IAP Seminar: Aktuelle Probleme der Angewandten Physik

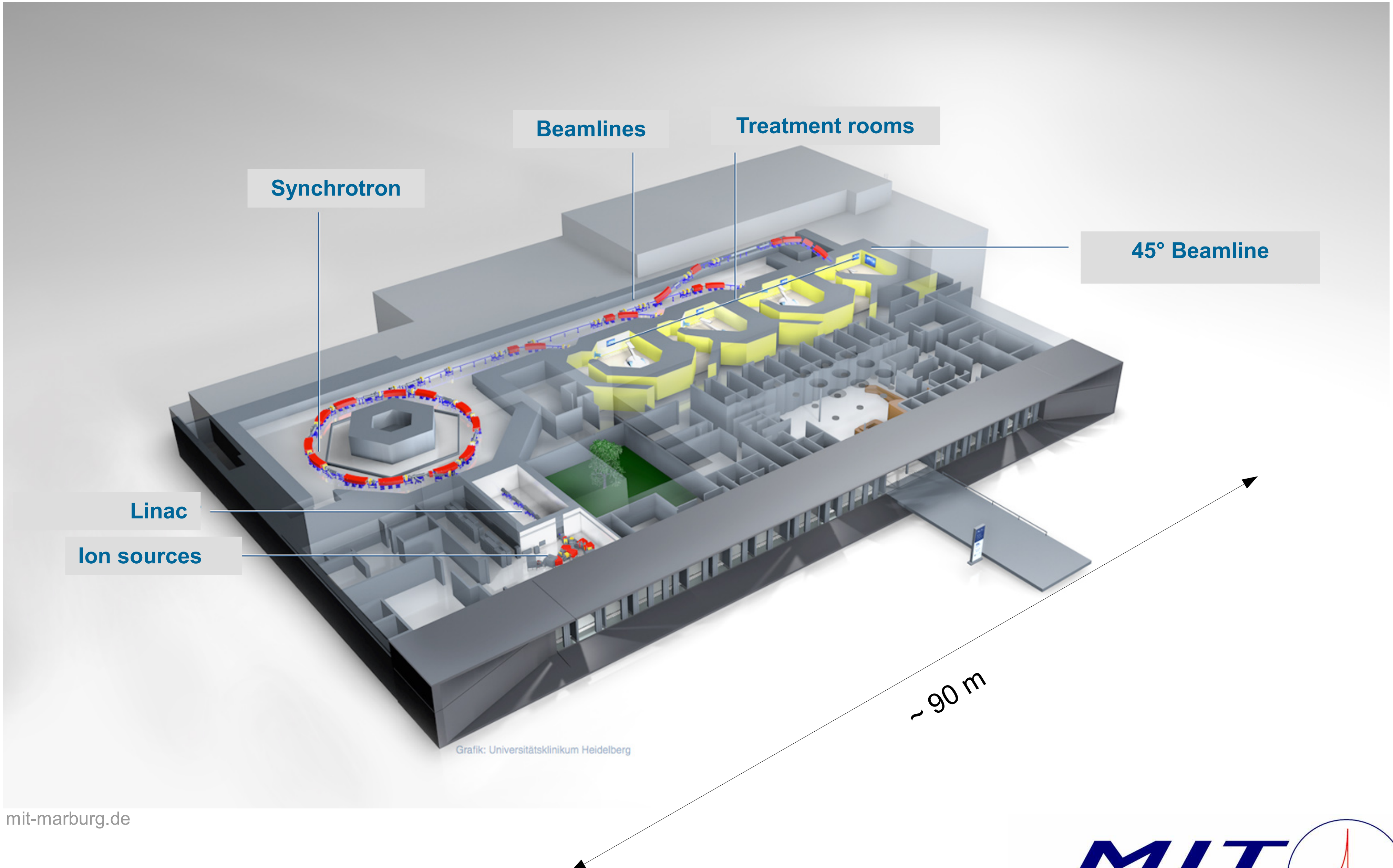
Techniques for Slow Extraction at the Marburg Ion-Beam Therapy Synchrotron

Claude Krantz

Marburger Ionenstrahl-Therapiezentrum

30 November 2018

MIT: The Marburg Ion-Beam Therapy Centre



mit-marburg.de

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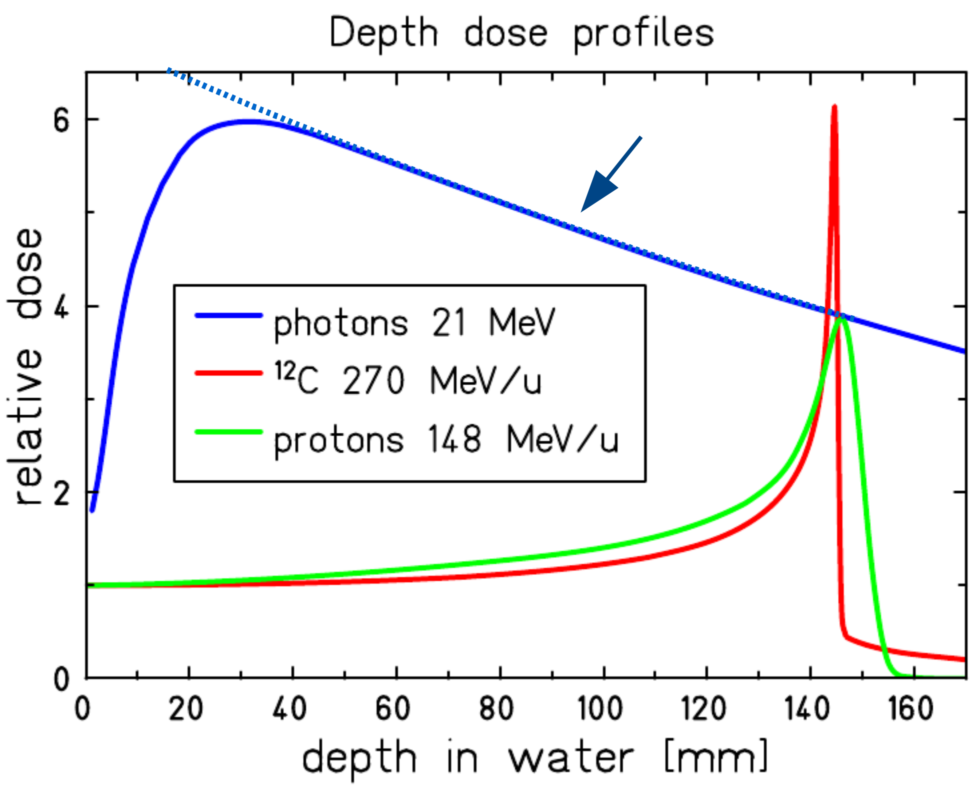
Radiation therapy with ~~ion beams~~ photon beams



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

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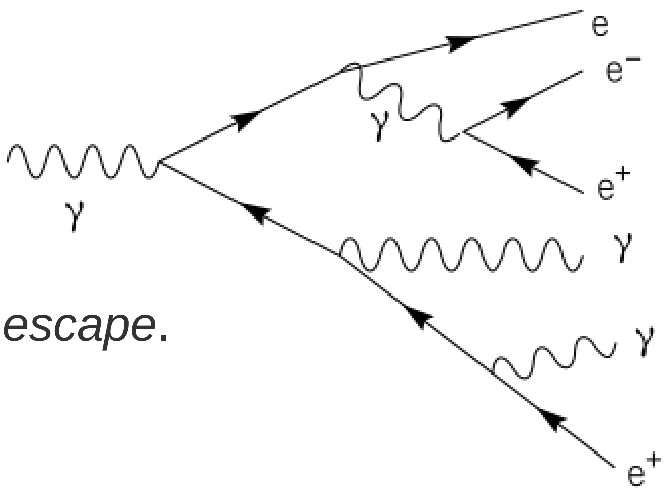
Primary (multi-MeV) photon consumed in a (somwhat localised) e.m. shower in a single interaction.



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

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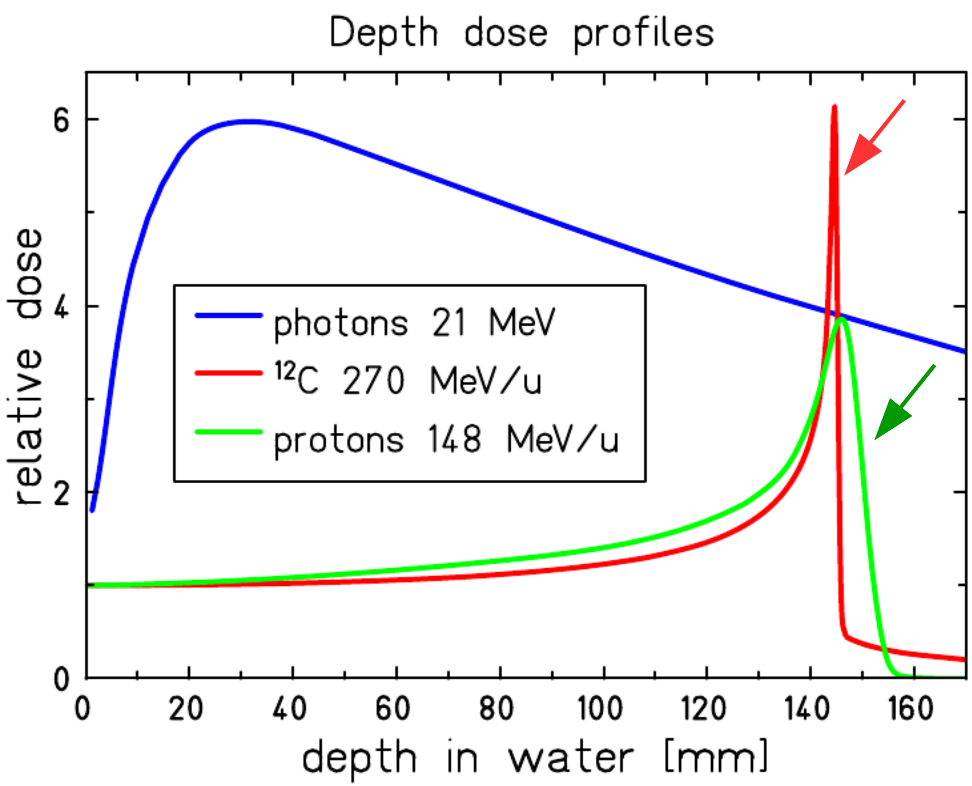
Radiation therapy with ion beams



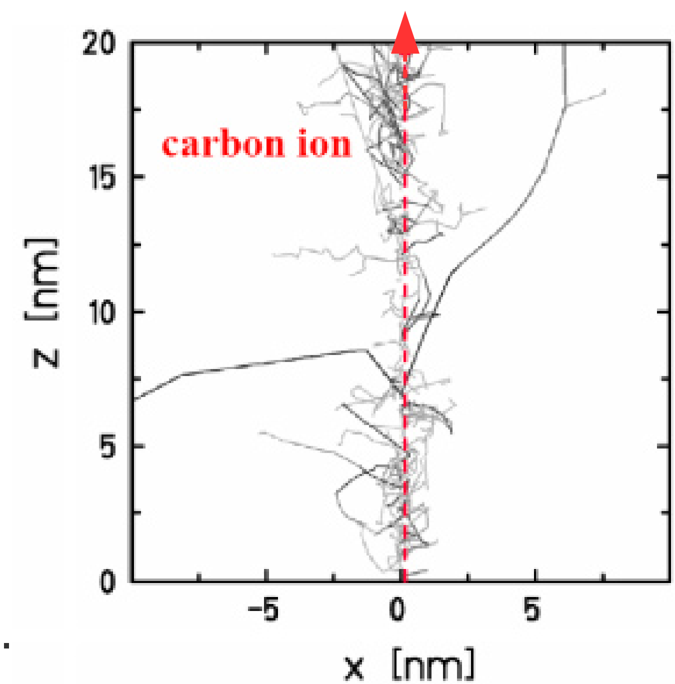
Krämer & Durante, Eur. Phys. J. D 60 (2010)

Primary ion deposits energy (mainly) by multiple ionisation.

Stopping force: Bethe formula

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

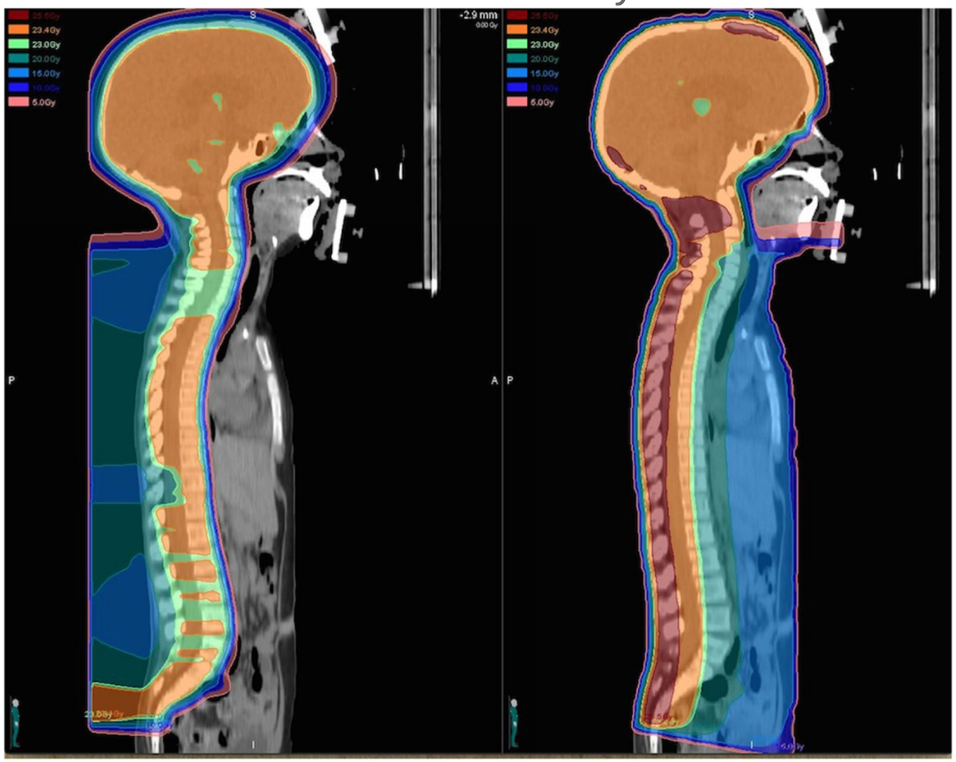
→ **d*E*/dx ~ *E*$^{-1}$**



Amaldi & Kraft, Rep. Prog. Phys. 68 (2005)

Ion beam:
Range sharply defined by starting energy (“*Bragg peak*”).

Radiation therapy with ion beams



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

"Bragg" stopping behaviour can be used to spare healthy tissue during irradation.

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

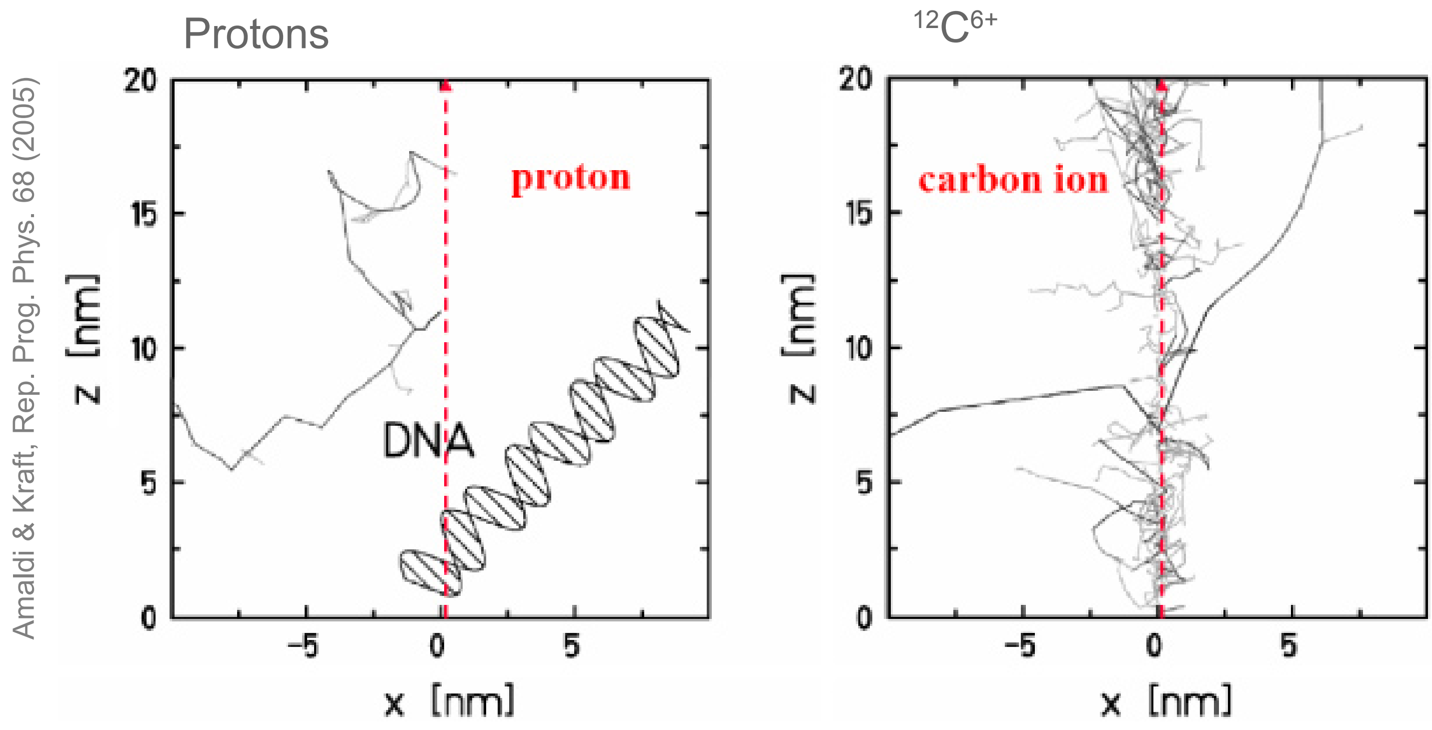
Ion beam:
Range sharply defined by starting energy ("*Bragg peak*").

Radiation therapy with ion beams

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

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

Stopping force rises strongly with projectile nuclear charge!



Heavier ions ($^{12}C^{6+}$) are characterised by higher *biological effectiveness* compared to protons (and photons).

Dose delivery techniques

The techniques used for dose delivery define the required properties of the ion beam.

What kind of accelerator do we need for ion beam therapy?

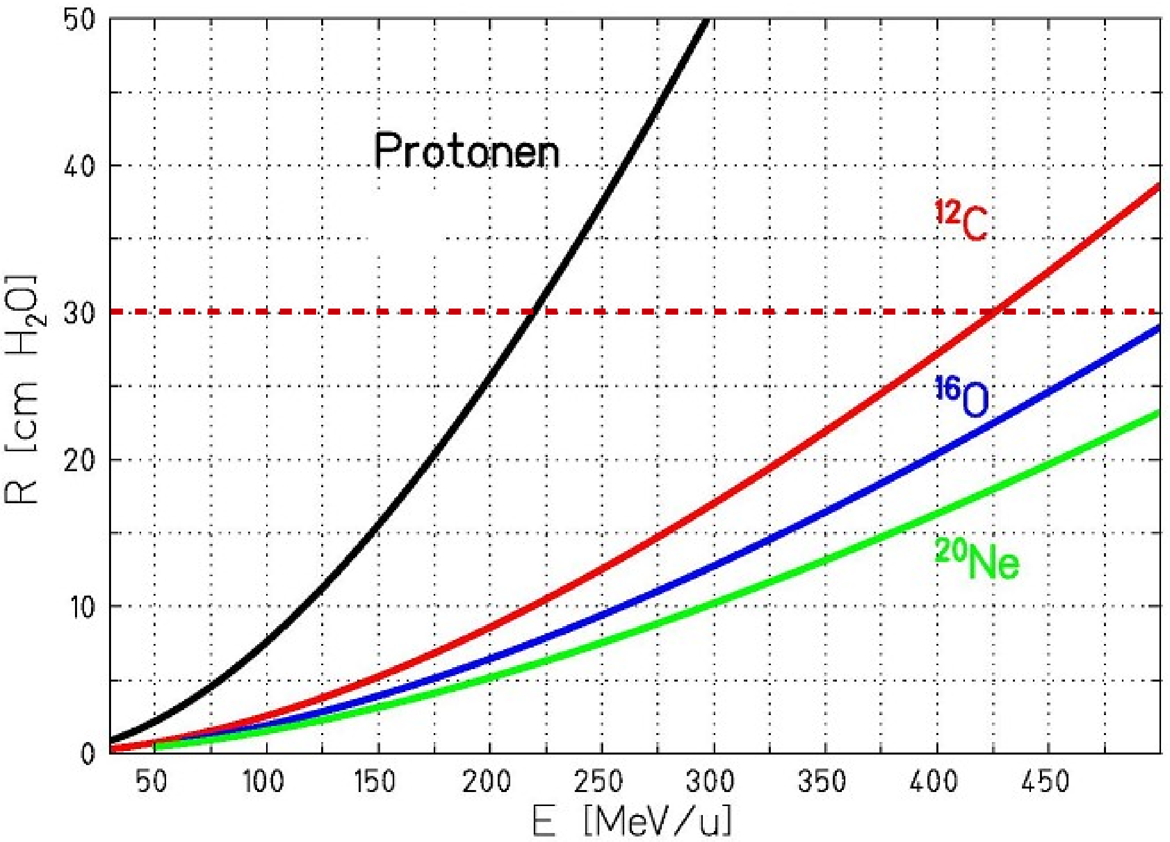
Dose delivery techniques

Particle energy:

30 cm are the de-facto standard maximum specified irradiation depth.

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

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

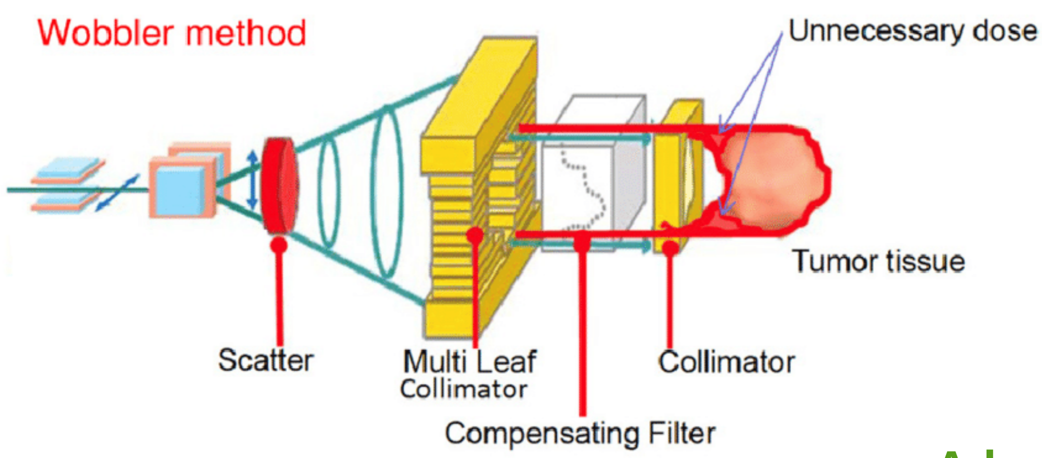


Remark: Today, cyclotrons (available commercially) provide only p beams for therapy.

All $^{12}C^{6+}$-enabled facilities use (larger) ion synchrotrons.

Dose delivery techniques: Lateral distribution

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



Old method: Collimation + filtering

1) Create a *homogeneous field* from the ion beam (wobbling).

2) *Collimate* to match the transverse profile of the target.

3) *Moderate* parts of the field to match the far-side depth profile.

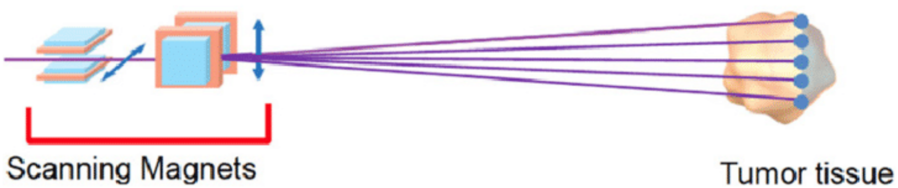
Advantages: Well-established in conventional (X-ray) radiotherapy.

Requirements on beam quality (profile, pointing, time-structure) are relaxed.

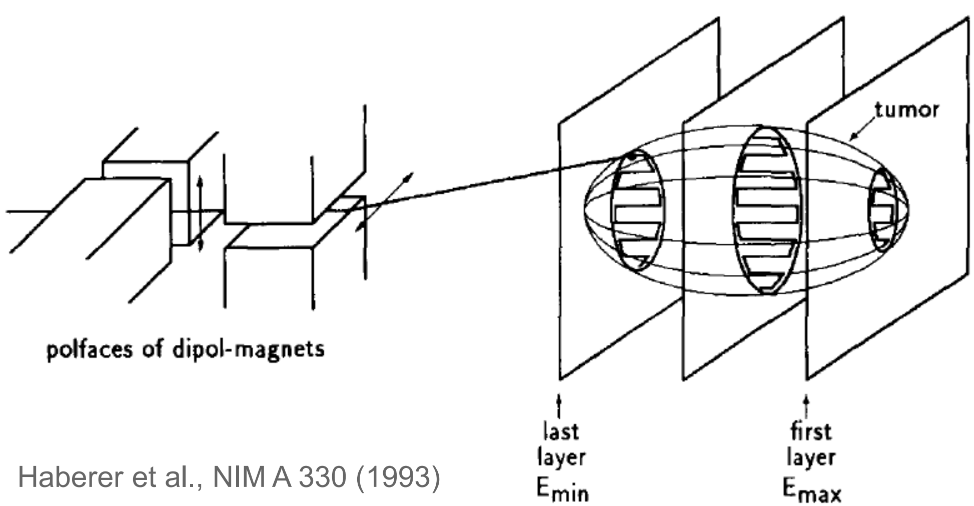
Disadvantage: Regions of *unnecessary dose* at beam-facing side of tumour!

Dose delivery techniques: Lateral distribution

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



Raster scanning



Haberer et al., NIM A 330 (1993)

State-of-the-art: Raster scanning

1) Use sequence of fine *pencil-beams* of sharply defined range.

2) “Paint” each iso-energetic slice of the target using actively-controlled *scanning magnets*.

Advantage: Optimum 3D tumour conformity of dose-distribution.

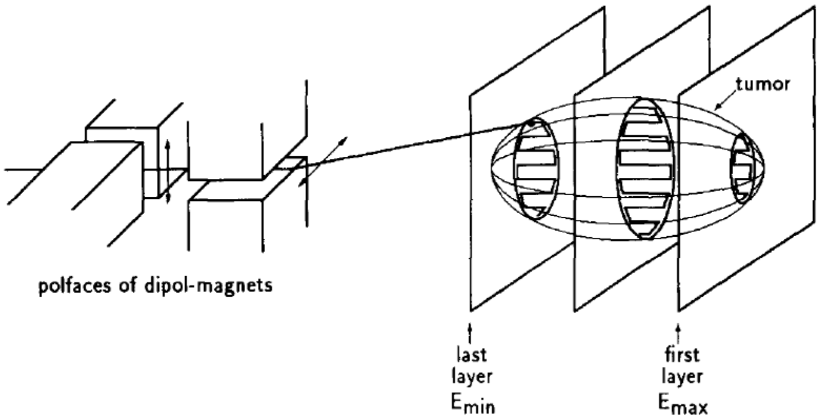
But: Requires a *high-quality* ion beam in pulses of **~ few seconds** duration:

→ Stable pointing direction
→ Stable spot size
→ Stable intensity

Dose delivery techniques: Longitudinal distribution

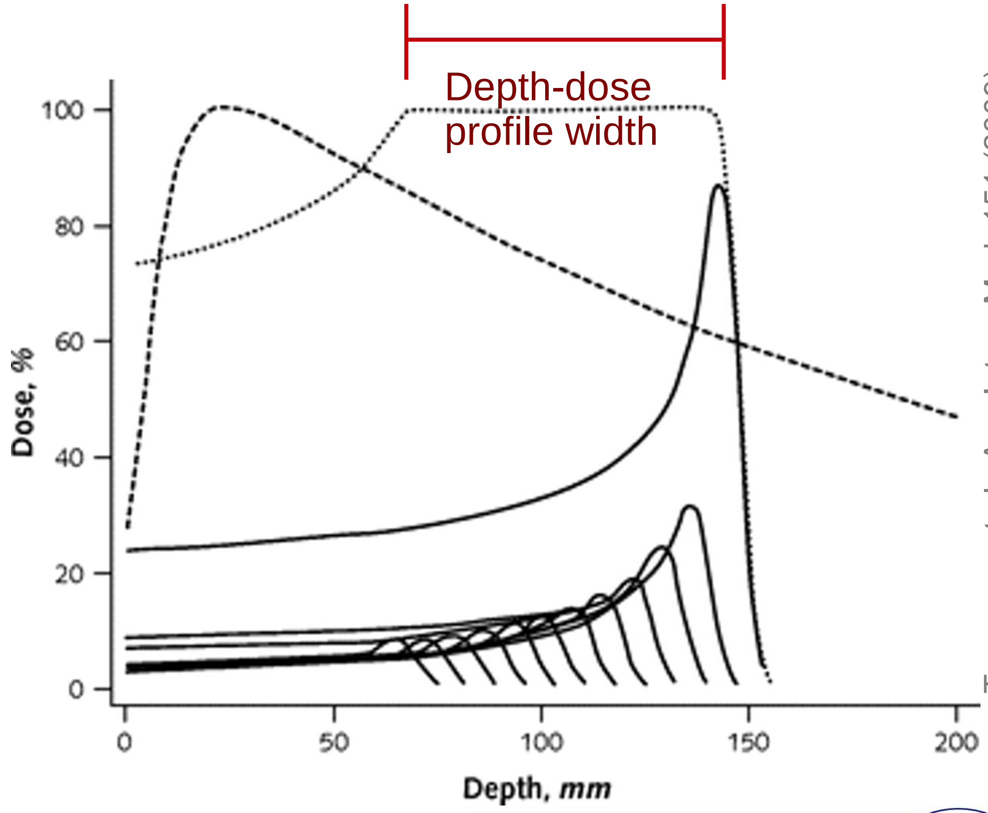
Particle energy (revisited):

Depth-profile of the target region is matched by *stacking* of several beams of different energies.



~	**48 … 220 MeV**	for p
	88 … 430 MeV/u	for $^{12}C^{6+}$

~	1.0 … 2.3 Tm	for p
	3.0 … 6.6 Tm	for $^{12}C^{6+}$



Terasawa et al., Ann Intern Med. 151 (2009)

The scanning method requires a dense *spectrum of ion energies* to be available from the accelerator.

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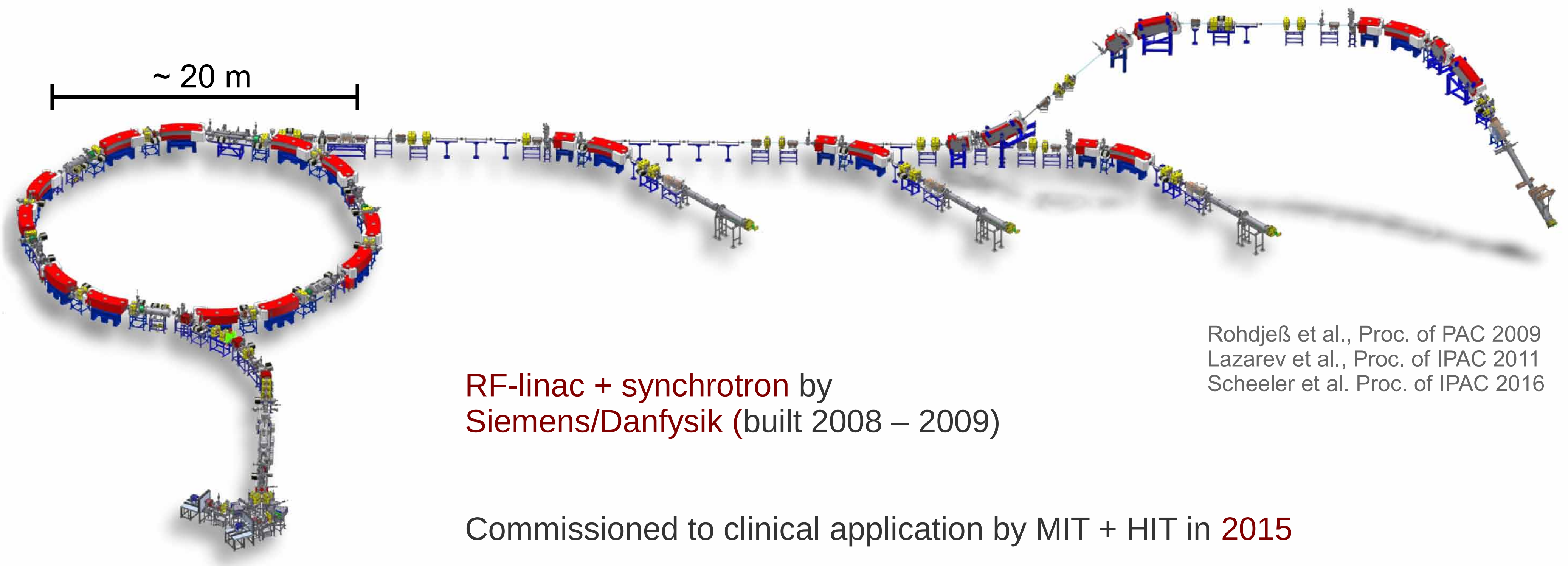
The MIT Accelerator



Rohdjeß et al., Proc. of PAC 2009
Lazarev et al., Proc. of IPAC 2011
Scheeler et al. Proc. of IPAC 2016

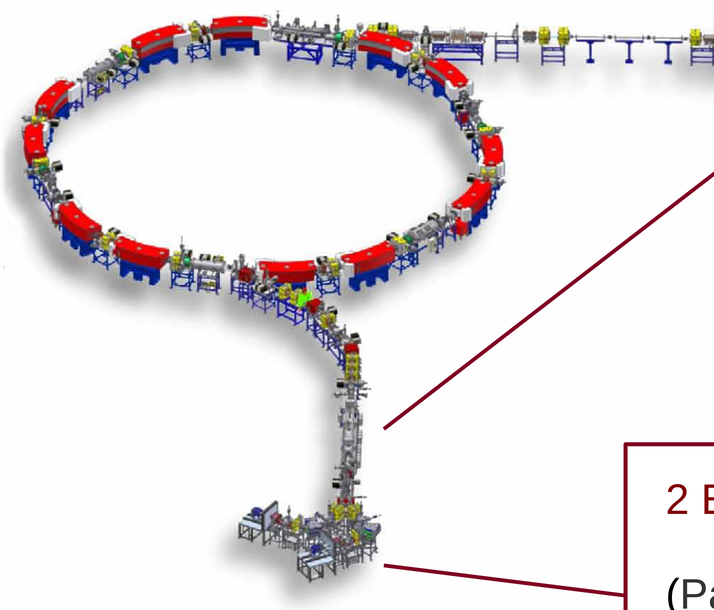
RF-linac + synchrotron by
Siemens/Danfysik (built 2008 – 2009)

Commissioned to clinical application by MIT + HIT in 2015

Similar to HIT accelerator and
PIMMS-types (CNAO, MedAustron).

Prototype of SPHIC machine in Shanghai (in op. 2014).

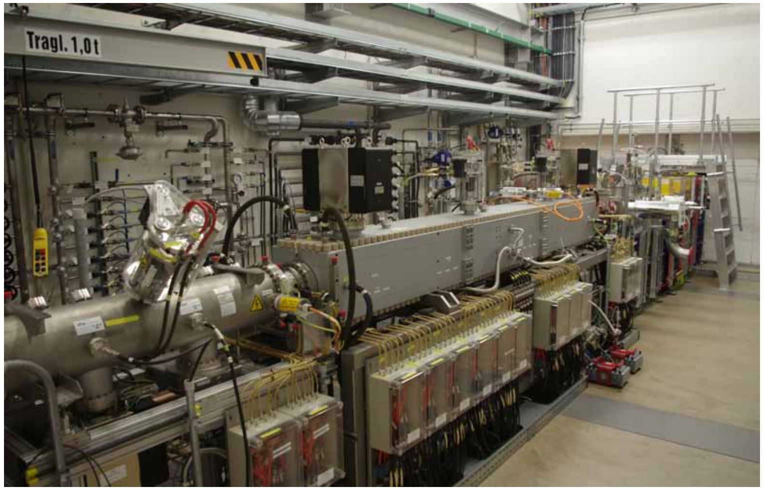
The MIT Accelerator



Linear accelerator

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

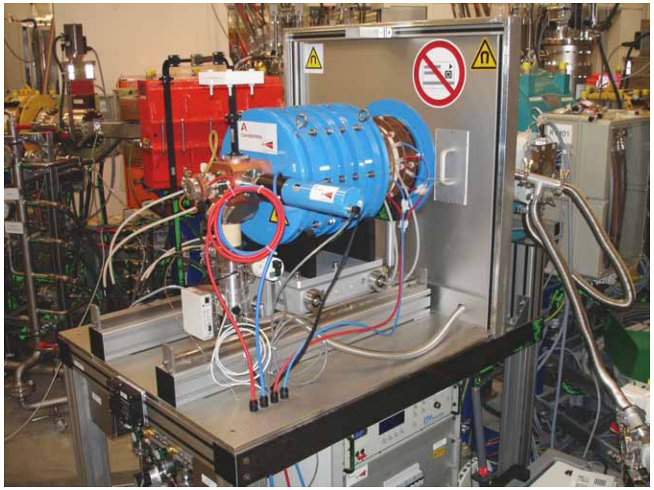
then stripping to
p and C^{6+}



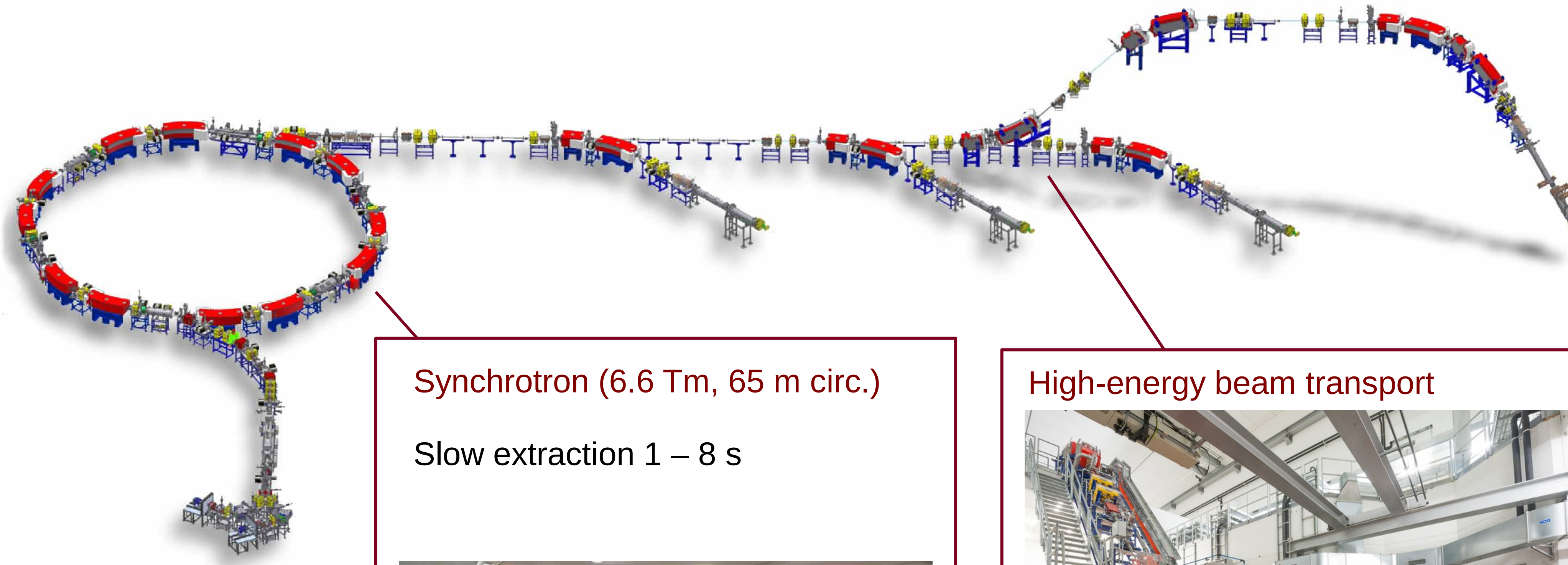
2 ECR ion sources

(Pantechnik Supernanogan)

H_3^+ : ~700 µA
C^{4+} : ~140 µA



The MIT Accelerator



Synchrotron (6.6 Tm, 65 m circ.)

Slow extraction 1 – 8 s

Møller et al., Proc. of PAC 2007

High-energy beam transport

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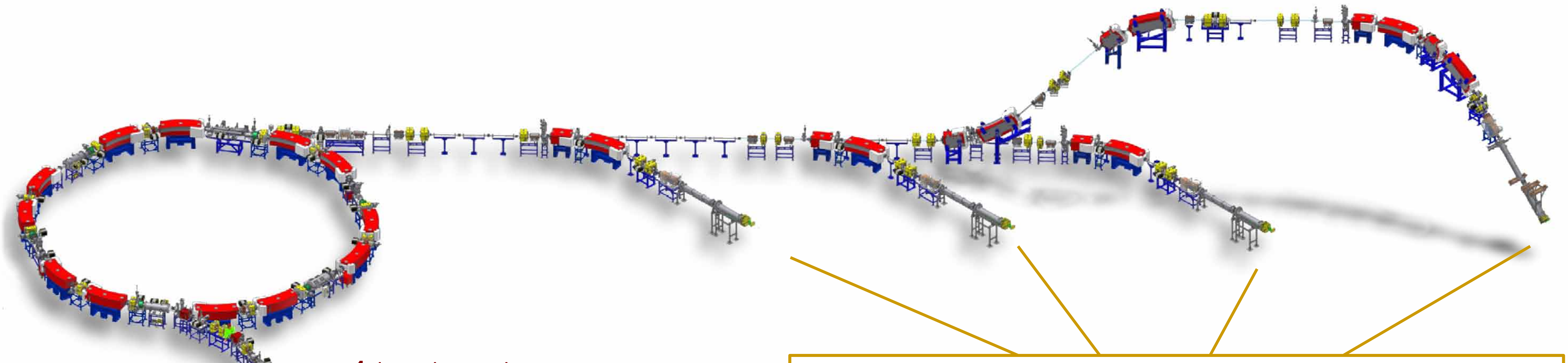
The MIT Accelerator

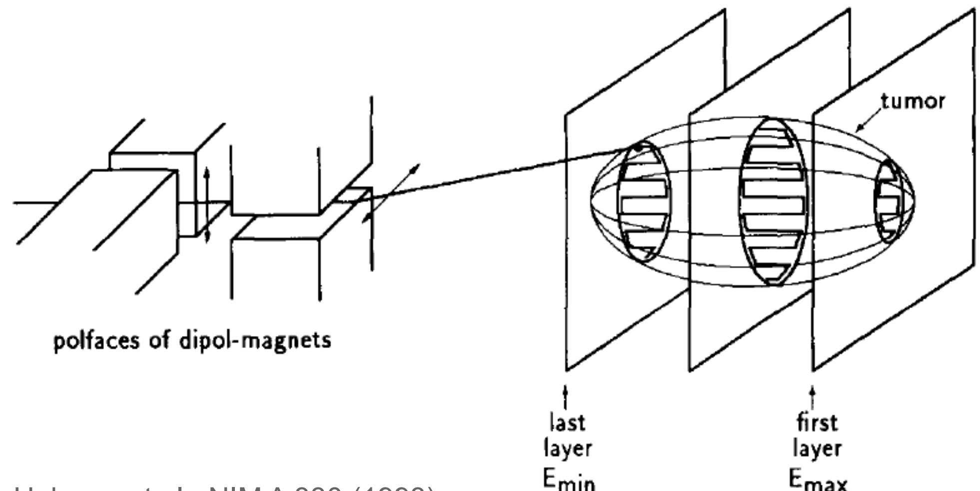


4 treatment rooms:

3 x horizontal,

1 x 45°-vertical.

Pencil-beam scanning
dose delivery systems.



Haberer et al., NIM A 330 (1993)

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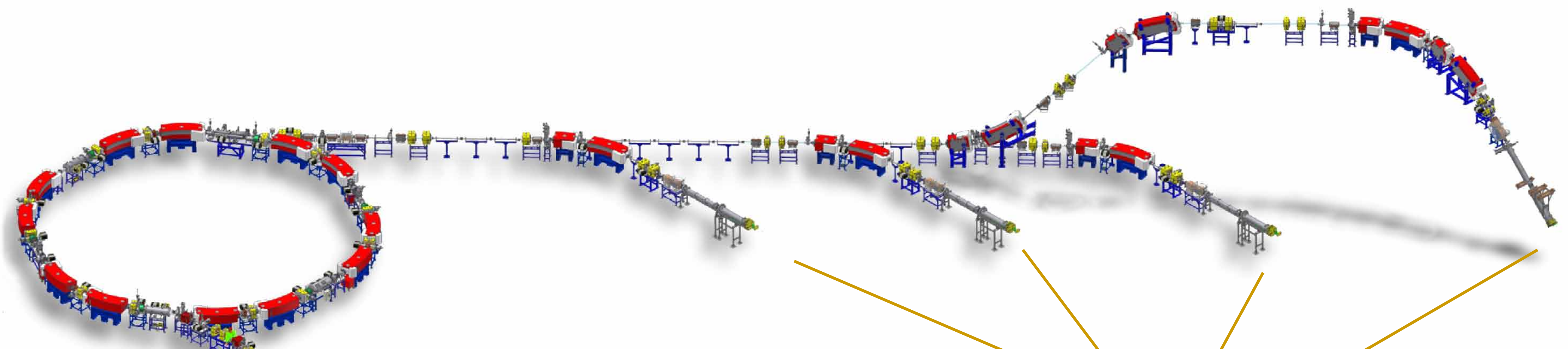
The MIT Accelerator




2 x 290 rigidities:

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

Stored beam intensities:

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

per cycle

“Dynamic Intensity Control”

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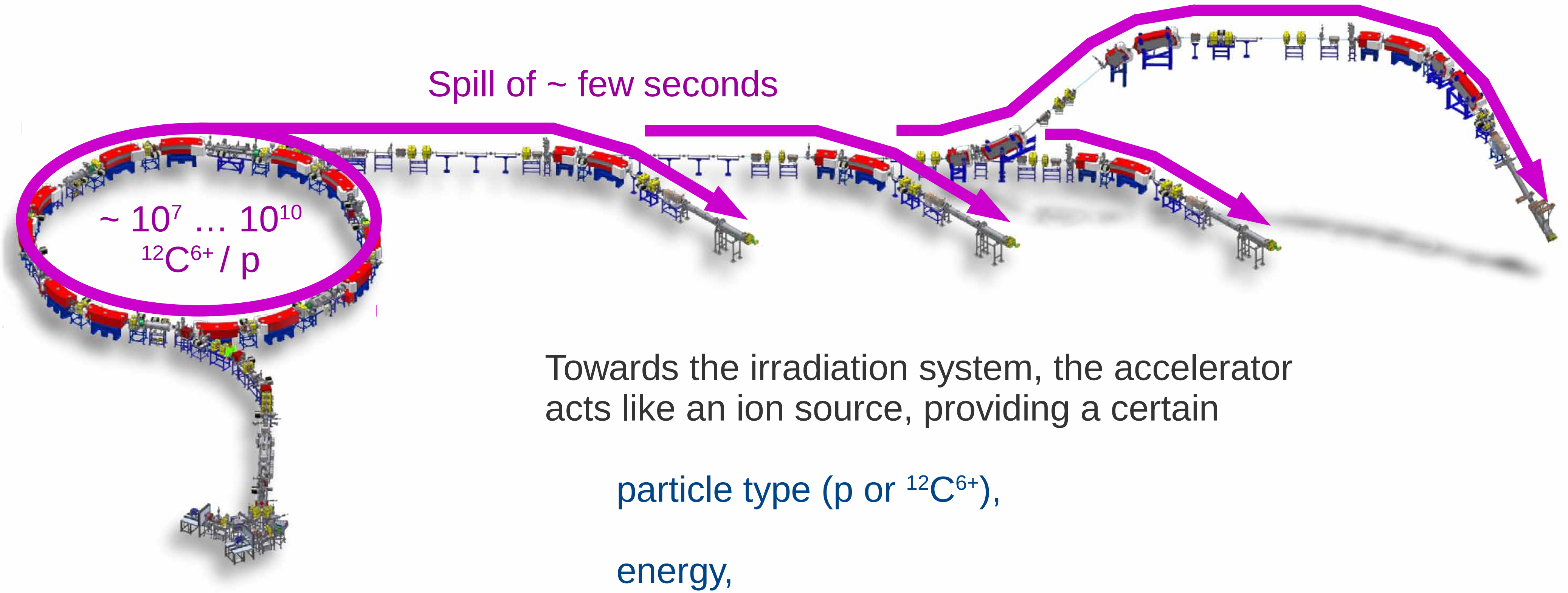
Beam Extraction from a Therapy Synchrotron



Towards the irradiation system, the accelerator acts like an ion source, providing a certain

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

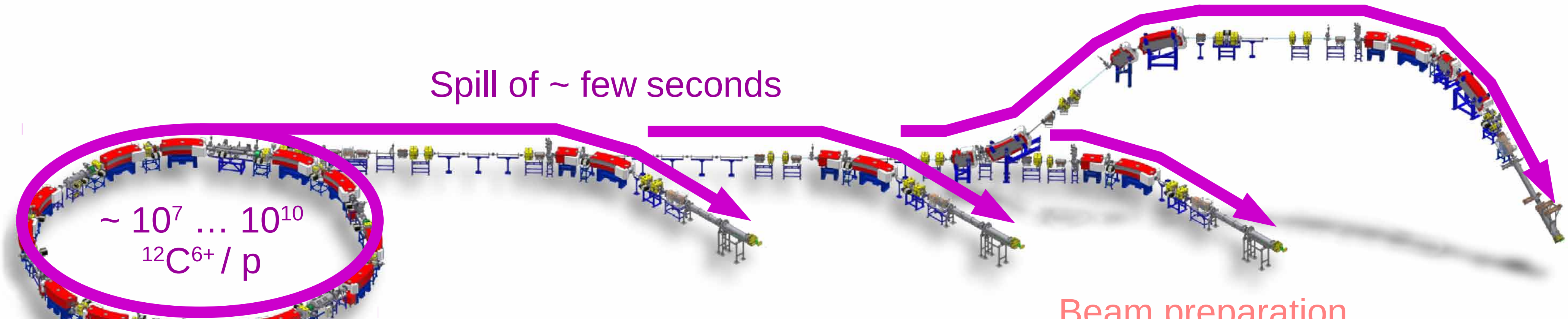
energy,

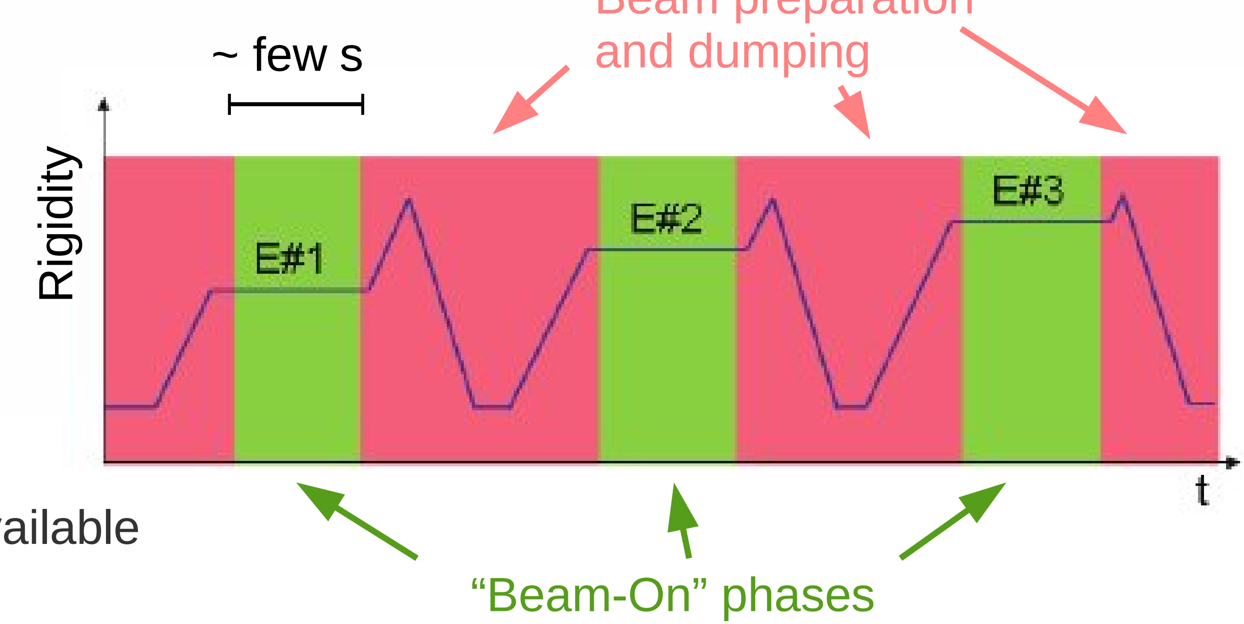
spot size, and

intensity (particles/s)

on command.

Beam Extraction from a Therapy Synchrotron

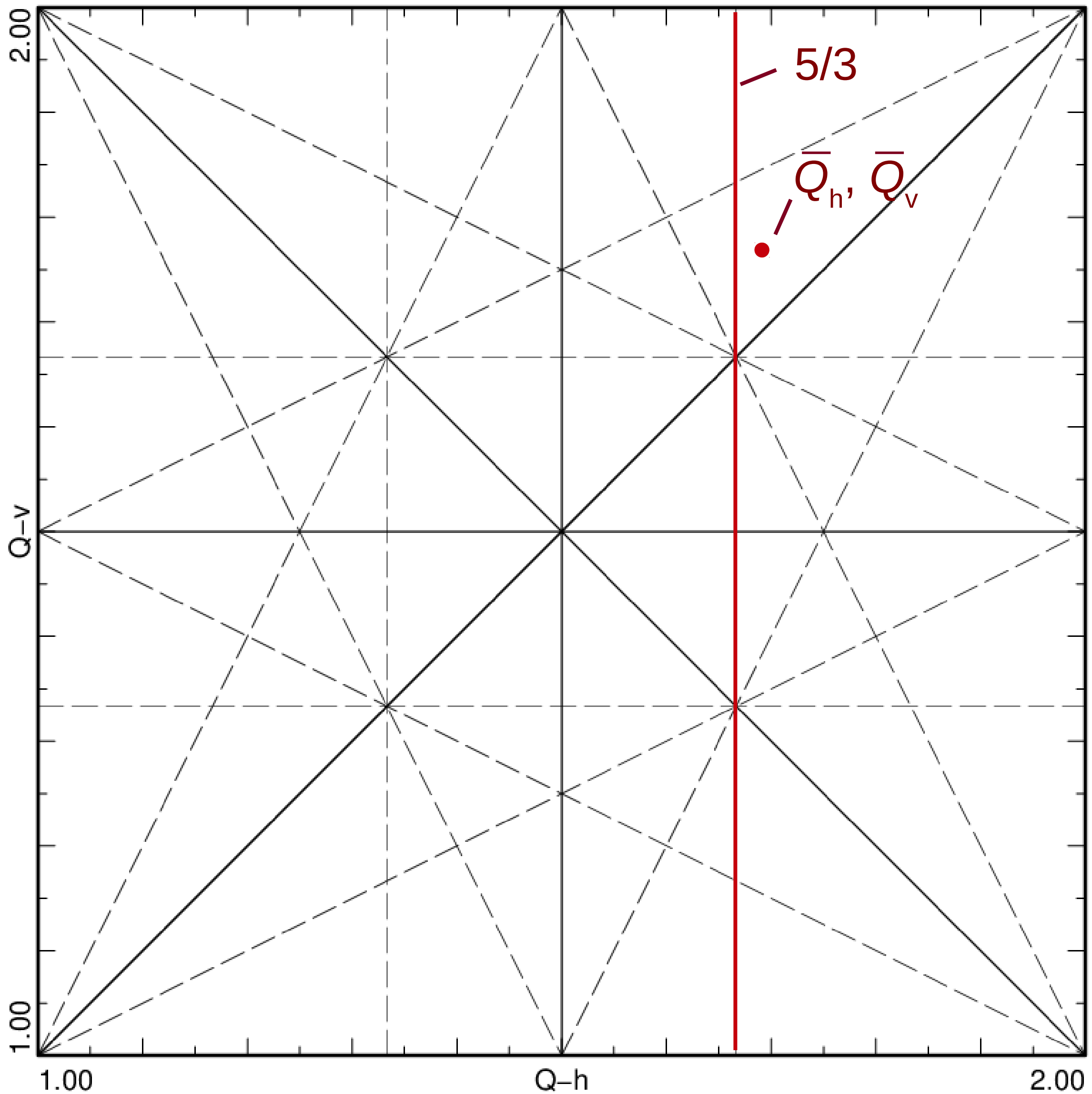




For a raster-scanning irradiation system, a stable beam must be available over a period of ~ few seconds.

→ Slow extraction

Beam Extraction from a Therapy Synchrotron

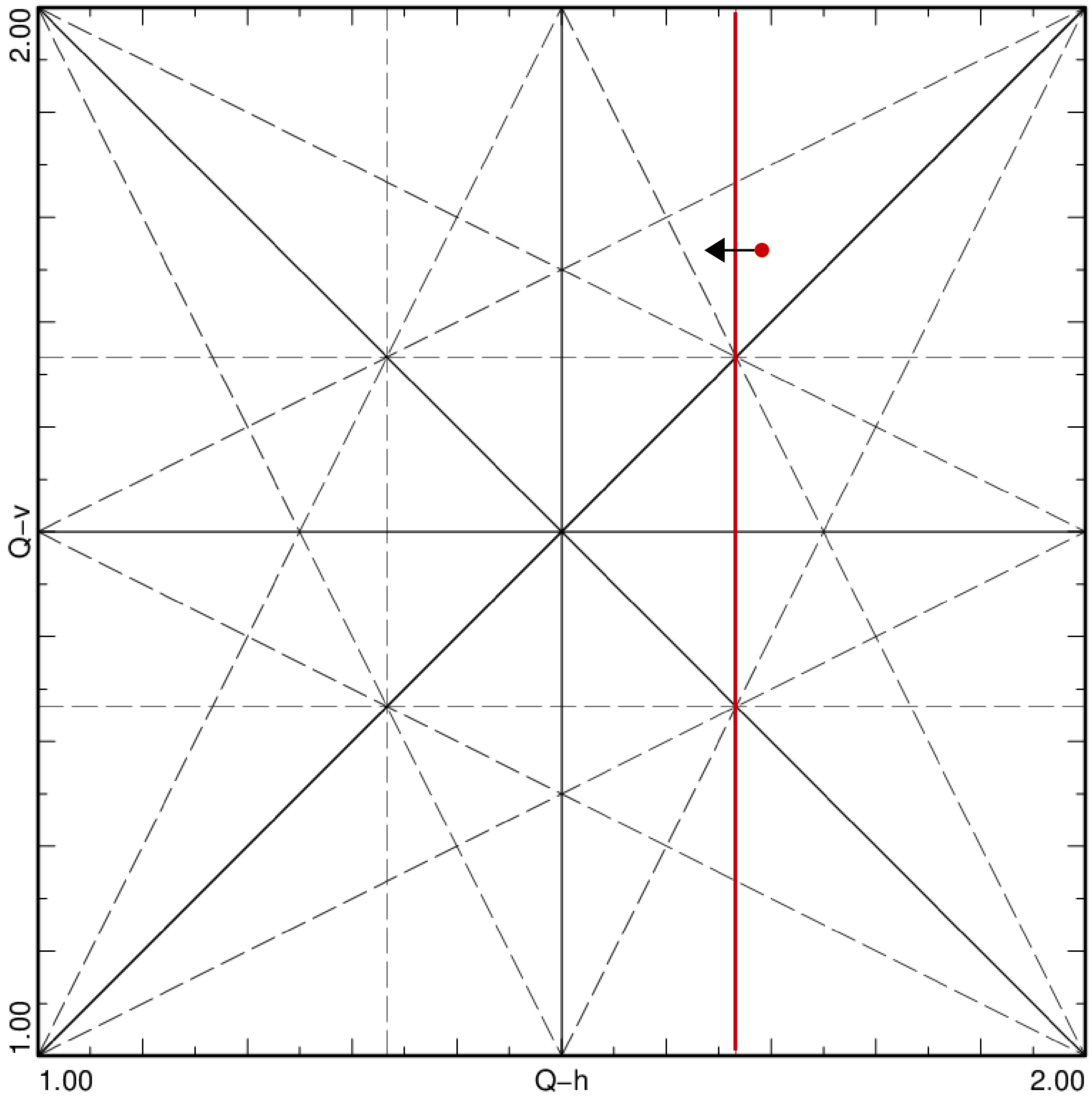


Basic principle of slow extraction

1) Choose machine working point next to a *horizontal resonance*.

   (Most often a 3rd-order resonance is used.)

Beam Extraction from a Therapy Synchrotron



Basic principle of slow extraction

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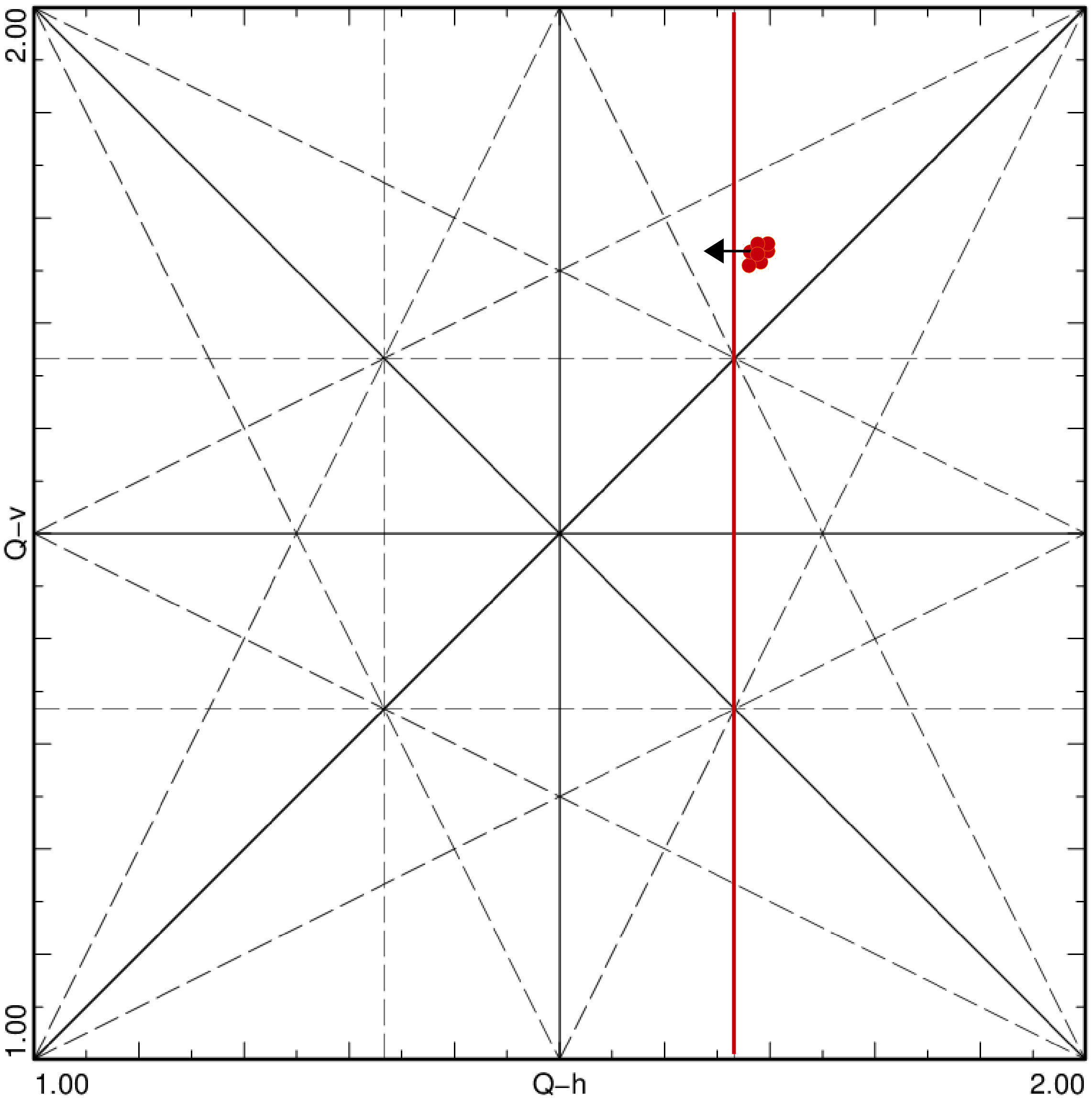
2) Slowly “move” the horizontal particle tunes into resonance.

Beam Extraction from a Therapy Synchrotron



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3) Particle tunes are *distributed* along Q_h axis (due to e.g. chromaticity or space charge …).

   → In a perfect world: Particles could be *destabilised* "one-by-one".

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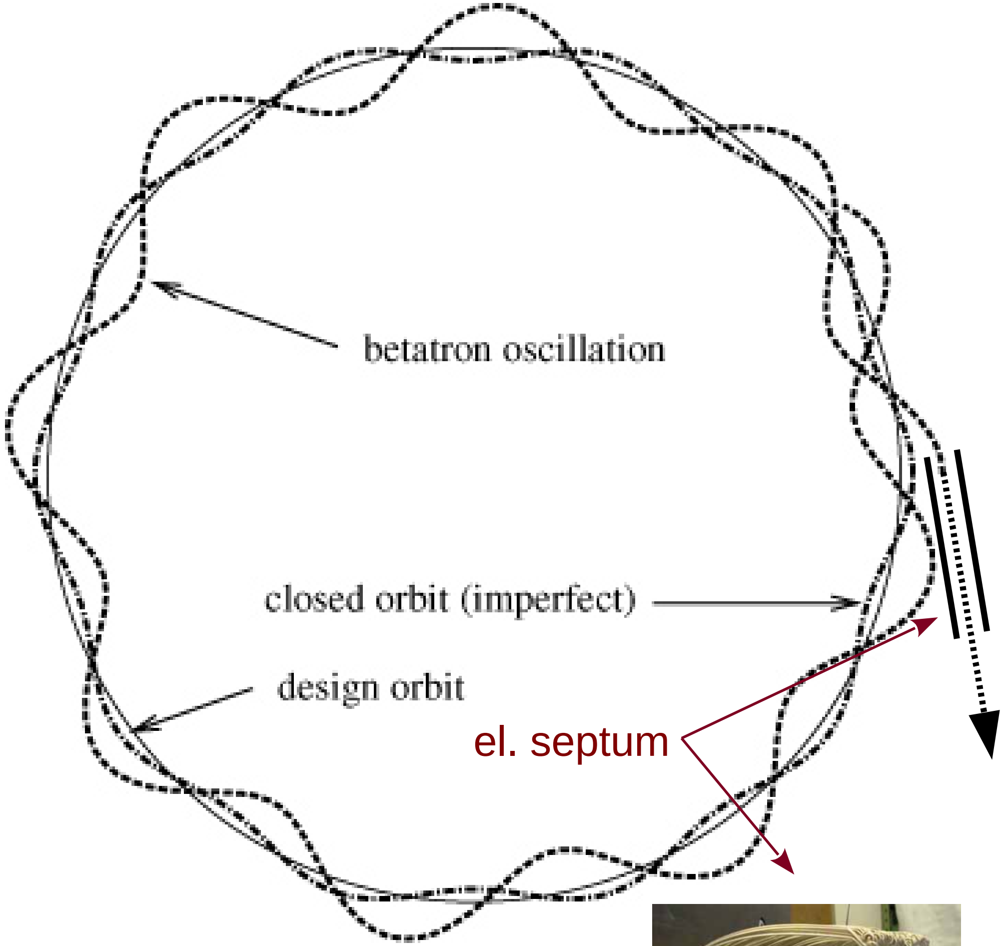
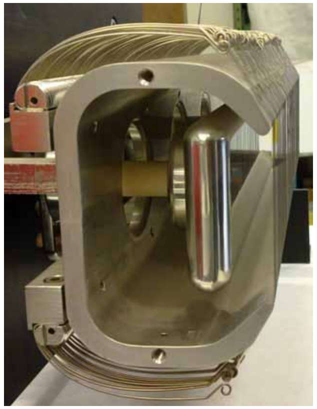
Beam Extraction from a Therapy Synchrotron



Mane et al., Rep. Prog. Phys. 68 (2005)



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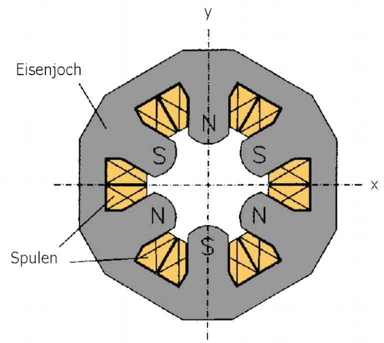
3) Particle tunes are *distributed* along Q_h axis (due to e.g. chromaticity or space charge …).

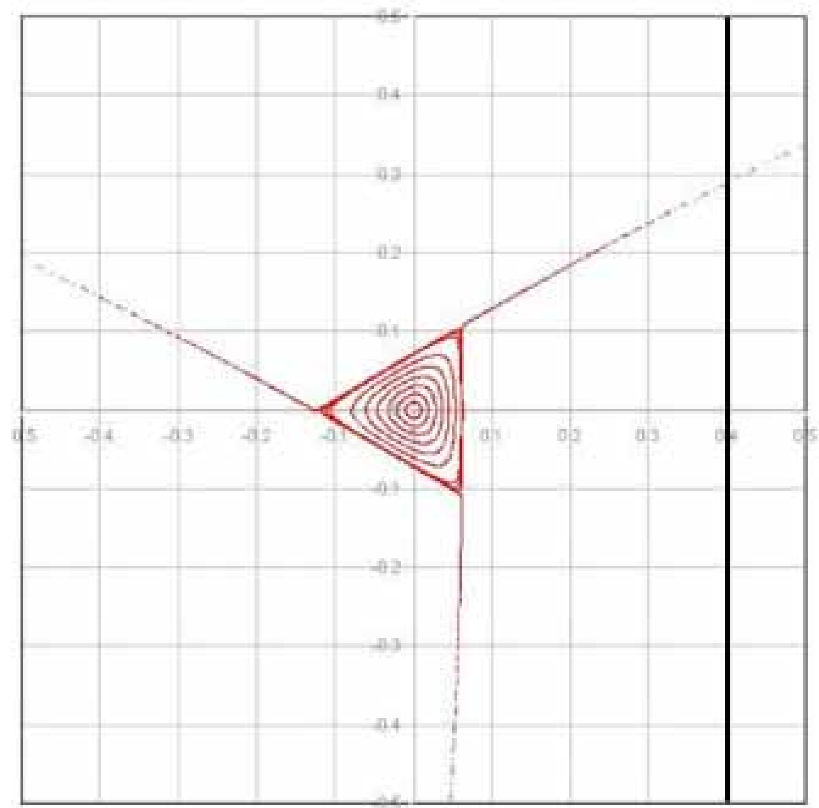
   → In a perfect world: Particles could be *destabilised* "one-by-one".

4) Catch (most of) the unstable orbits in an extraction septum.

Beam Extraction from a Therapy Synchrotron

The 3rd-order resonance can be excited by sextupole magnets (available anyway for chromaticity correction)





As the width of the 3rd-order stop band is amplitude-dependent:

Low betatron amplitudes → stable.

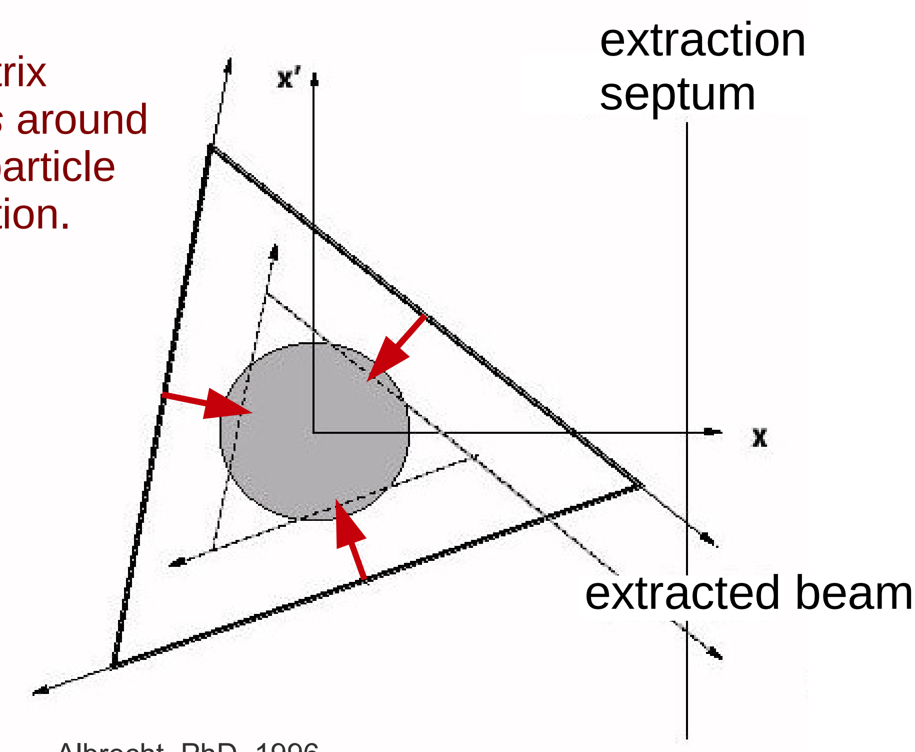
High amplitudes → Sync with 3rd-order perturbation, destabilised.

Fixed points and size of ***separatrix*** depend on distance tune–resonance.

Beam Extraction from a Therapy Synchrotron

There are two methods of slowly “feeding” the resonance:

Separatrix ***shrinks*** around stable particle distribution.



Albrecht, PhD, 1996

(1) Change betatron tune of the low-amplitude particles.

Examples:

Slow quadrupole ramp

→ changes linear focussing.

Slow acceleration (using cavities, induction cores, stochastic noise)

→ changes particle momenta.

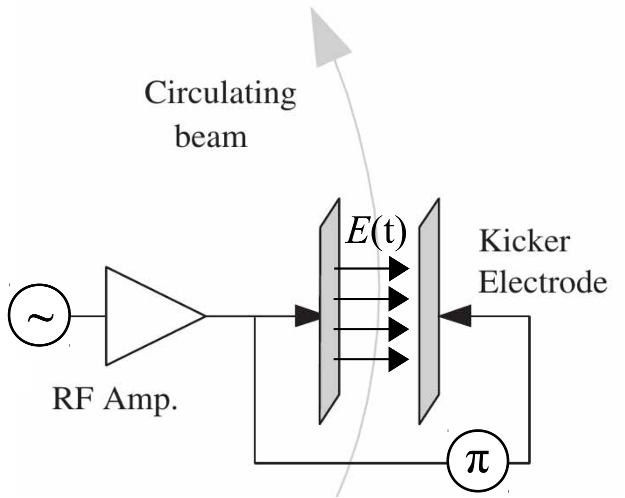
→ changes particle tunes via chromaticity.

Beam Extraction from a Therapy Synchrotron

There are two methods for slowly "feeding" the resonance:

(2) Excite horizontal betatron motion of stable particles

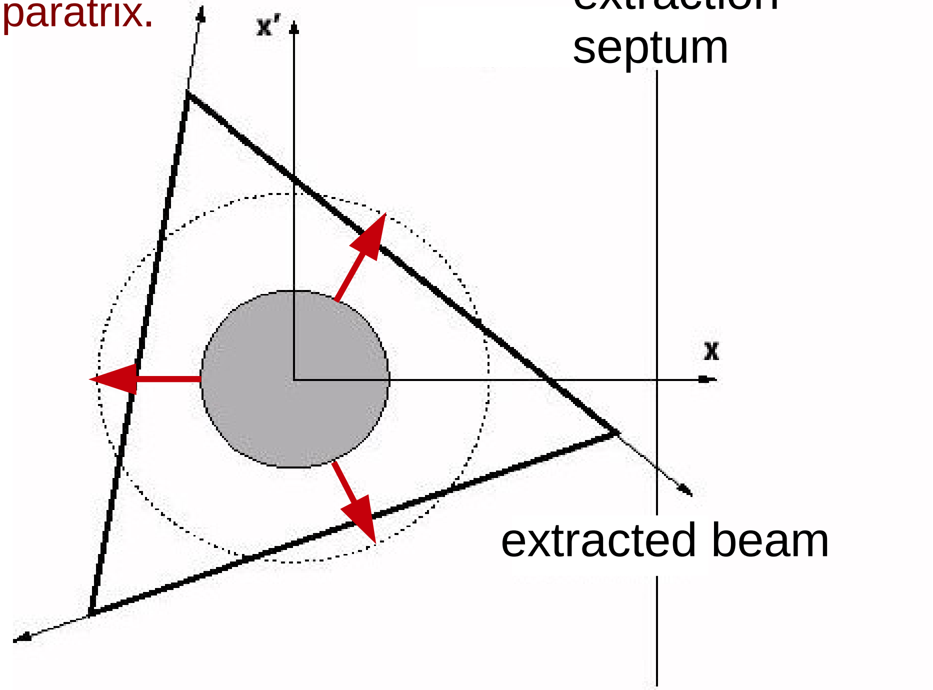
Horizontal RF-kicker electrode
~ in sync with horizontal particle tune.



"Transverse RF-Knock-Out" (RF-KO) technique.

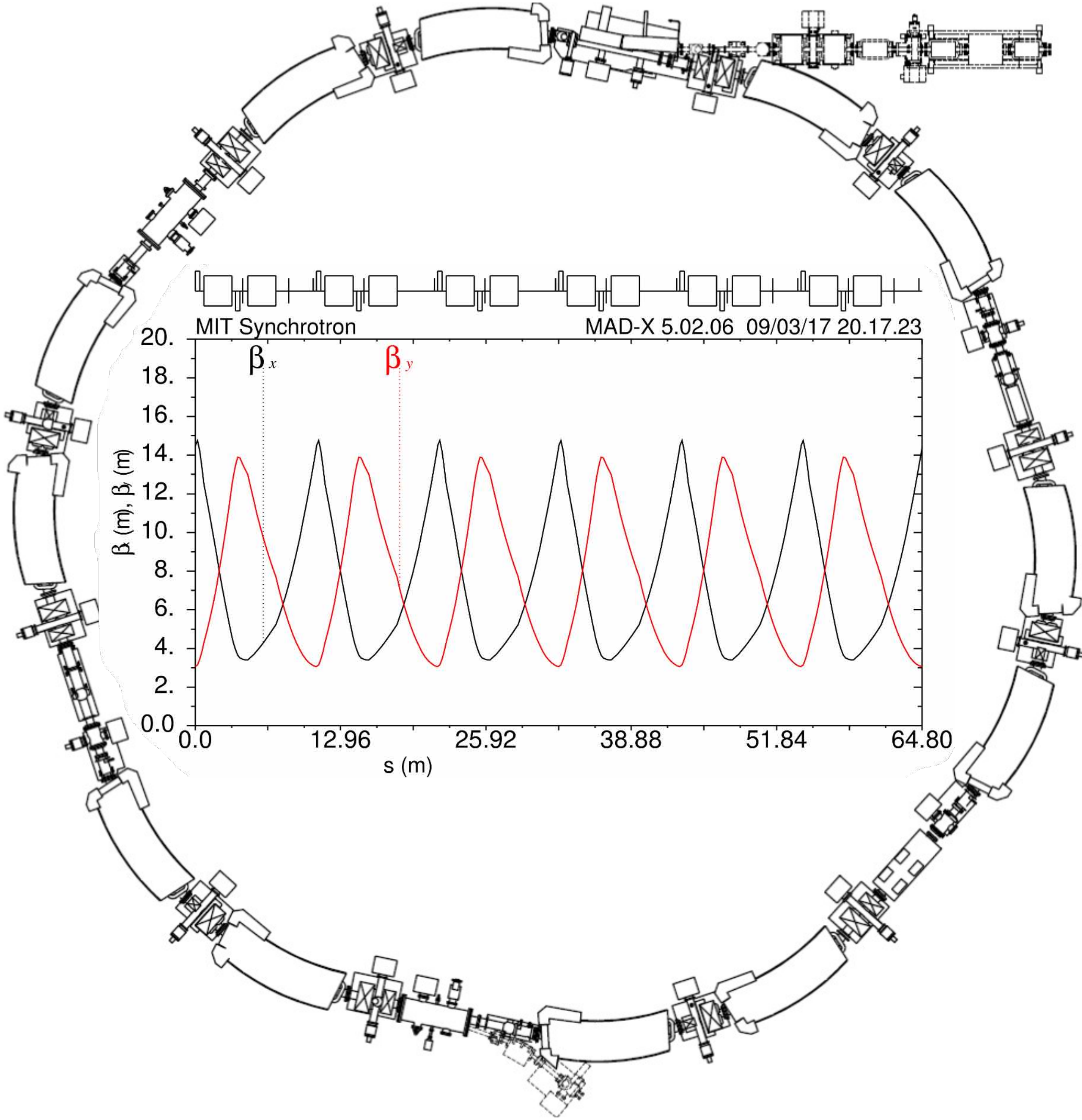
Used e.g. at the MIT, HIT, and HIMAC therapy synchrotrons.

Horizontal envelope ***grows*** towards separatrix.



Albrecht, PhD, 1996

The MIT extraction system



Synchrotron:

65 m circumference

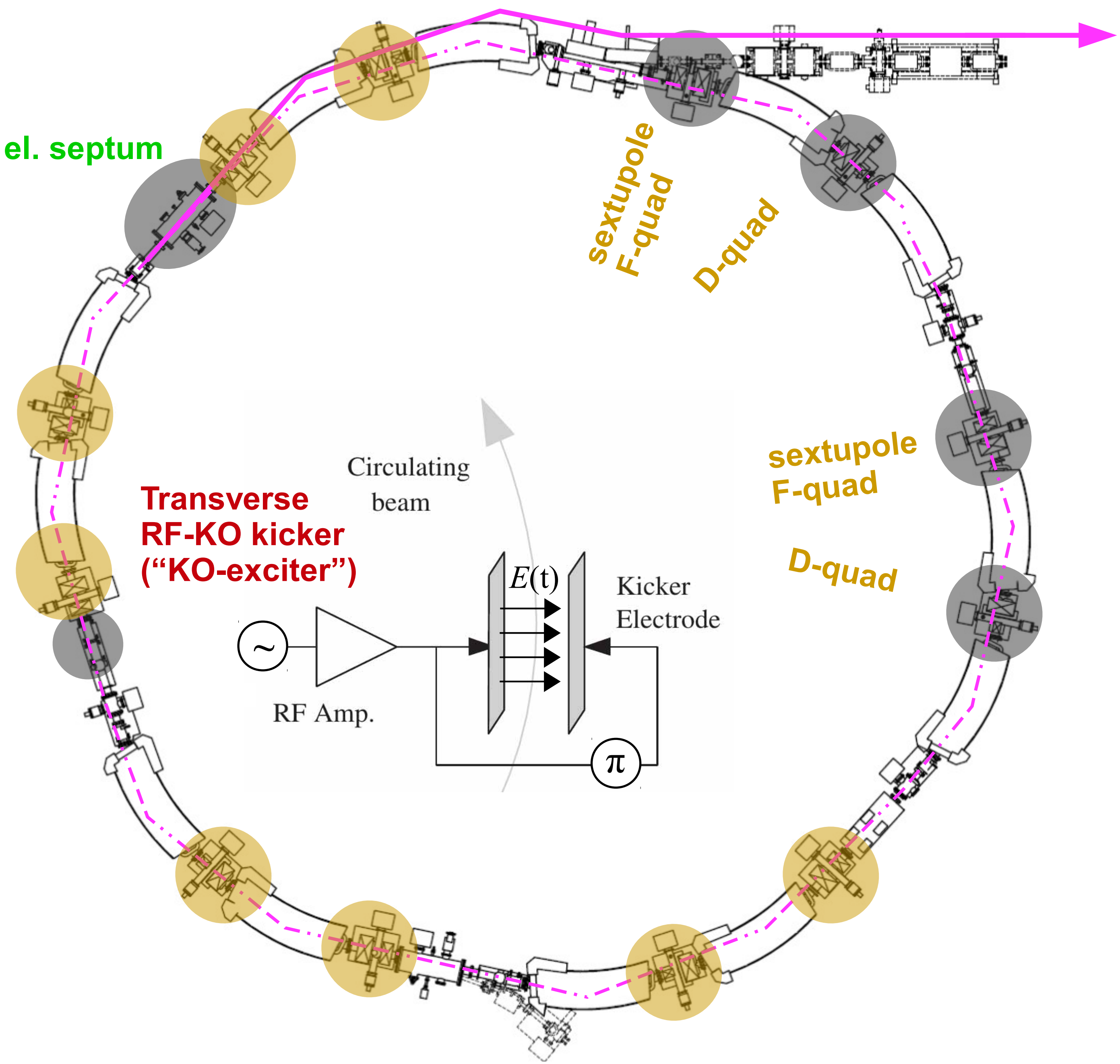
0.5 … 6.6 Tm

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

Multiturn injection at 7 MeV/u

Ramp to final *E*: ~ 0.2 … 0.9 s

The MIT extraction system



p: 48 … 221 MeV
$^{12}C^{6+}$: 88 … 430 MeV/u

Fixed optics during extraction (Q_h ~ 1.69).

Slow extraction via 2/3 resonance (Q_{extr} = 1.666...).

Transverse beam excitation by RF-KO kicker.

→ Can *control* the extraction rate on short time scales!

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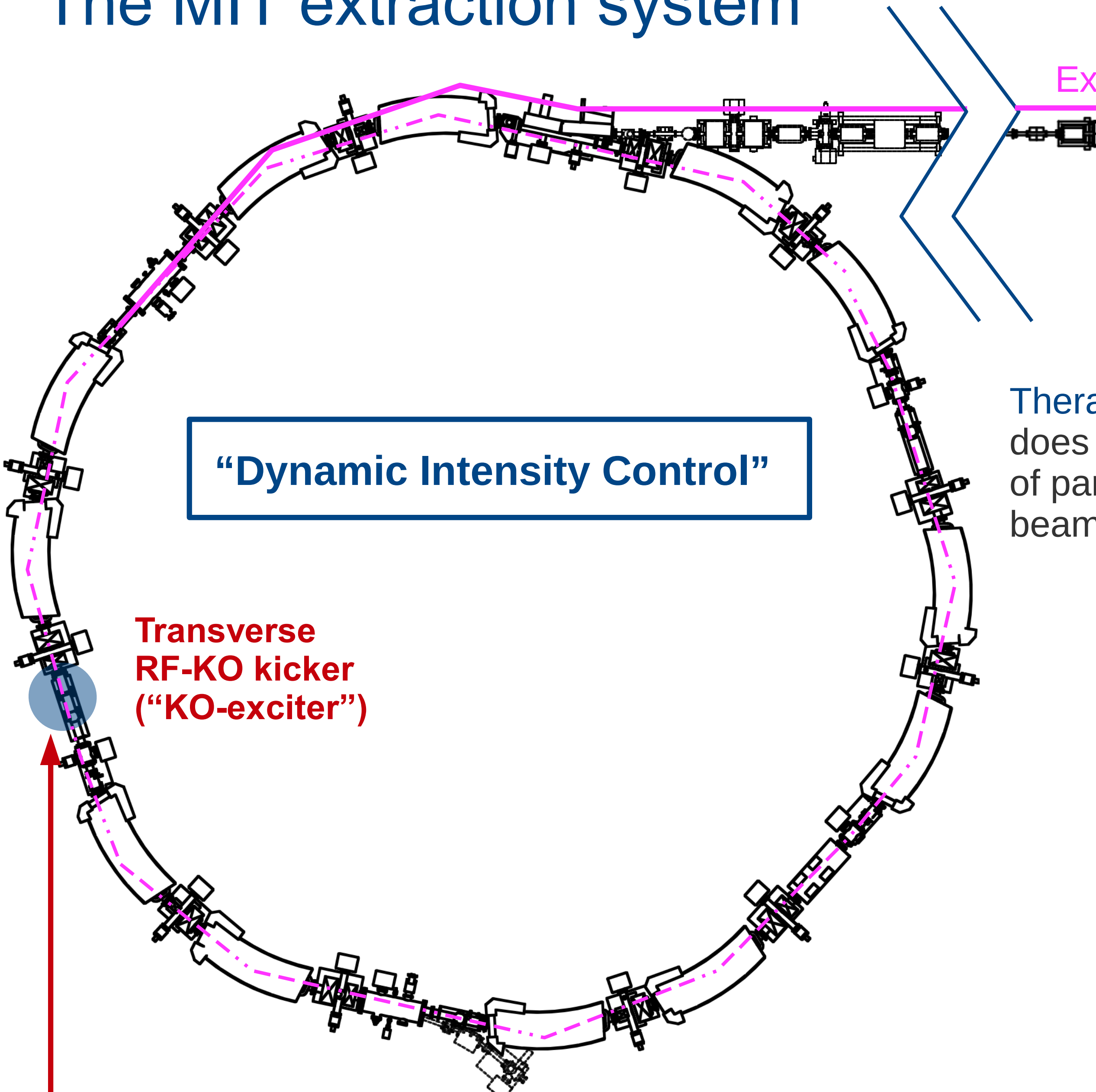
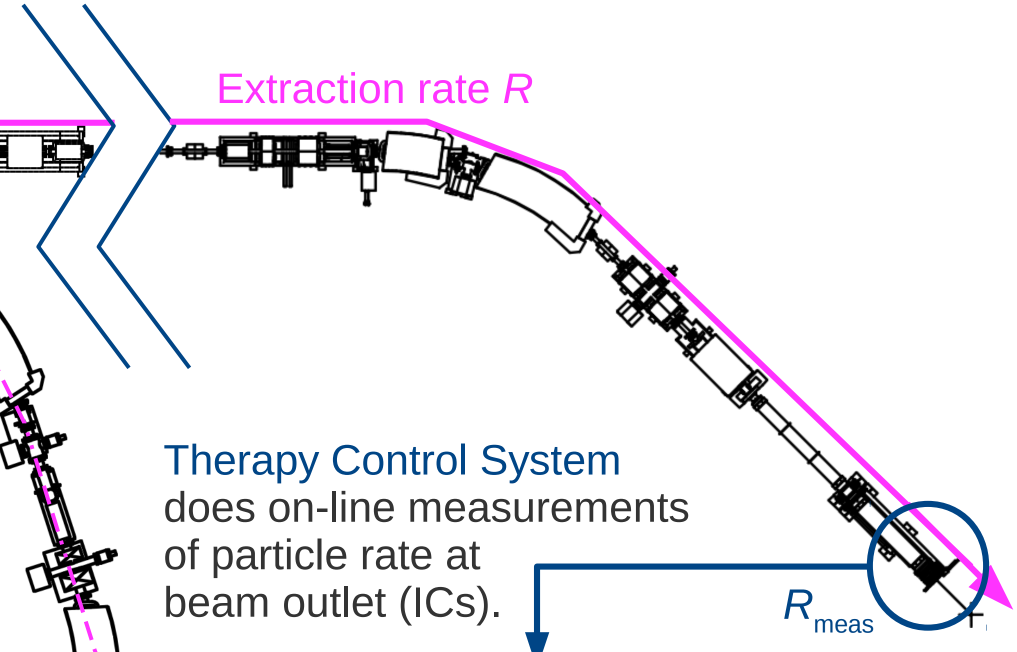
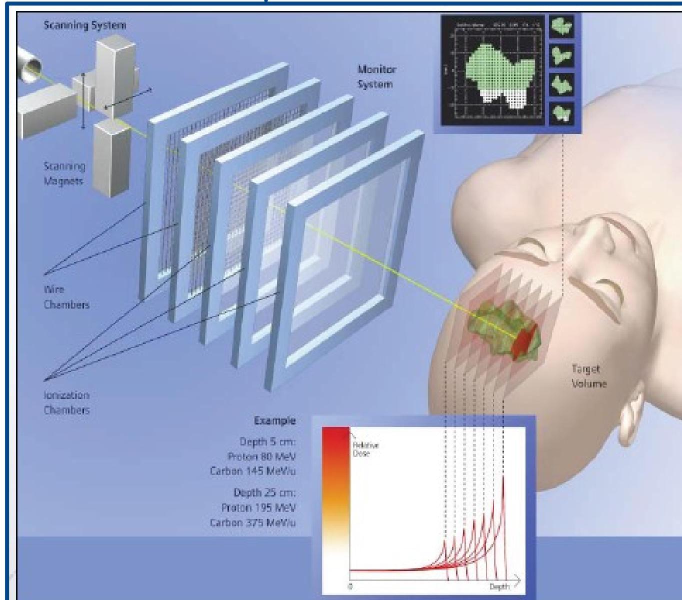
The MIT extraction system



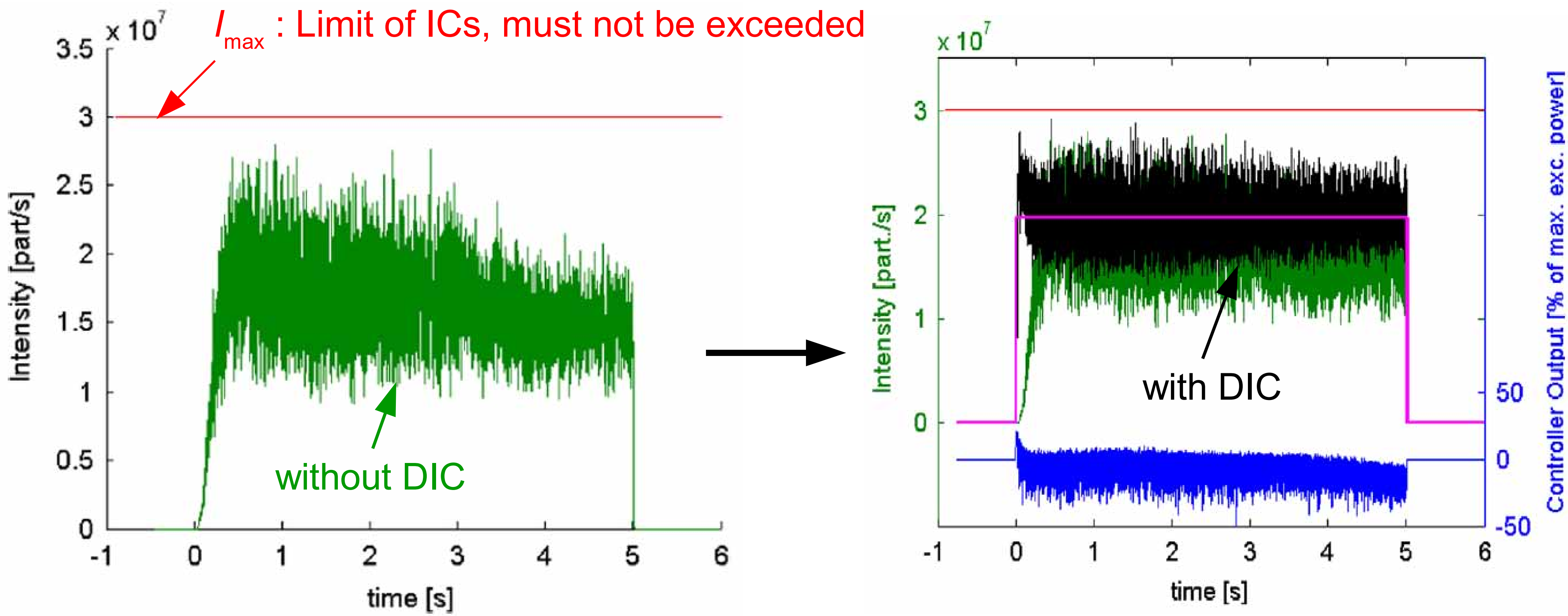
Intensity-Controlled Rasterscan Technique, Haberer et al., GSI, NIM A,1993

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

Dynamic Intensity Control

"Dynamic Intensity Control" (DIC) System – nearly identical to the equivalent system at HIT.
(cf. C. Schömers, NIM A 795 (2015) 92)

→ Automatically stabilises (average!) extraction rate at given set-point.

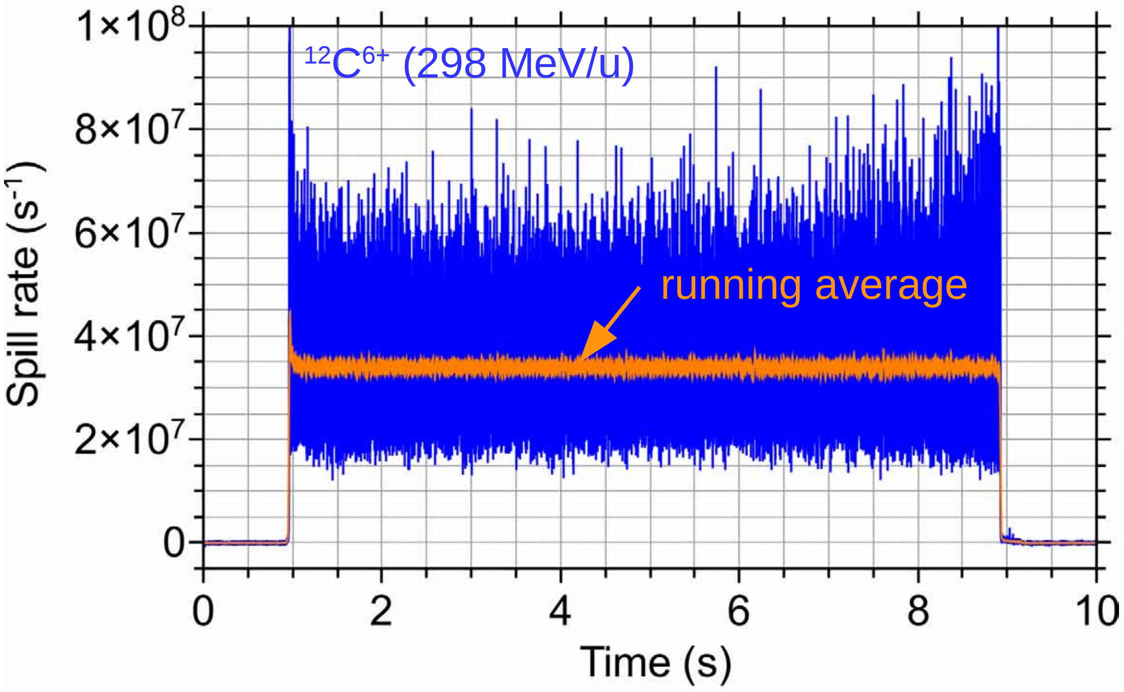


Schoemers, NIM A 795 (2015) 92–99

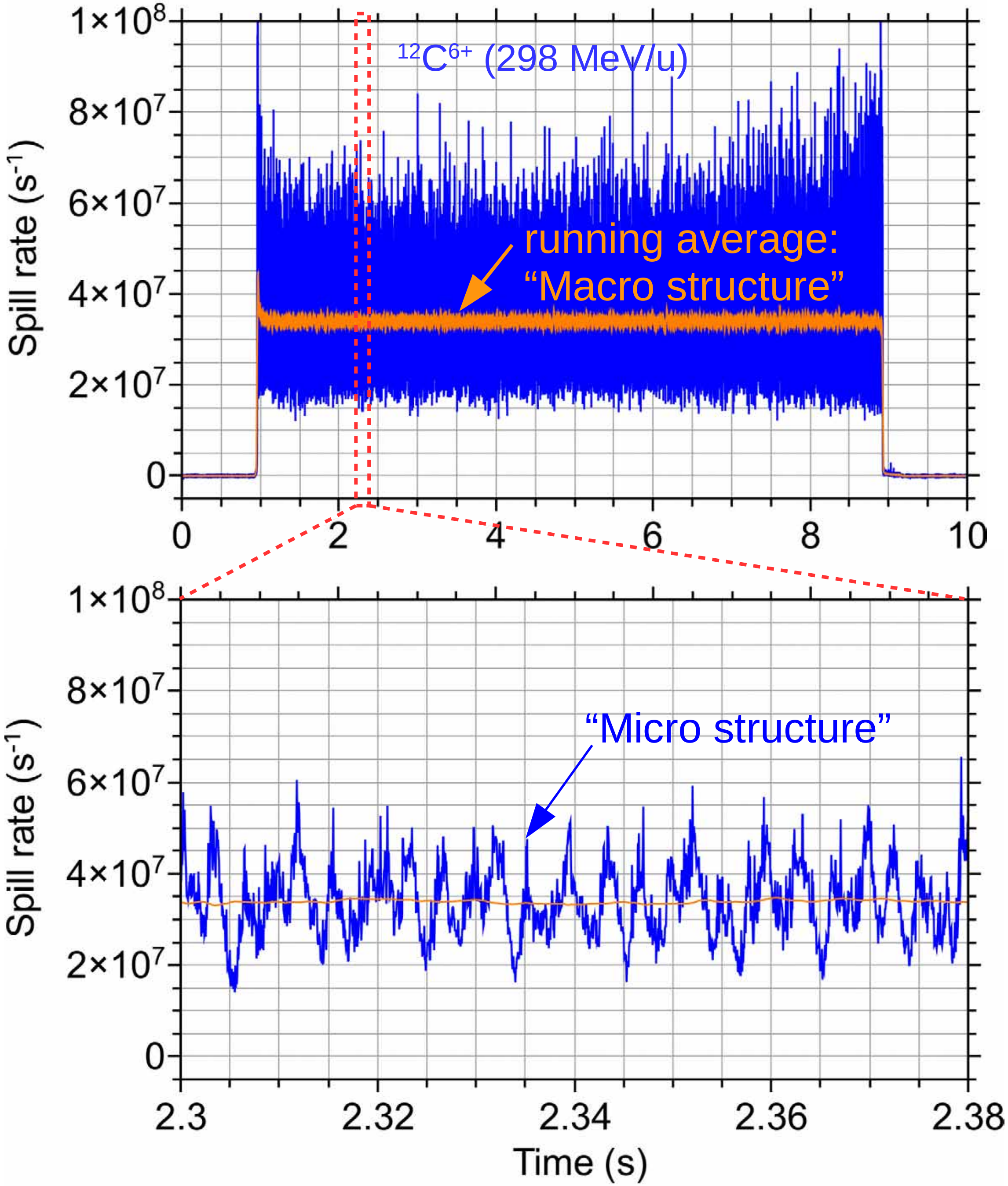
Spill quality

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

C^{6+} (298 MeV/u), with DIC, 50 µs binning (IC at beam outlet)



Spill quality



RF-KO extraction combined with DIC

→ provides very good **"macro structure"**

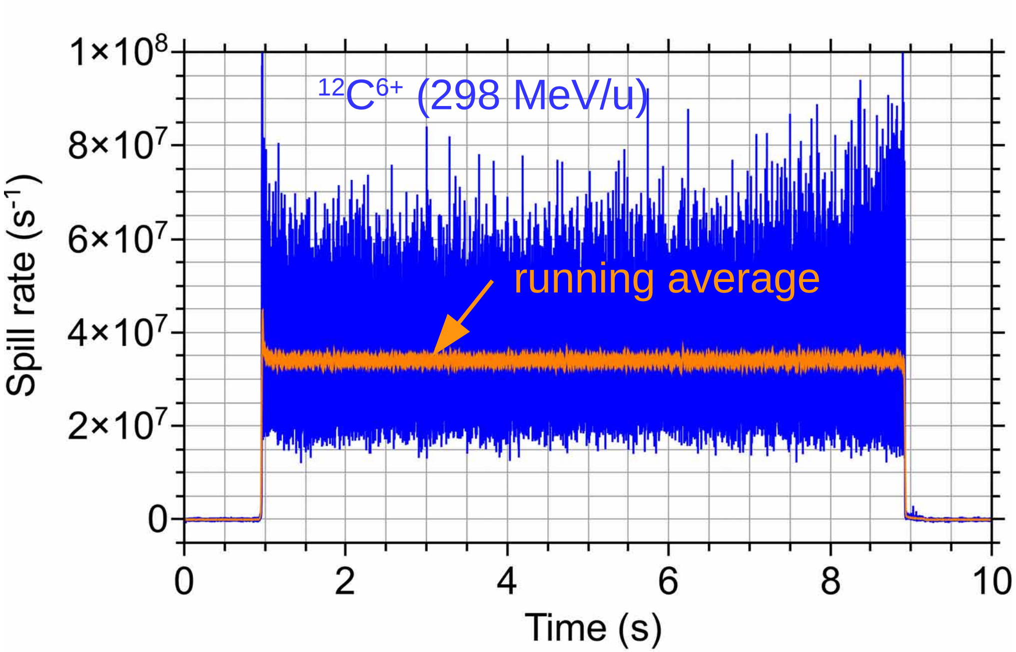
(time scales down to ~ 10 ms),

→ cannot change much about the spill **"micro structure"**

(kHz ... MHz components).

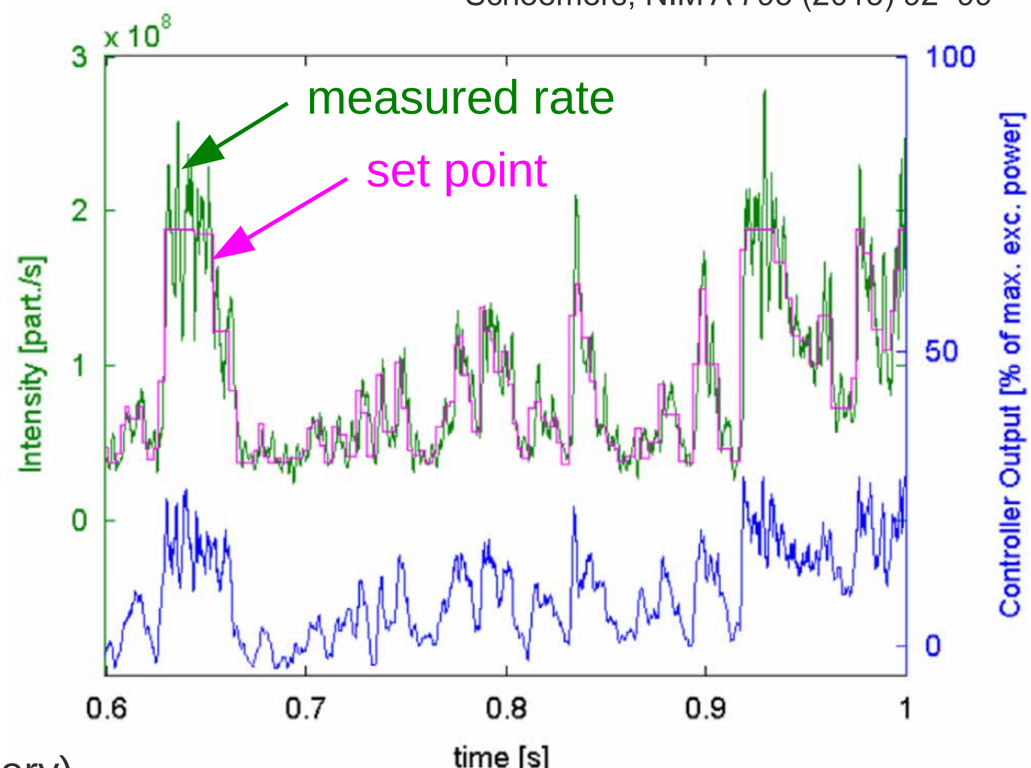
Note:
At therapy accelerators, the time resolution of IC detectors blurs structures below ~ 100 µs!

Macro structure



From spill rate **stabilisation** ...

Schoemers, NIM A 795 (2015) 92–99



… to spill rate **modulation**.

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

→ Allows for more *time-efficient irradiation* (while still on-line monitoring the dose delivery).

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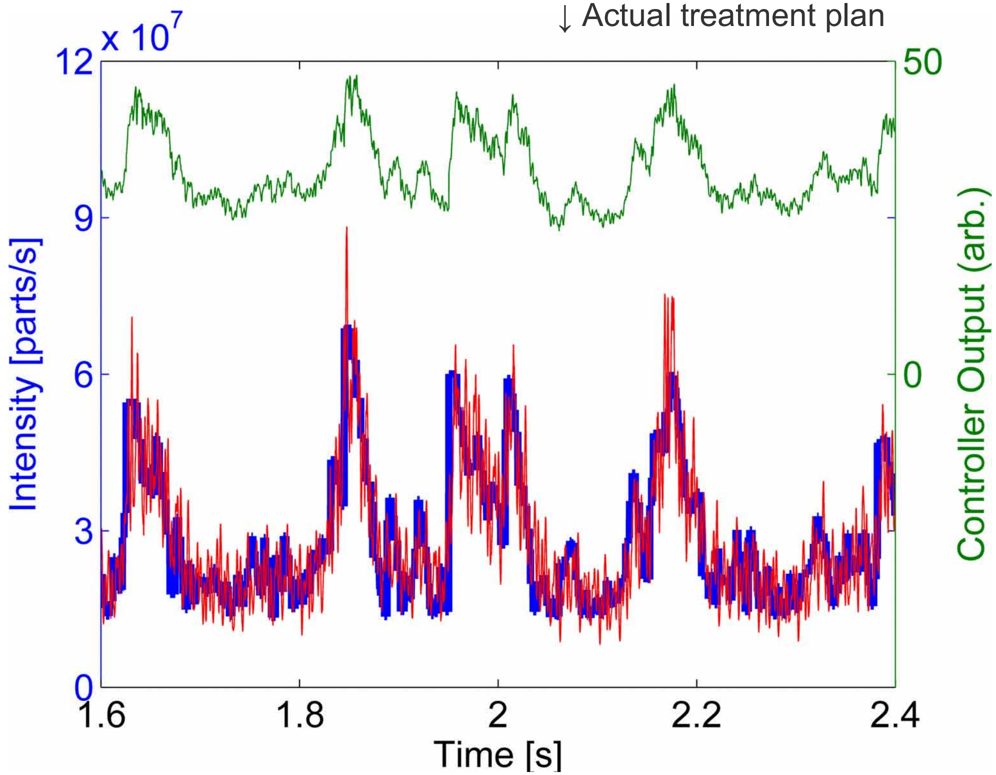
Macro structure

The Marburg system uses DIC-modulation heavily.

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



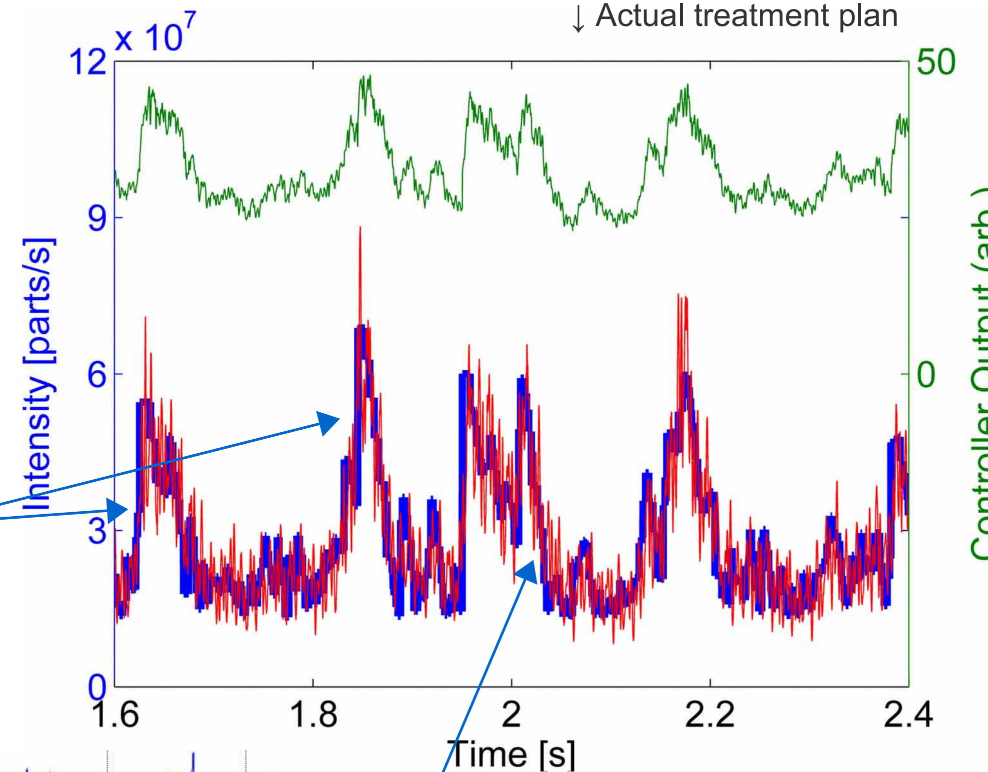
Macro structure

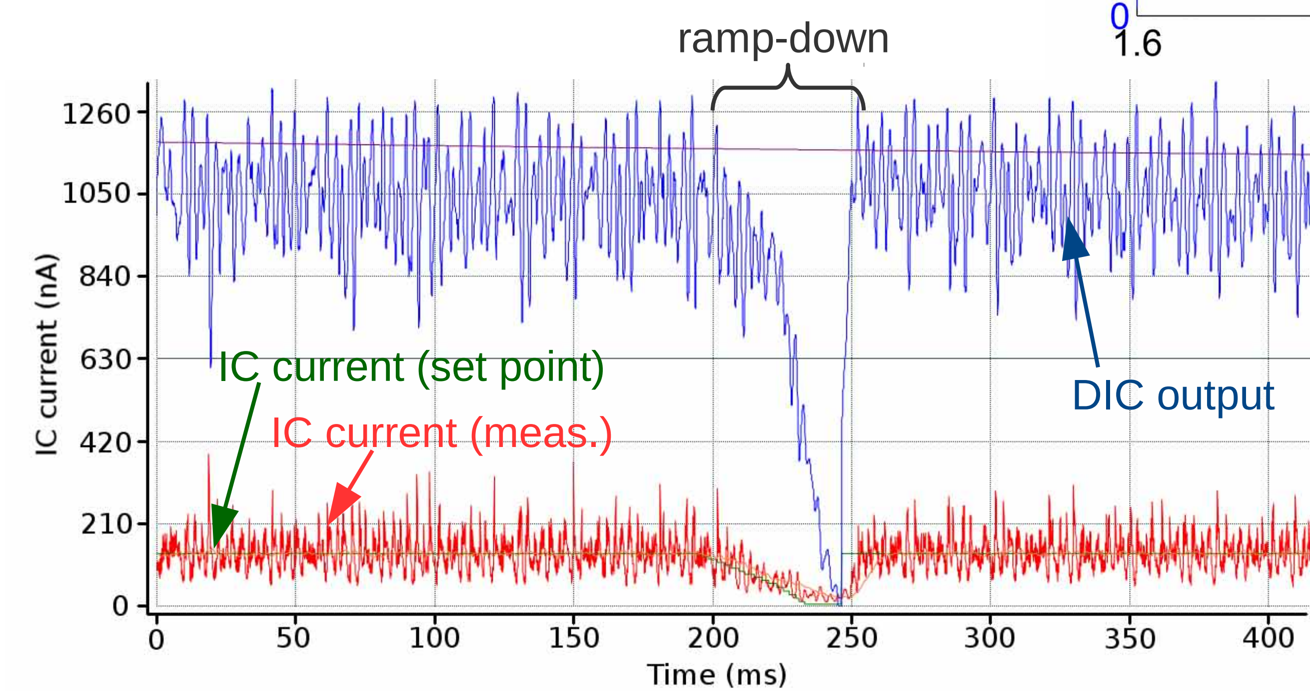
The Marburg system uses DIC-modulation heavily.

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





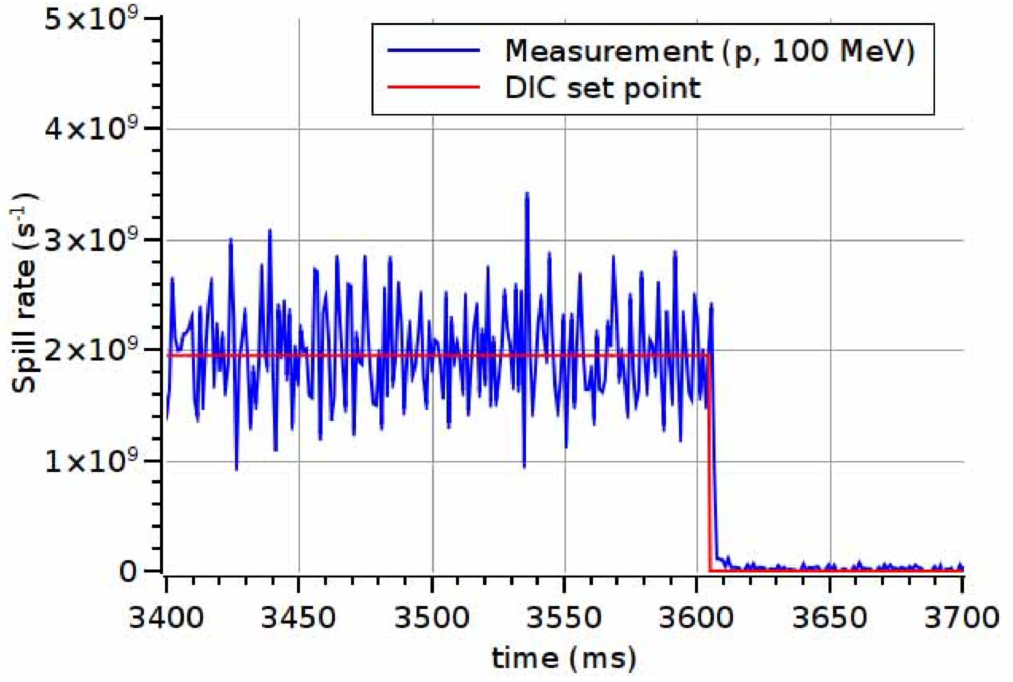
More challenging:

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

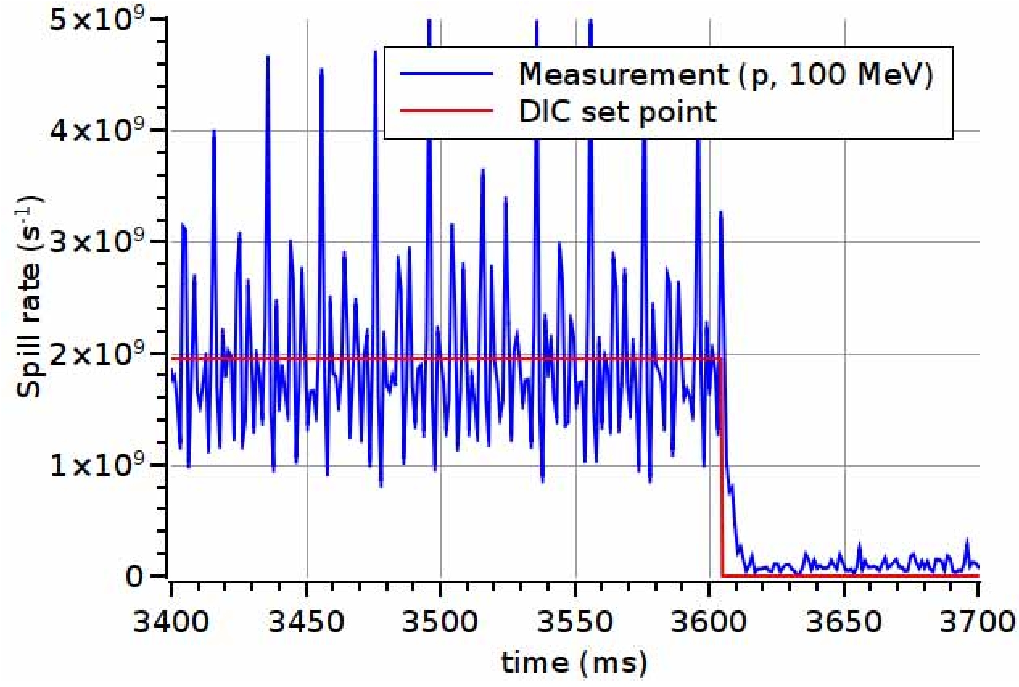
←
Benchmark plan to test ramping-down behaviour of extraction rate.

Macro structure: Optimal response to DIC

Good machine setting



Bad machine setting



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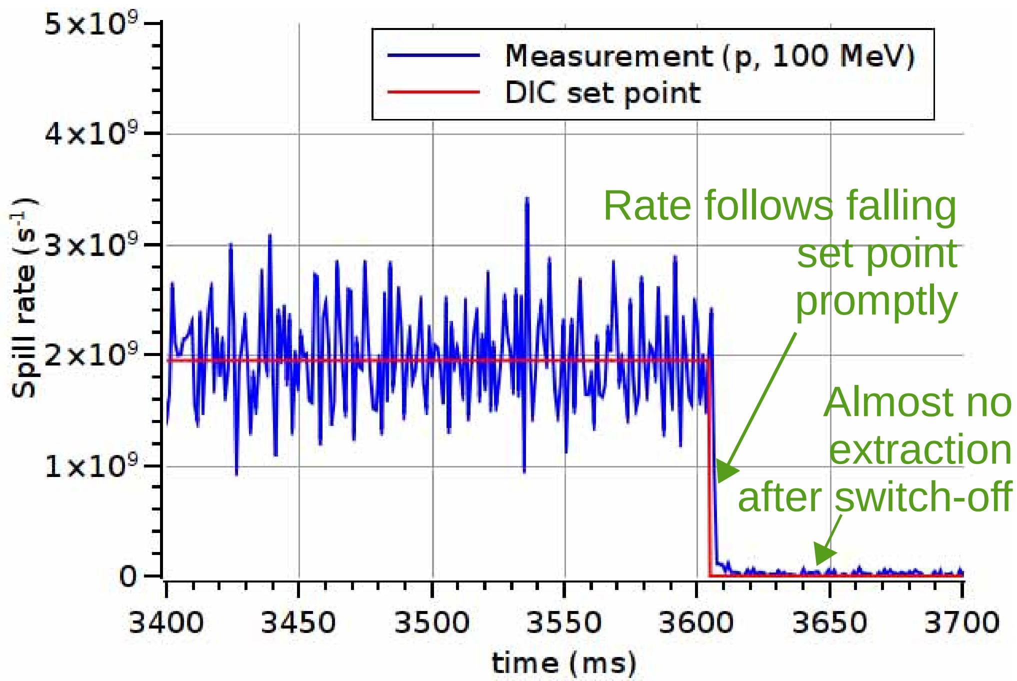
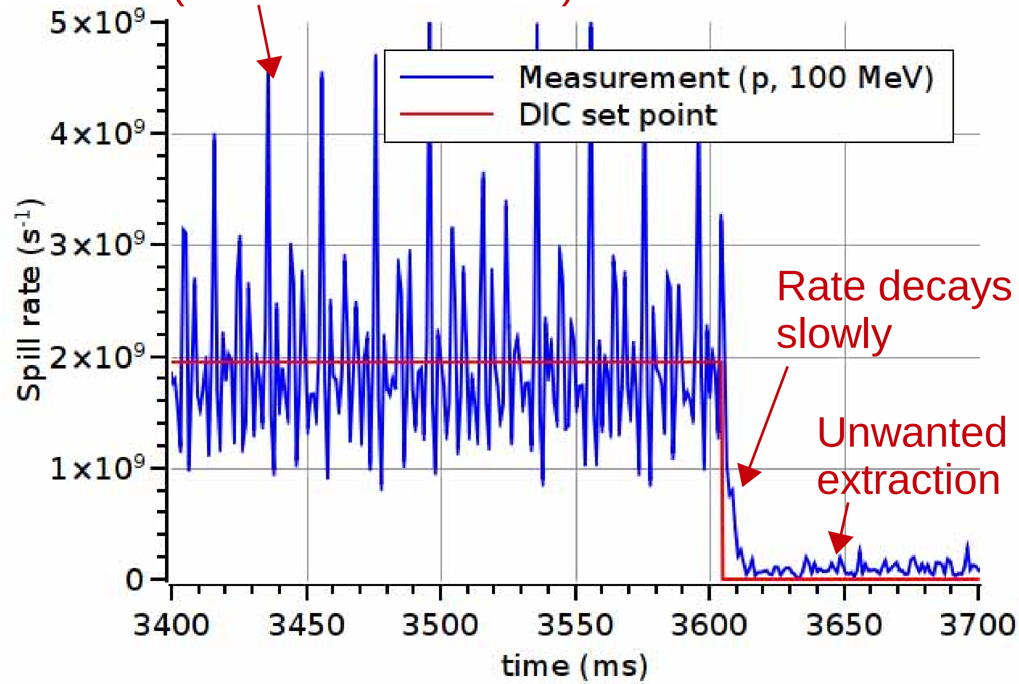
Macro structure: Optimal response to DIC

Good machine setting



Bad machine setting



Only difference between the two measurements:

RF-KO exciter noise spectrum

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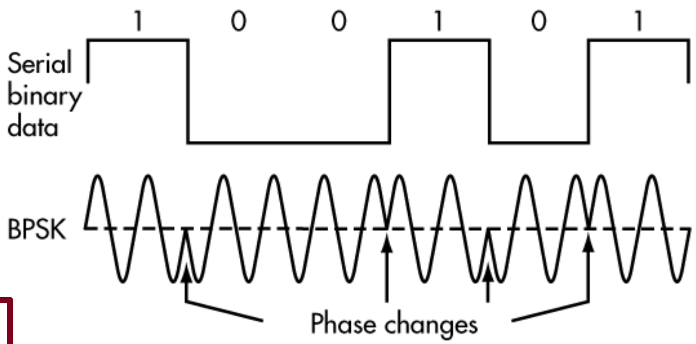
Macro structure: Optimal response to DIC

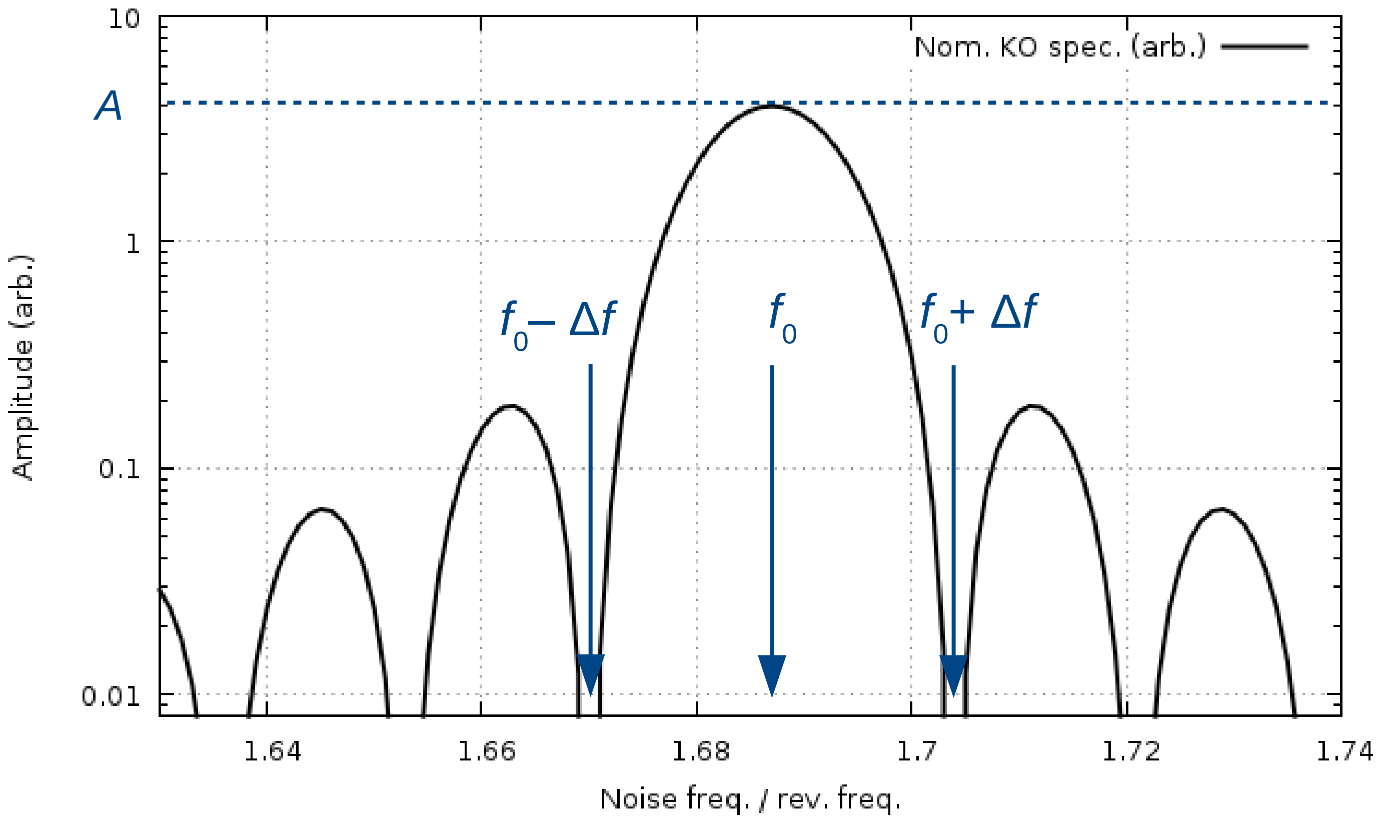
KO exciter noise is generated by **random phase-shift keying** (PSK).

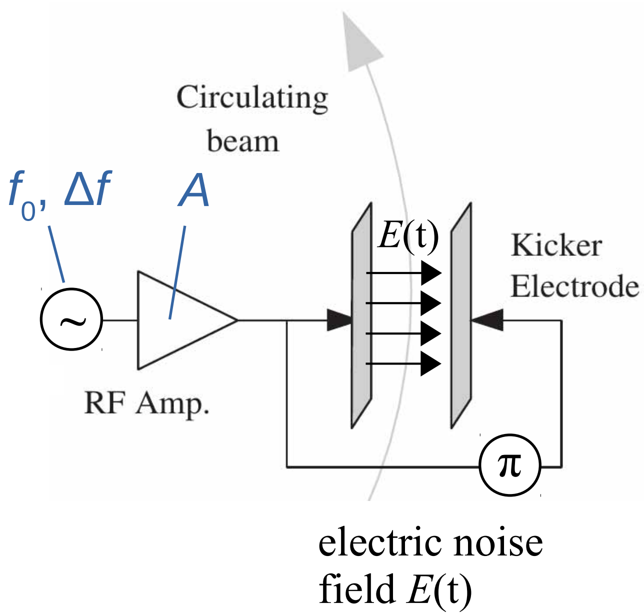
3 parameters define the noise kicker spectrum:

- *A*: Amplitude
- f_0: Main sine frequency
- Δf : Random PSK frequency

Only *A* is controlled dynamically at run-time (via DIC)!







Macro structure: Optimal response to DIC

KO exciter noise is generated by **random phase-shift keying** (PSK).

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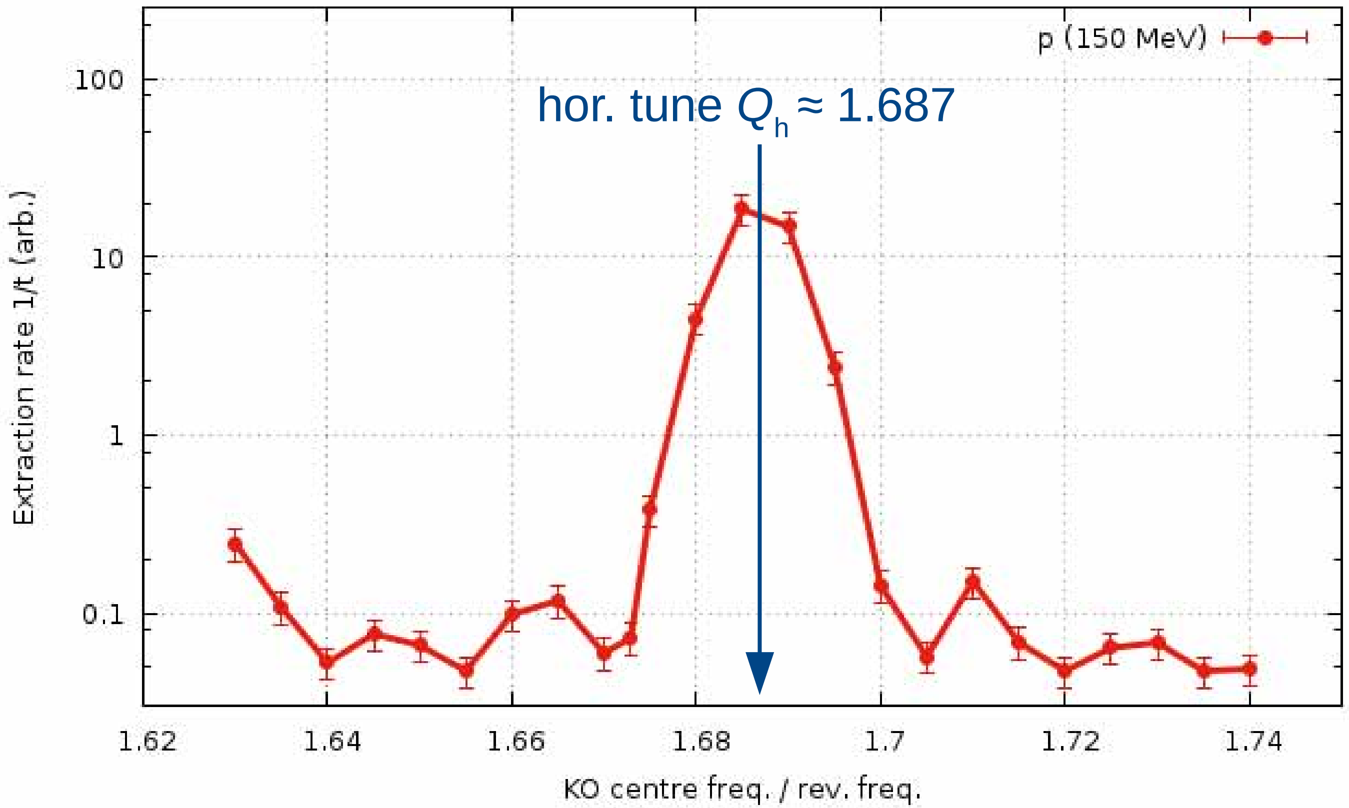


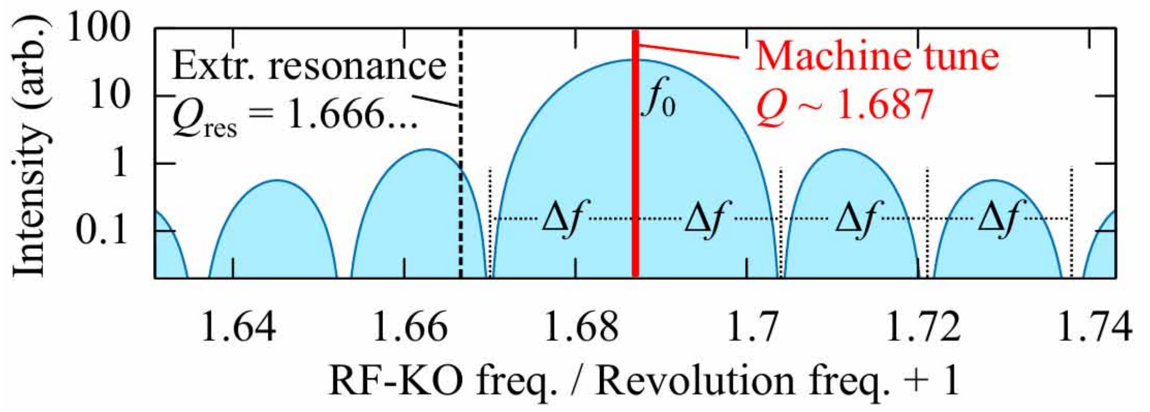
Measure beam loss rate while sweeping f_0 over the betatron frequency:

RF-KO spectrum becomes visible

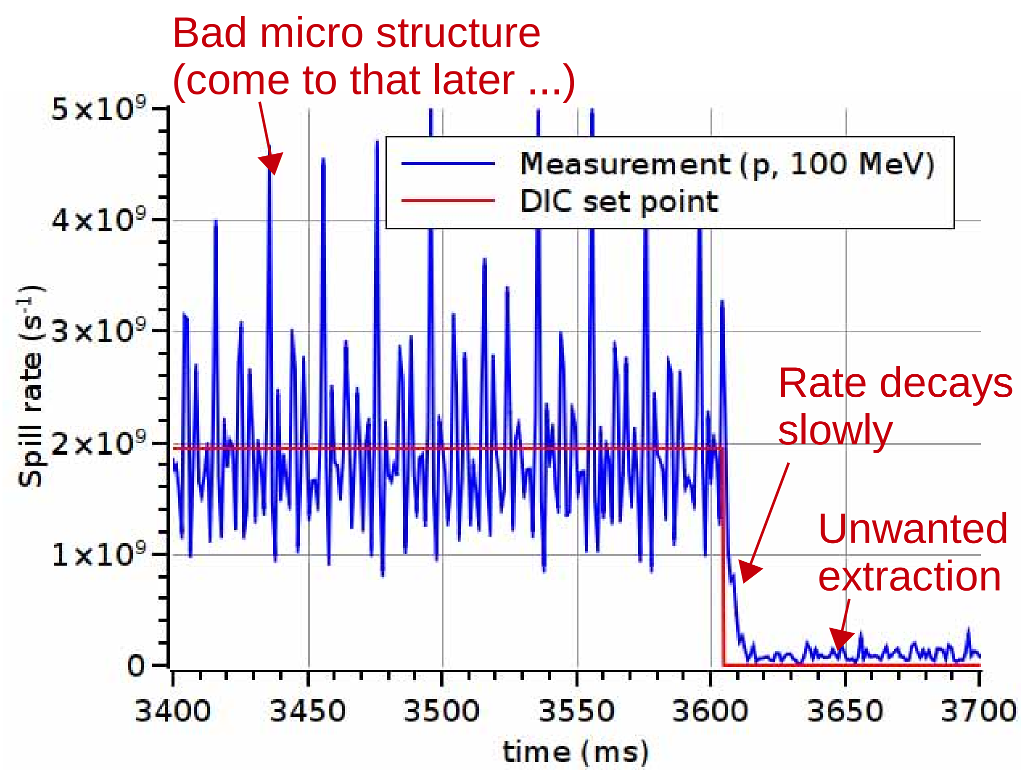
→ Highest extraction rate:

$$f_0 \,/\, f_{rev} = Q_h \ [\,1\,]$$

Macro structure: Optimal response to DIC



Intuitively, one might thus choose to align the KO noise spectrum with the machine tune …



… however, this results in the **“bad”** ramp-down behaviour!

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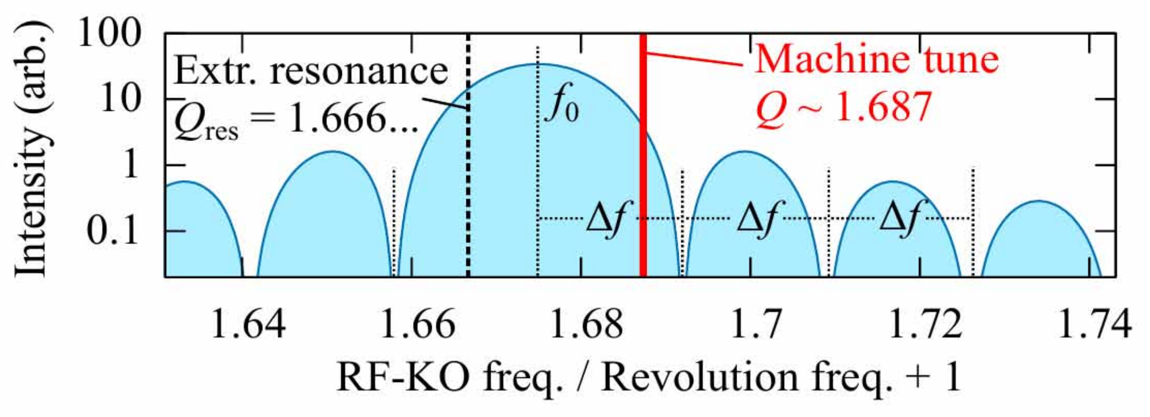
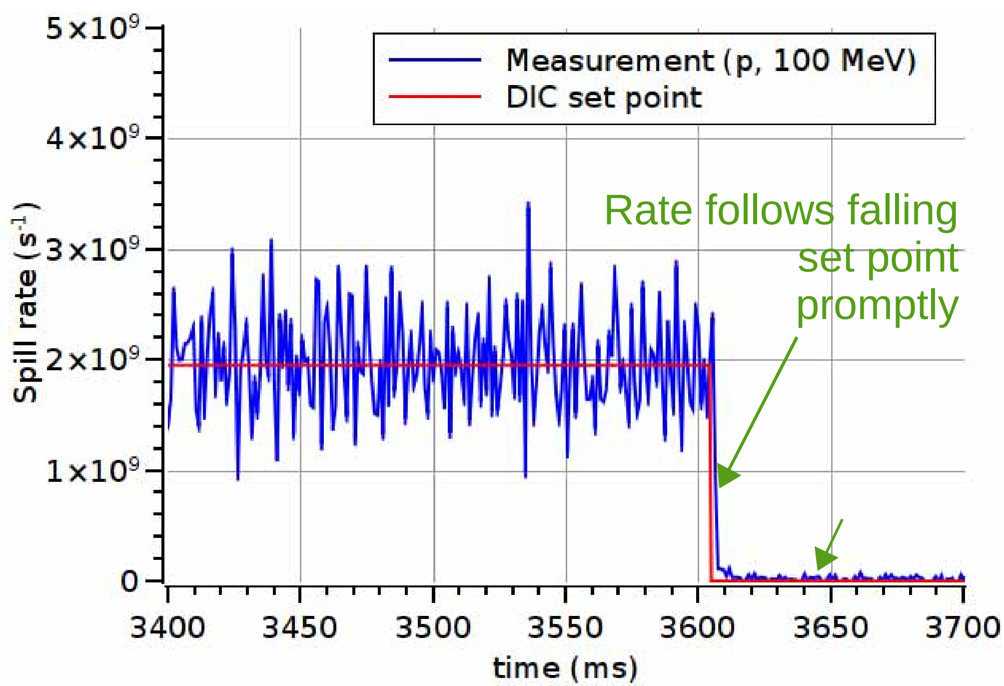
Macro structure: Optimal response to DIC





A much better result is obtained if the spectral maximum is shifted towards the 5/3 resonance.

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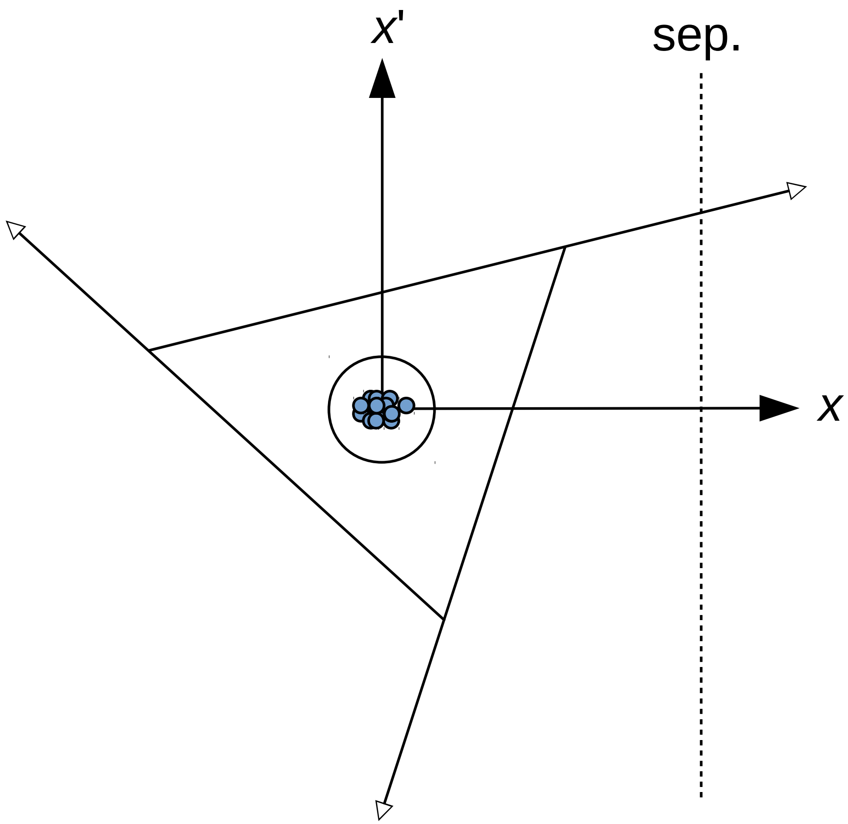
Macro structure: Optimal response to DIC

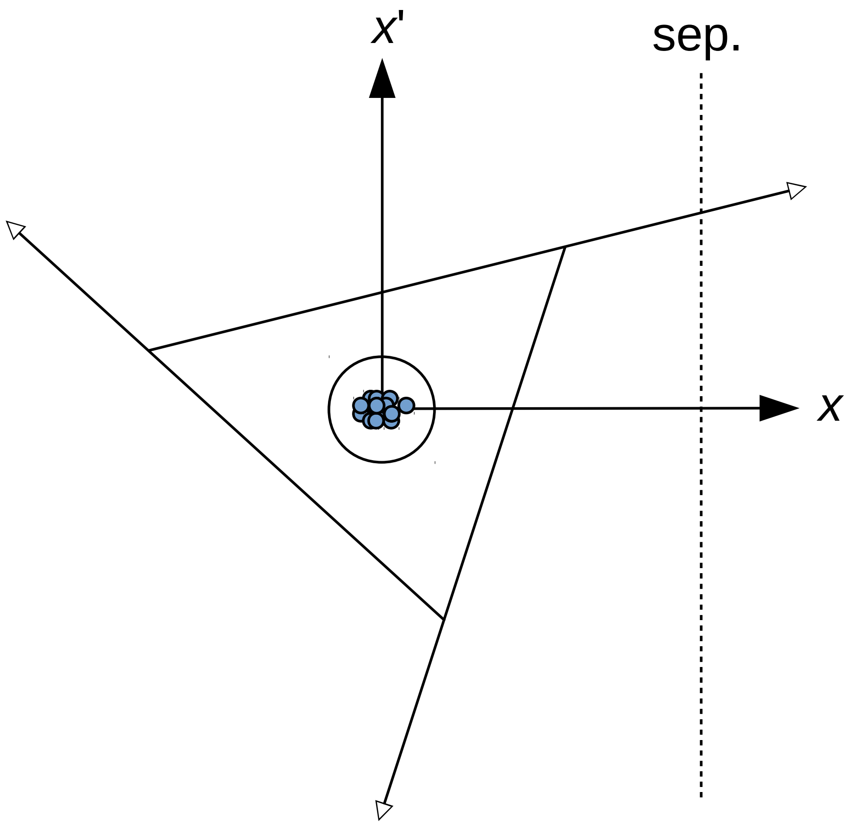


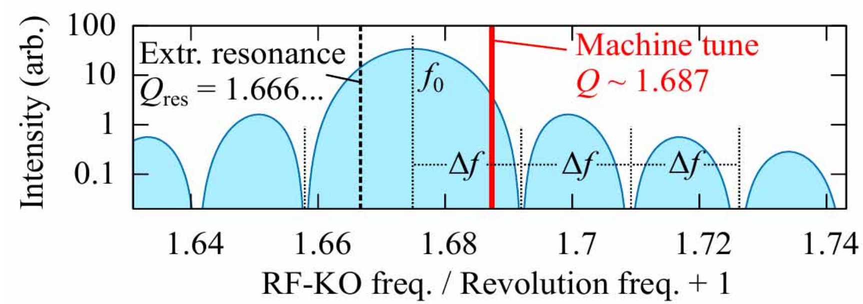
Explanation?

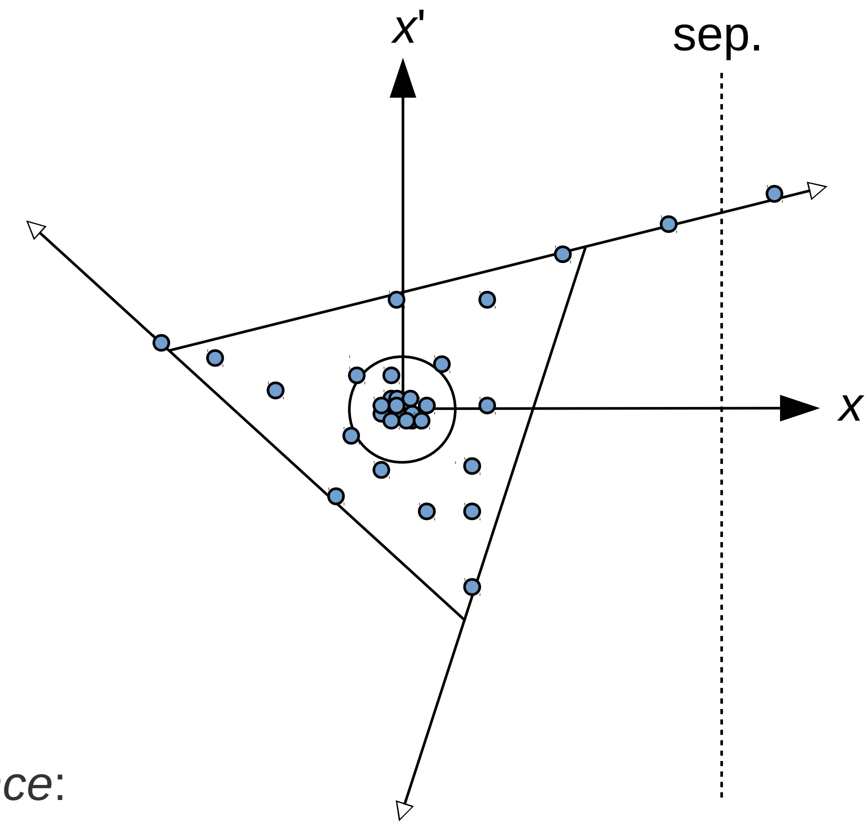
Before RF-KO:

Low-emittance ion beam

Macro structure: Optimal response to DIC



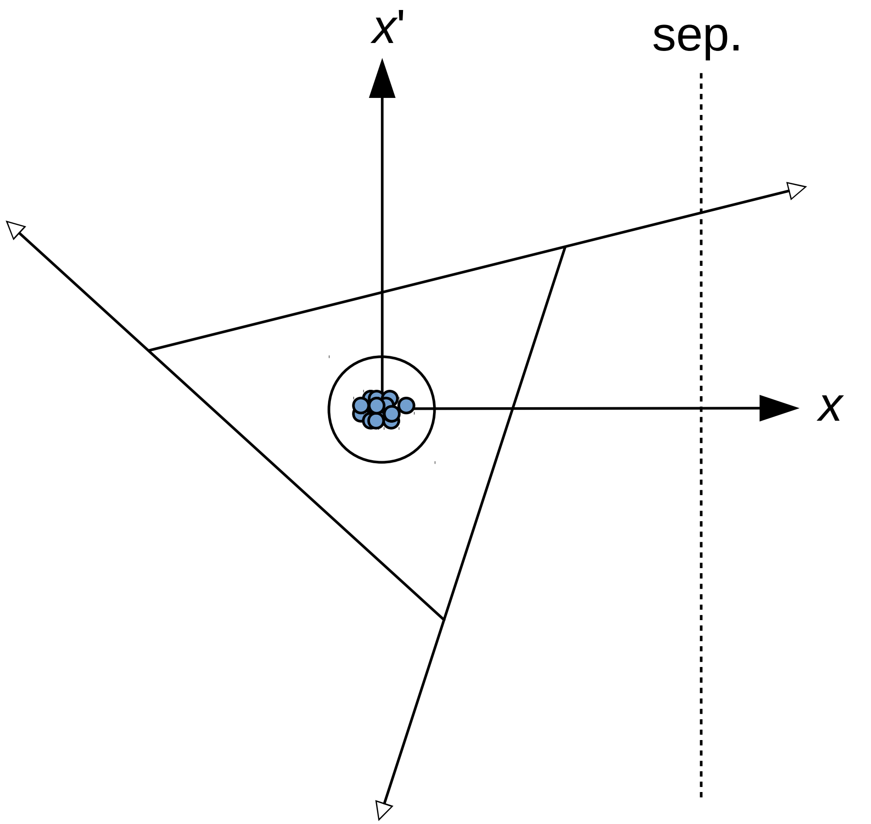


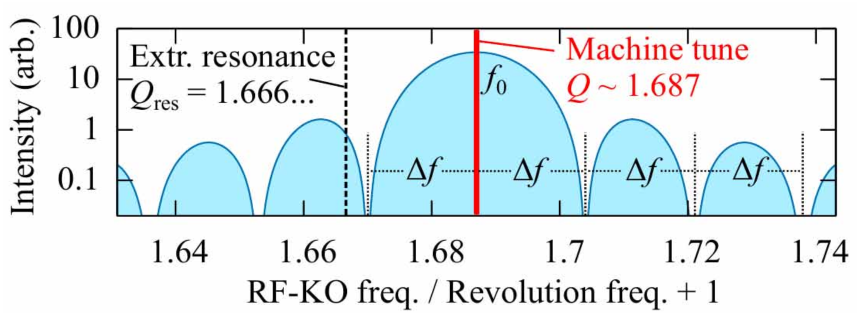


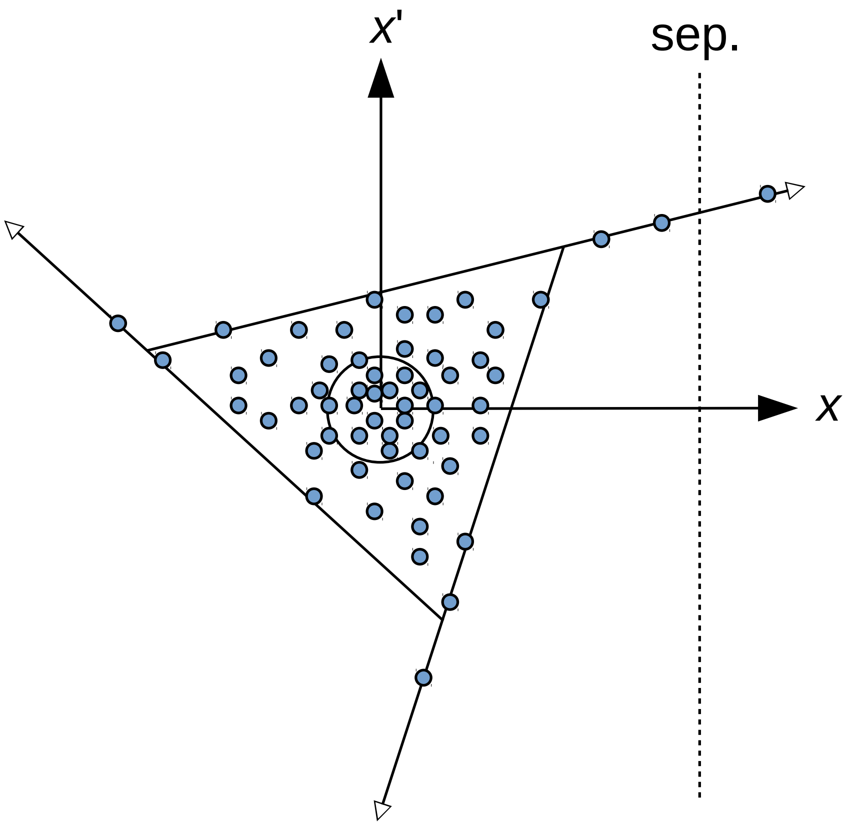
Noise spectrum detuned towards *extraction resonance*:

→ RF-KO excites large amplitudes preferentially.

Macro structure: Optimal response to DIC



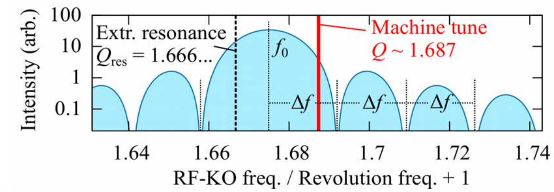




Noise spectrum centred on *machine tune*:

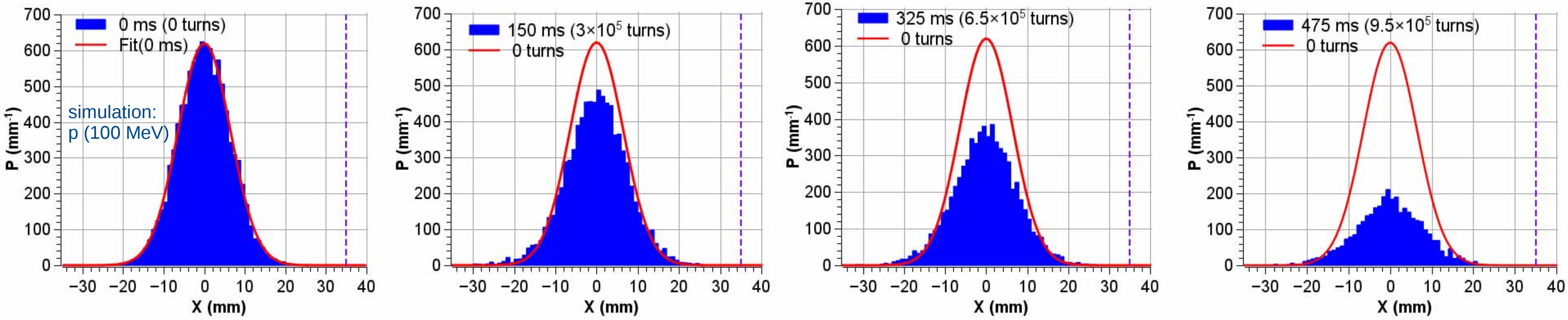
→ RF-KO excites low amplitudes preferentially.

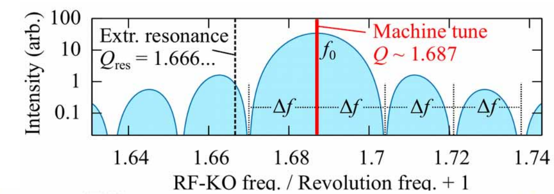
Macro structure: Optimal response to DIC



Tracking simulation 1: KO centre freq. detuned – **"Good"** setting

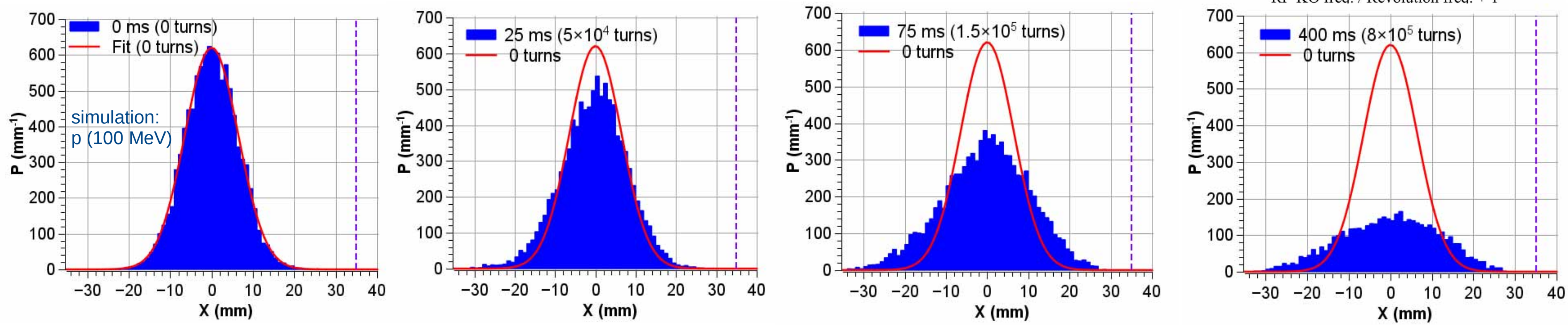
Particles in halo are rapidly extracted, beam core "keeps shape".





Tracking simulation 2: KO centre freq. = machine tune – **"Bad"** setting

Beam core is excited preferentially, large unstable halo.



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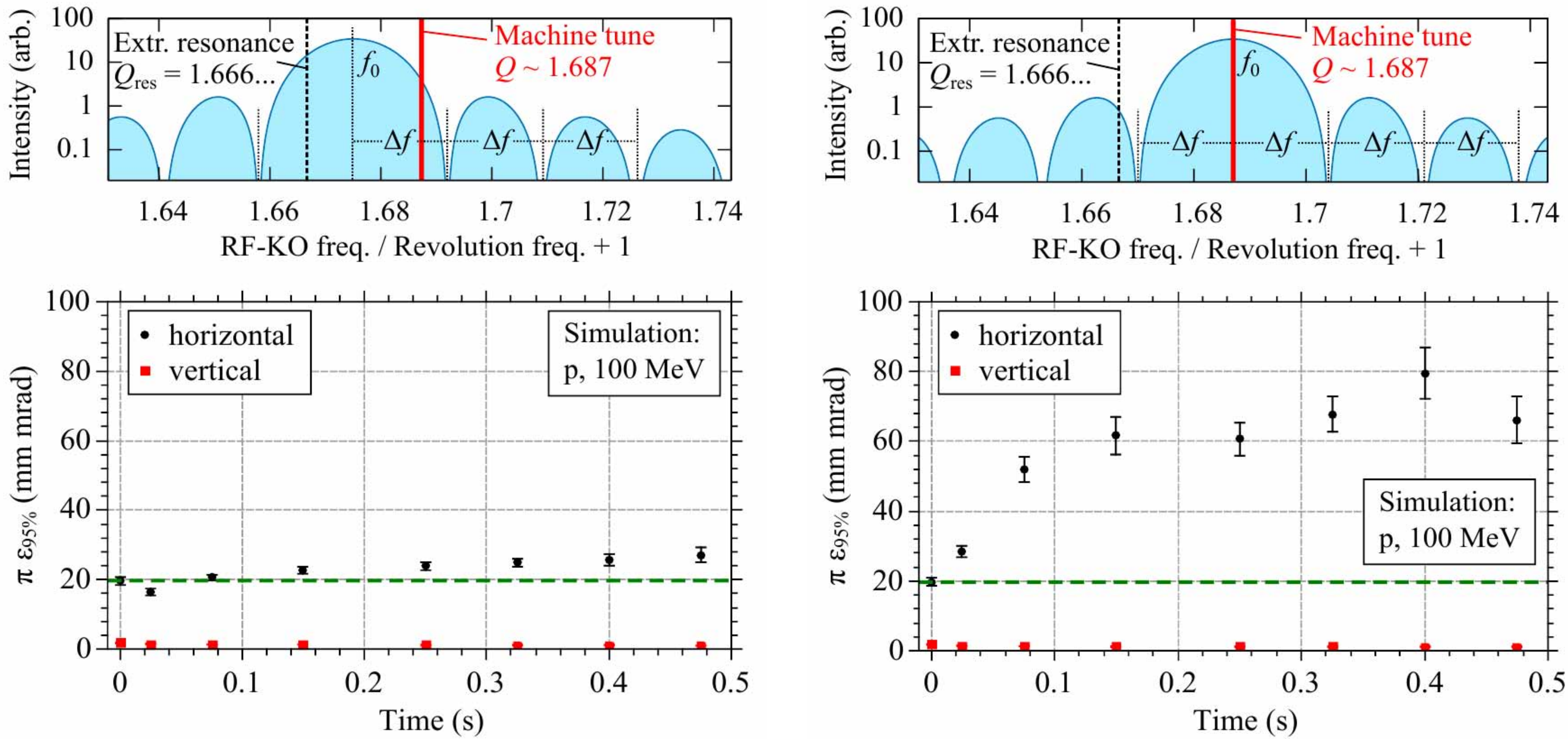
Macro structure: Optimal response to DIC

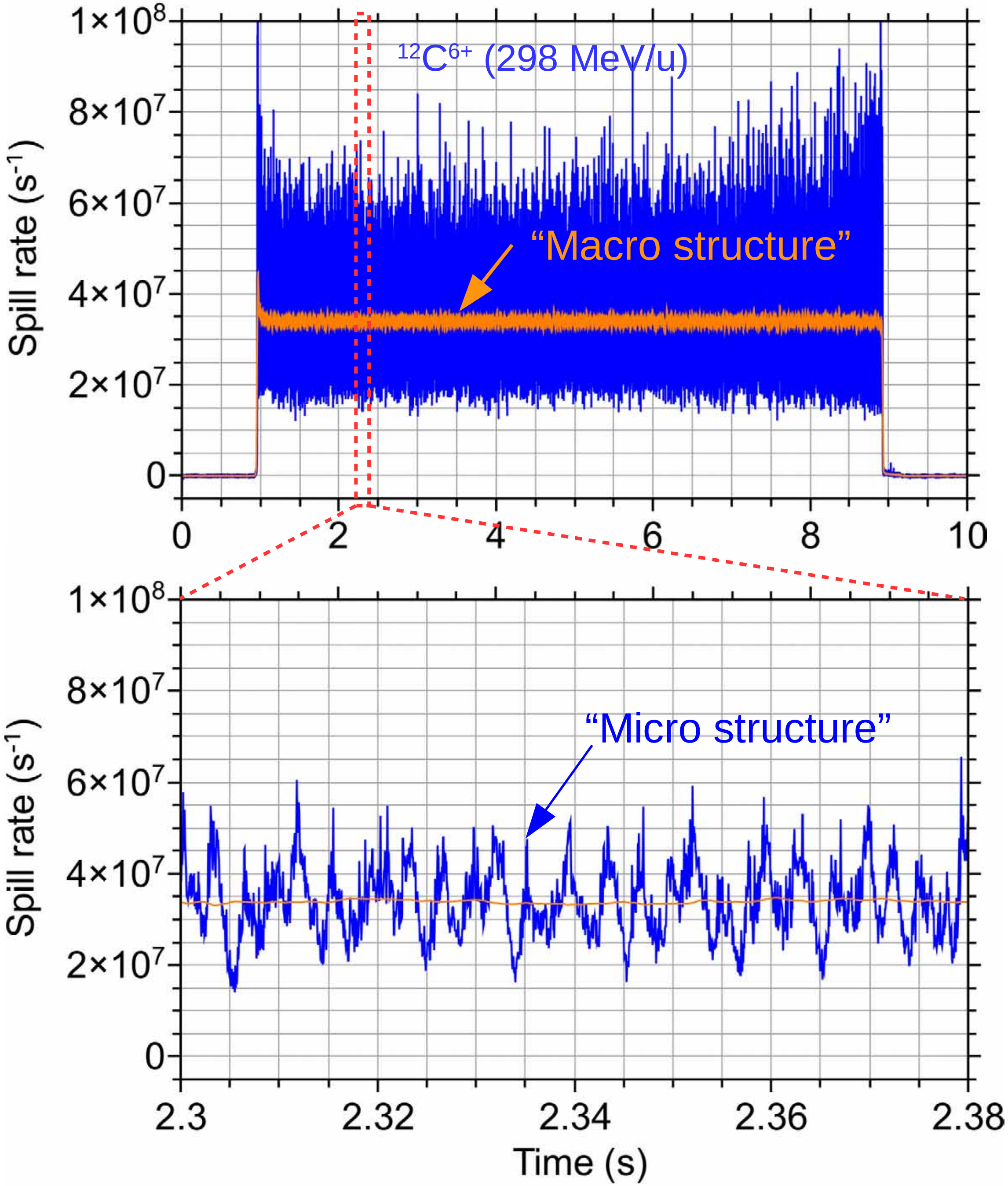
Noise centre freq. “detuned”
→ Sim. shows weak horizontal emittance growth.

Noise centre freq. = machine tune
→ Strong horizontal emittance growth.



Krantz, Proc. of IPAC 2018, pp. 1084

Micro structure



DIC combined with RF-KO extraction

→ provides very good **"macro structure"**

(time scales down to ~ 10 ms),

→ cannot change much about the spill **"micro structure"**

(kHz ... MHz components).

Note:
At therapy accelerators, the time resolution of IC detectors blurs structures below ~ 100 µs!

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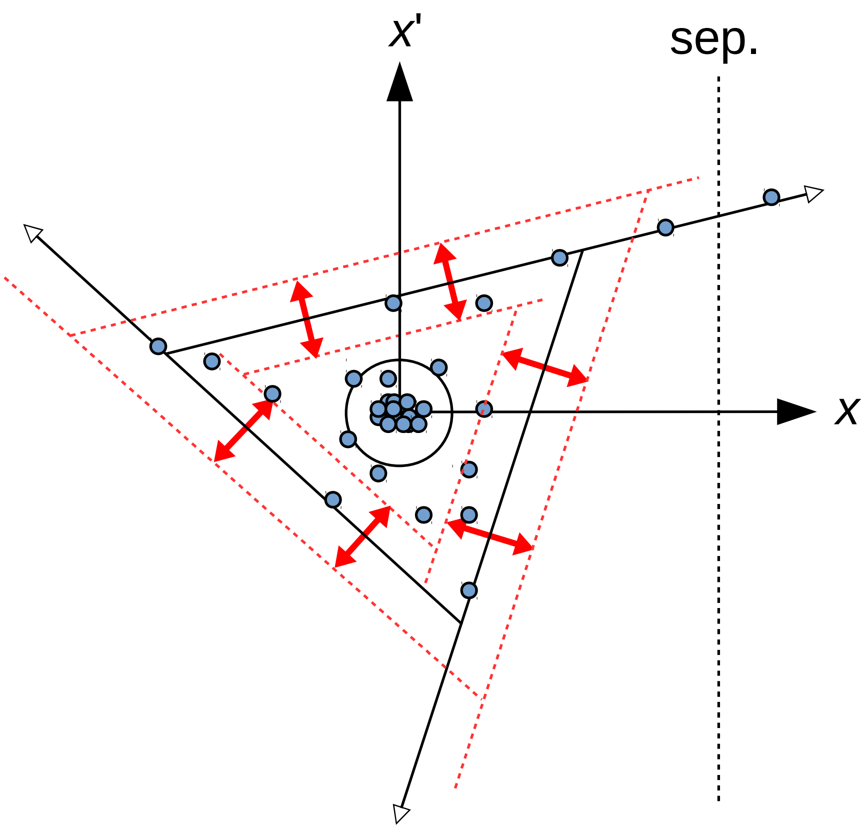
Micro structure

Major source of spill micro structure:
Power supply ripple

→ Machine tune ripple

→ “Pulsing” of separatrix



Example: Sensitivity of SPS spill to power supply ripples
[Prieto et al., Proc. of IPAC 2018]

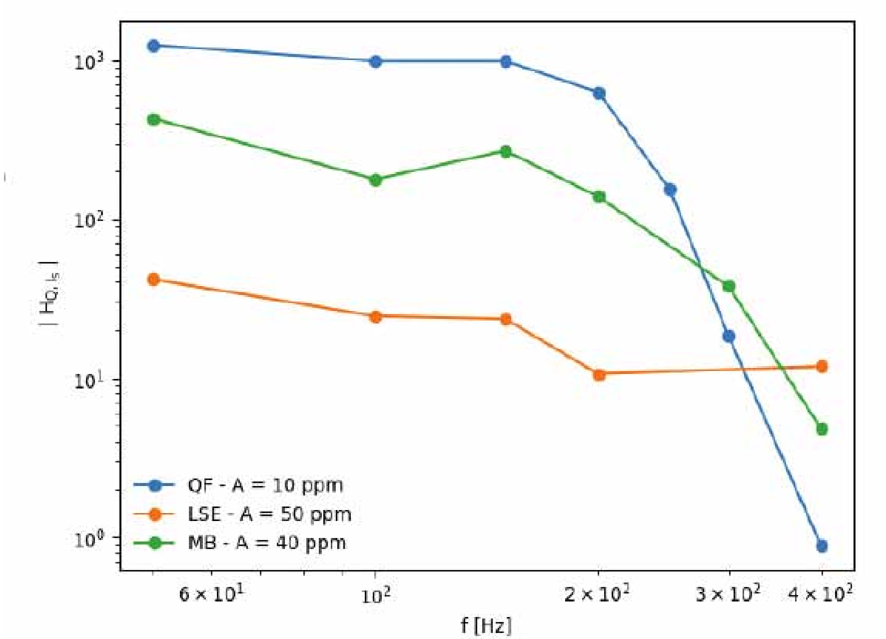


Figure 3: Transfer function for focusing quadrupoles (blue), extraction sextupoles (orange) and main bends (green).

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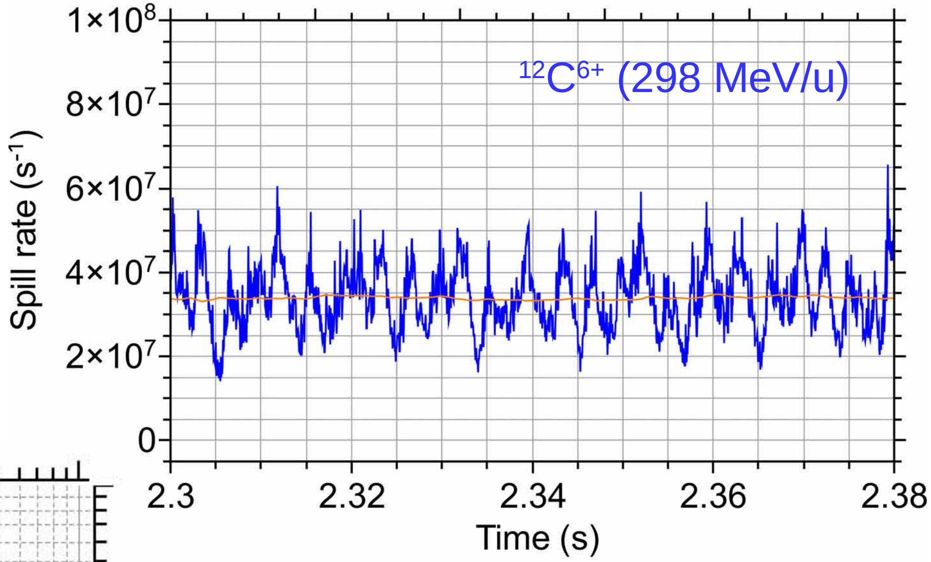
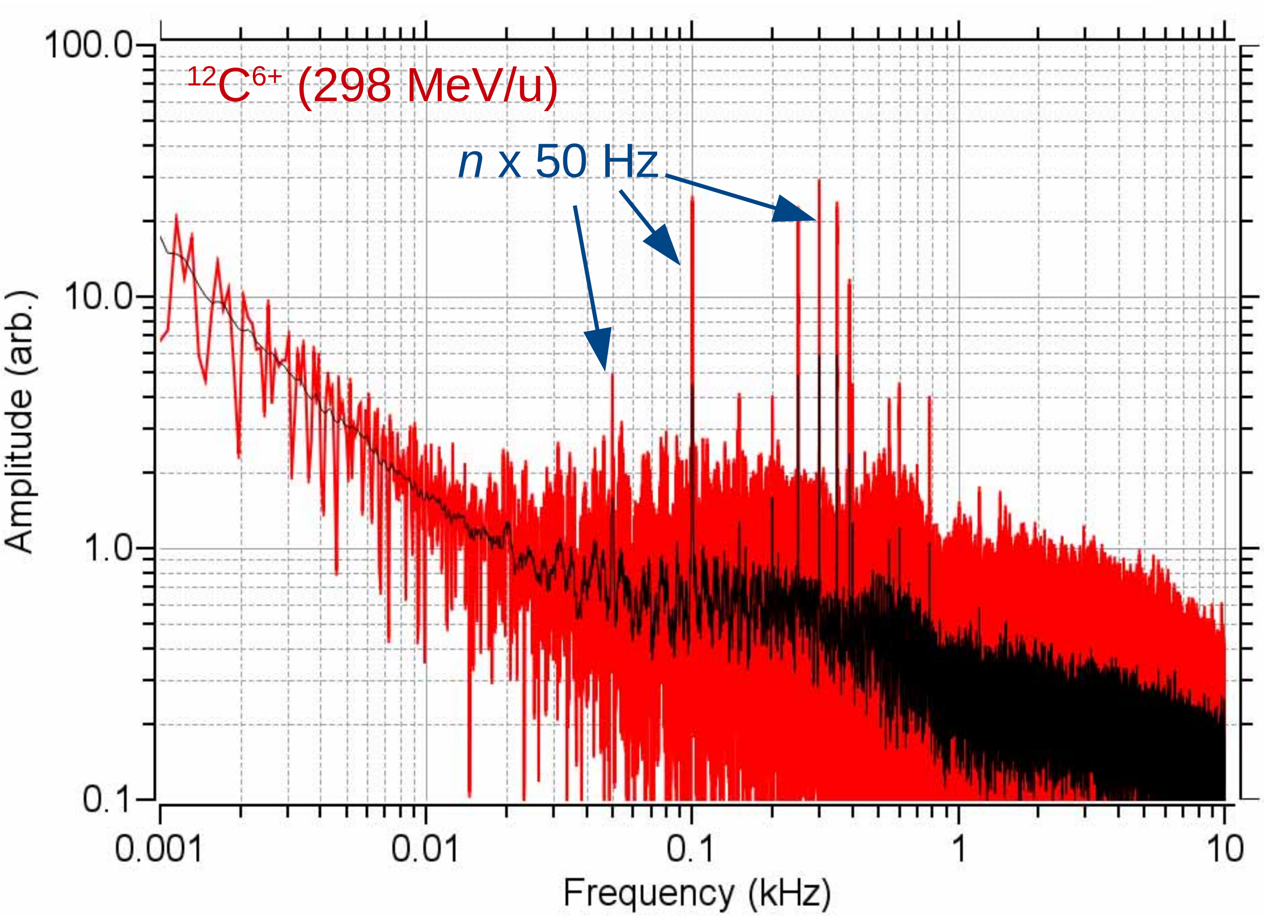
Micro structure



FFT



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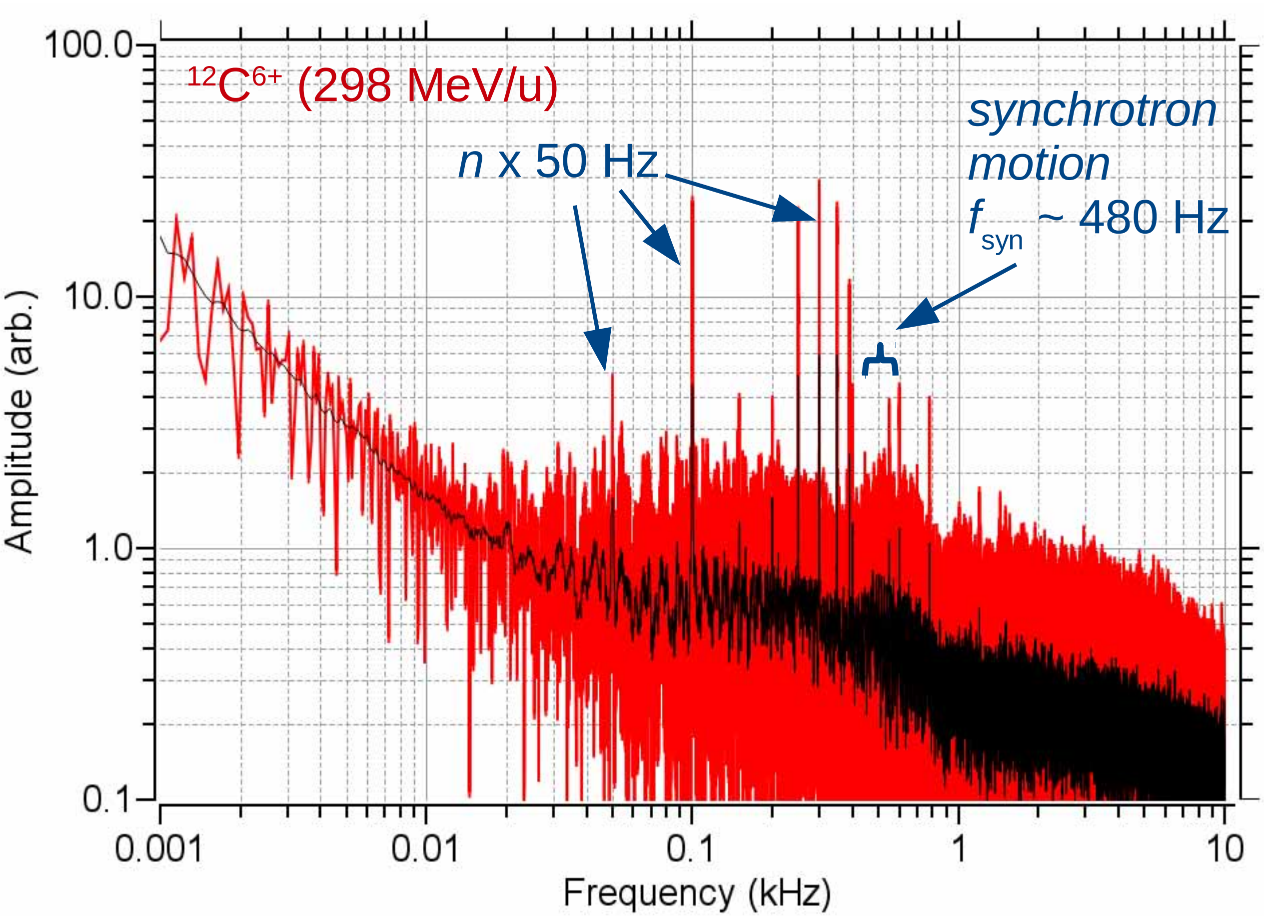
Micro structure



The MIT synchrotron uses extraction from bunched beam.

Adopted from previous GSI and HIT experiments:

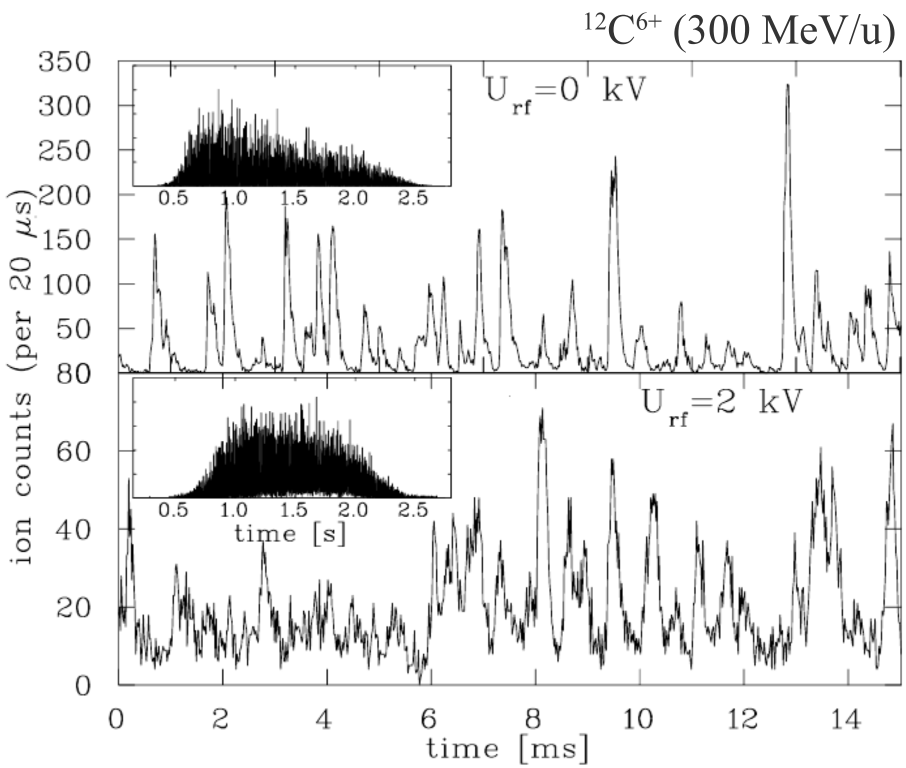
→ Better > kHz-scale microstructure.
[Forck et al., Proc. of EPAC 2000]

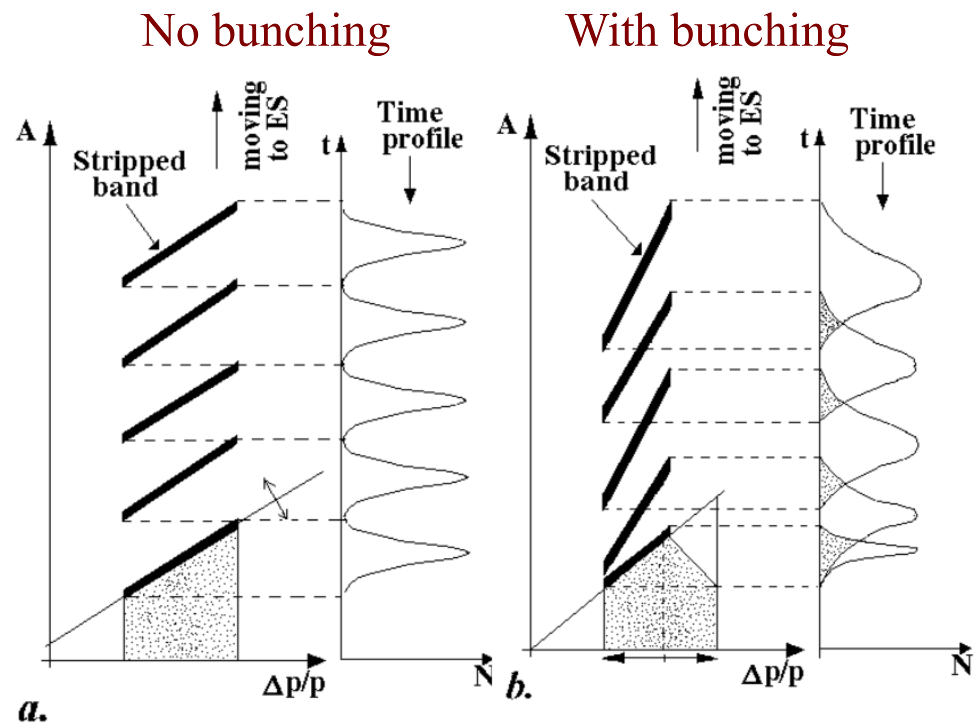
Marburger Ionenstrahl-Therapiezentrum

Micro structure: Effect of synchrotron motion

Original observation at SIS18:

Bunching during slow extraction smooths the spill on the > kHz time scale.





a) An ensemble of particles that has been destabilised by a separatrix ripple moves towards the septum coherently.

b) Sync. oscillation changes the individual particles tune after destabilisation, leading to broadening of the packet.

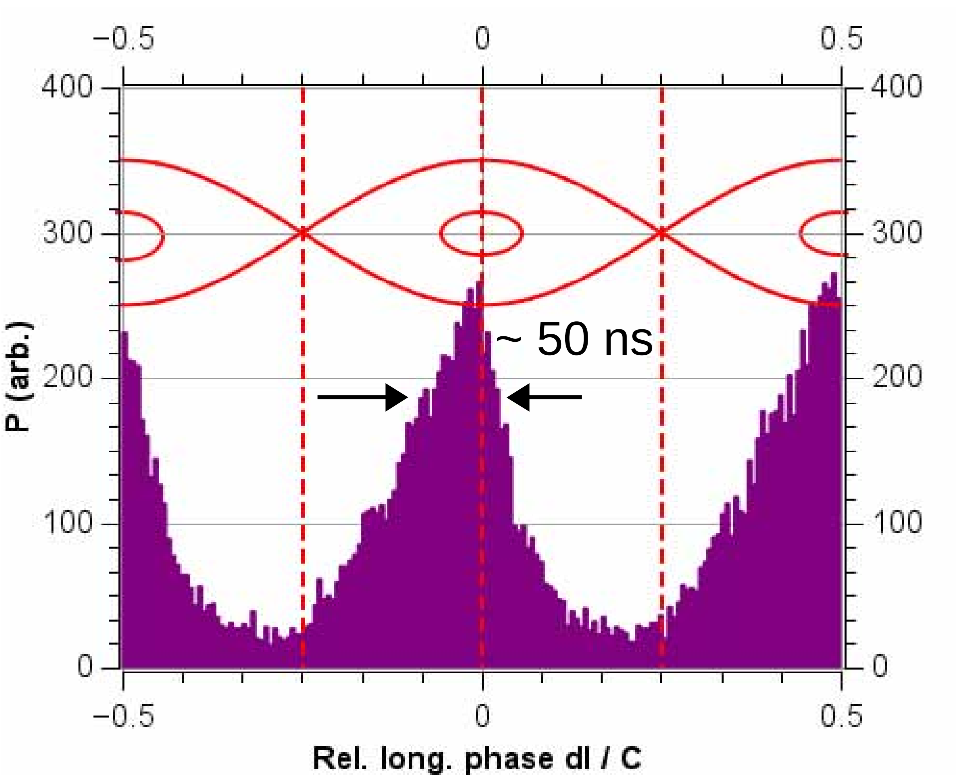
Forck et al., Proc. of EPAC 2000

Marburger Ionenstrahl-Therapiezentrum

Micro structure: Effect of synchrotron motion

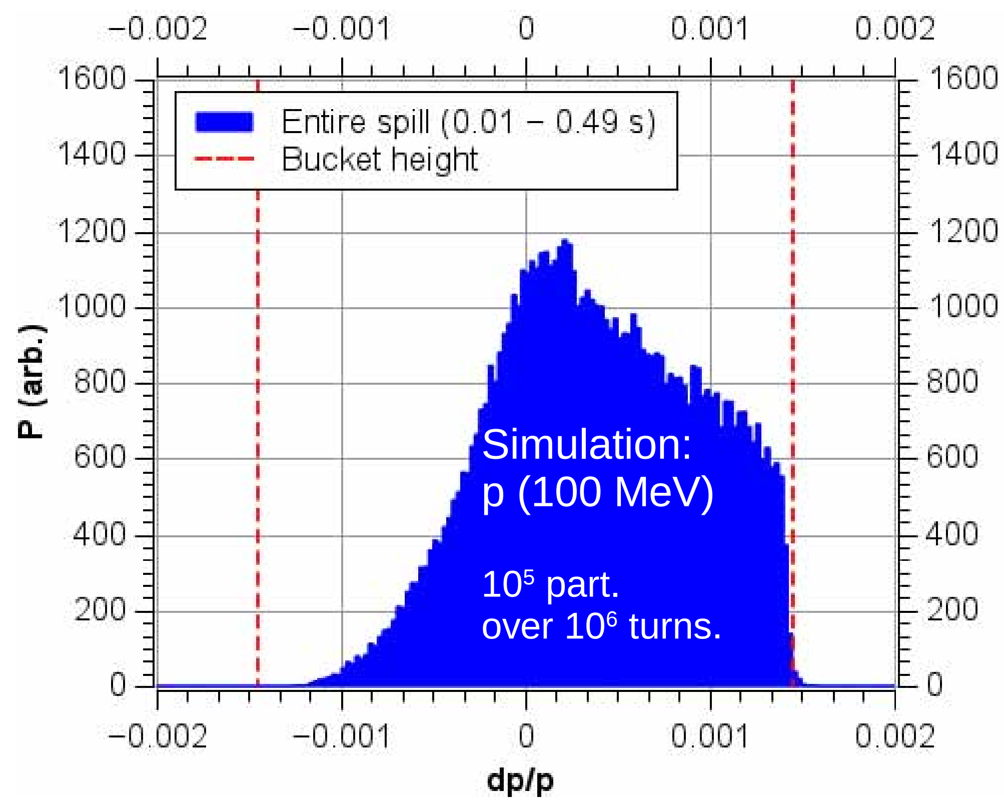
Tracking simulation (MIT)

Longitudinal phase of extracted particles relative to bunching rf:



→ Very sharp micro-bunching of extracted beam
(invisible in therapy application)

Momentum deviation of extracted particles:



At MIT: $Q_h \sim 1.7$, $Q_{extr} = 1.666\ldots$

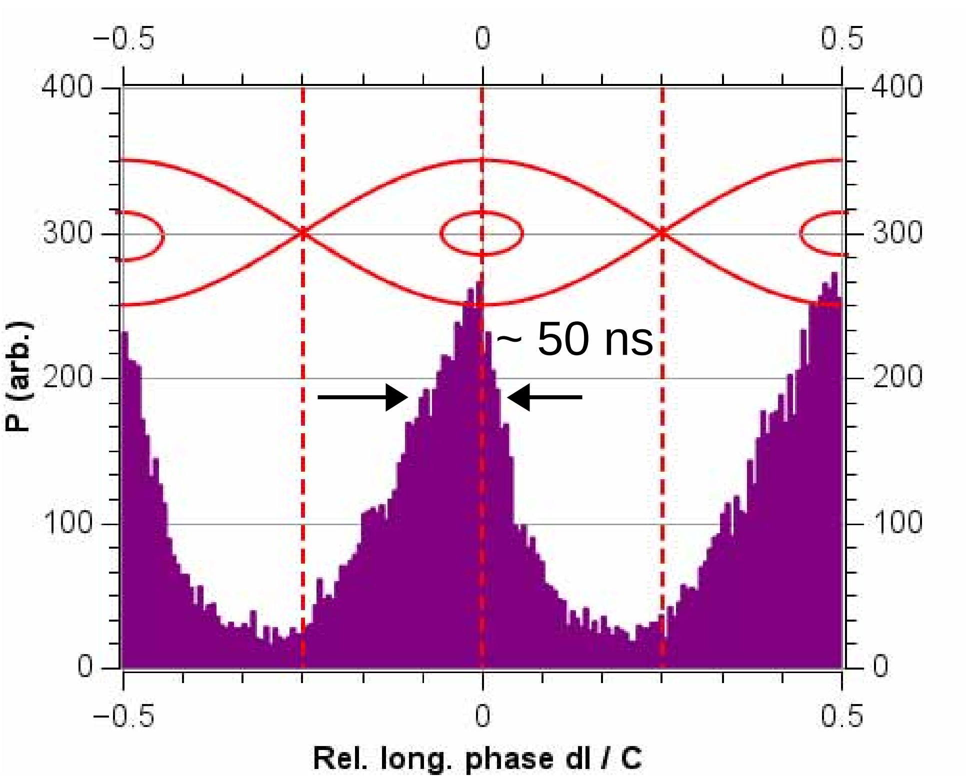
→ We need dQ < 0 to get close to resonance.
→ Due to chromaticity (ξ ~ –1): dp/p > 0 is preferred.

Marburger Ionenstrahl-Therapiezentrum

Micro structure: Effect of synchrotron motion

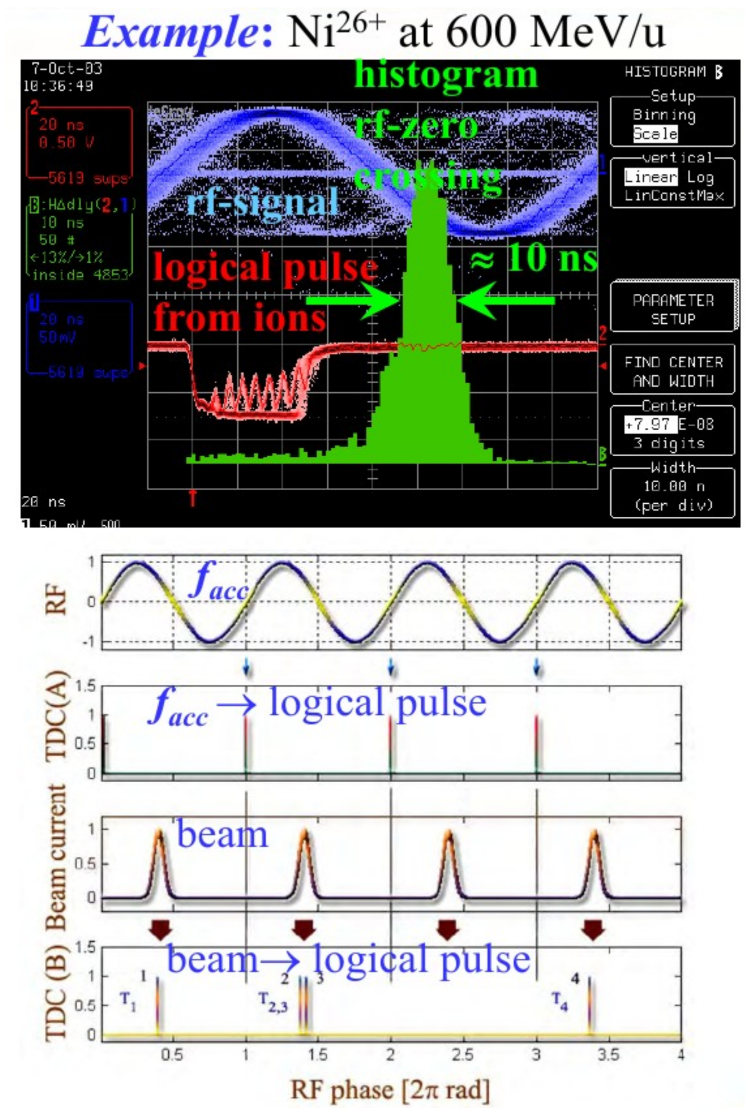
Tracking simulation (MIT)

Longitudinal phase of extracted particles relative to bunching rf:



→ Very sharp micro-bunching of extracted beam
(invisible in therapy application)

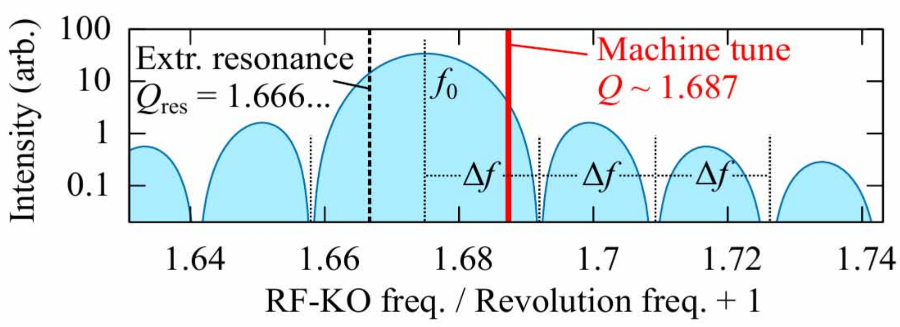
Measurement at SIS18 (Forck et al.):

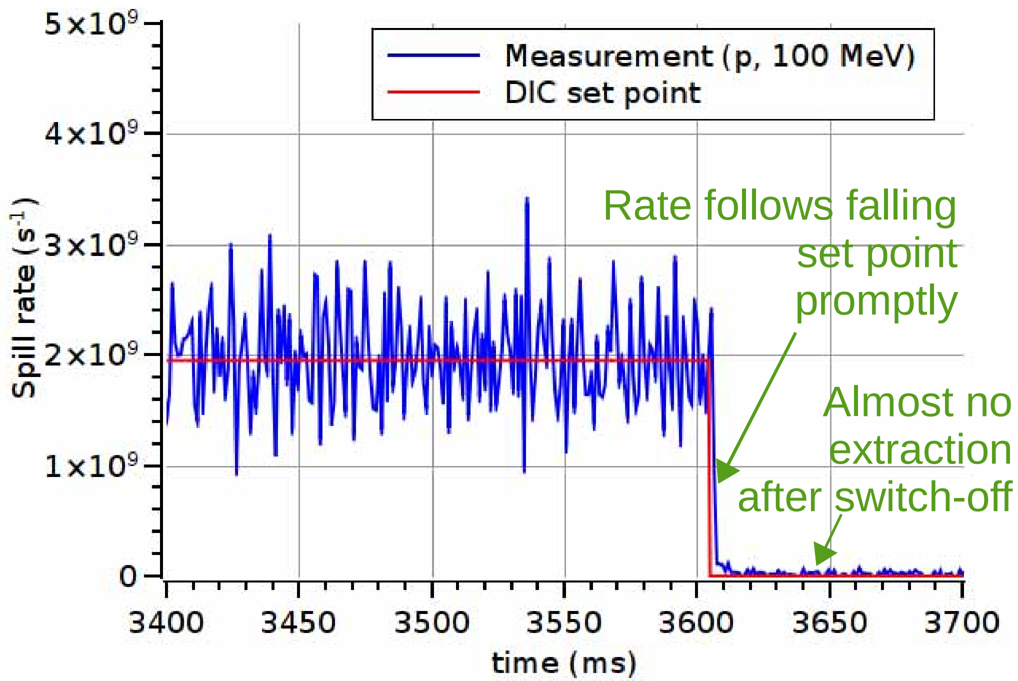


(Courtesy of P. Forck)

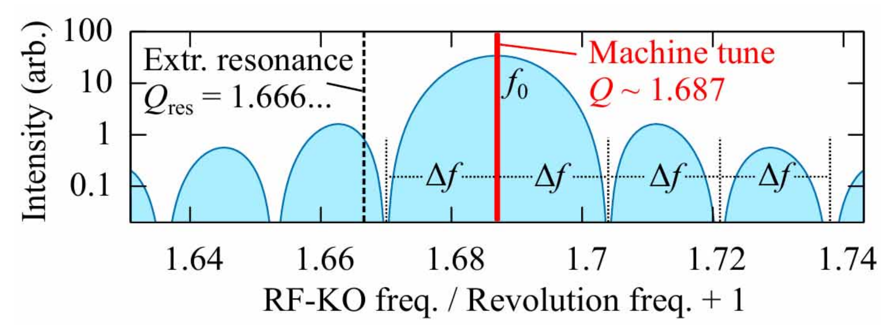
Micro structure: Effect of RF-KO spectrum

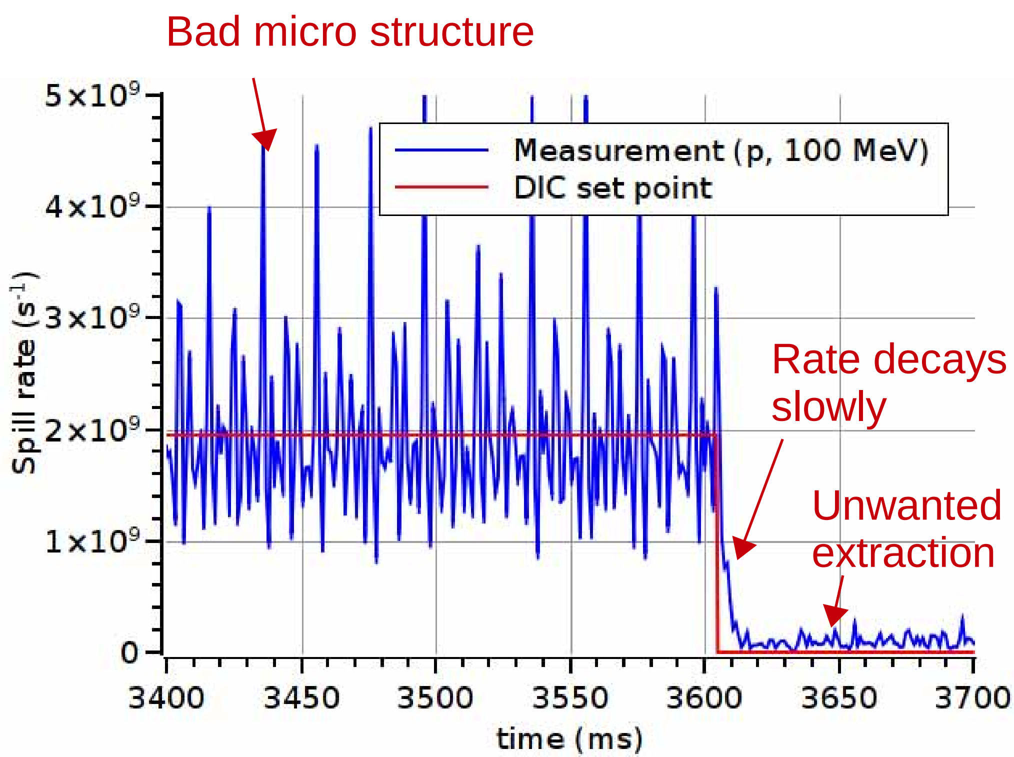
Good machine setting





Bad machine setting

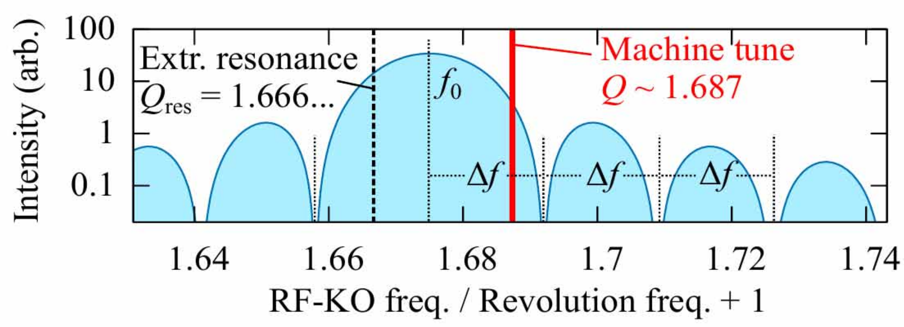




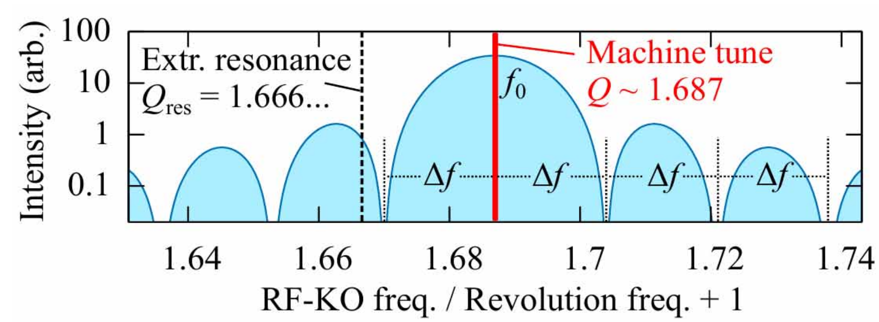
MIT Marburger Ionenstrahl-Therapiezentrum

Micro structure: Effect of RF-KO spectrum

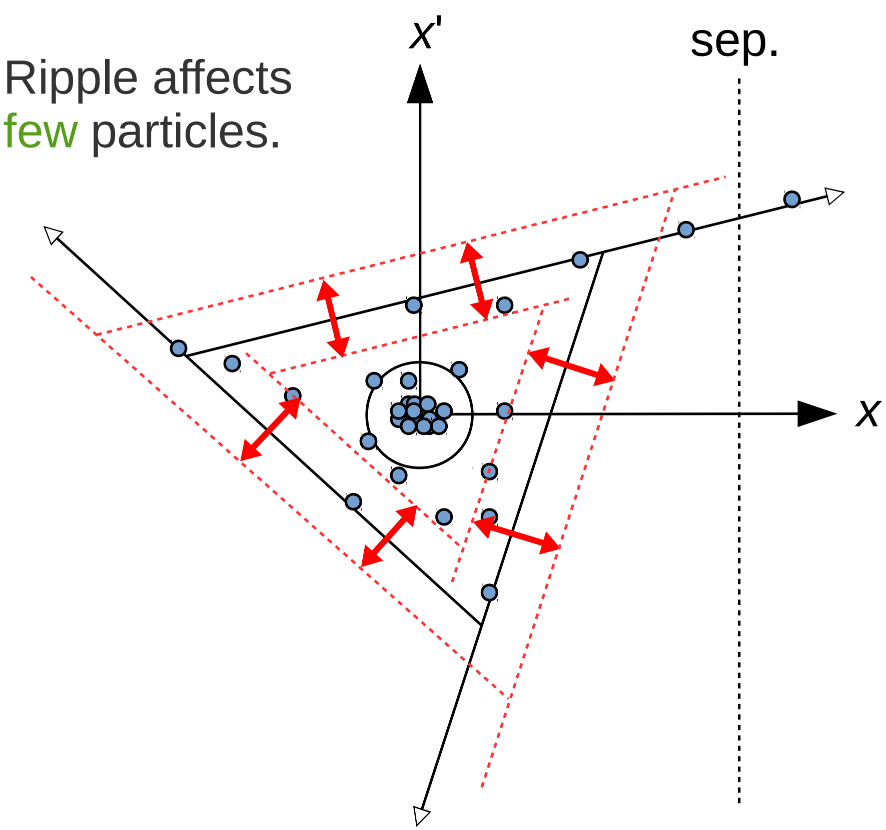
Good machine setting



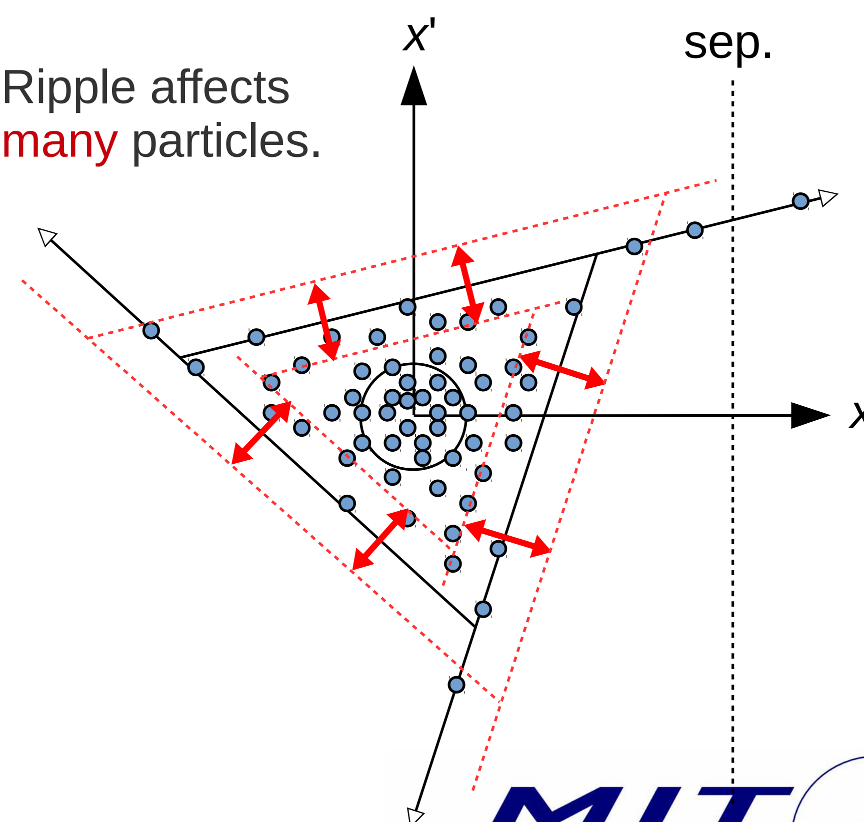
Bad machine setting



Ripple affects few particles.



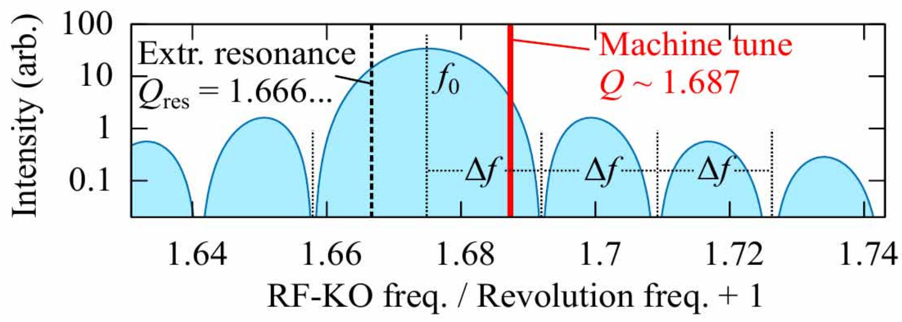
Ripple affects many particles.



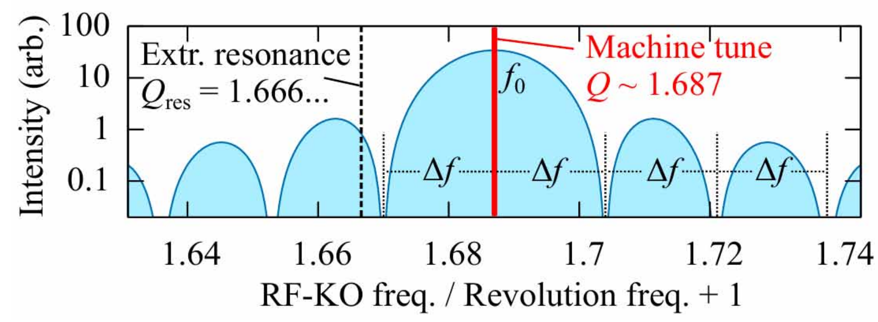
MIT Marburger Ionenstrahl-Therapiezentrum

Micro structure: Effect of RF-KO spectrum

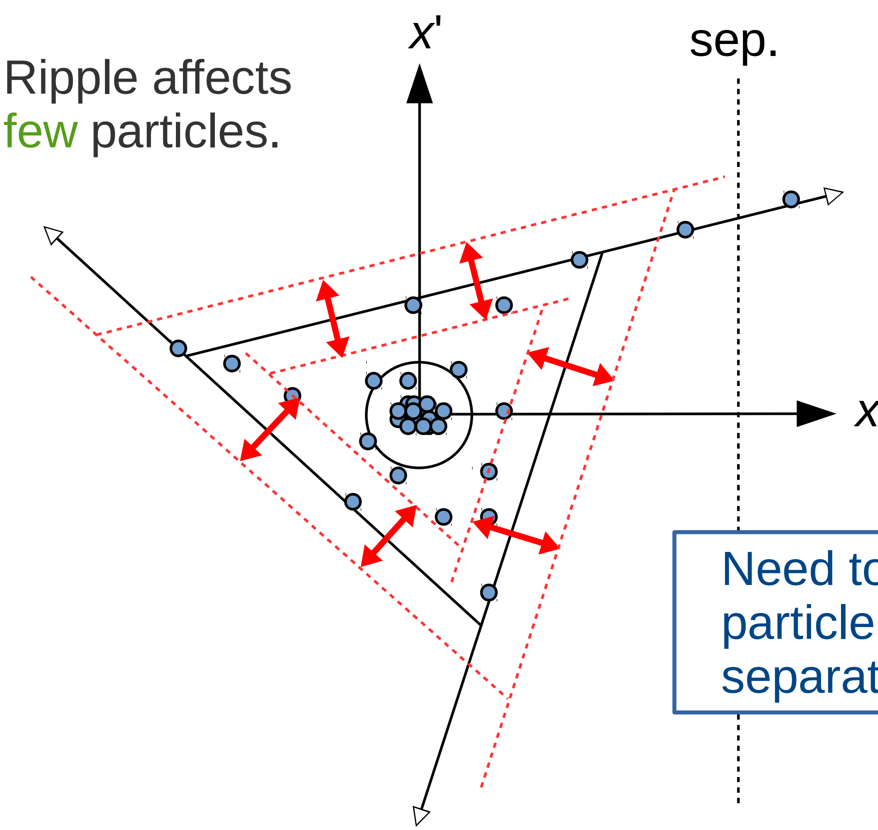
Good machine setting



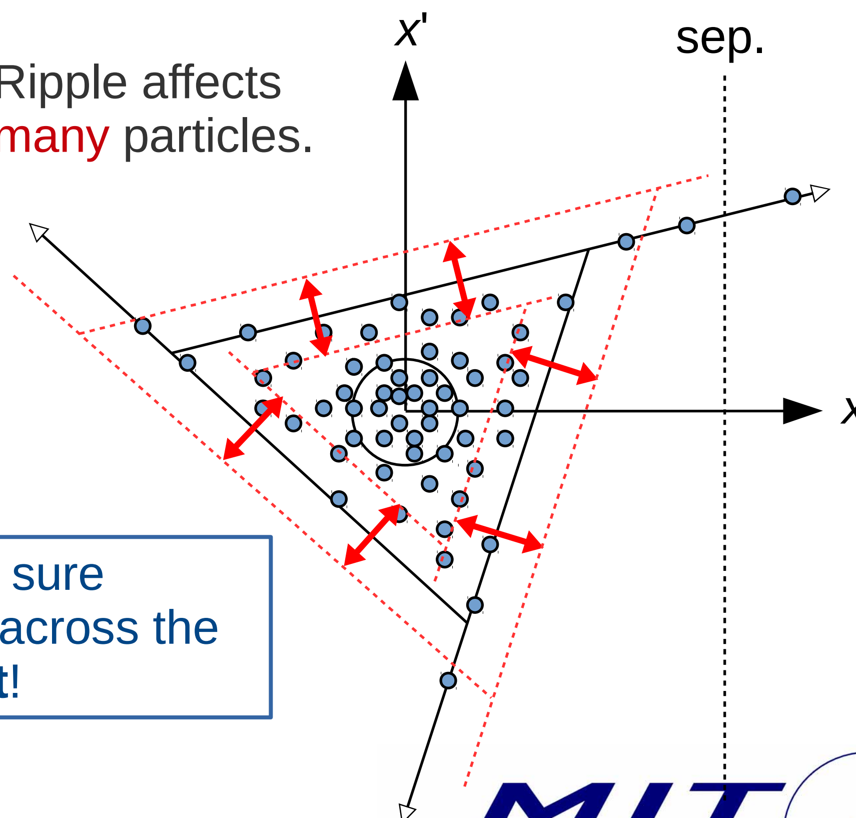
Bad machine setting



Ripple affects
few particles.



Ripple affects
many particles.



Need to make sure particle move across the separatrix **fast**!

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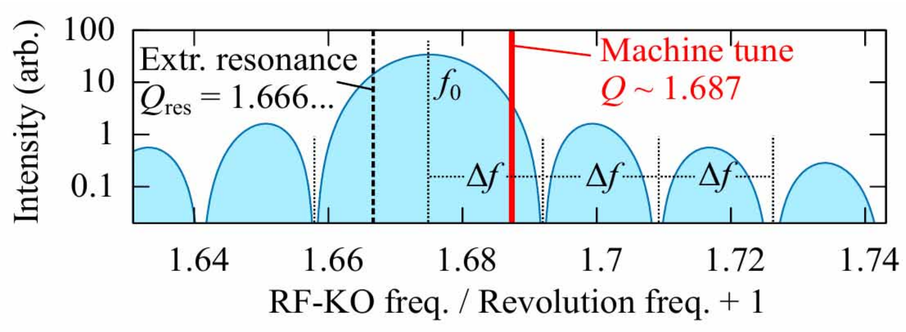
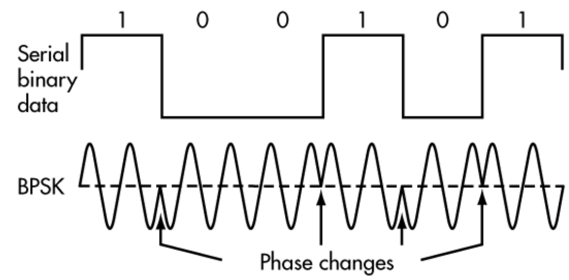
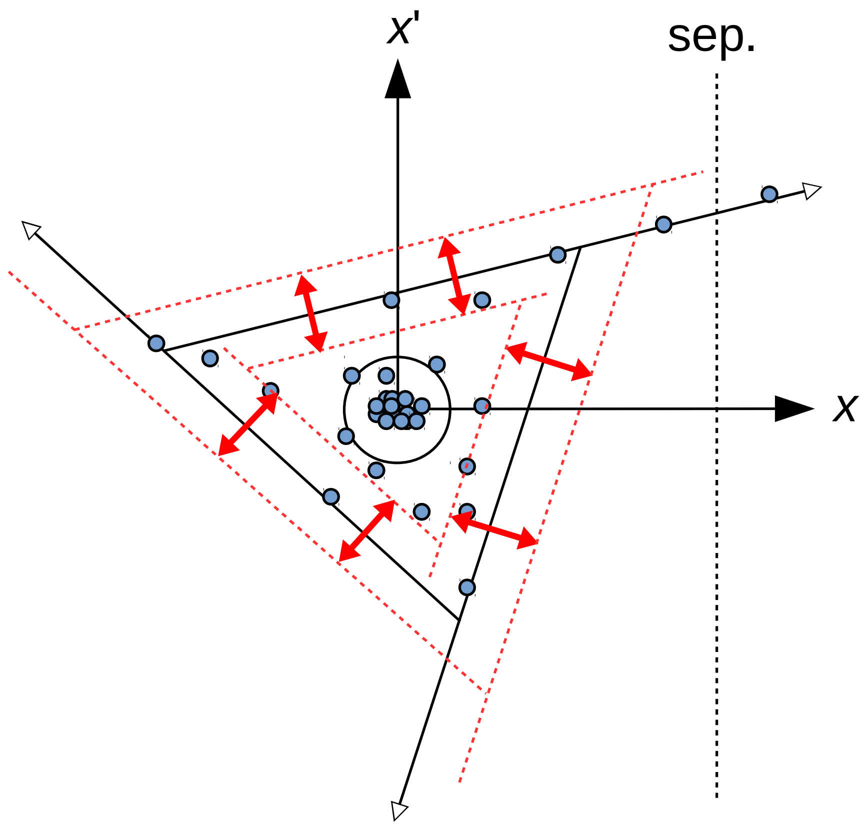
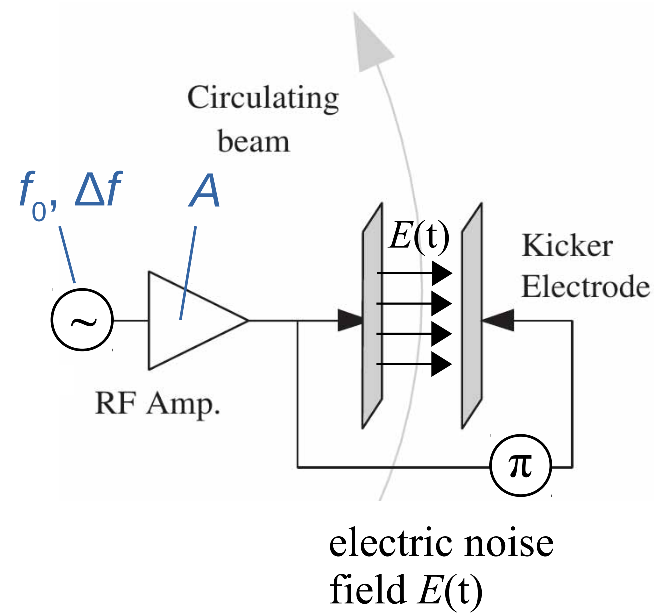
Micro structure: Effect of RF-KO spectrum

Work in progress: What can we gain by using more “elaborate” noise spectra?









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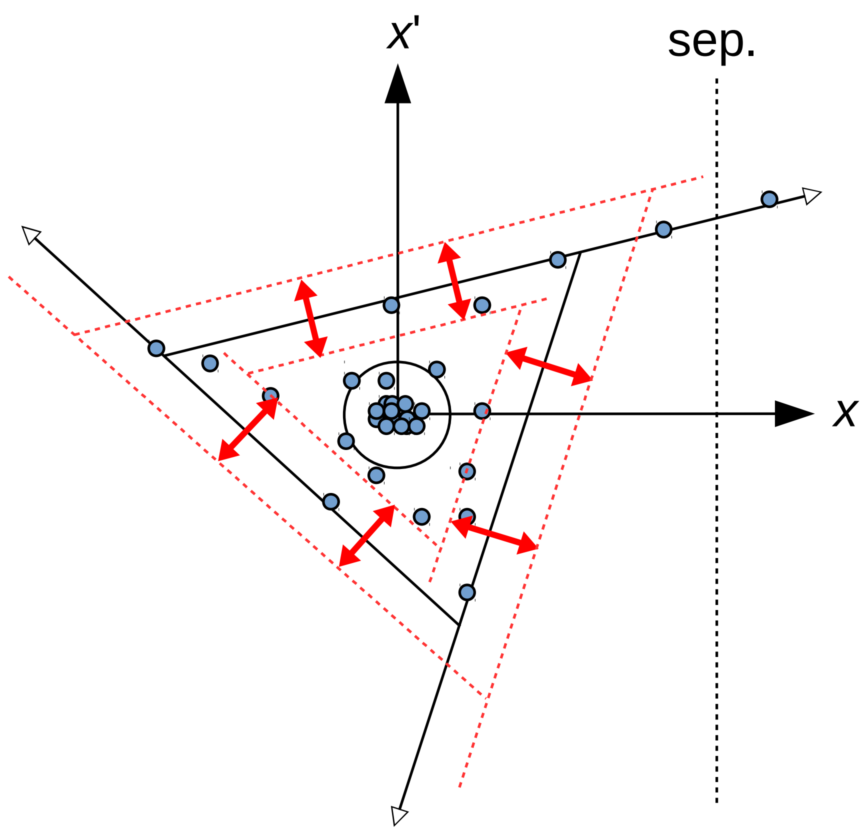
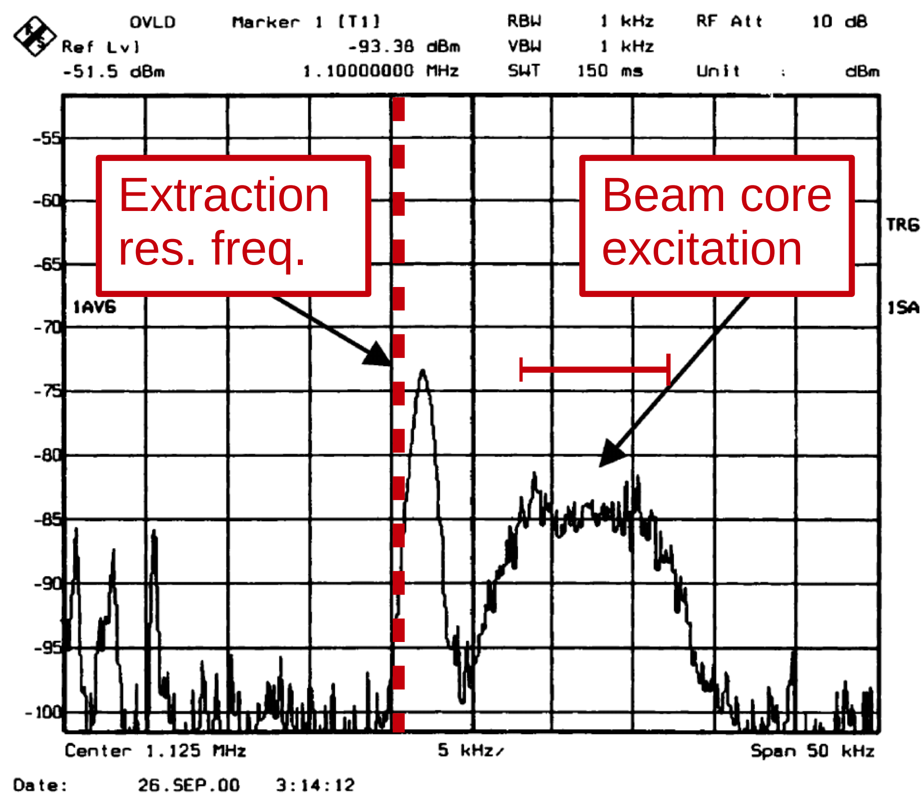
Micro structure: Effect of RF-KO spectrum

Work in progress: What can we gain by using more “elaborate” noise spectra?

Presently under investigation at HIT.

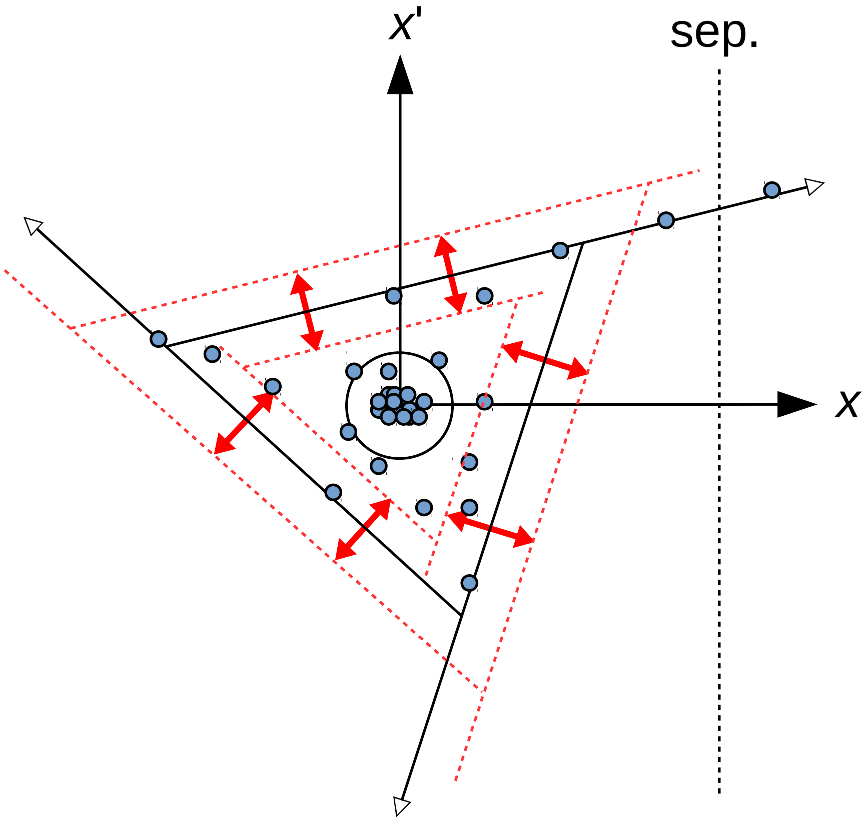


Dual-function RF-KO spectrum at HIMAC (NIRS, J):



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

Micro structure: Ripple compensation



How to get rid of the separatrix ripple?

1) Get better power supplies.

   – Expensive!
   – People have tried …

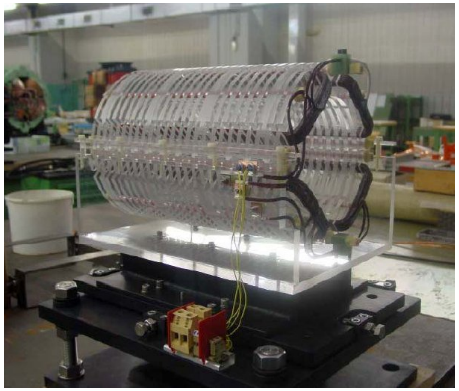
2) Active tune correction:

   Feed-back measured spill signal to a fast correction magnet.

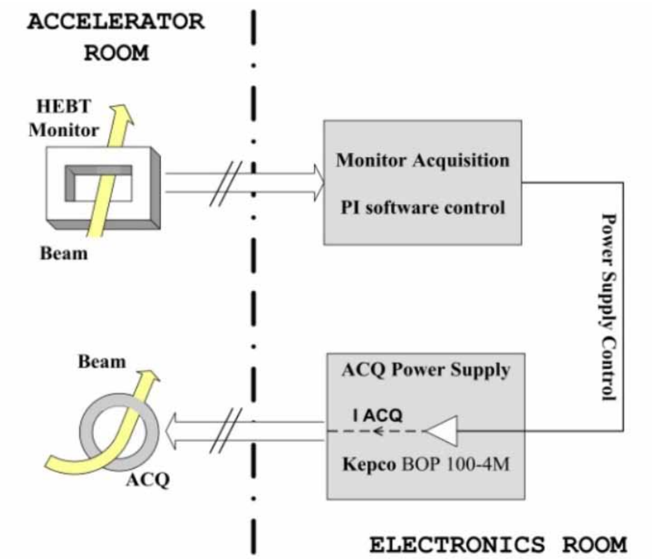
   (“noise cancellation”)

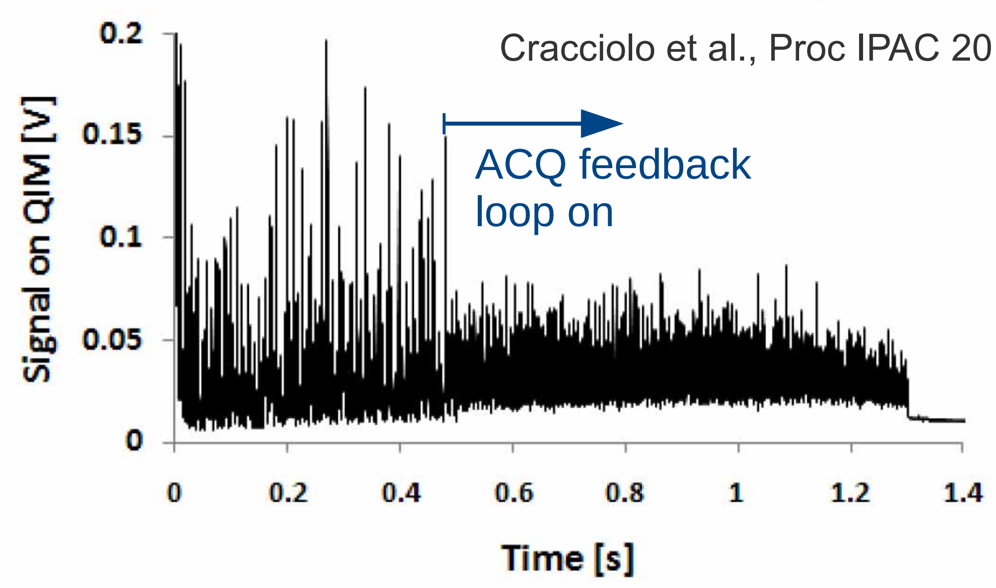
Micro structure: Ripple compensation

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



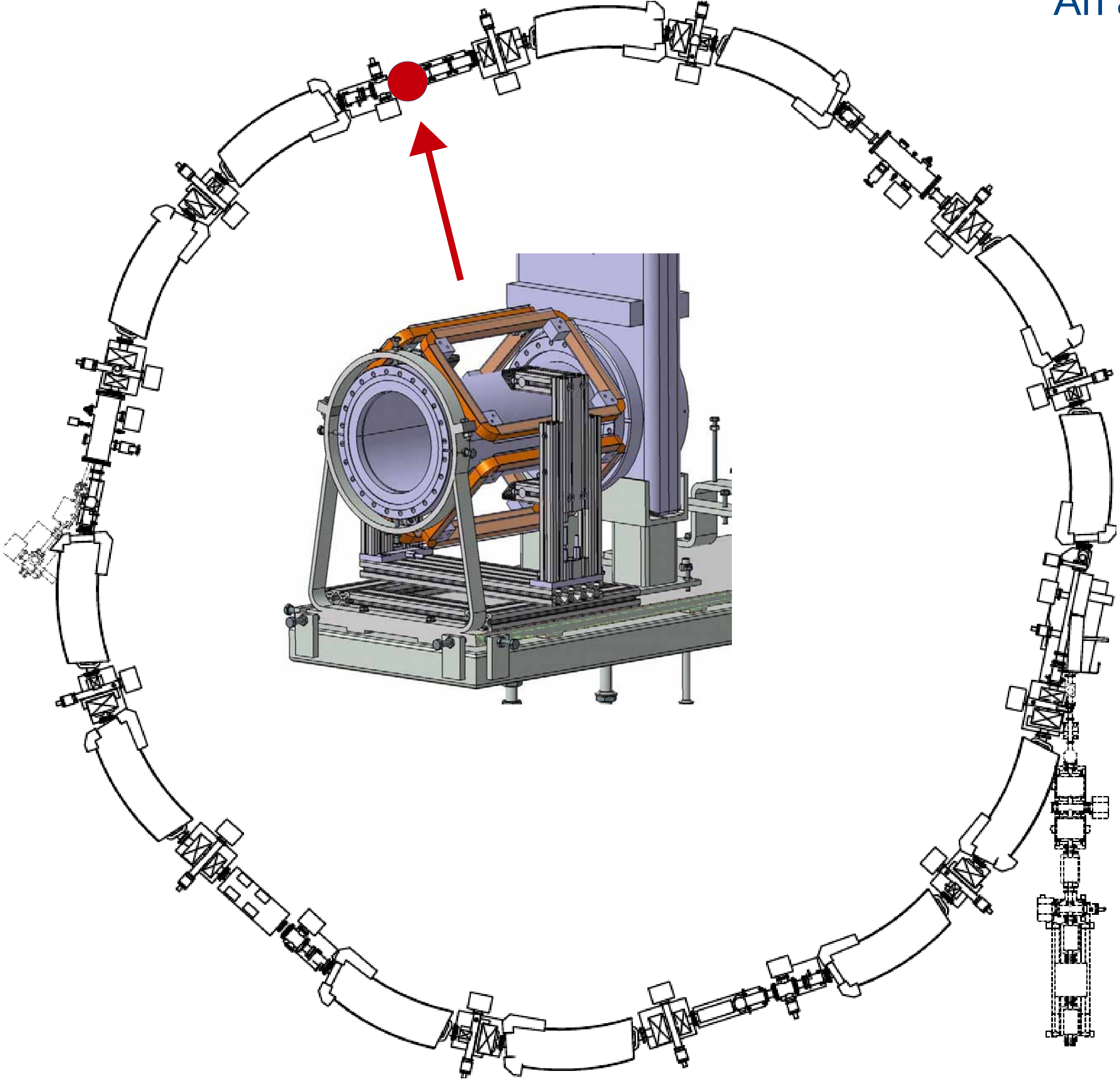
fondazionecnao.it



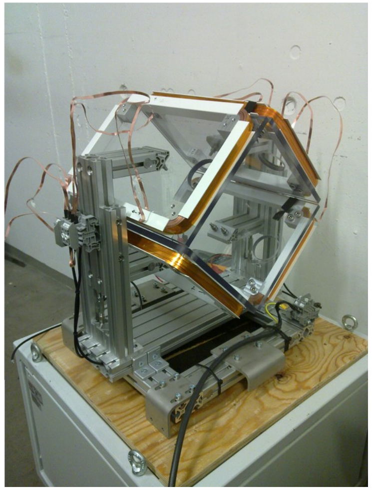


Cracciolo et al., Proc IPAC 2011

Micro structure: Ripple compensation



An air core quad for MIT (and HIT) …



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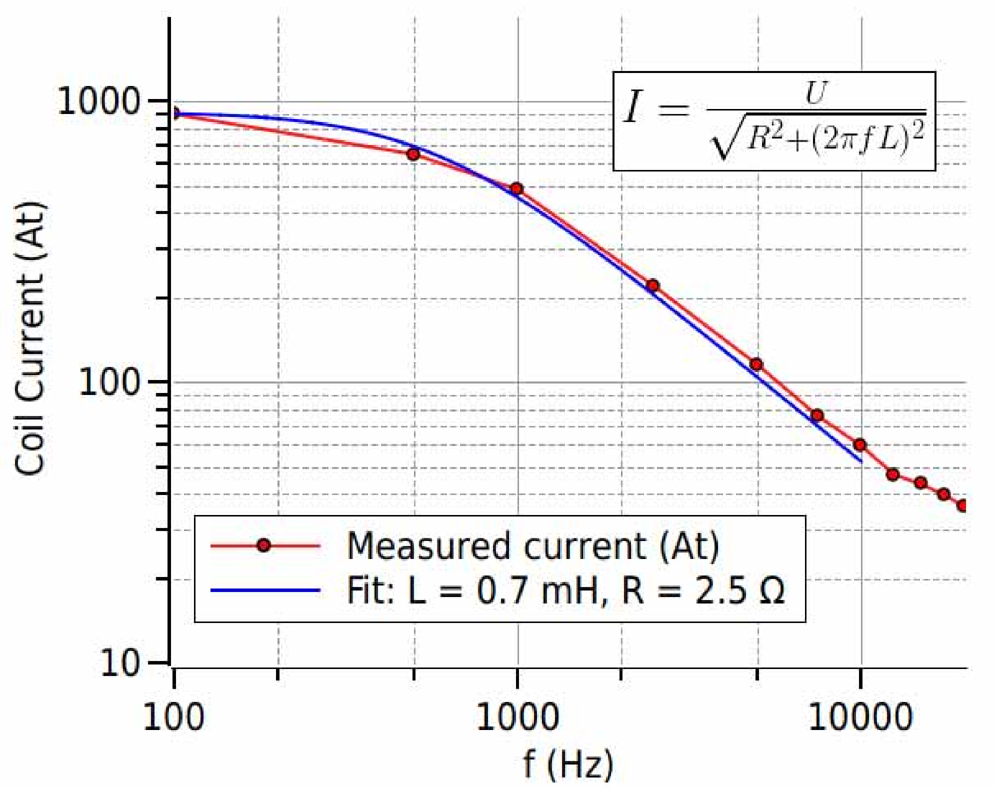
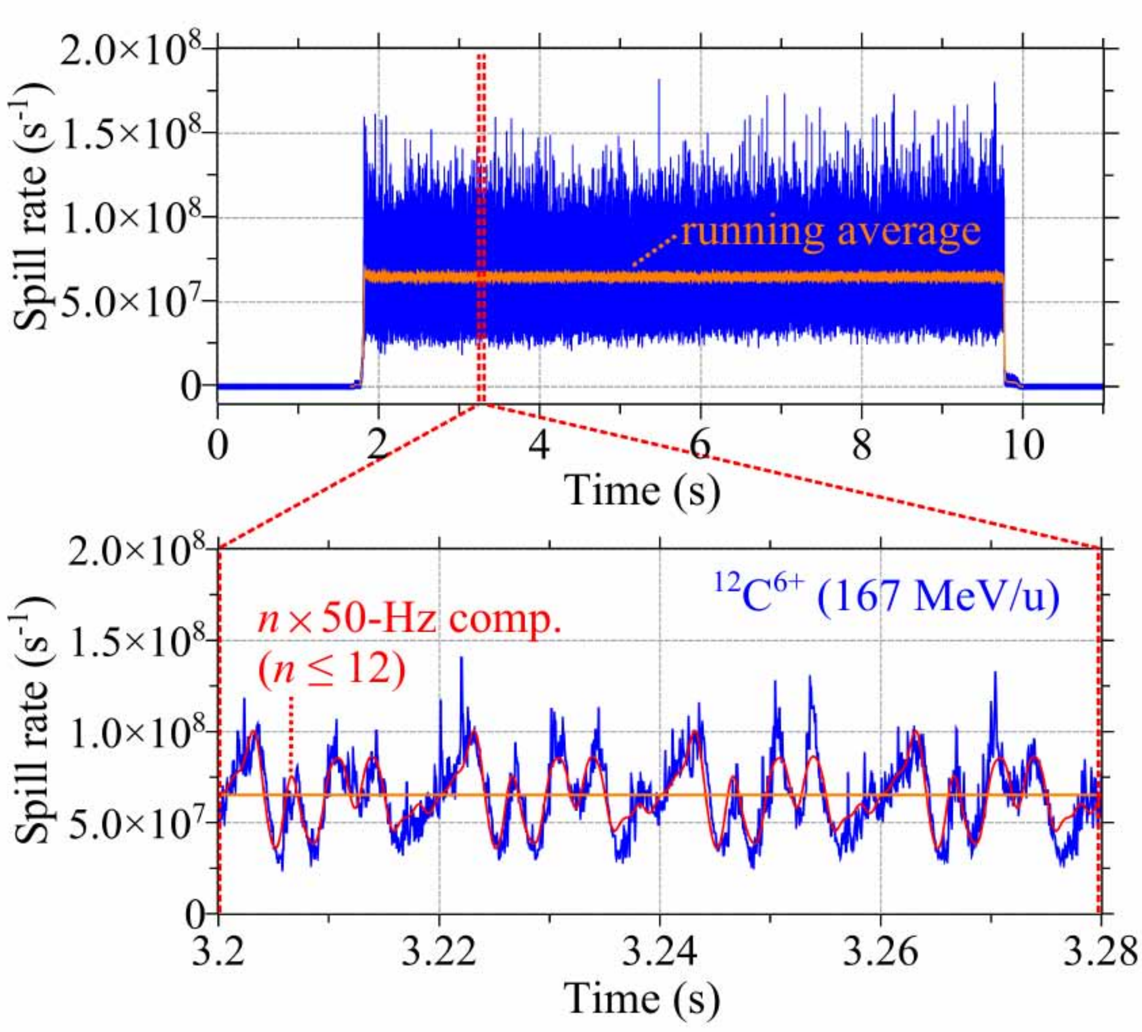
Micro structure: Ripple compensation



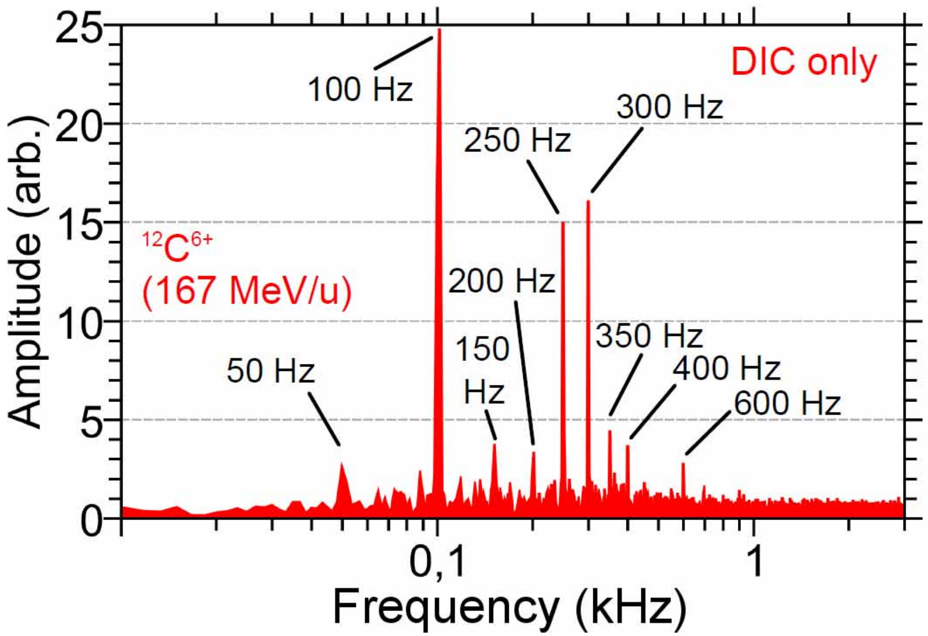
Can induce noticeable tune modulations (~ 10^{-3}) up to 10 kHz even at highest rigidities.

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

Micro structure: Ripple compensation



Would expect significant improvement even when cancelling only the most dominant (< 1 kHz) power-grid harmonics …



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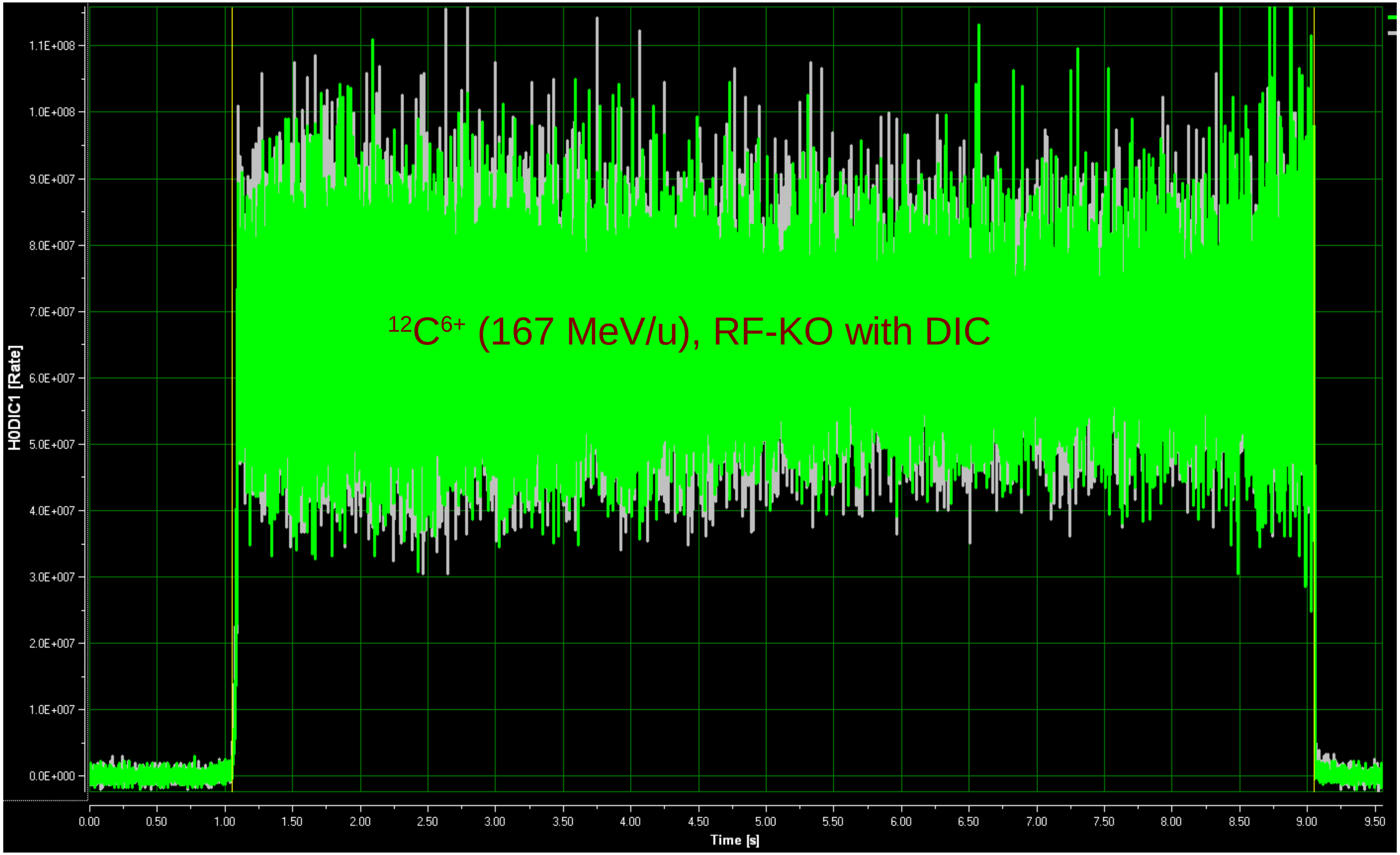
Micro structure: Ripple compensation

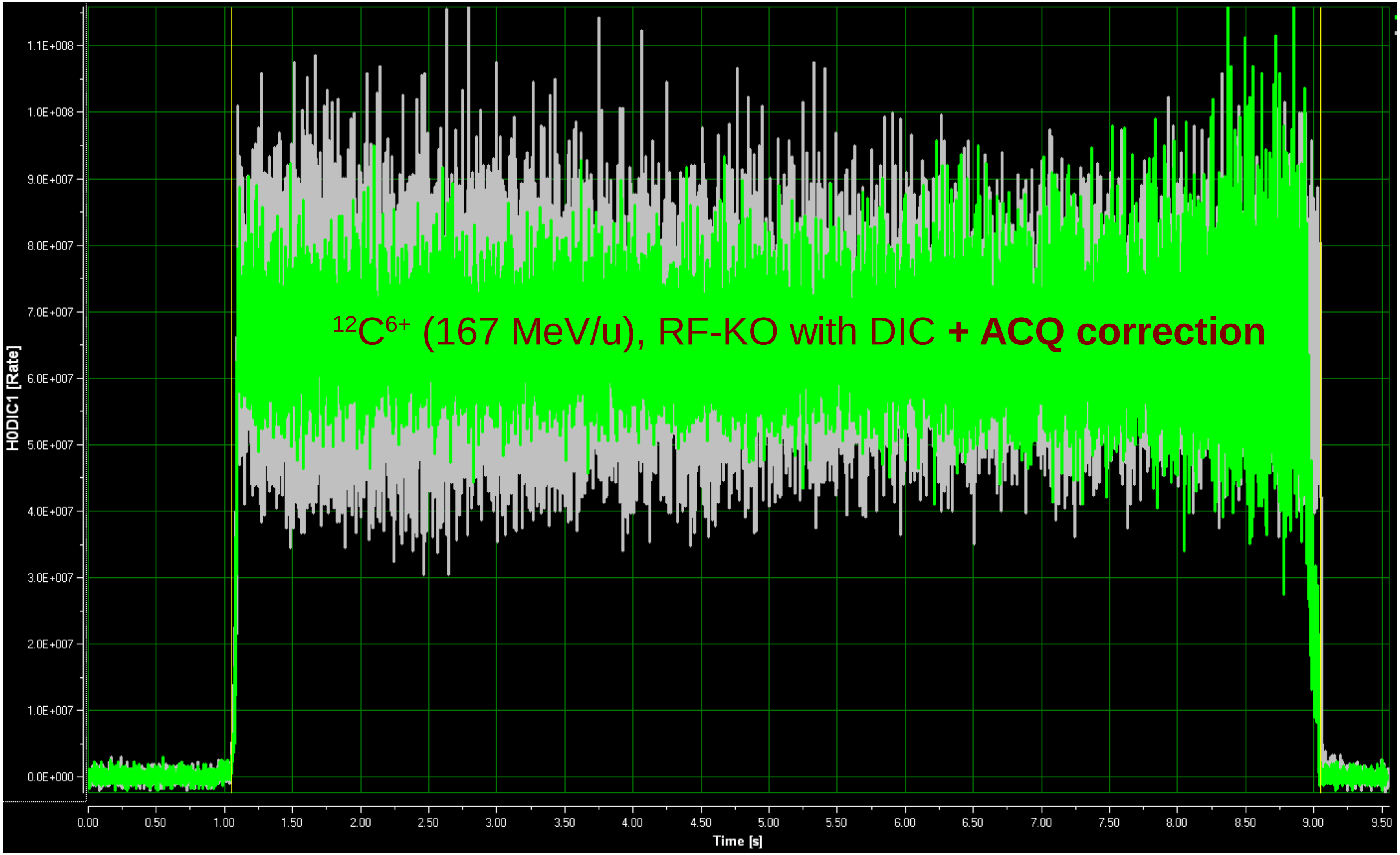
First tests (work in progress!)



Data: Ionisation chamber in extraction beam line.

Micro structure: Ripple compensation

First tests (work in progress!)



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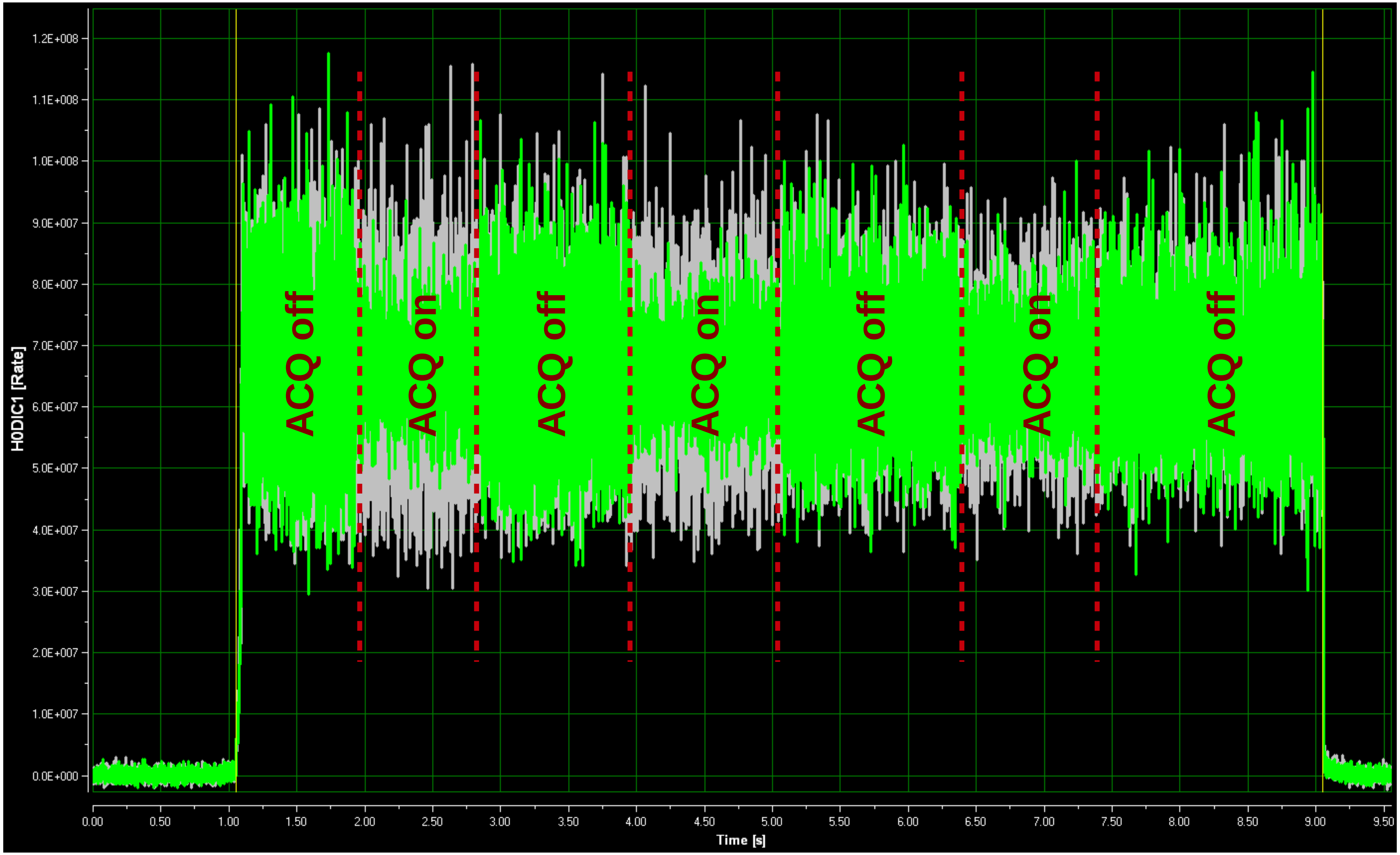
Micro structure: Ripple compensation

First tests (work in progress!)

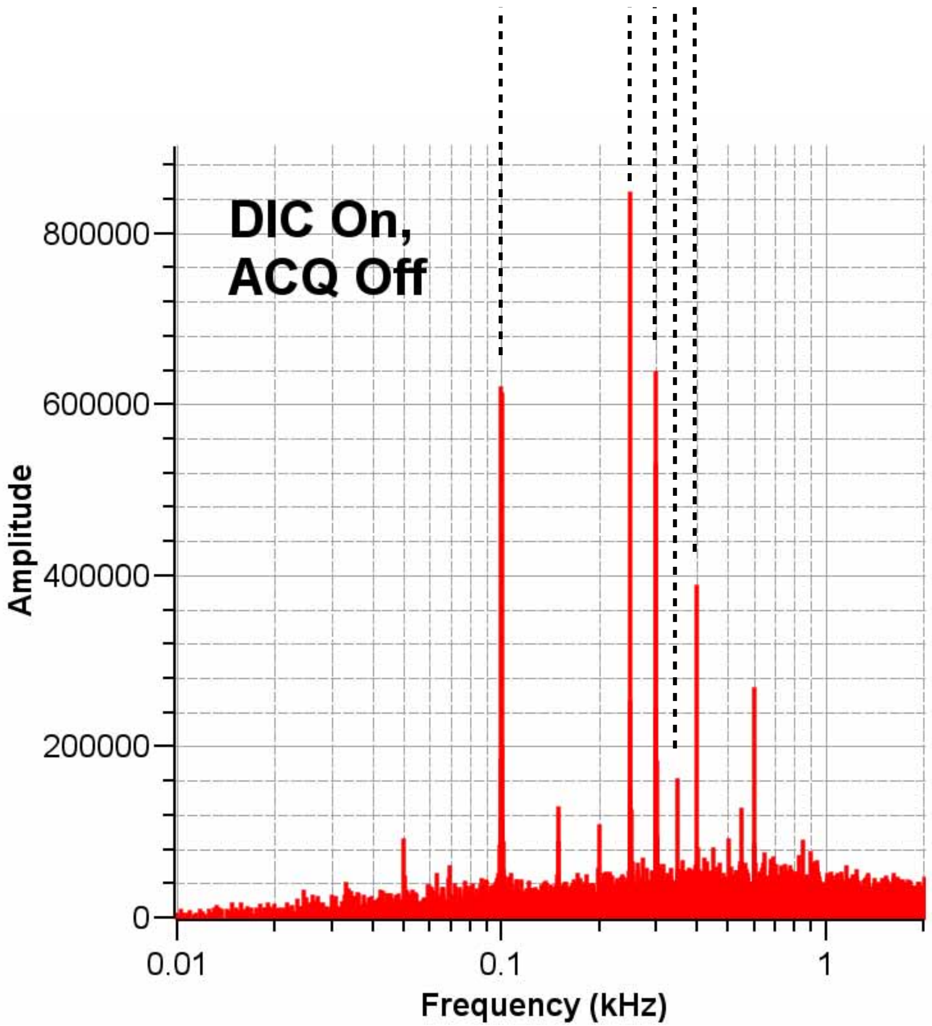


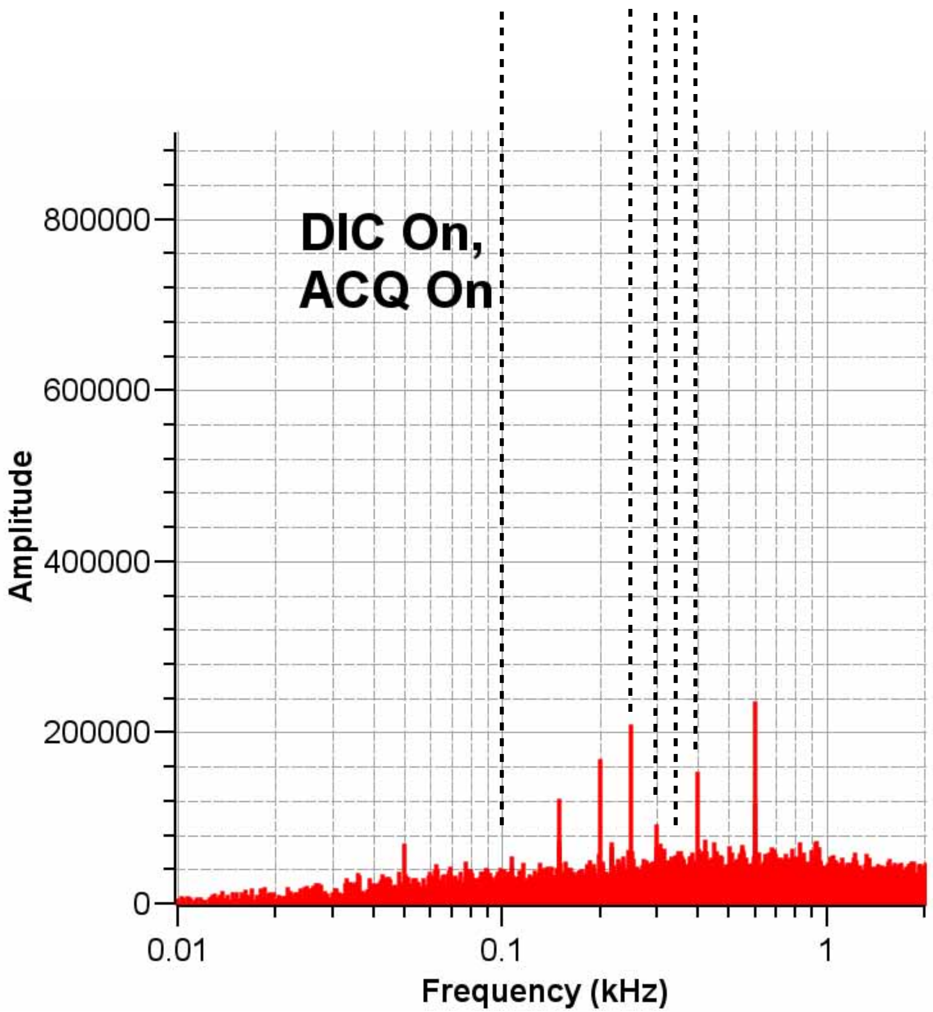
Data: Ionisation chamber in extraction beam line.

Micro structure: Ripple compensation

5 power grid harmonics included in correction function.

Components cancelled-out by ACQ modulation.





Micro structure: Ripple compensation

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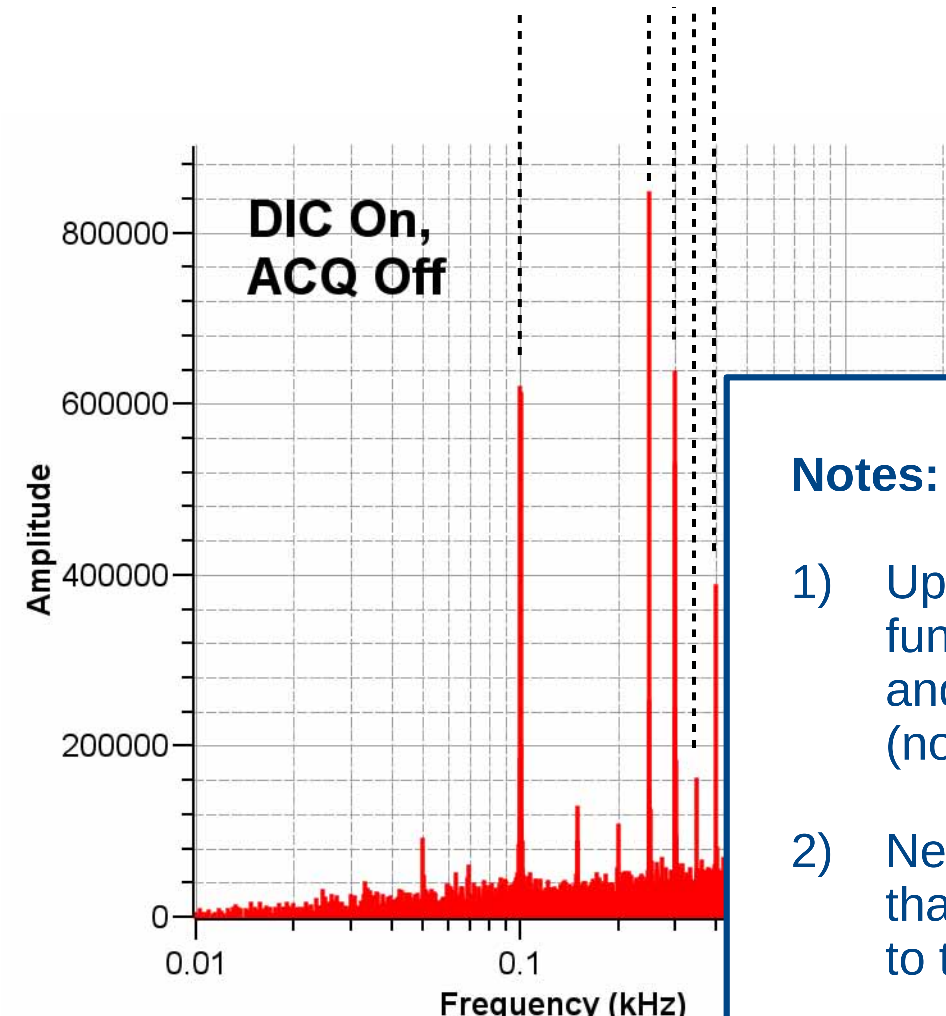
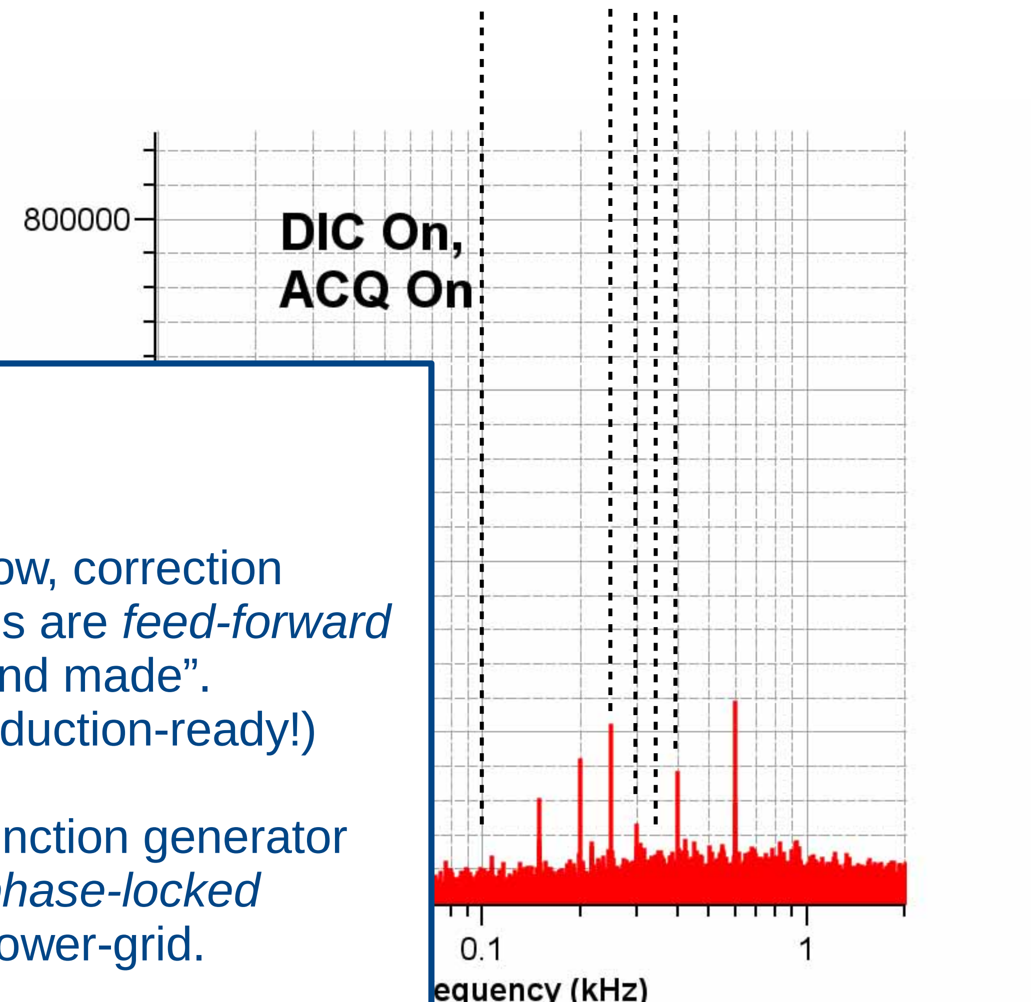




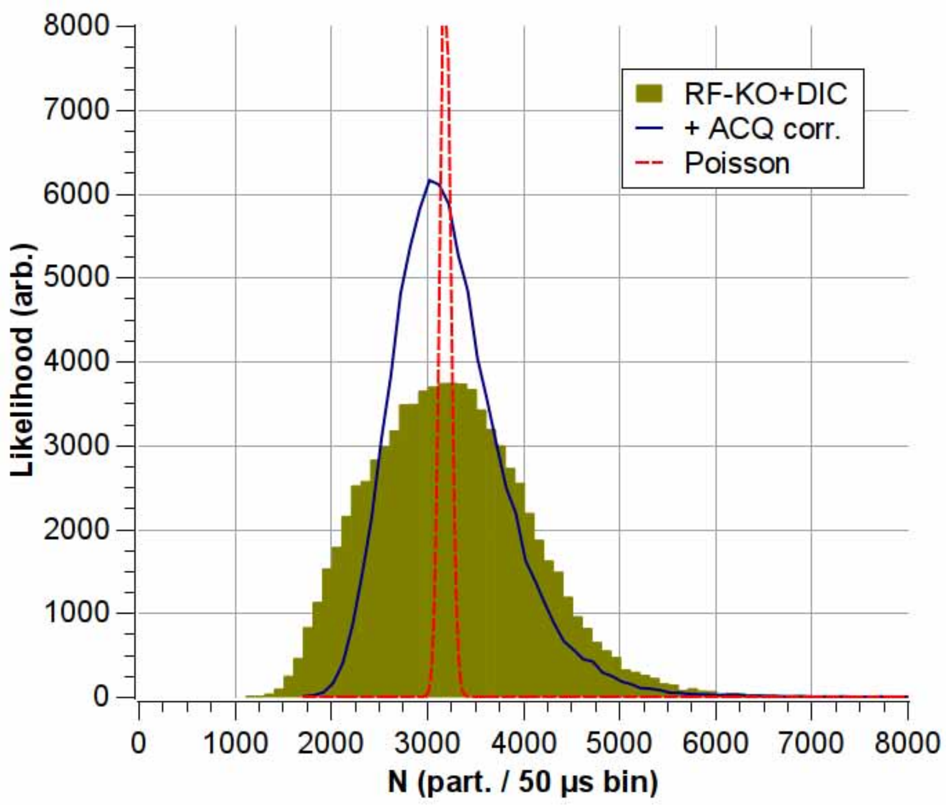
Notes:

1) Up to now, correction functions are *feed-forward* and “hand made”. (not production-ready!)

2) Need function generator that is *phase-locked* to the power-grid.

Micro structure: Ripple compensation

Marburg (MIT): $^{12}C^{6+}$ (167 MeV/u)



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Micro structure: Ripple compensation

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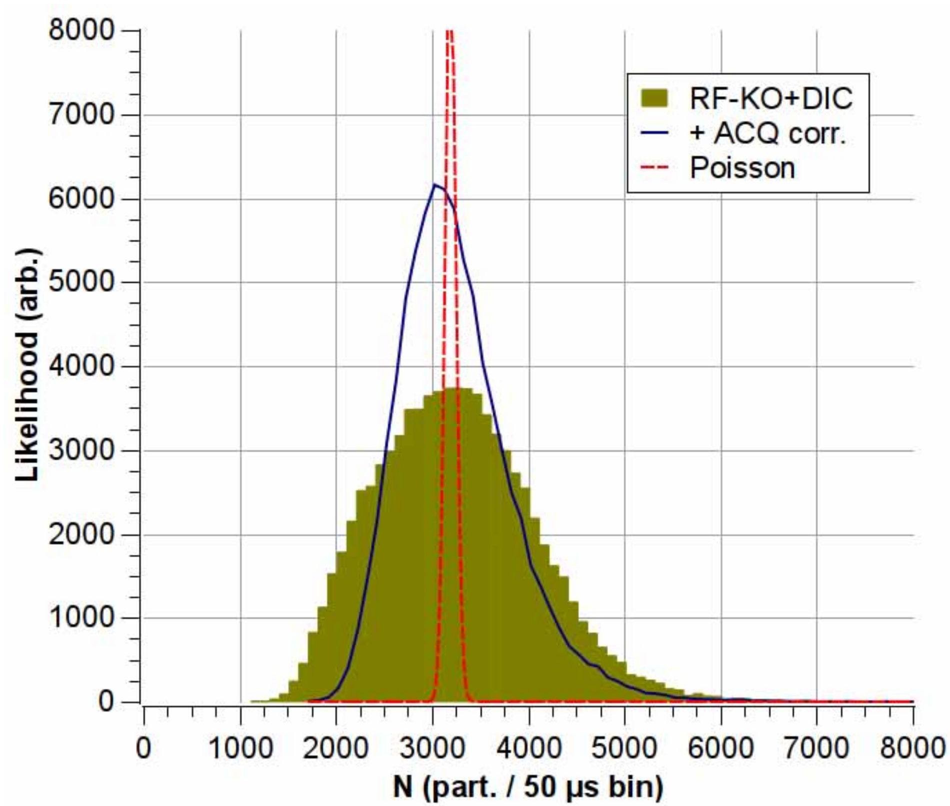
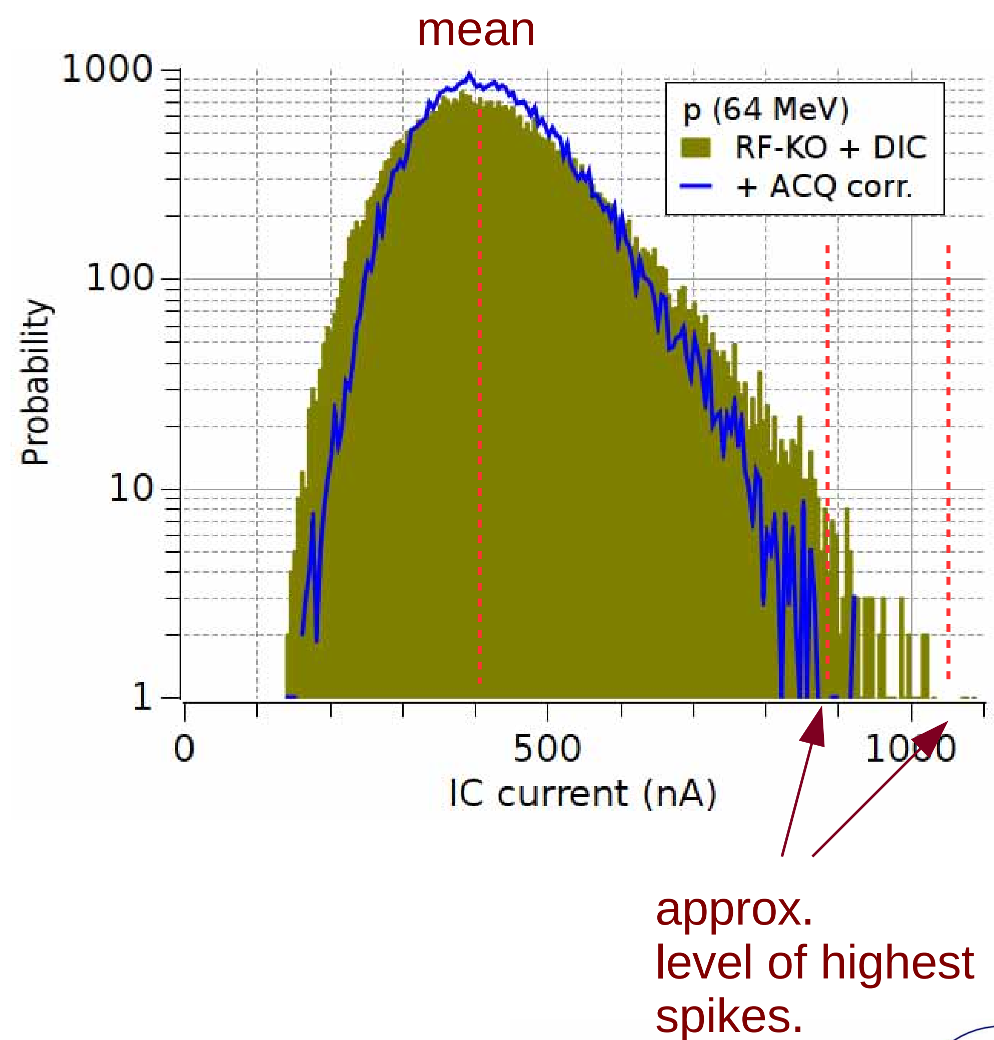


Heidelberg (HIT): p (64 MeV)



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Micro structure: Ripple compensation

Tune ripple compensation by air core quadrupole?

First results look promising.

System needs to be automated:

→ Self-learing correction function?

→ Direct inverse feedback (CNAO)?

...

If successful: Needs to be *certified for clinical application*!

Work in progress

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.

Careful adaptation of the **RF-KO spectrum** to the machine tune and extraction resonance improves **macro- and micro-**properties of the spill.

First experiments towards **ripple cancellation** using a fast **air-core quadrupole** magnet have been conducted at the MIT and HIT synchrotrons.

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Thank You for Your Attention.

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