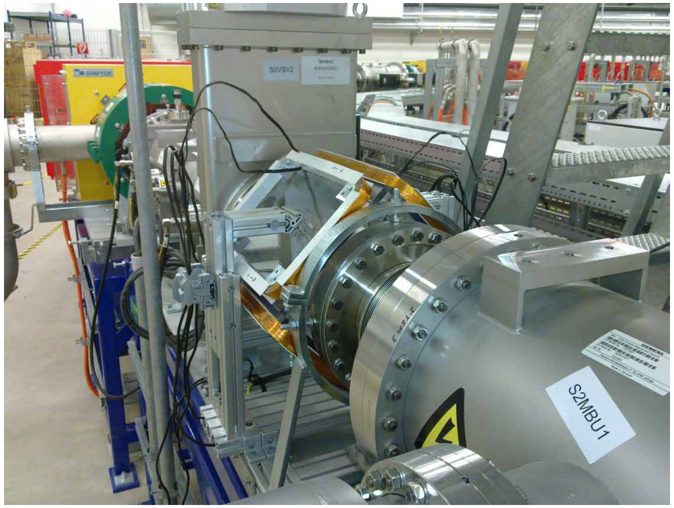
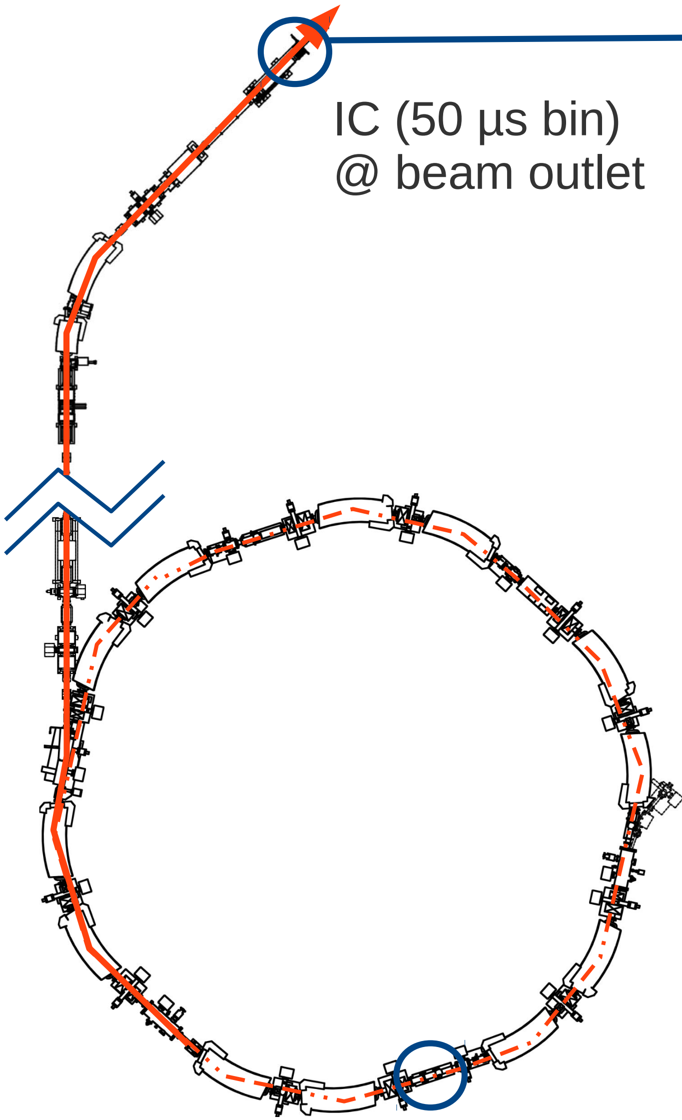



Off-the shelft HiFi amplifier

Can induce spill modulations
up to 10 kHz at all rigidities.

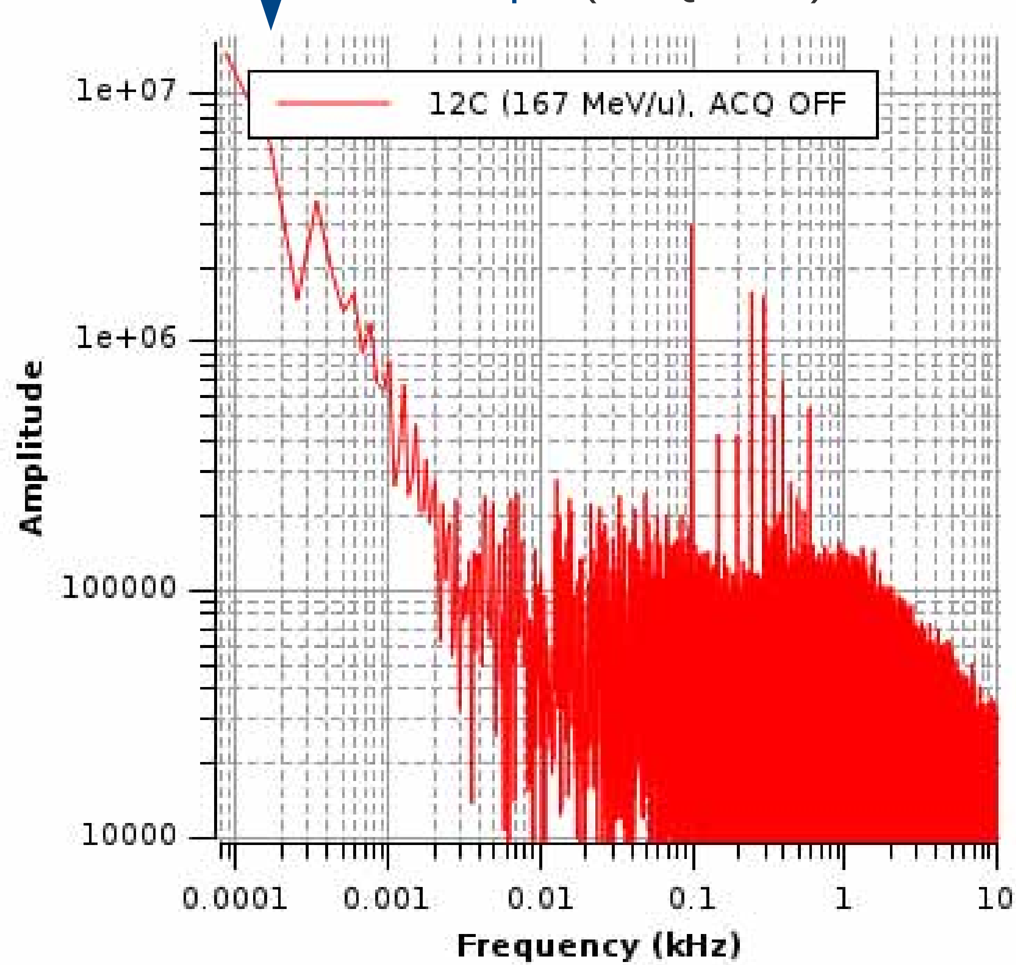
# Beam Response to ACQ



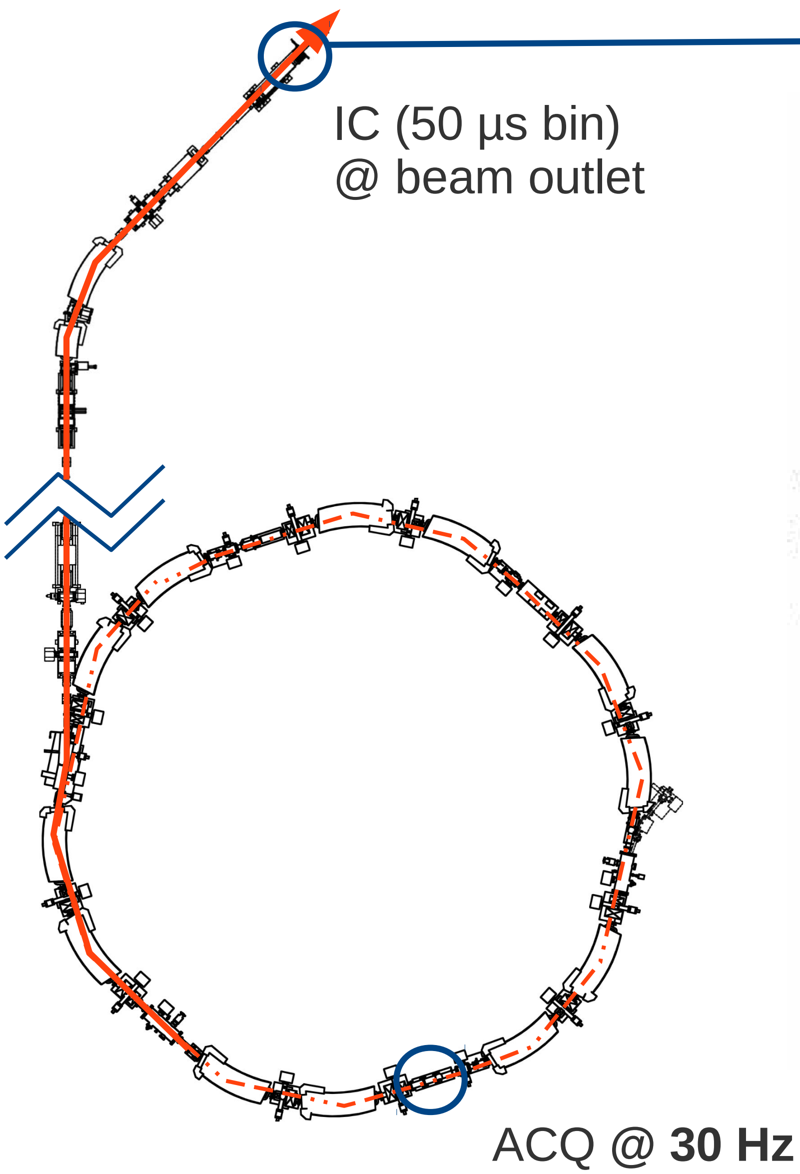
IC (50 µs bin)
@ beam outlet

ACQ **OFF**

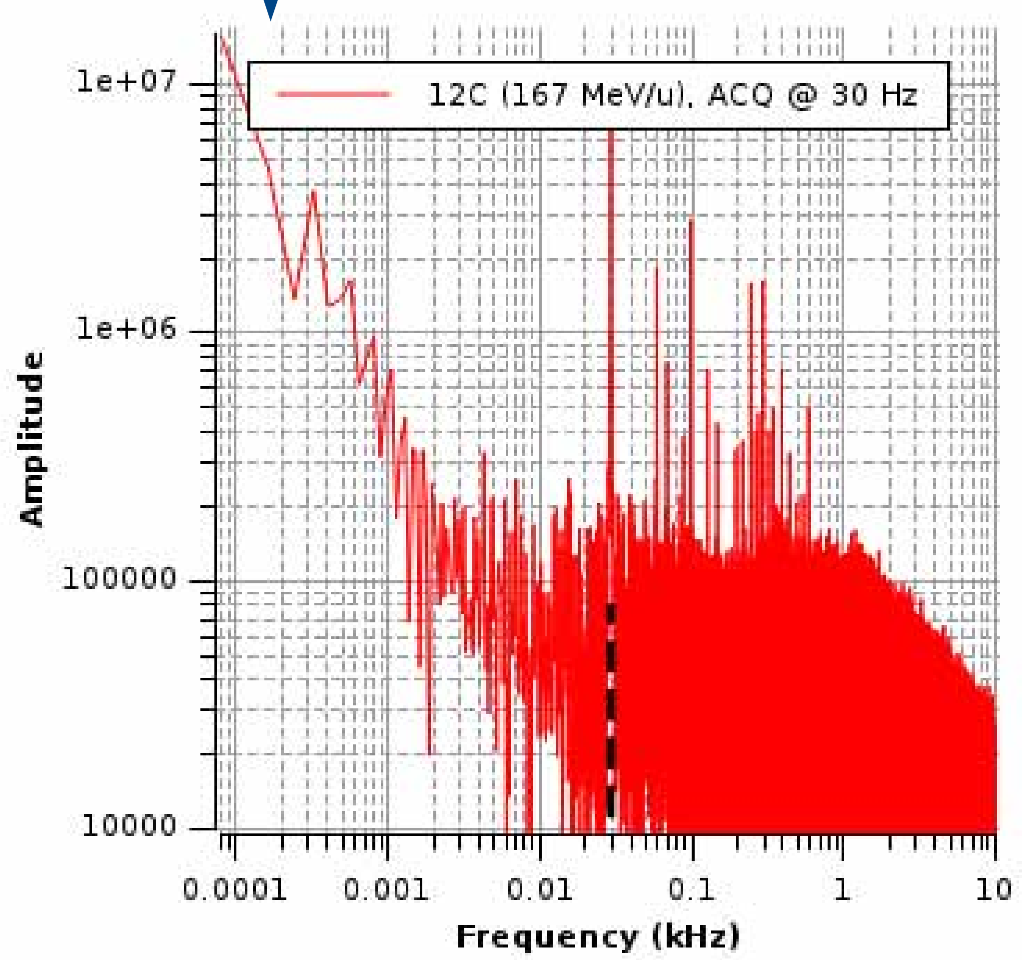
FFT of spill (ACQ OFF)



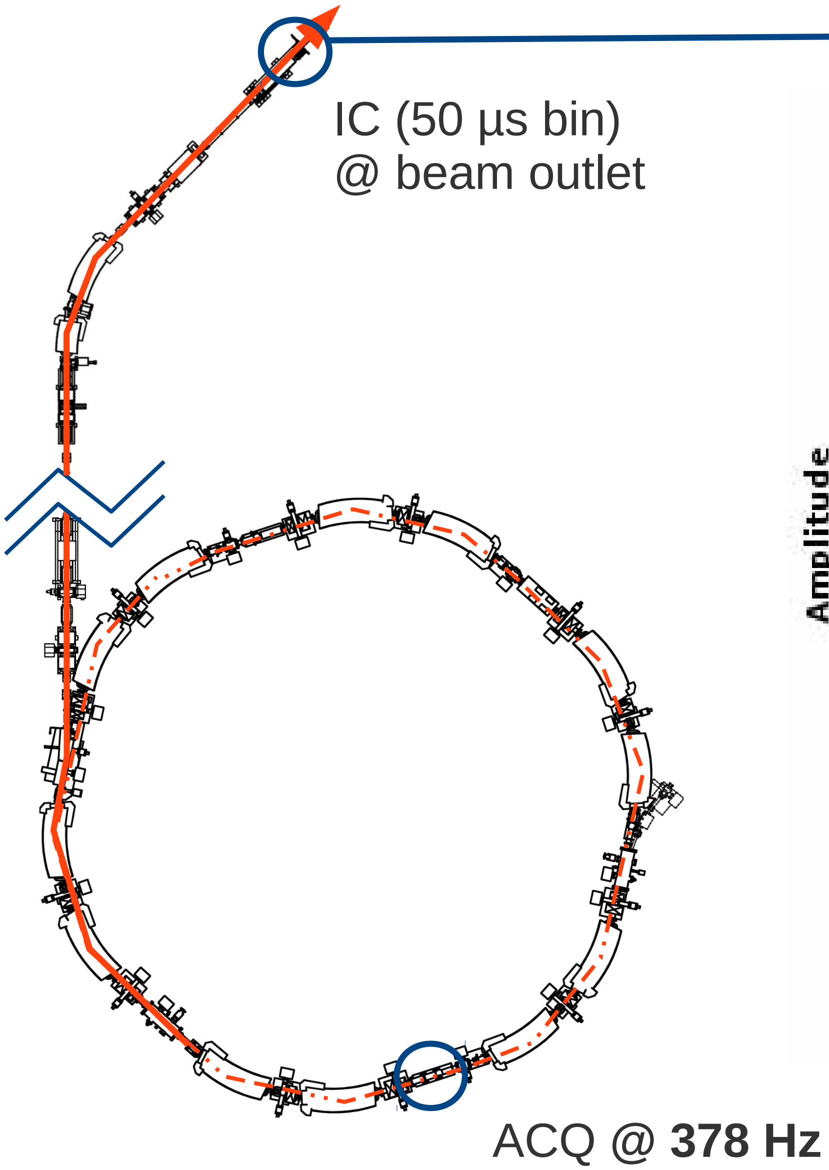
# Beam Response to ACQ



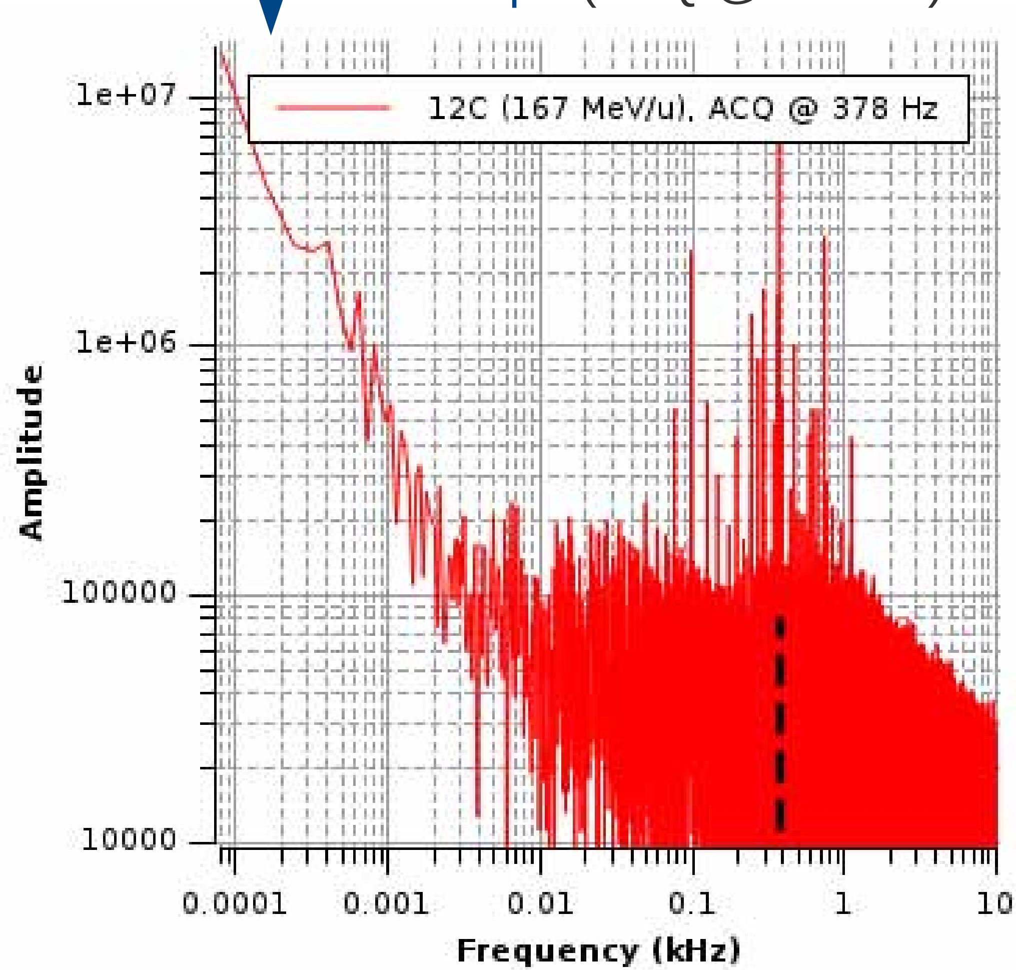

FFT of spill (ACQ @ 30 Hz)



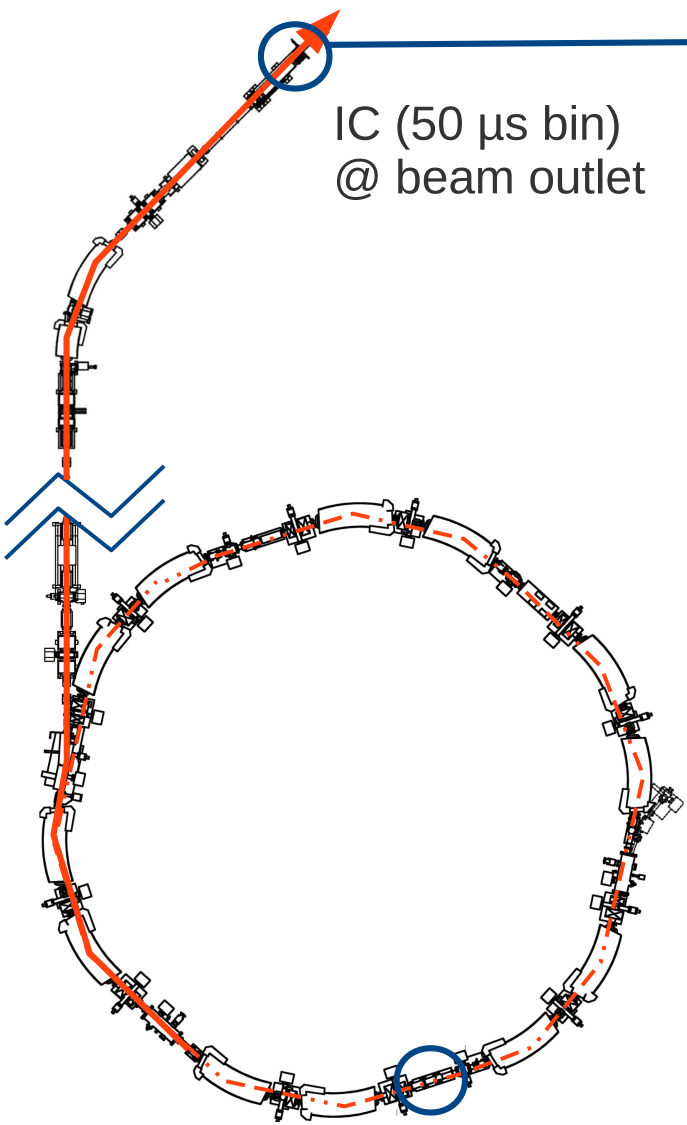
# Beam Response to ACQ




FFT of spill (ACQ @ 378 Hz)



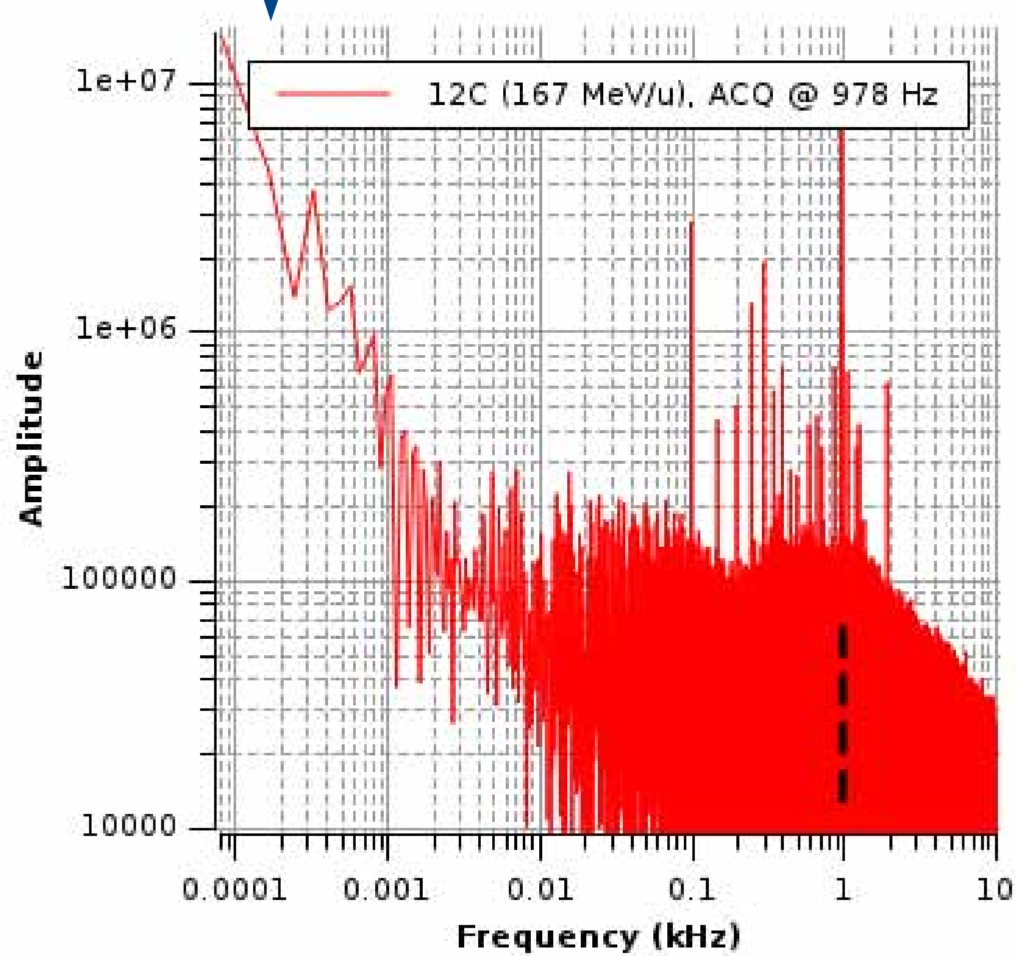
# Beam Response to ACQ



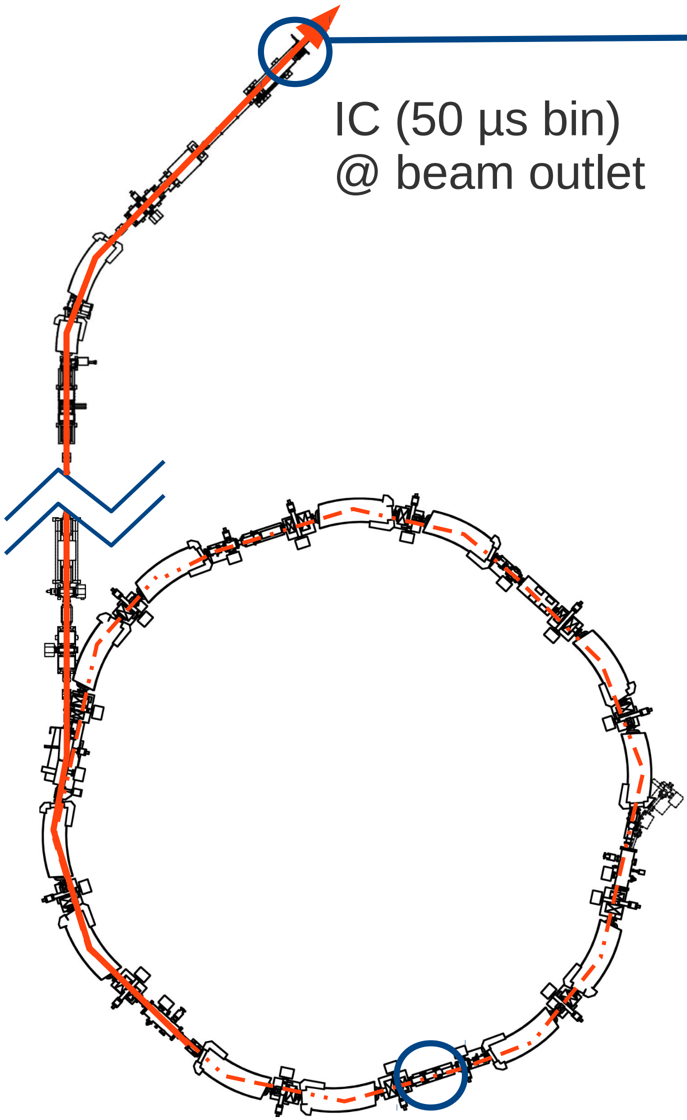
IC (50 µs bin)
@ beam outlet

ACQ @ **978 Hz**

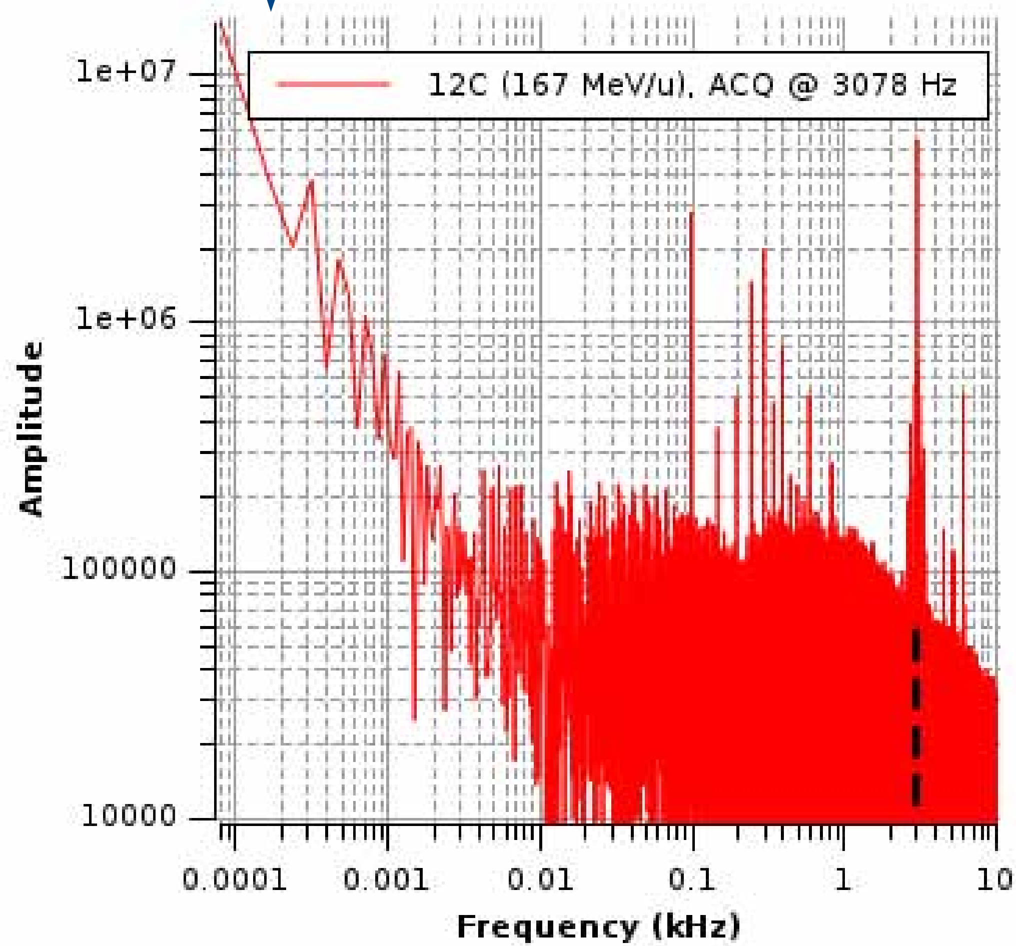
FFT of spill (ACQ @ 978 Hz)



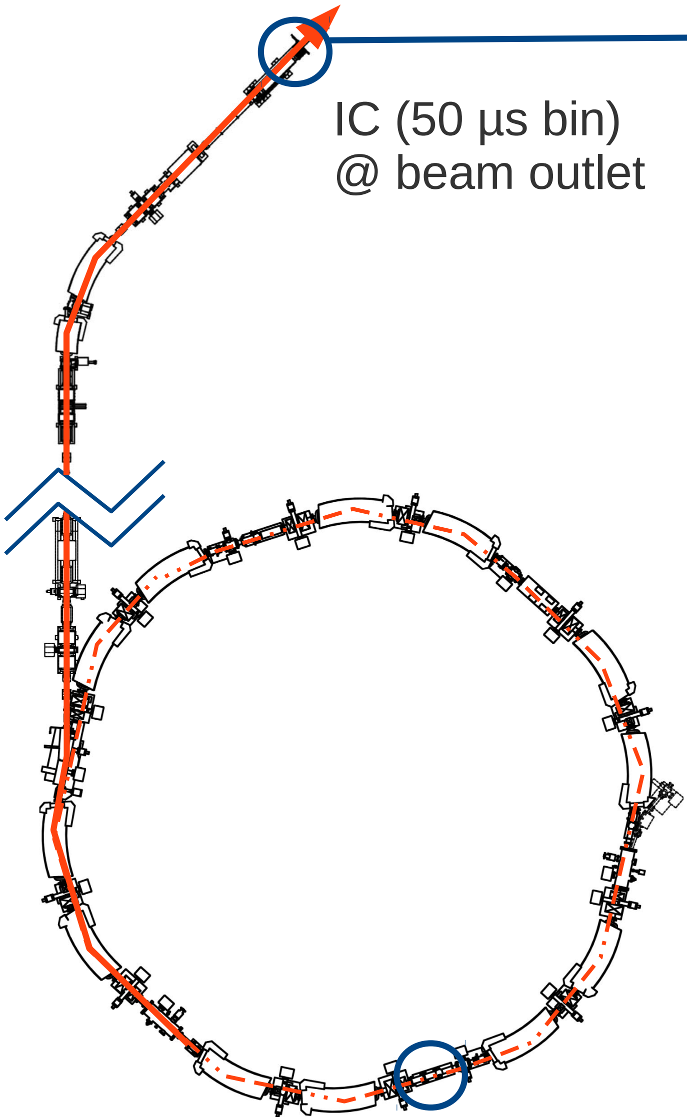
# Beam Response to ACQ



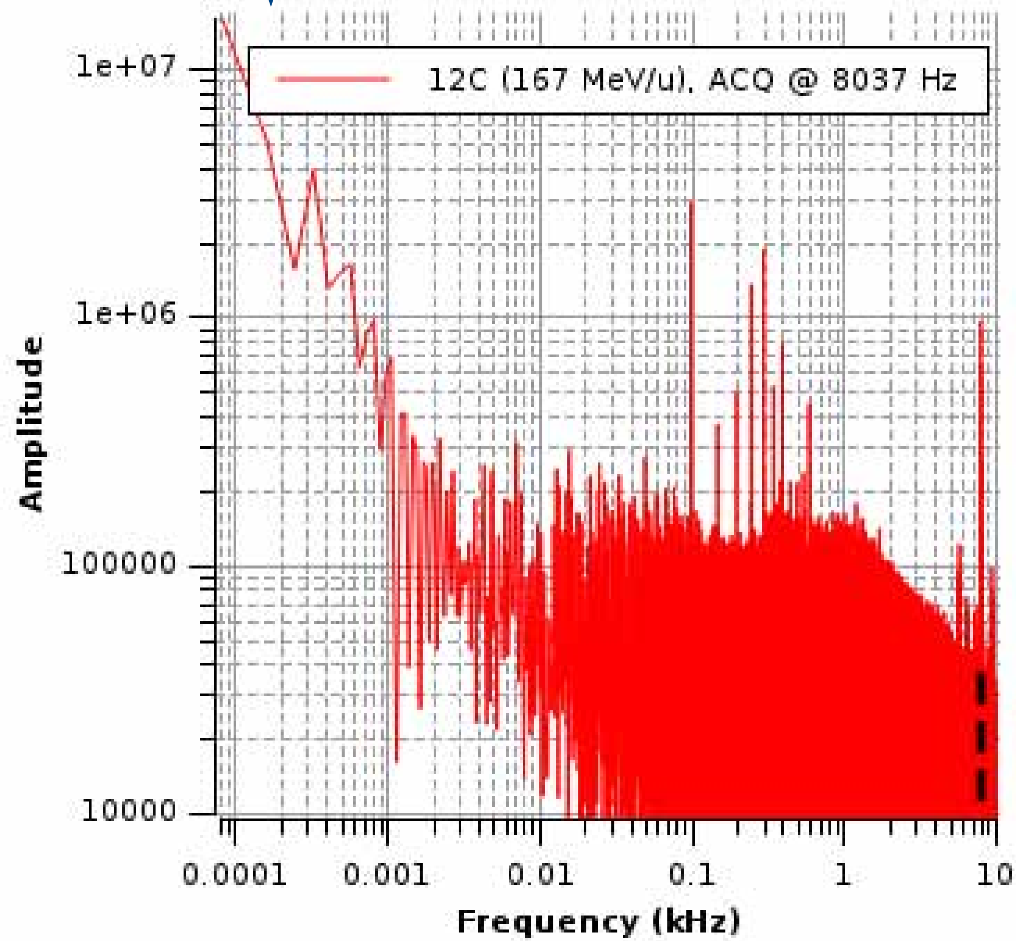

FFT of spill (ACQ @ 3078 Hz)



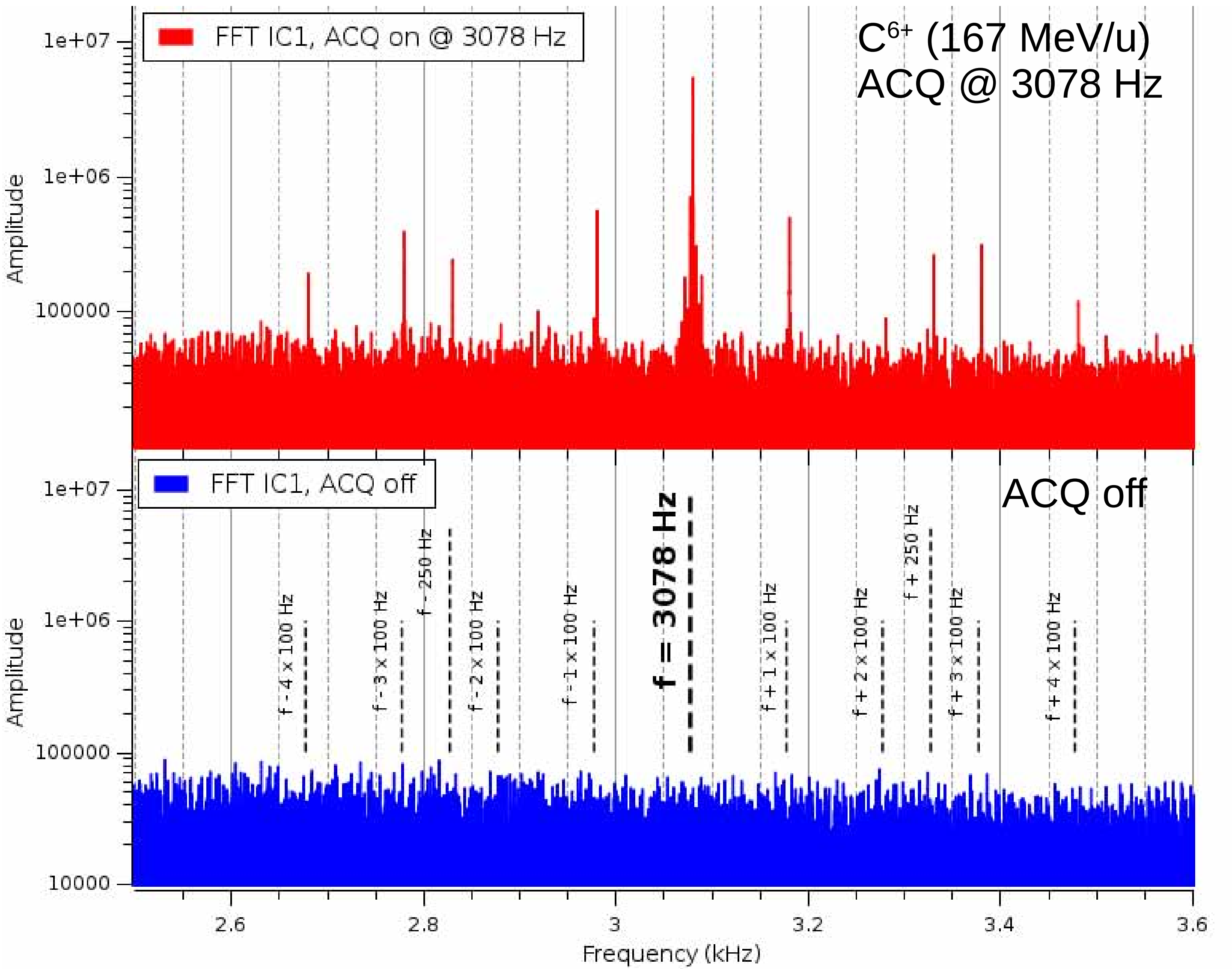
# Beam Response to ACQ




FFT of spill (ACQ @ 8037 Hz)



# Beam Response to ACQ



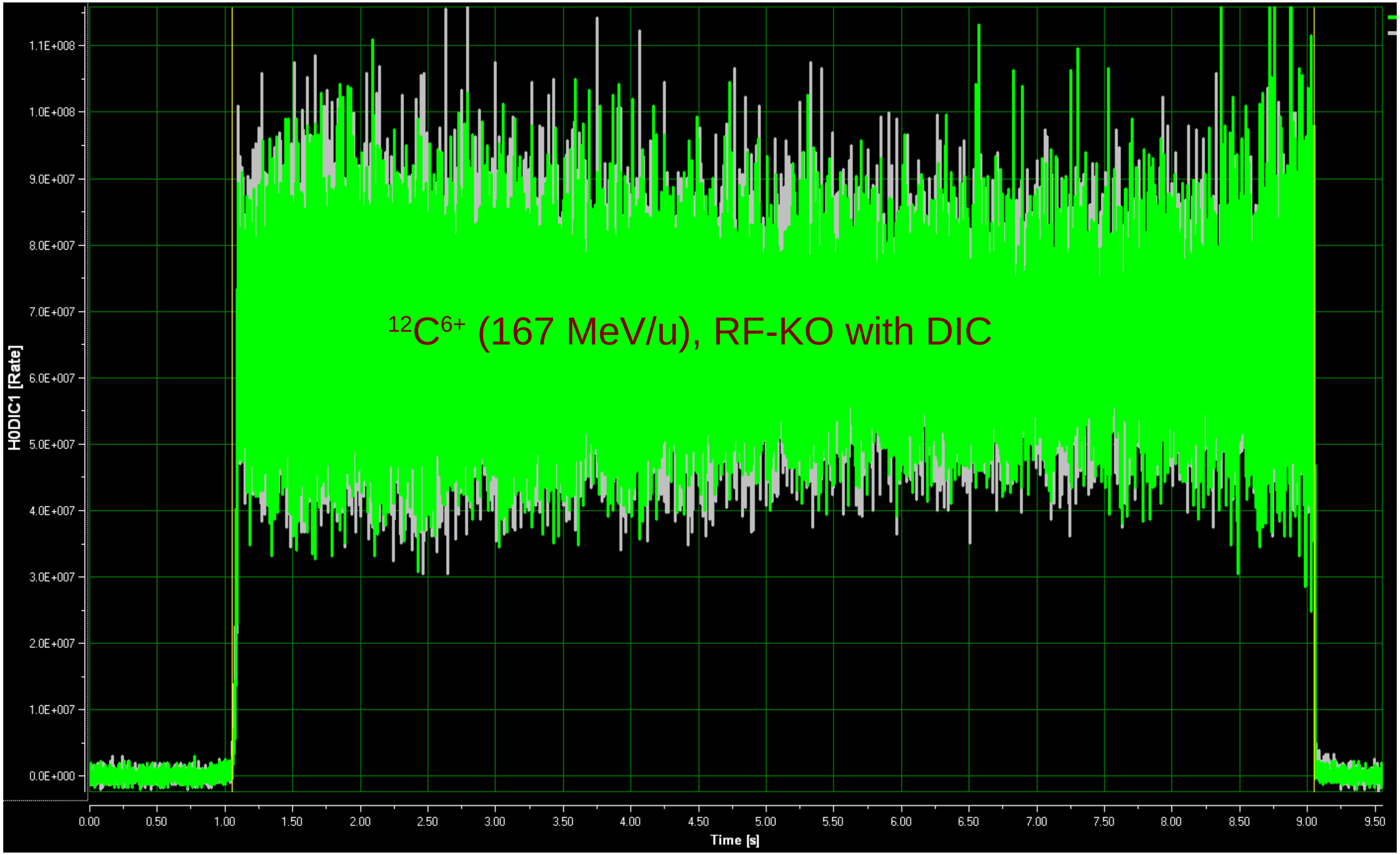

Beam response is
a **single line** at operating frequency of ACQ

+

**mixing** with existing power-grid spectrum.

# Does it work?

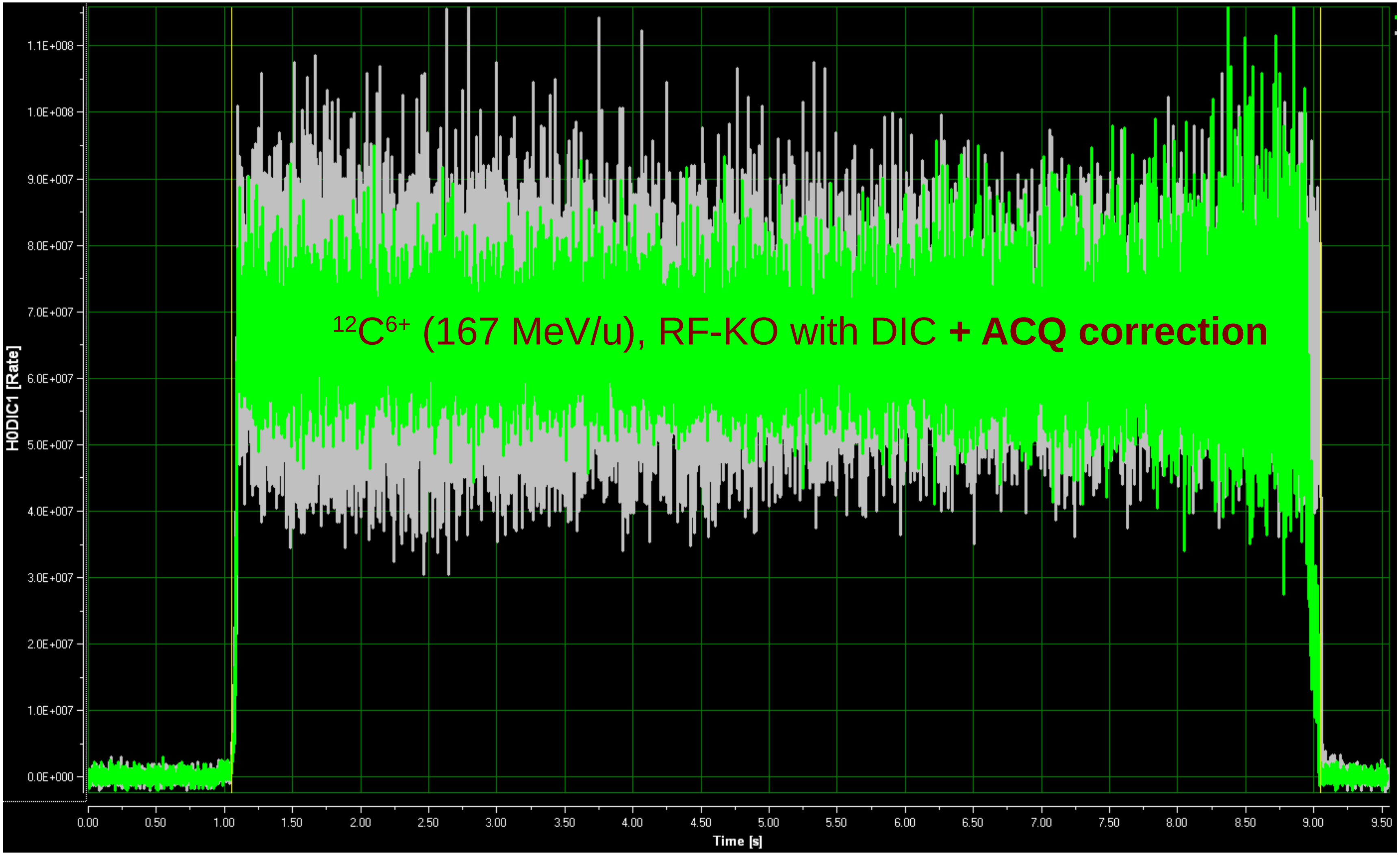
## First tests (work in progress!)




Data: Ionisation chamber in extraction beam line.

# Does it work?

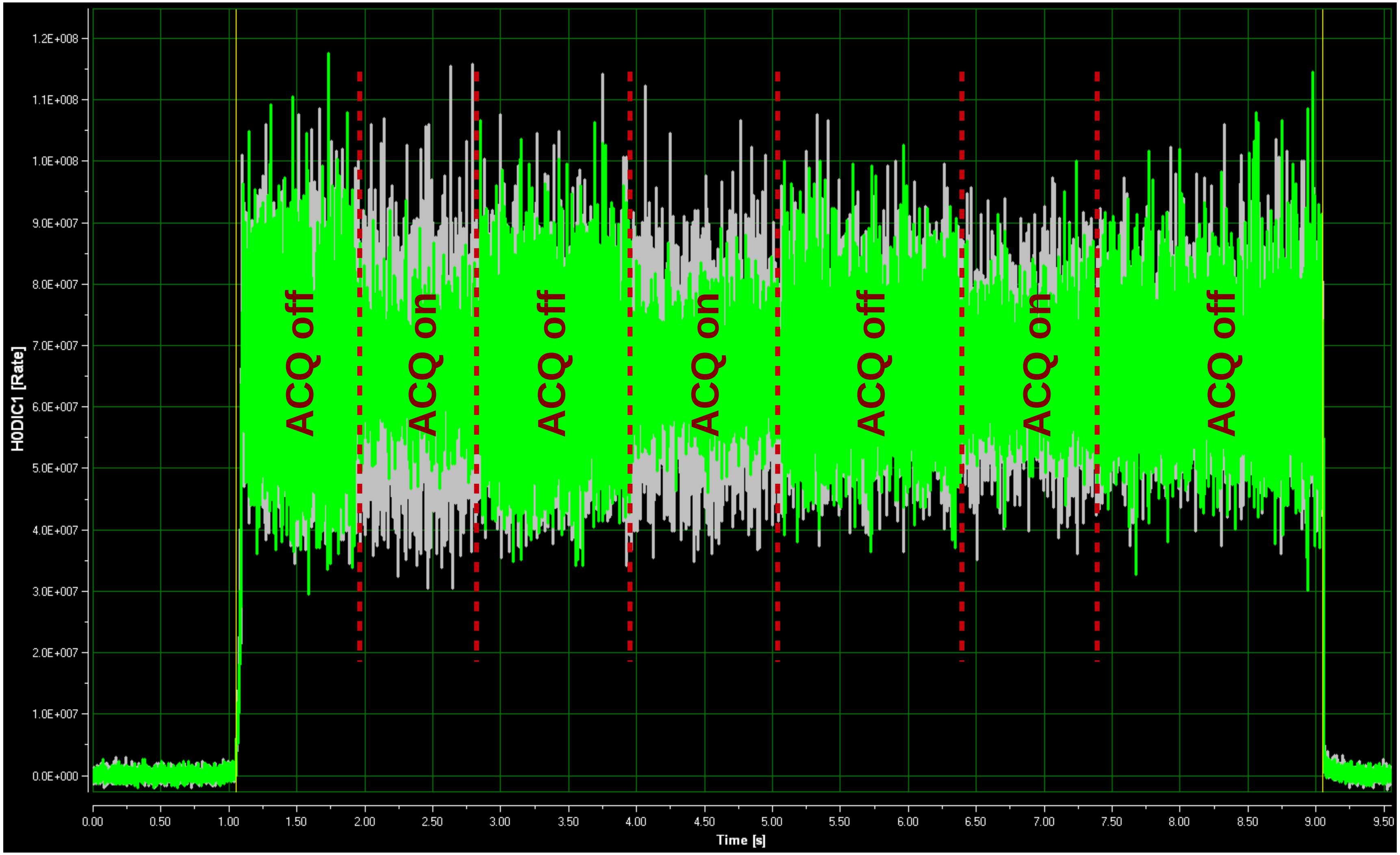
## First tests (work in progress!)




Data: Ionisation chamber in extraction beam line.

# Does it work?

## First tests (work in progress!)



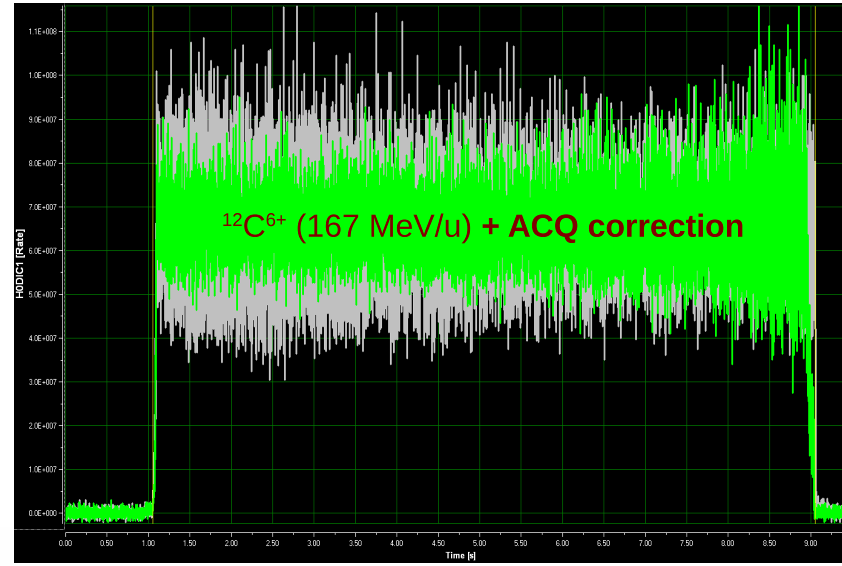

Data: Ionisation chamber in extraction beam line.

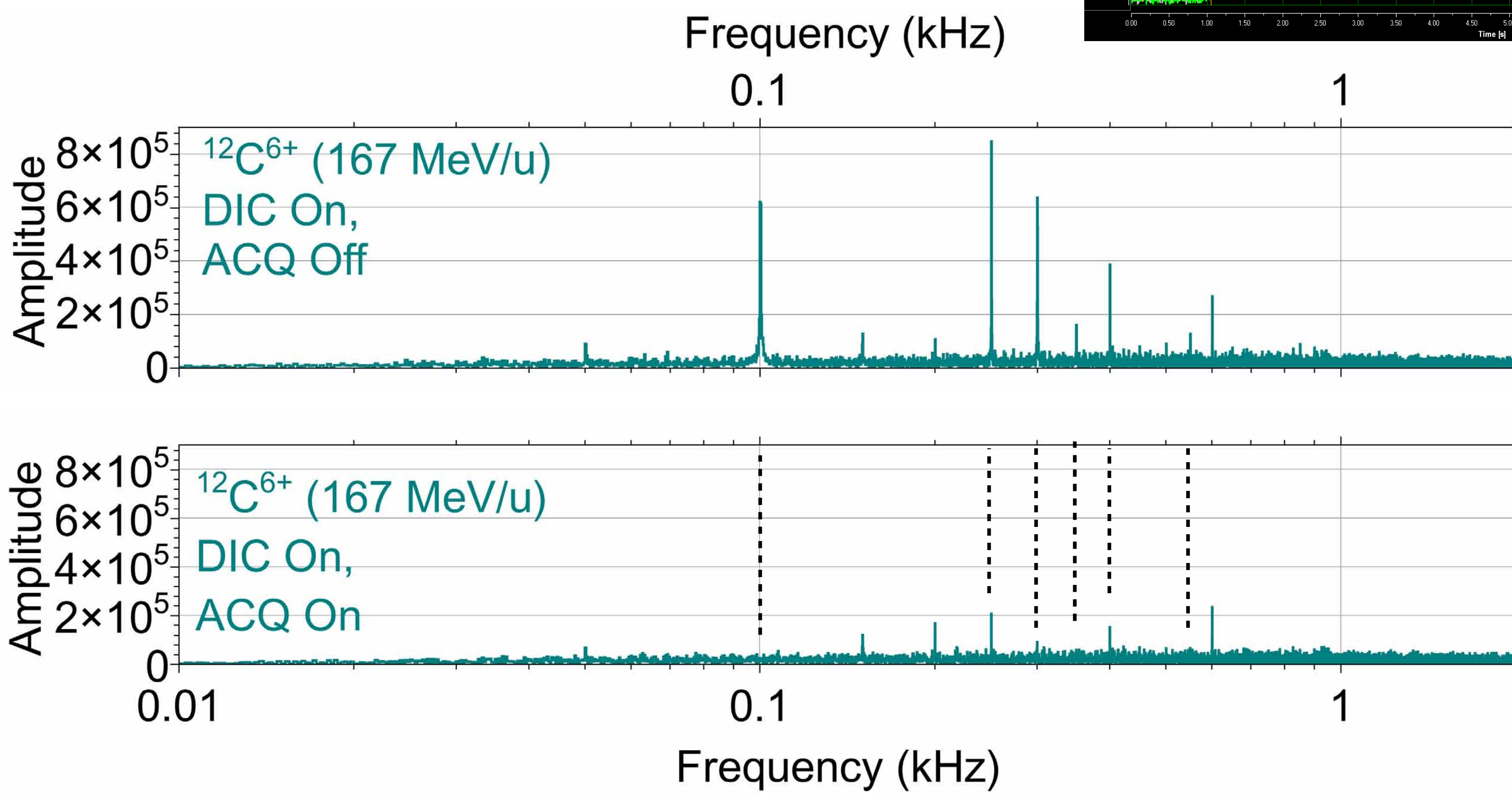
# Does it work?

Up to now:

Correction function is “hand-made”.

Operator programs signal generator while observing the spill FFT.

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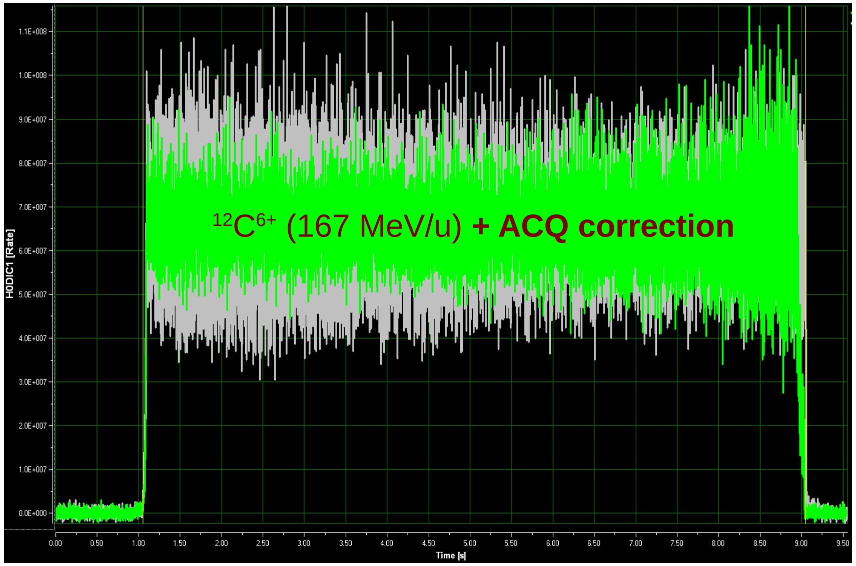
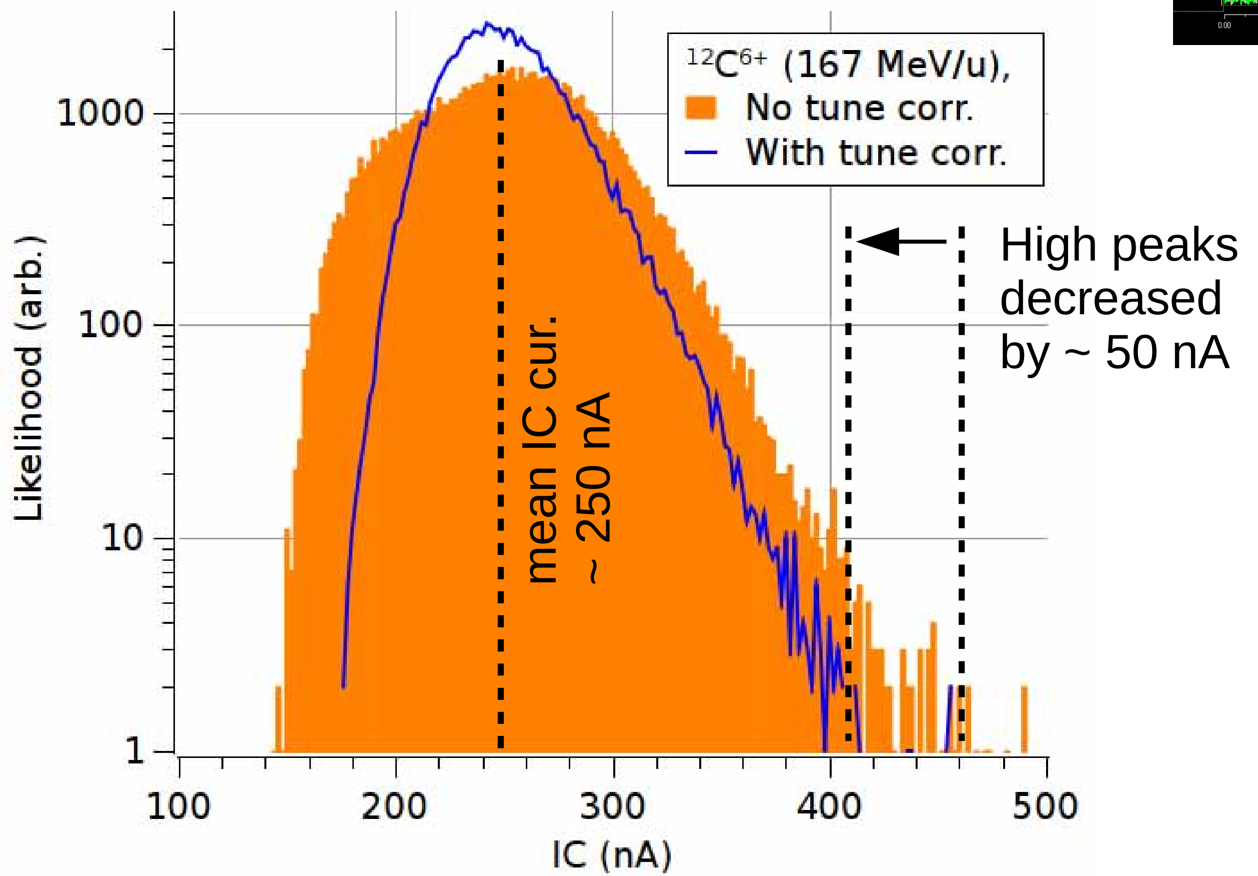
# Does it work?




Histogram of IC measurements
(50 µs sampling)



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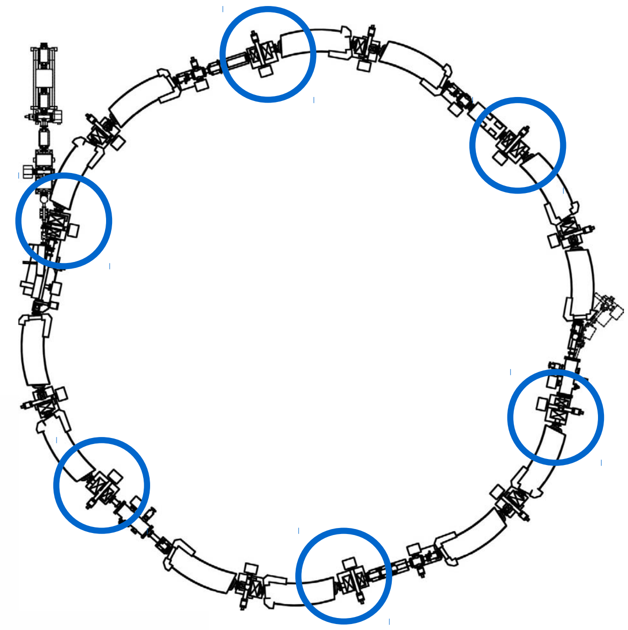
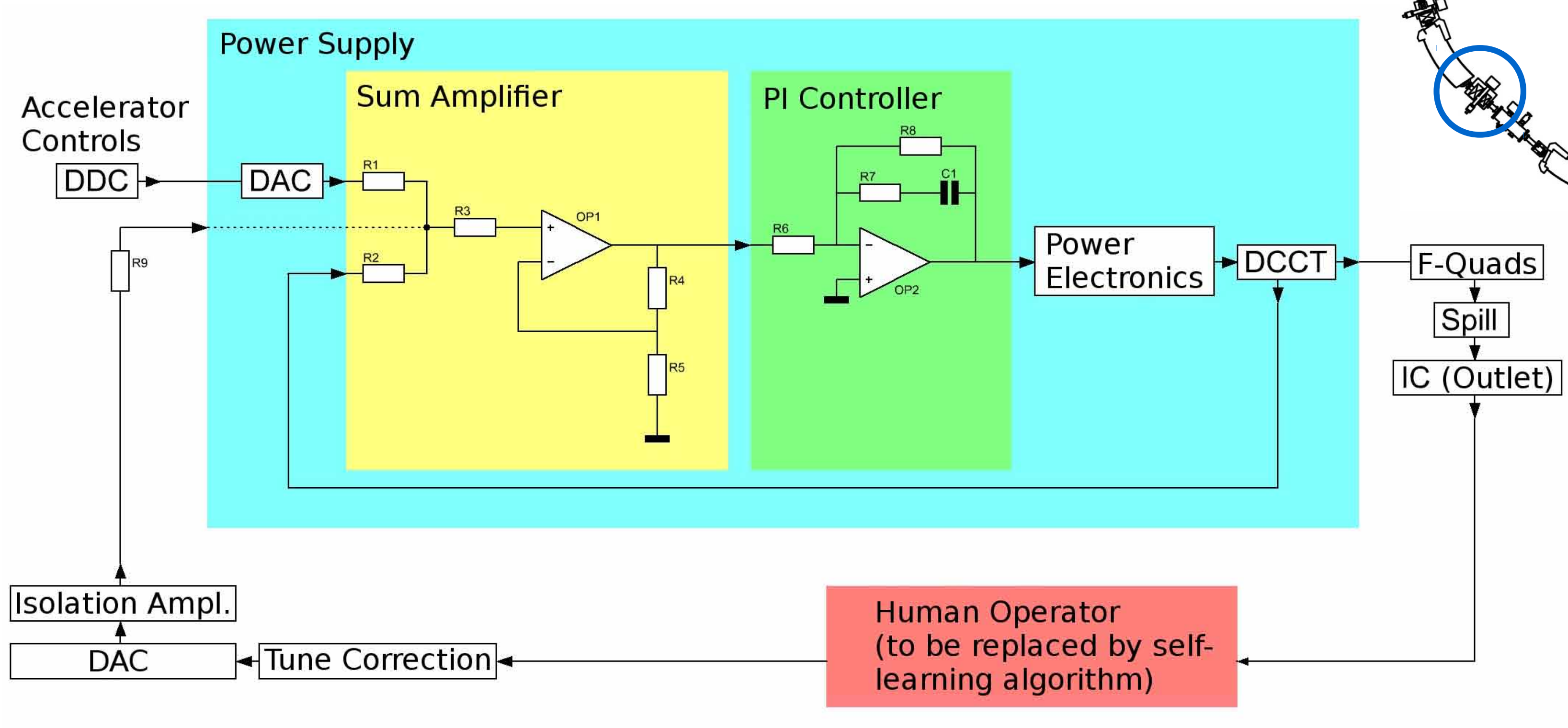
# Outlook: Do we actually need the ACQ?

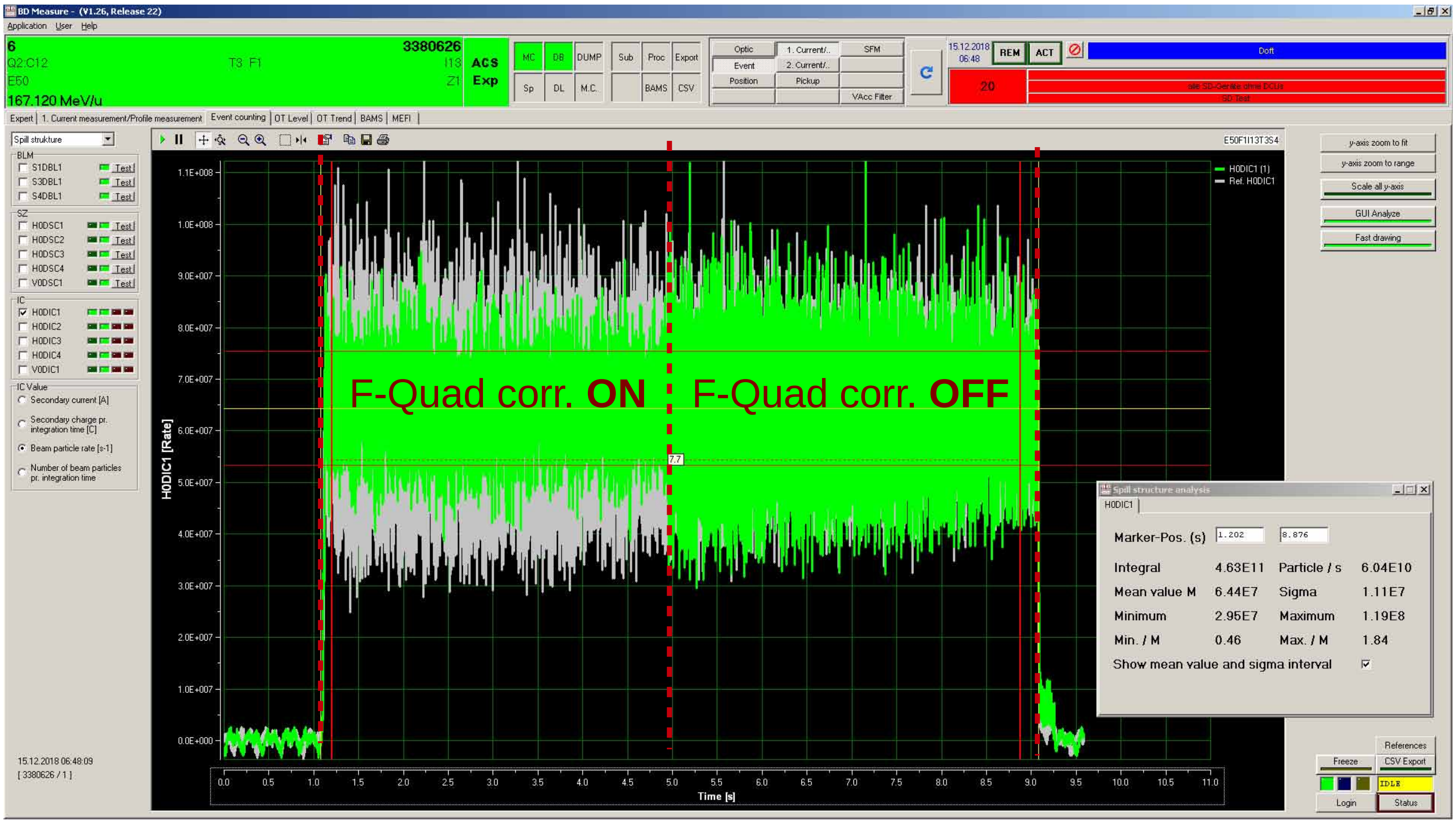
Idea: Apply tune ripple correction directly to F-quad family
(→ Injection into PSU control loop)





# Outlook: Do we actually need the ACQ?

First tests: Seems to work equally well @ frequencies < 1 kHz ...



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# Summary

**Slow extraction is a key technology** at ion synchrotrons for radiation therapy.

Transverse **RF-KO excitation**, combined with **Dynamic Intensity Control** provides excellent spill macro-structure.

Adjustment of the **RF-KO spectrum** with resp. to tune and extraction resonance improves **macro- and micro-**properties of the spill.

First experiments towards **ripple cancellation** using an **ACQ** are promising.

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

Heidelberger Ionenstrahl-Therapiezentrum (HIT)

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


# Thank You for Your Attention.


UniversitätsKlinikum Heidelberg

RHÖN-KLINIKUM AKTIENGESELLSCHAFT