Slow Extraction Workshop 2017

Spill Control at the

Marburg Ion-Beam Therapy Centre

Claude Krantz

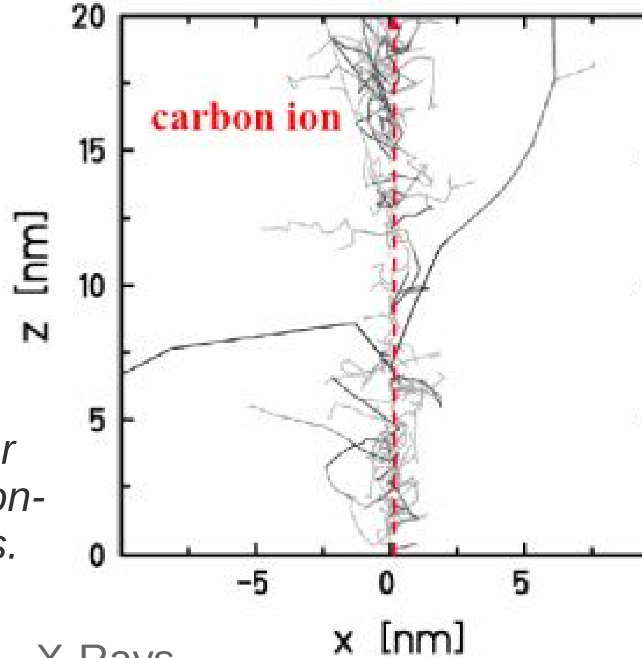
Marburg Ion-Beam Therapy Centre

10th November 2017

MIT: The Marburg Ion-Beam Therapy Centre

Radiation therapy with ion beams

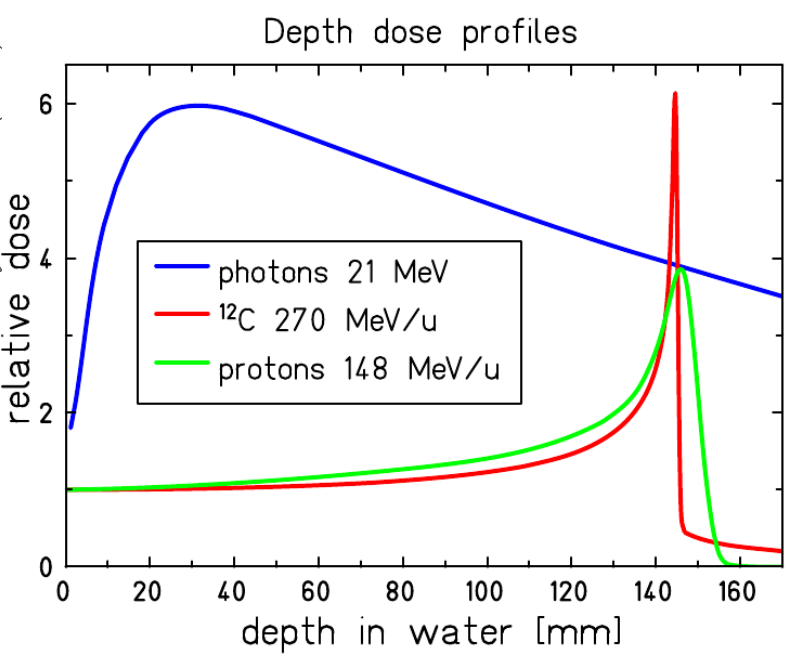
- p (up to 221 MeV)
- $^{12}C^{6+}$ (up to 430 MeV/u)



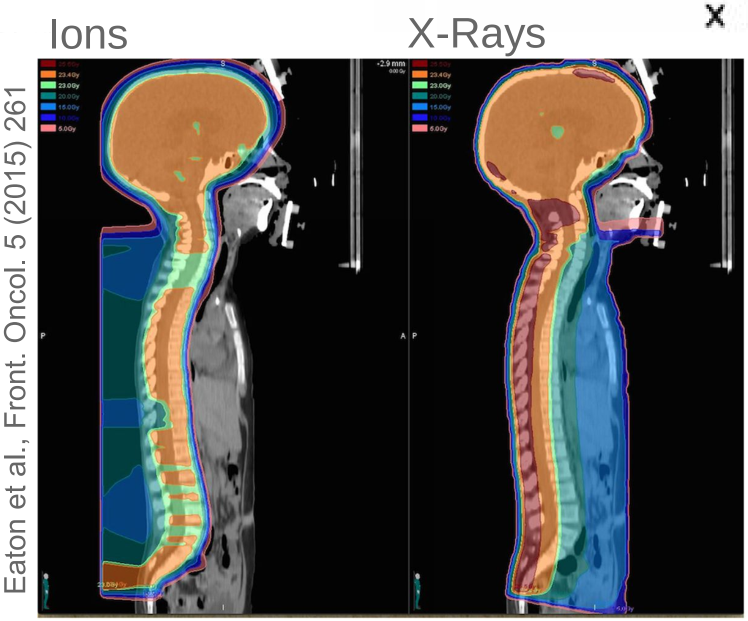
Amaldi & Kraft, Rep. Prog. Phys. 68 (2005)

Higher ionisation density: useful for control of radiation-resistant tumours.

Bragg-peaking energy deposition profile can help in sparing healthy tissue.



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



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

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maps.google.com

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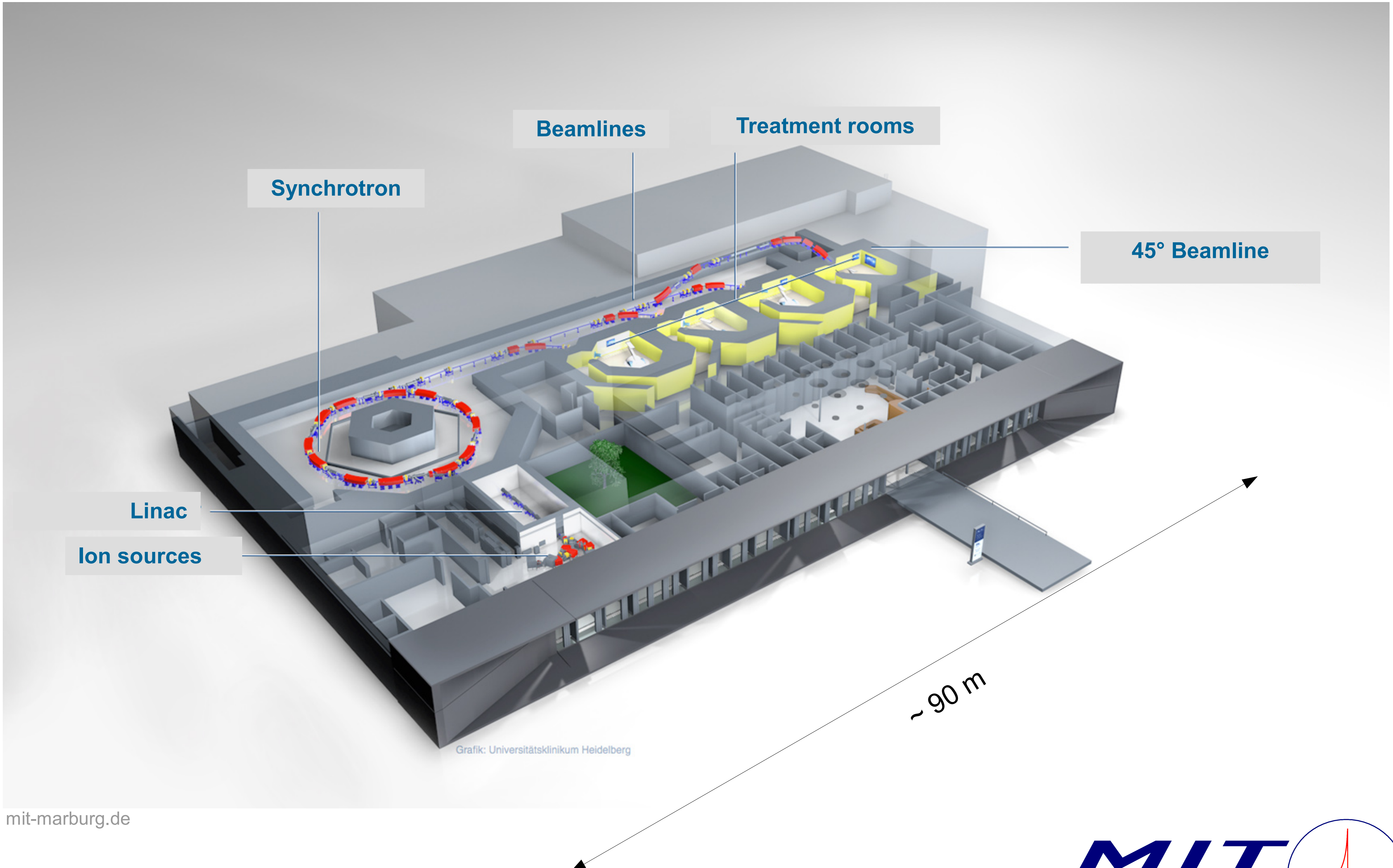

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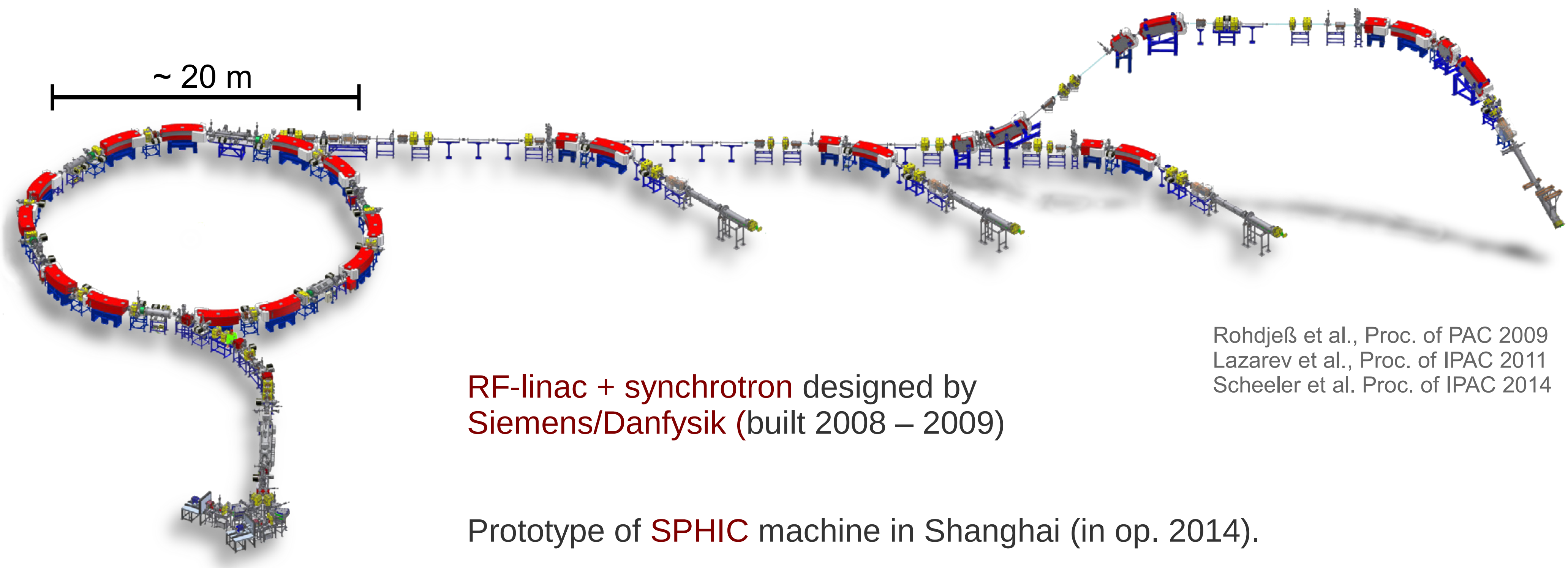
The MIT Accelerator



Rohdjeß et al., Proc. of PAC 2009
Lazarev et al., Proc. of IPAC 2011
Scheeler et al. Proc. of IPAC 2014

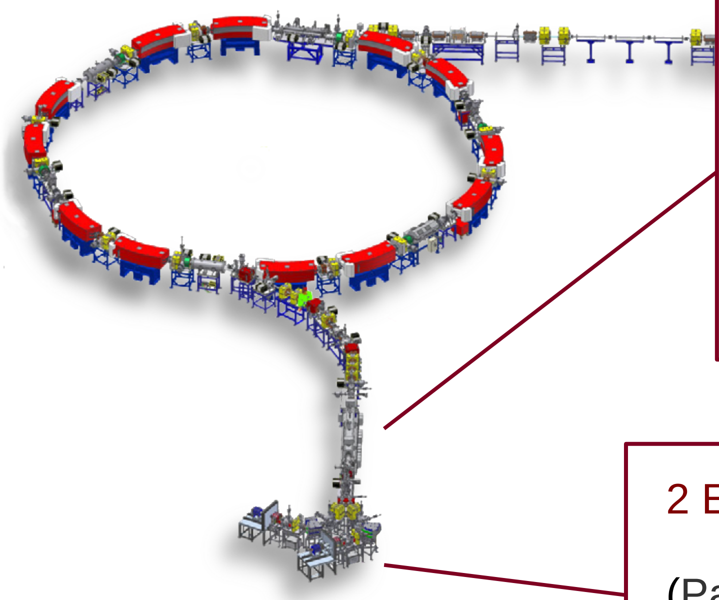
RF-linac + synchrotron designed by Siemens/Danfysik (built 2008 – 2009)

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

Commissioned to clinical application by MIT + HIT in 2015

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

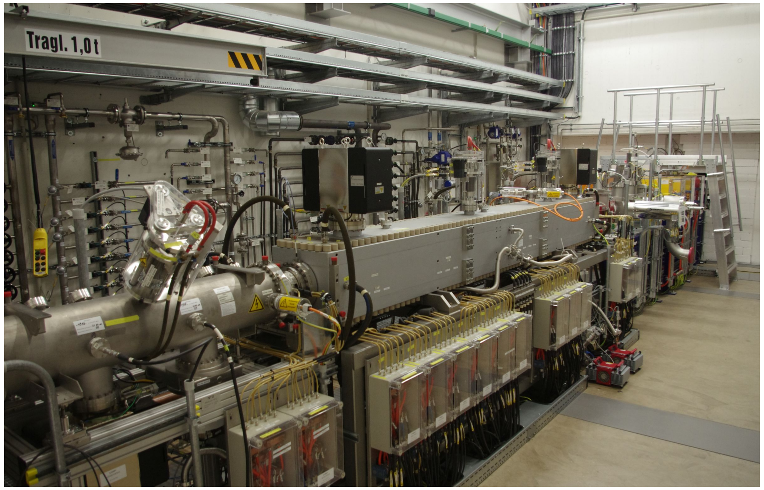
The MIT Accelerator



Linear accelerator

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

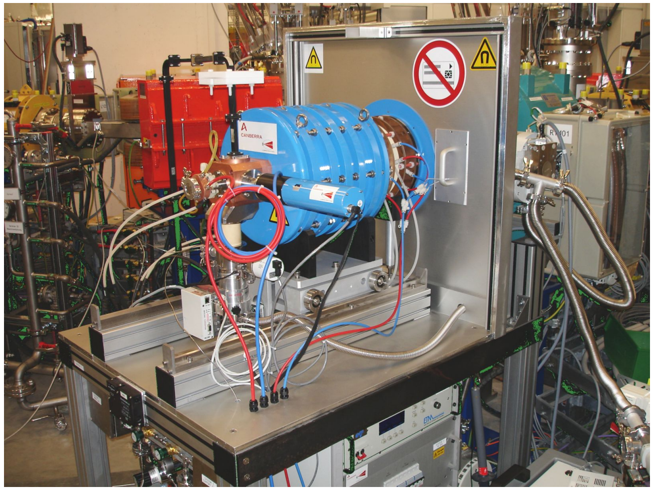
then stripping to
p and C^{6+}



2 ECR ion sources

(Pantechnik Supernanogan)

H_3^+ : 800 µA
C^{4+} : 180 µA



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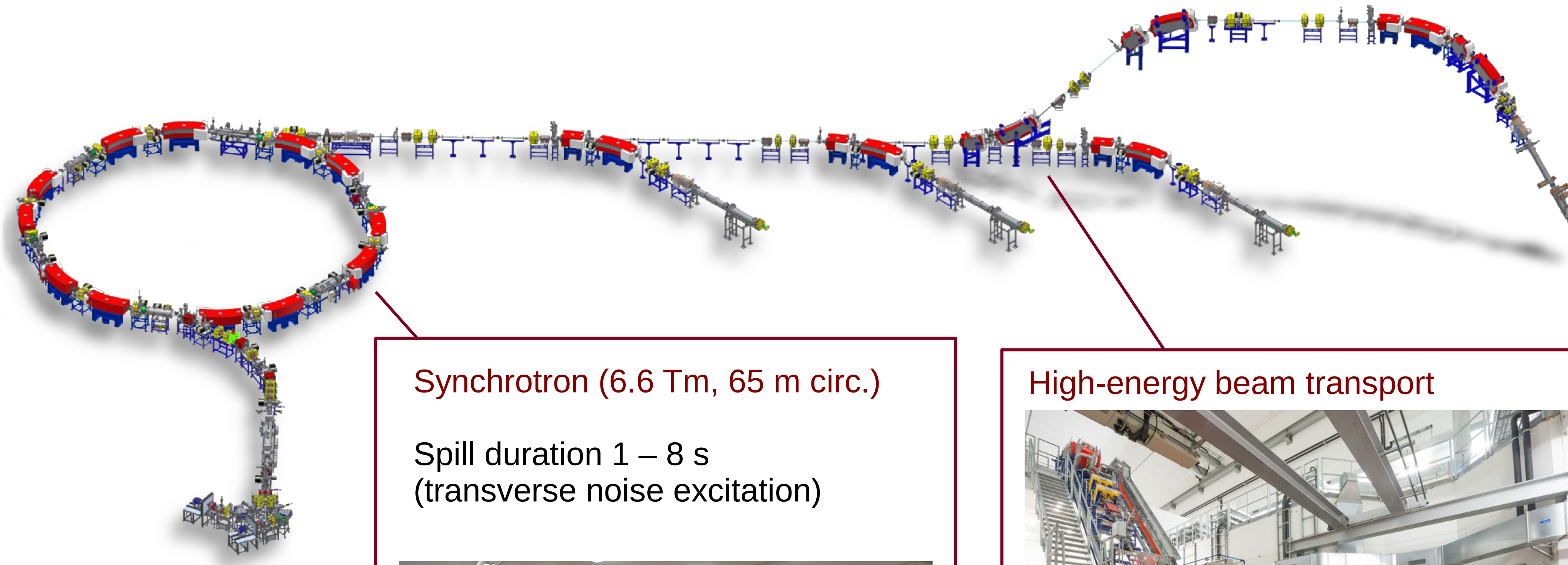


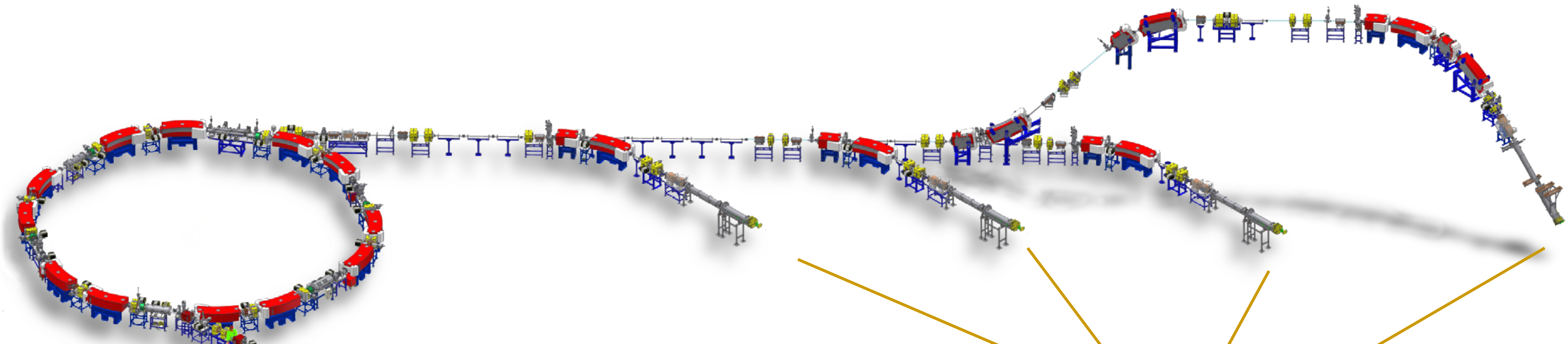
Synchrotron (6.6 Tm, 65 m circ.)

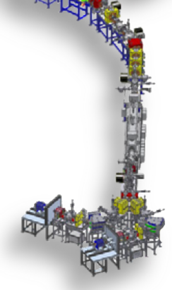
Spill duration 1 – 8 s
(transverse noise excitation)

Møller et al., Proc. of PAC 2007

High-energy beam transport

Beam outlets



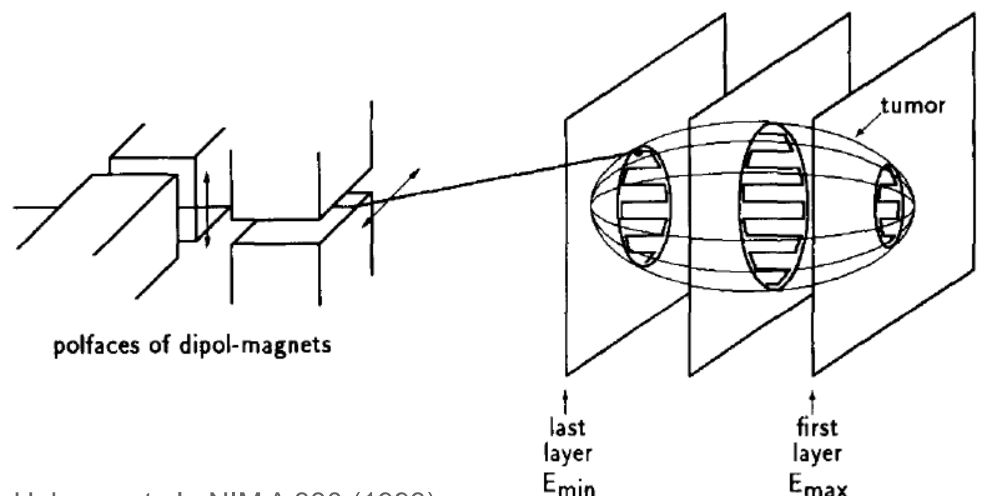


3 horizontal, 1 45°-vertical.

All equipped with pencil-beam scanning dose delivery systems.

Online beam monitoring, active steering, and in-spill intensity modulation (“Dynamic Intensity Control”).

→ Characteristic time scale: few ms per irradiated spot.



Haberer et al., NIM A 330 (1993)

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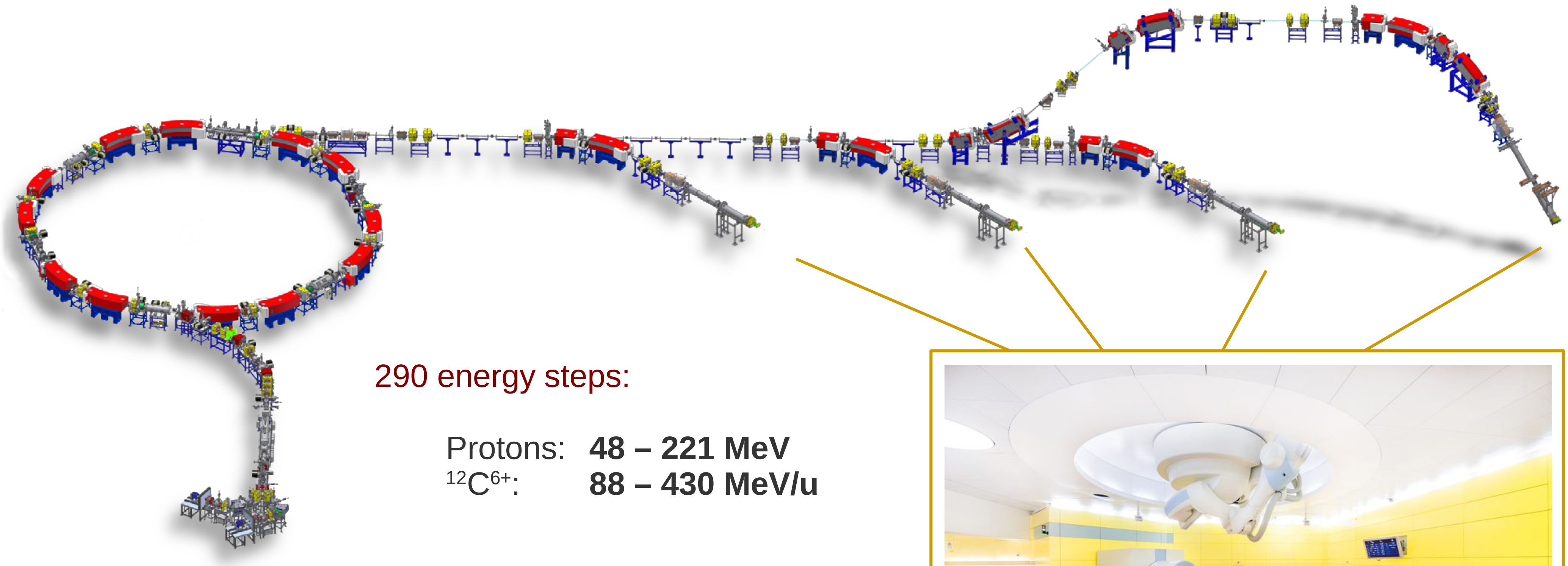
Beam outlets



290 energy steps:

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

13 base intensities:

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

per spill (nominal: 8 s)

+ “Dynamic Intensity Control”

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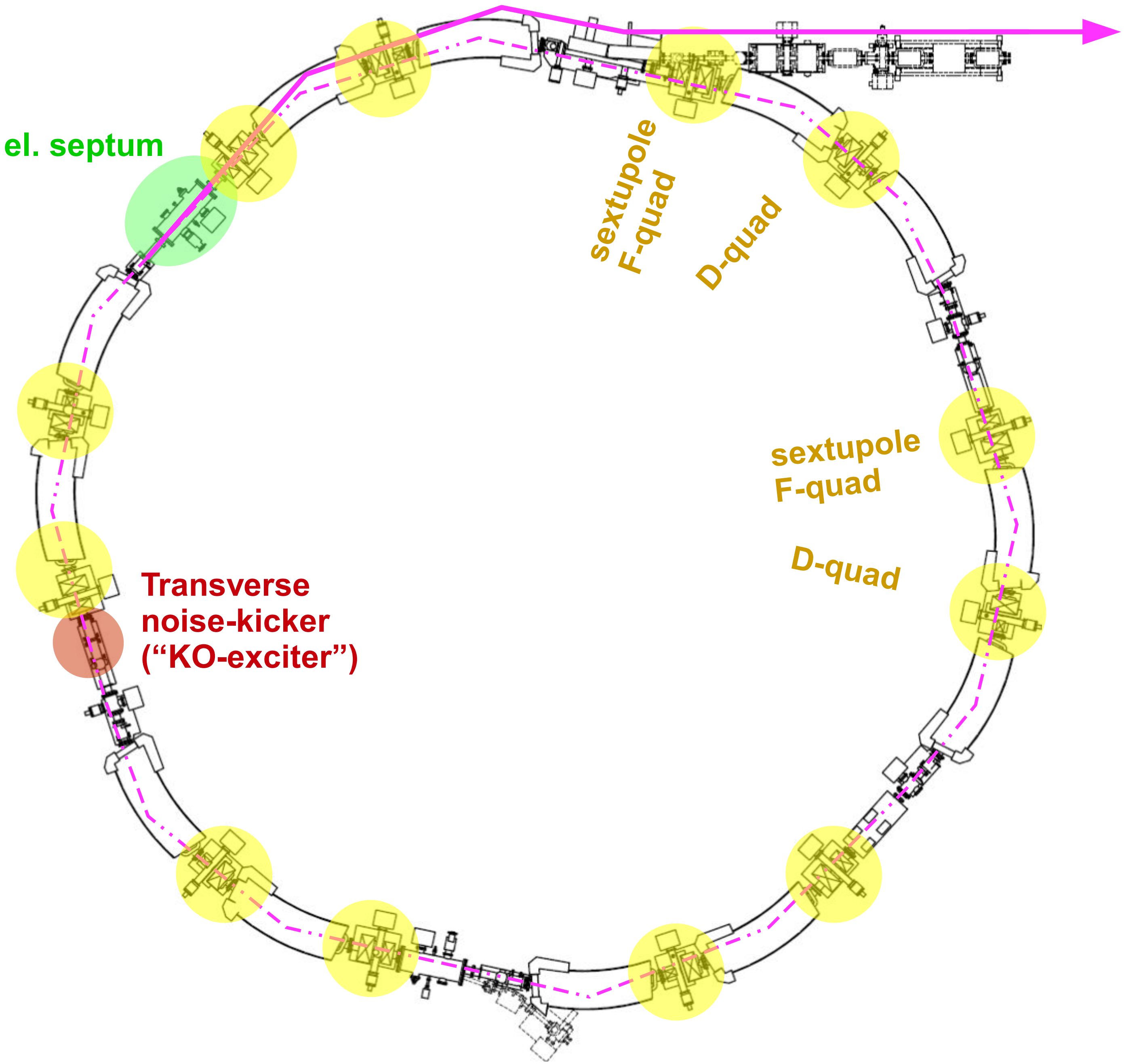
Extraction system



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

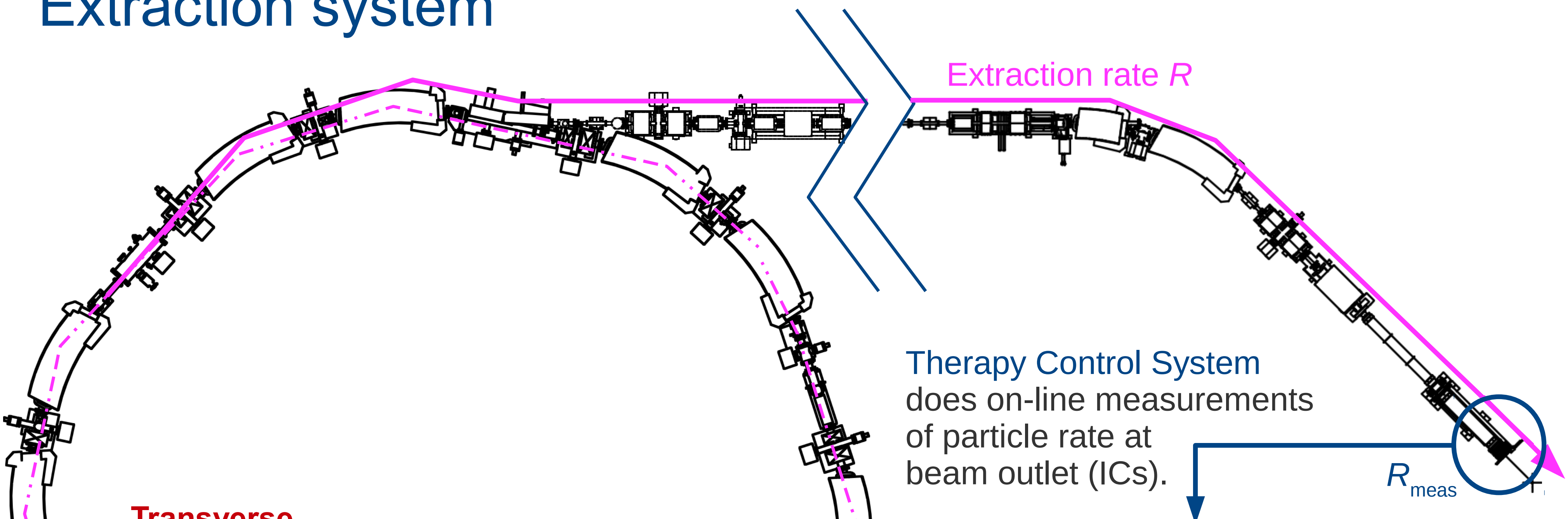
Slow extraction via 2/3 resonance (Q_{res} = 1.666...).

Fixed optics during extraction.

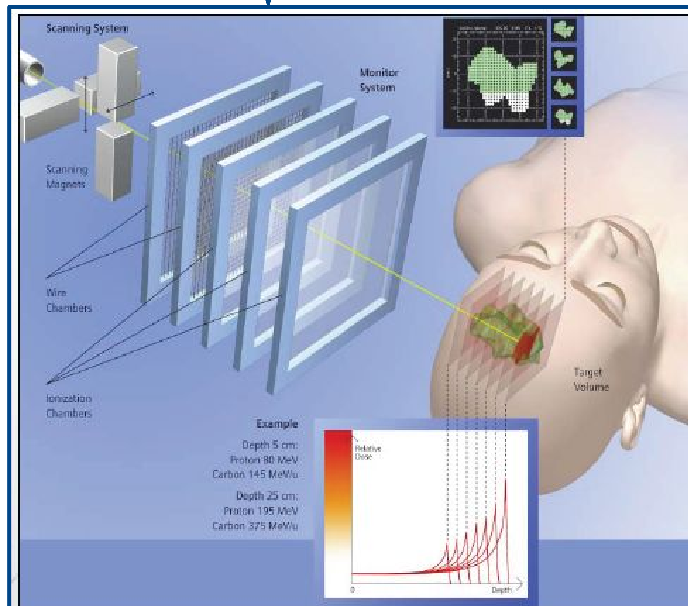
Transverse beam heating by noise kicker ("KO-excitation").

→ Can *control* the extraction rate on ms-timescales!

Extraction system



Therapy Control System does on-line measurements of particle rate at beam outlet (ICs).



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

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

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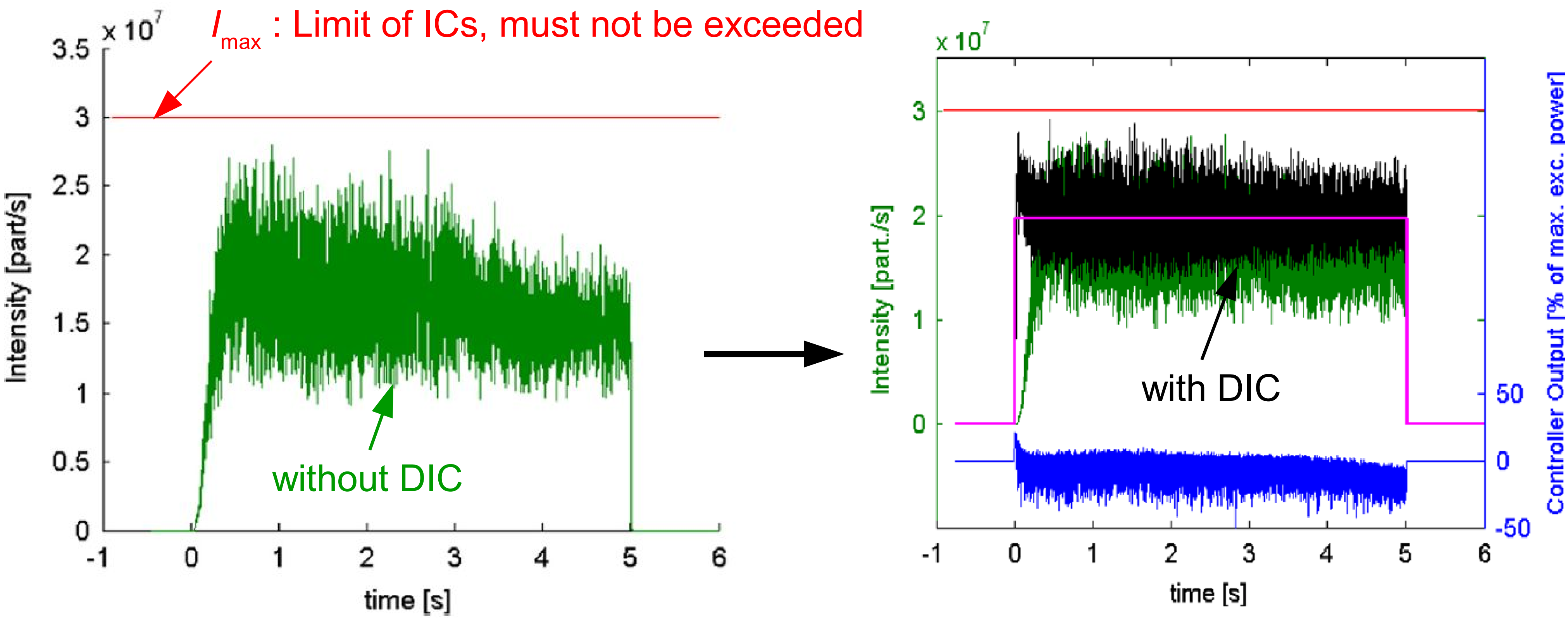
Dynamic Intensity Control (1)

"Dynamic Intensity Control" (DIC) – nearly identical to the equivalent system at HIT.
(cf. C. Schömers, *Slow Extraction Workshop 2016*)

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

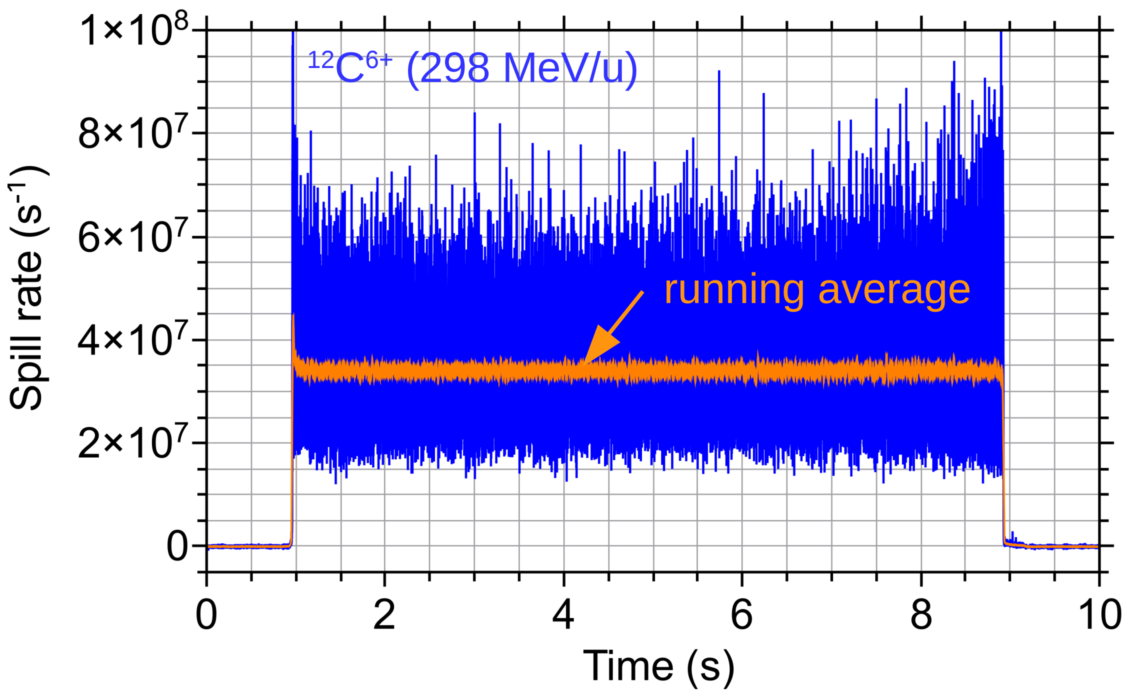


Schoemers, NIM A 795 (2015) 92–99

Spill quality

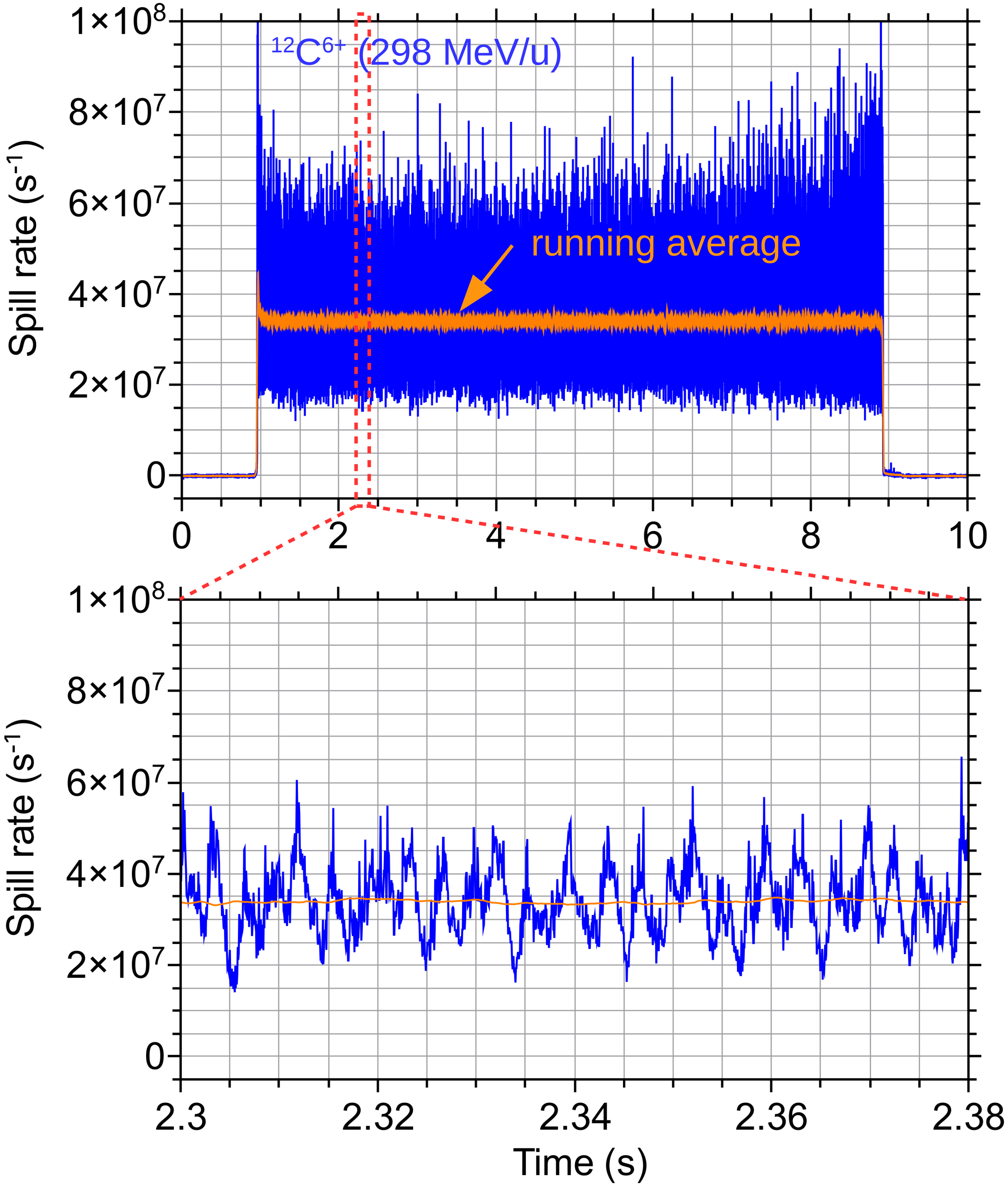
The spill we contributed to the “data collection” of the 2016 workshop:

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



DIC stabilises average extraction rate on time scales down to ~ 10 ms ...

Spill quality



DIC stabilises average extraction rate on time scales down to ~ 10 ms …

… but a spill "microstructure" on the kHz scale remains.

→ Average rate must be kept well below IC limit.

Note:
Intrinsic resolution of IC detectors blurs structures below ~ 100 µs!

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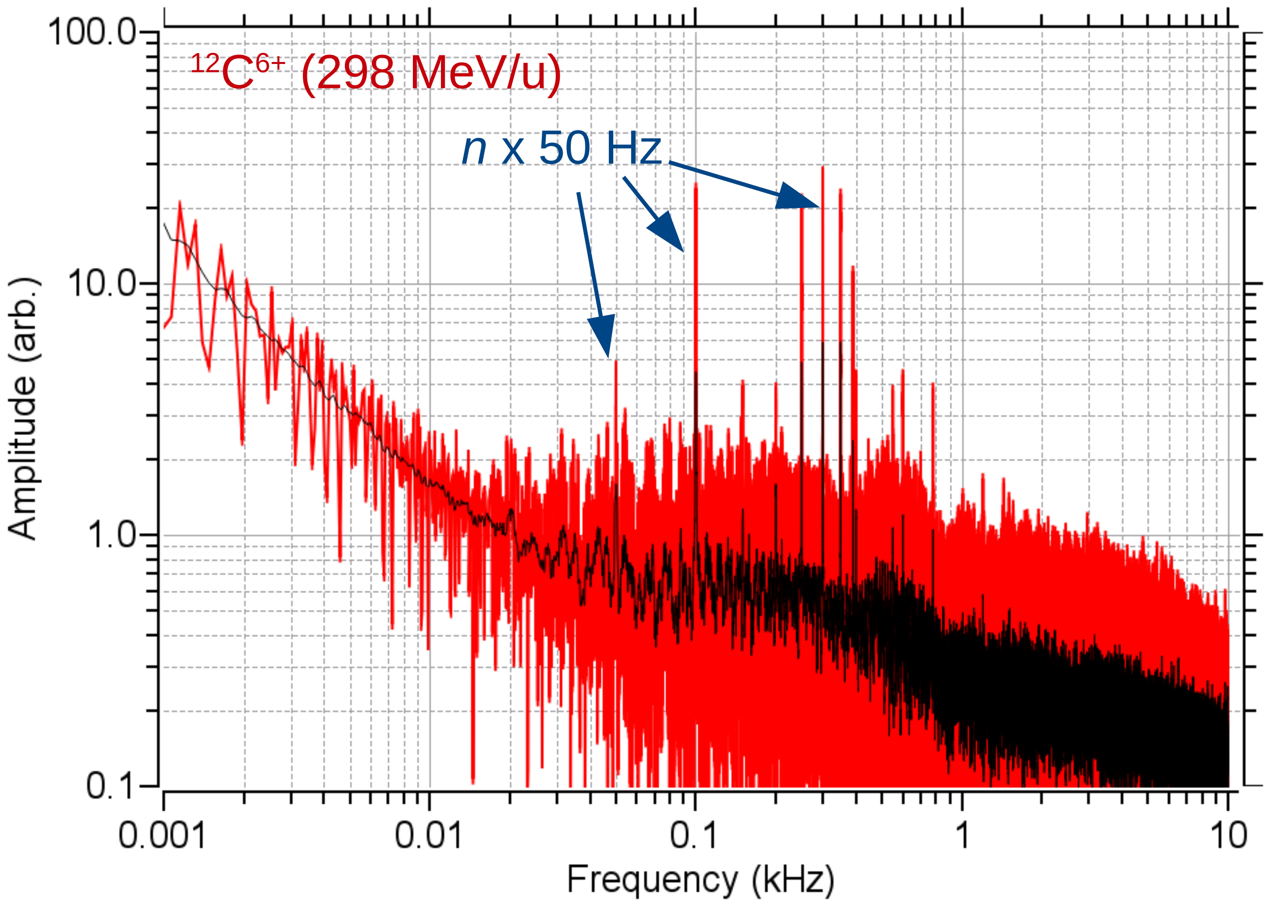
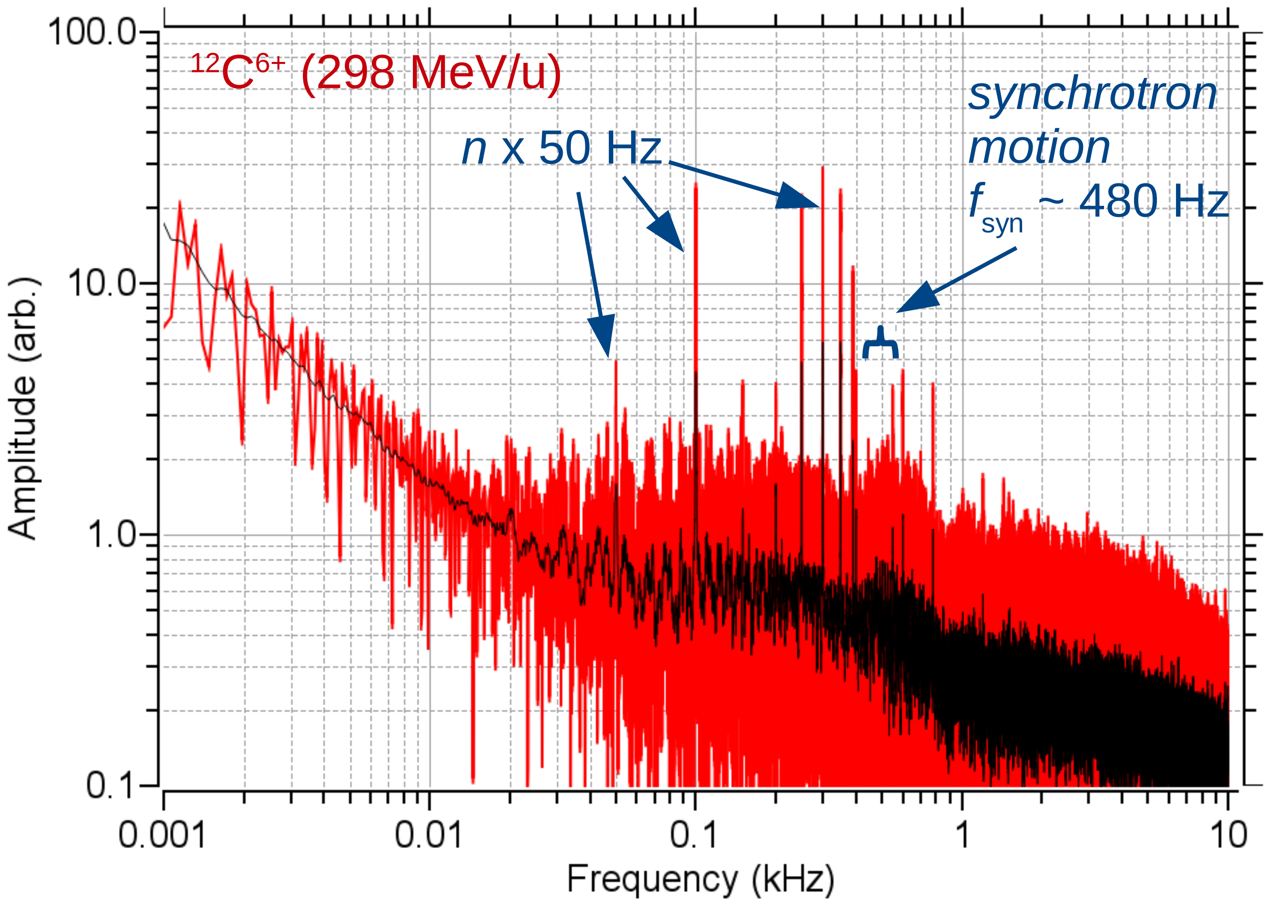
Spill quality



Spill quality



Production setting uses extraction from bunched beam.

Adopted from previous GSI and HIT experiments:

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

→ Bucket oscillation couples to transverse tune and extraction rate (non-zero chromaticity).

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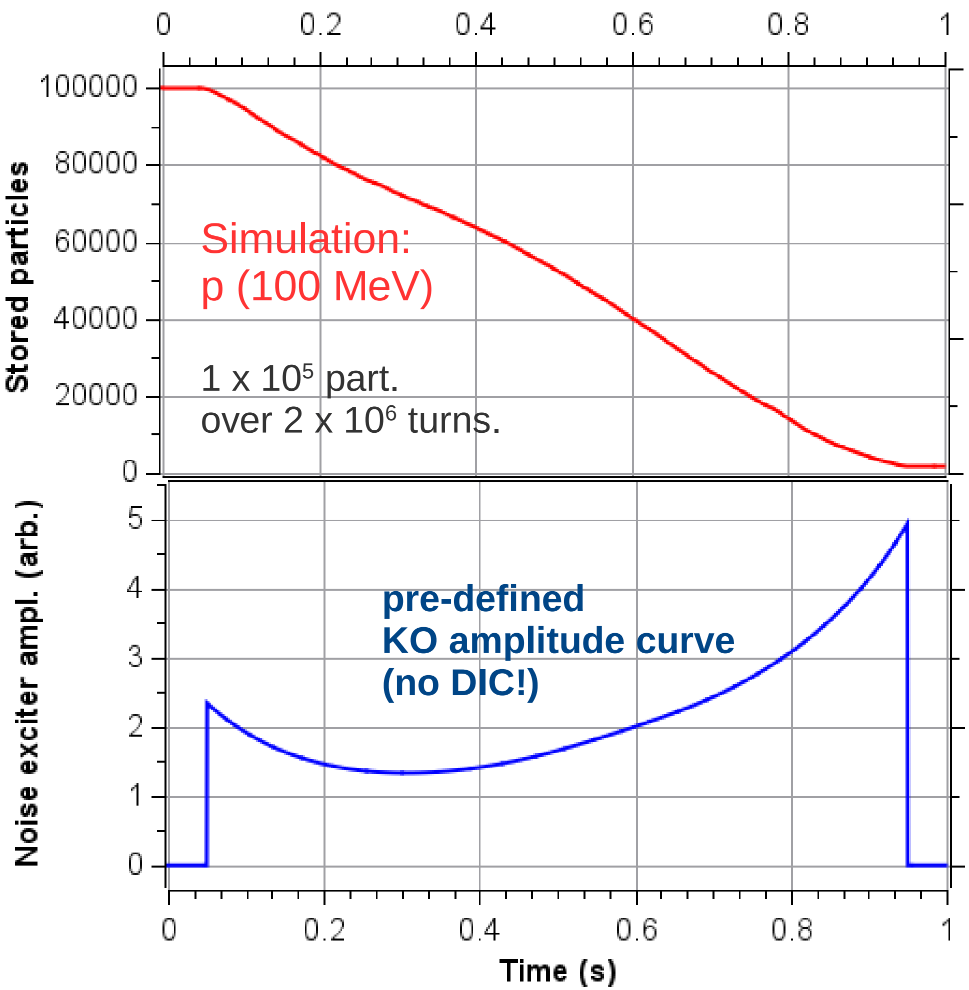
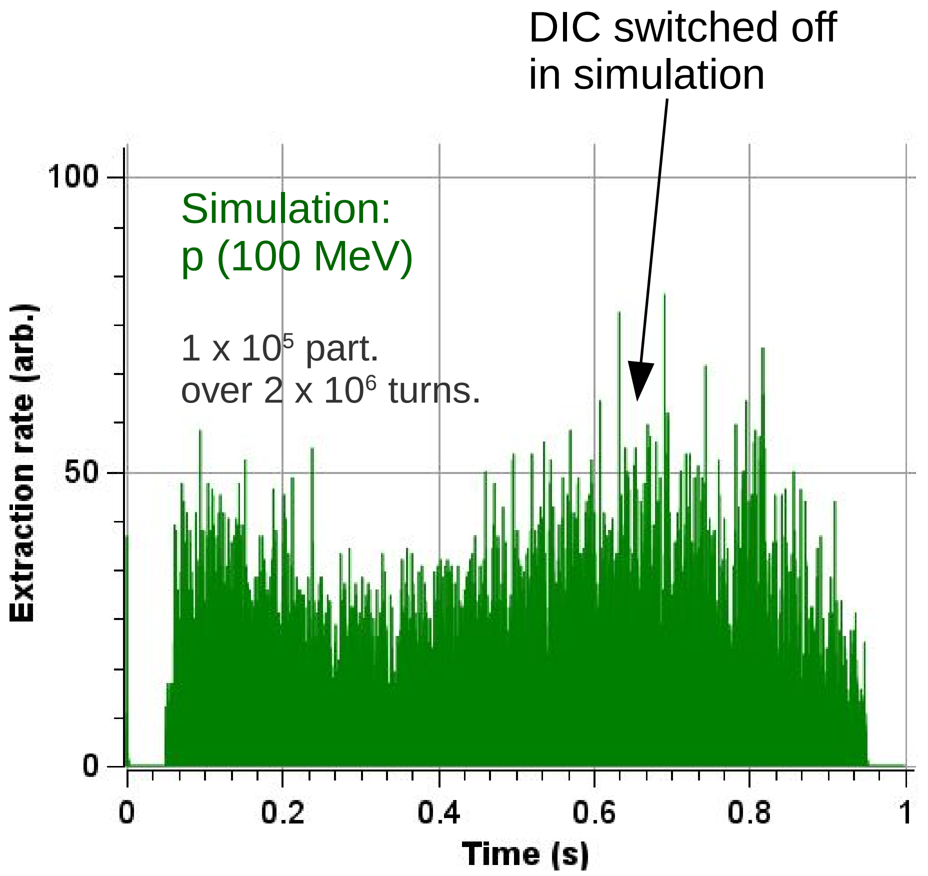
Simulations (1): Spill macro- and microstructure

Ongoing project (in collaboration with HIT): Simulations of particle extraction.

Aim at better understanding of spill micro-structure and variation of beam properties during spill.





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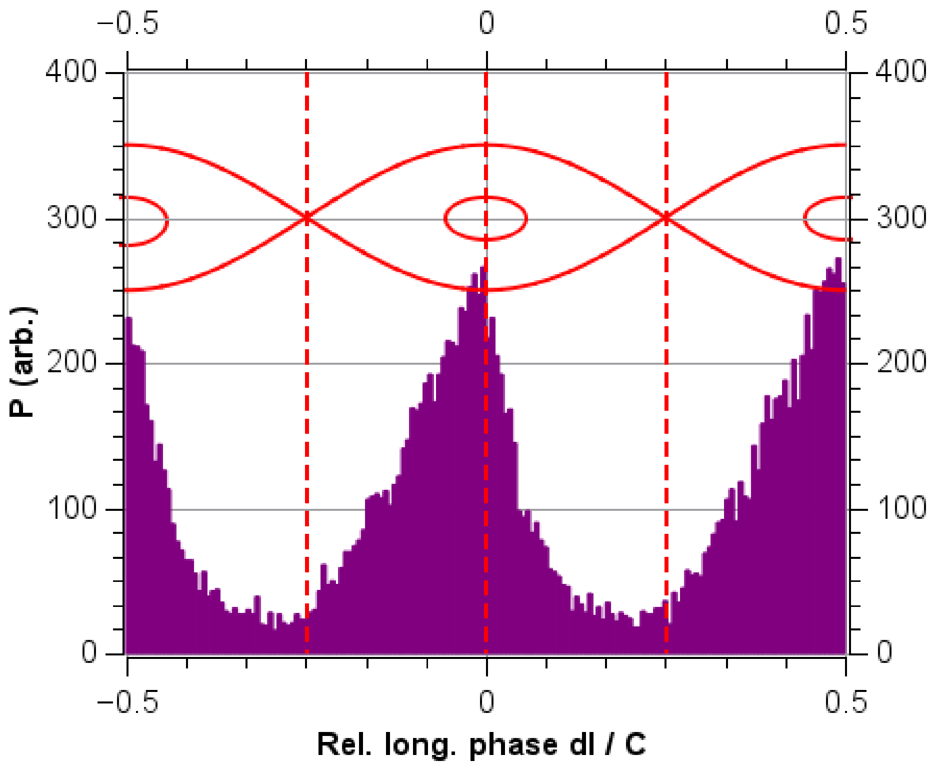
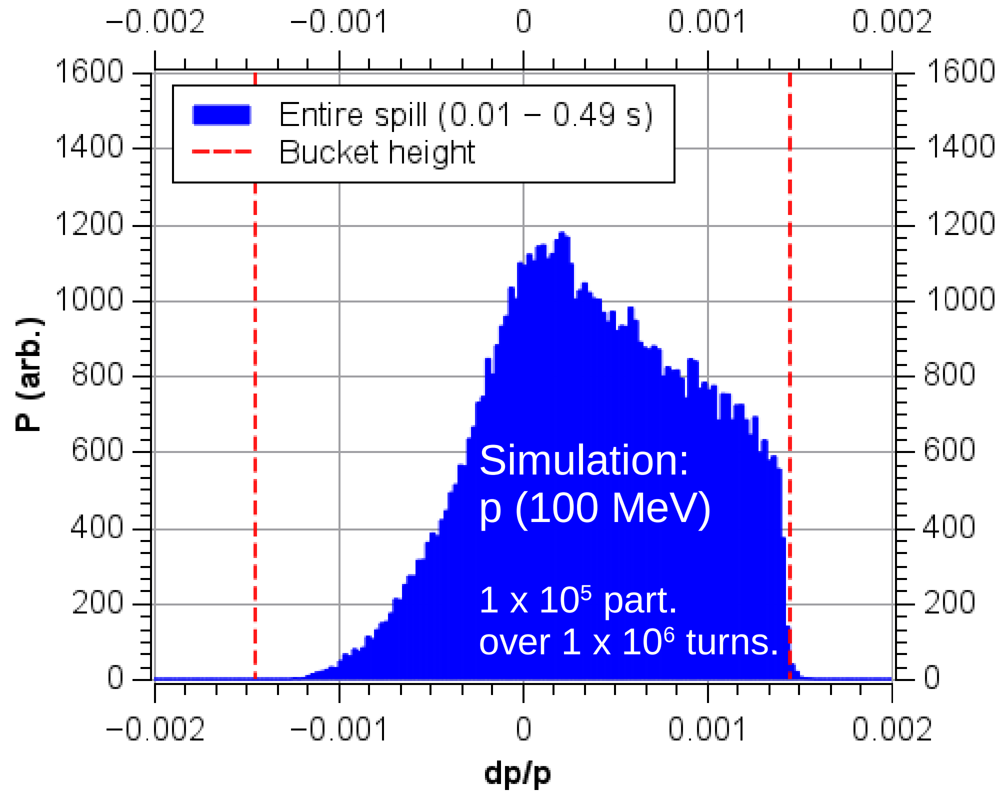
Simulations (1): Spill macro- and microstructure

Example: Effect of synchrotron motion:

Longitudinal coordinates of extracted particles relative to reference.





Due to chromaticity, particles in one half of the bucket are closer to resonance.

At MIT: $Q_h \sim 1.7$, $\xi < 0$ → dp/p > 0 is preferred.

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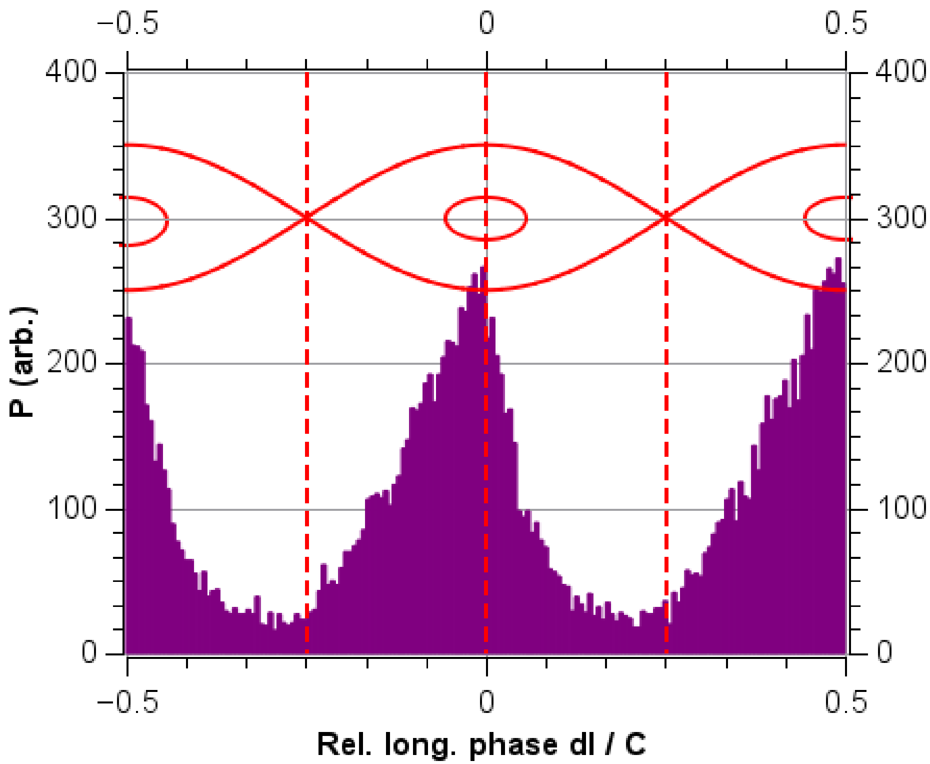

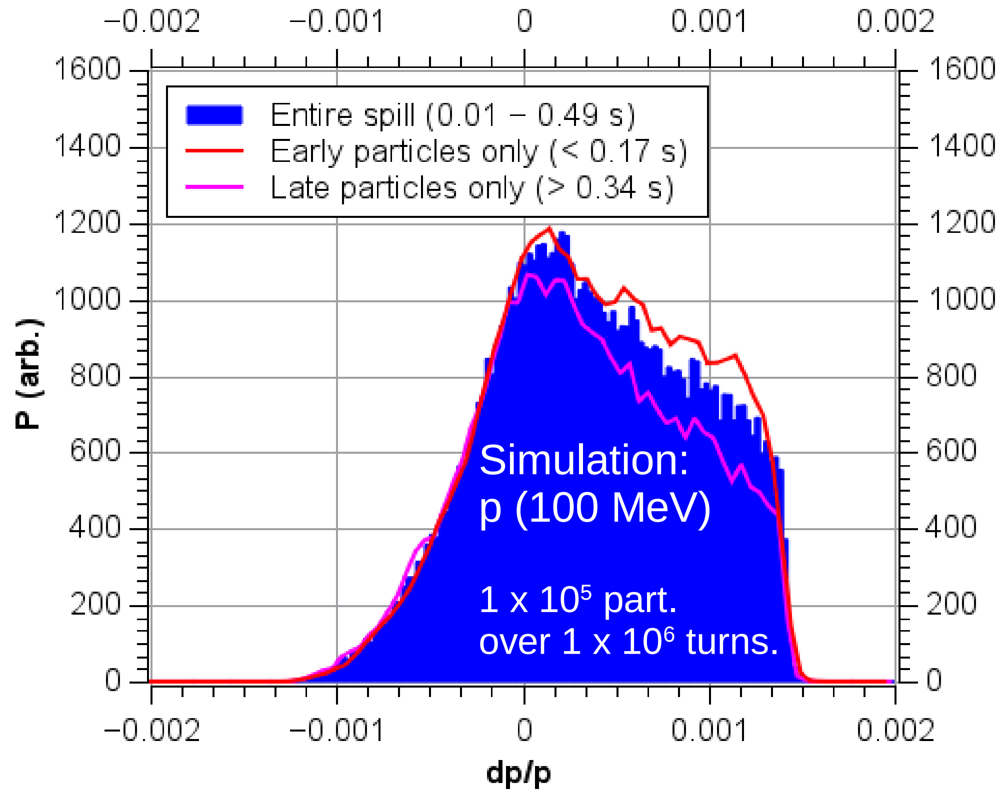

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At MIT: $Q_h \sim 1.7$, $\xi < 0$ → dp/p > 0 is preferred.

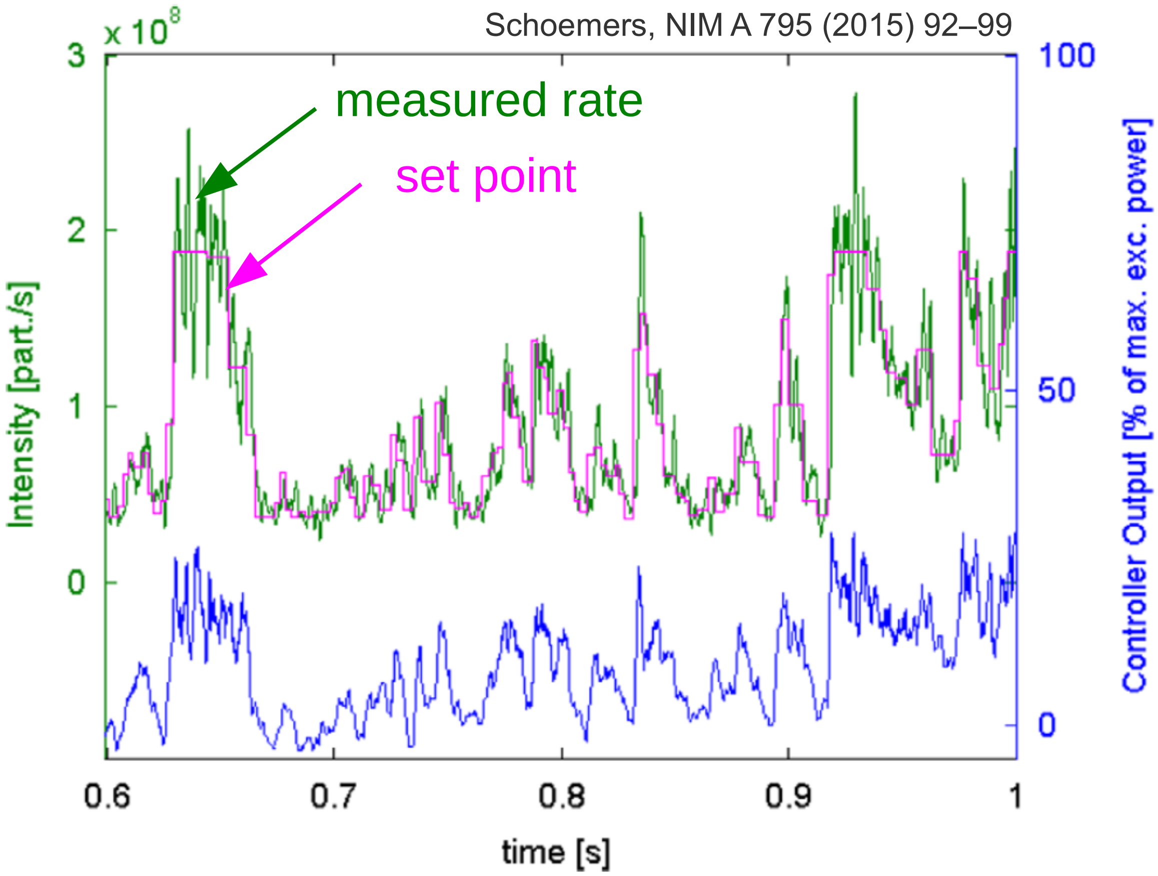
Large dp/p get extracted first. Does this affect observable beam properties (like envelope size and position)?

Work in progress!

Dynamic Intensity Control (2)

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).



Dynamic Intensity Control (2)

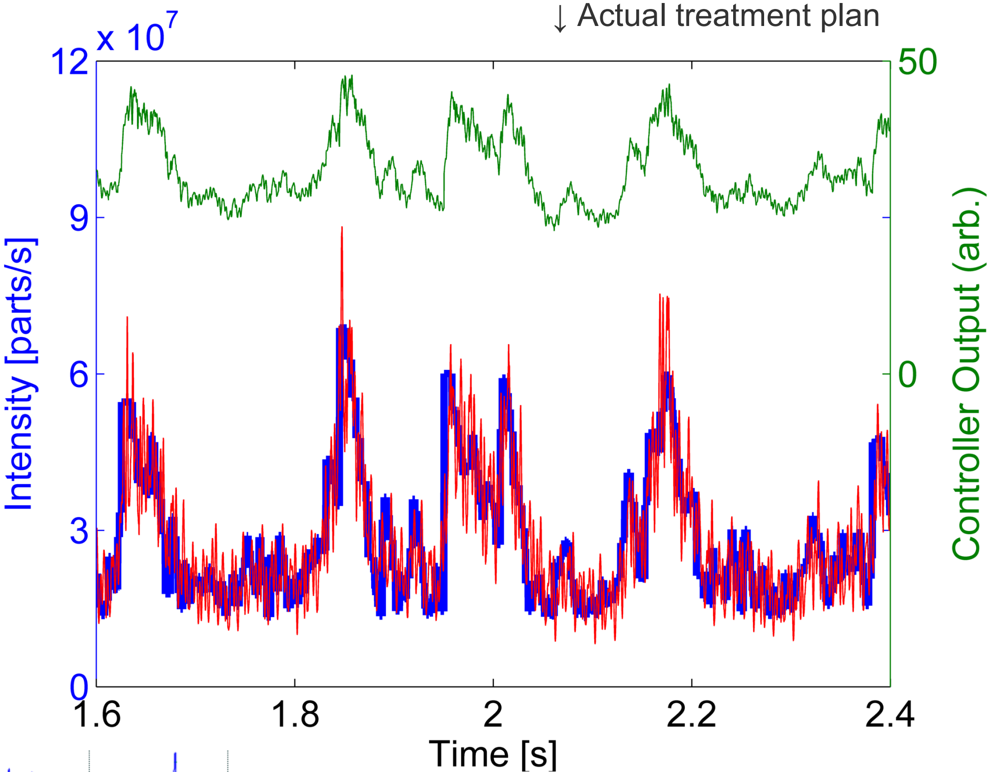
The Marburg system uses this feature heavily.

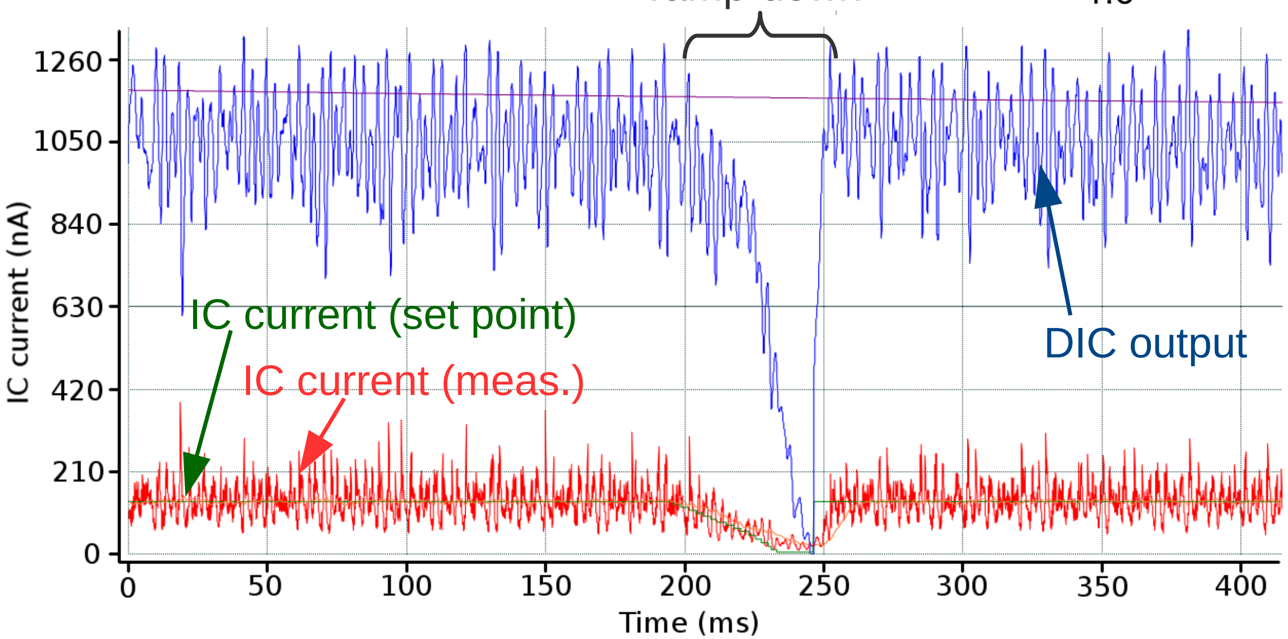
Irradiation plans may include jumps in the extraction rate by up 33 x
(in both directions!).

Most challenging (accelerator set-up):

Have extraction rate follow a fast (~ 10 ms) ramp-down from high to low intensity.

↓ Actual treatment plan





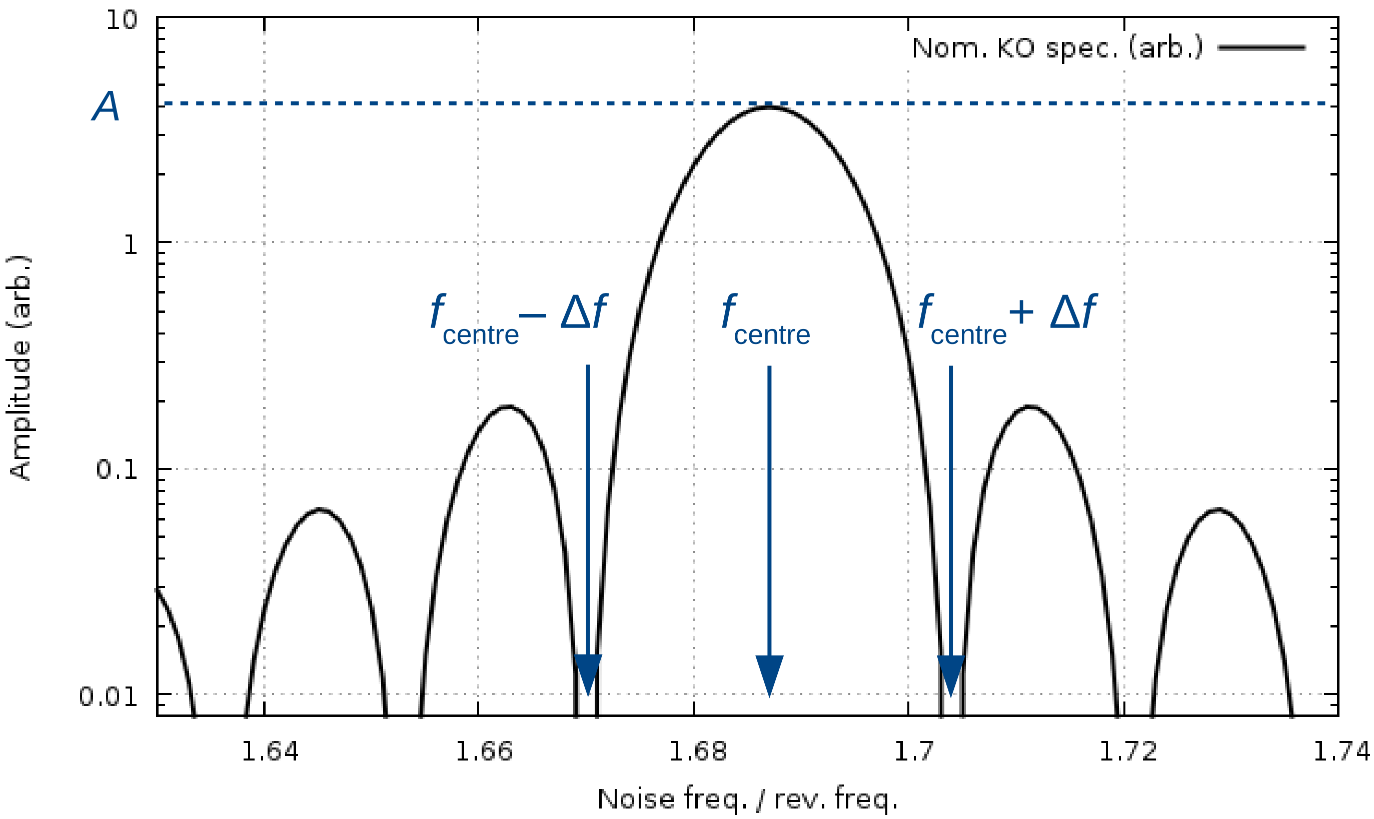
←
Benchmark plan to test ramping-down behaviour of extraction rate.

Dynamic Intensity Control (2)

KO exciter noise is generated by random phase-shift keying (PSK) of a sine signal.

→ During accelerator set-up, 3 parameters "predefine" the noise kicker spectrum: A, f_{centre}, Δf .

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



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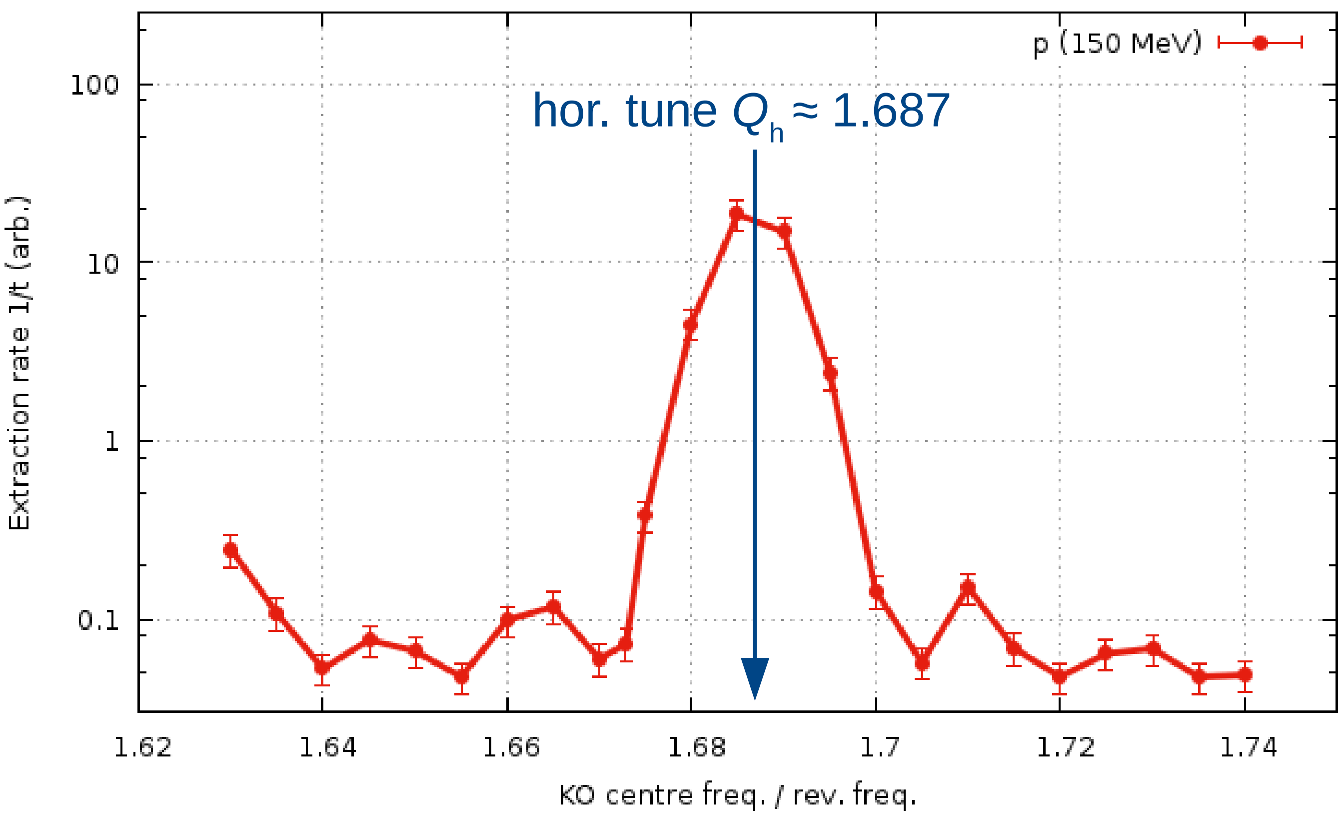


KO noise spectrum becomes visible when the mean beam loss rate 1/τ from the synchrotron is measured vs. f_{centre}

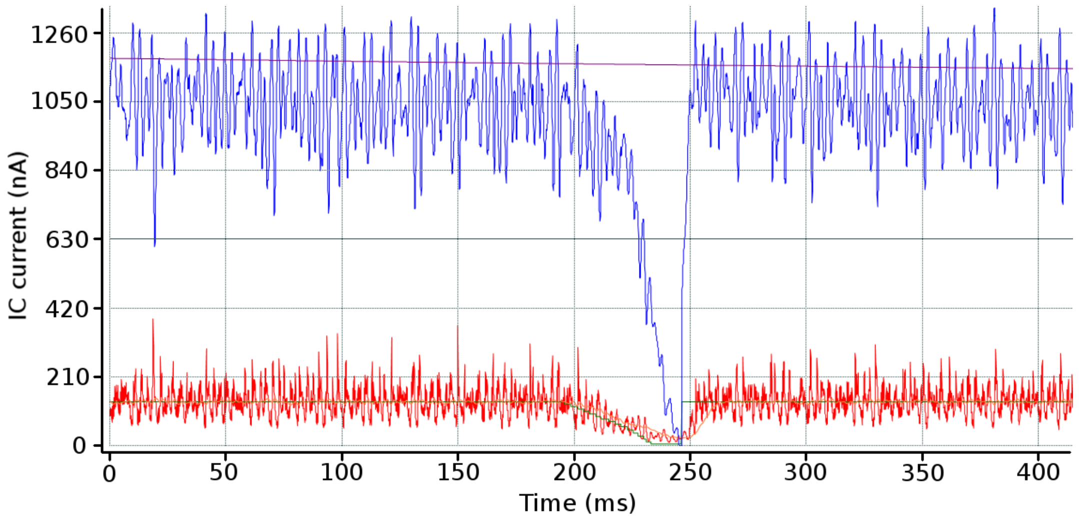
Highest extraction rate with $f_{centre} / f_0 = Q_h$

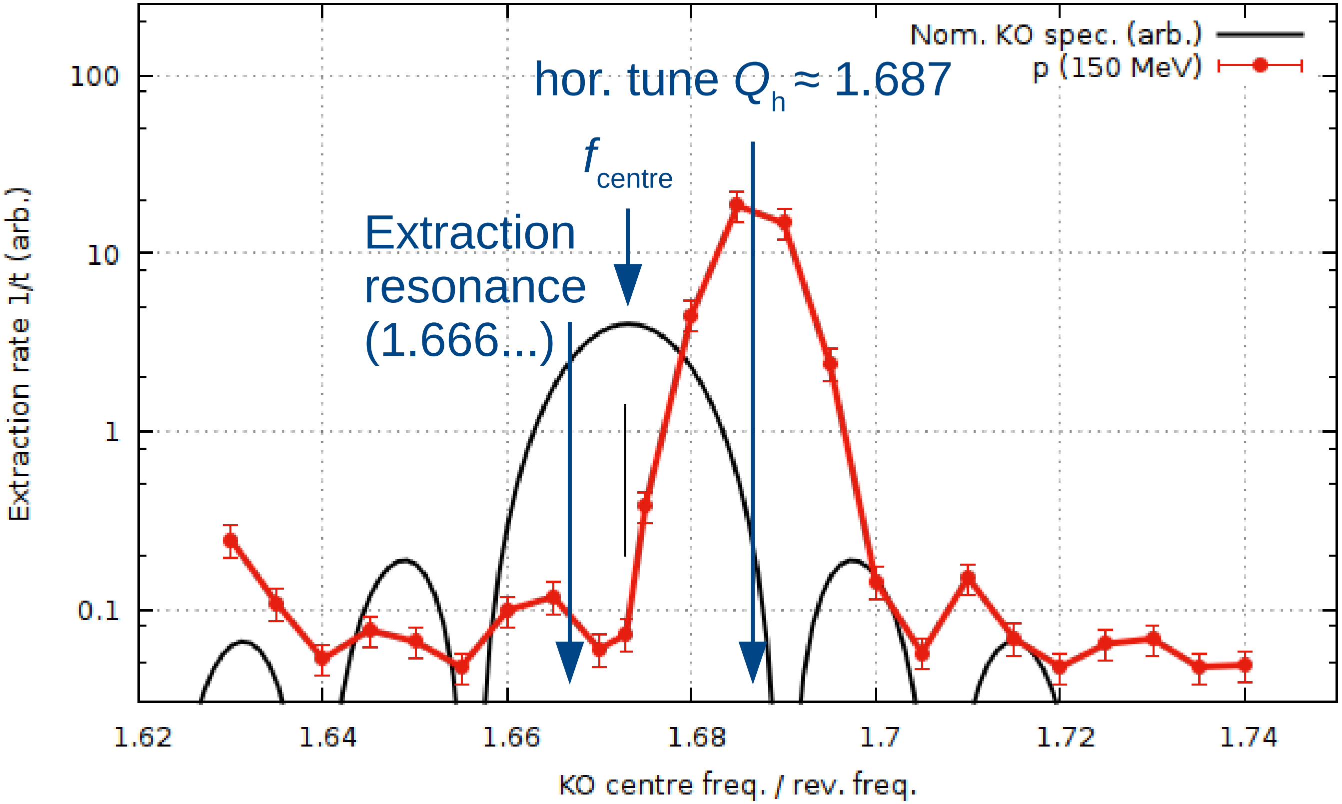
Dynamic Intensity Control (2)

Best ramp-down behaviour:

(lots of trouble at first ...)

KO spectrum "detuned" so that f_{centre} lies in-between the particle tune and the extraction resonance.





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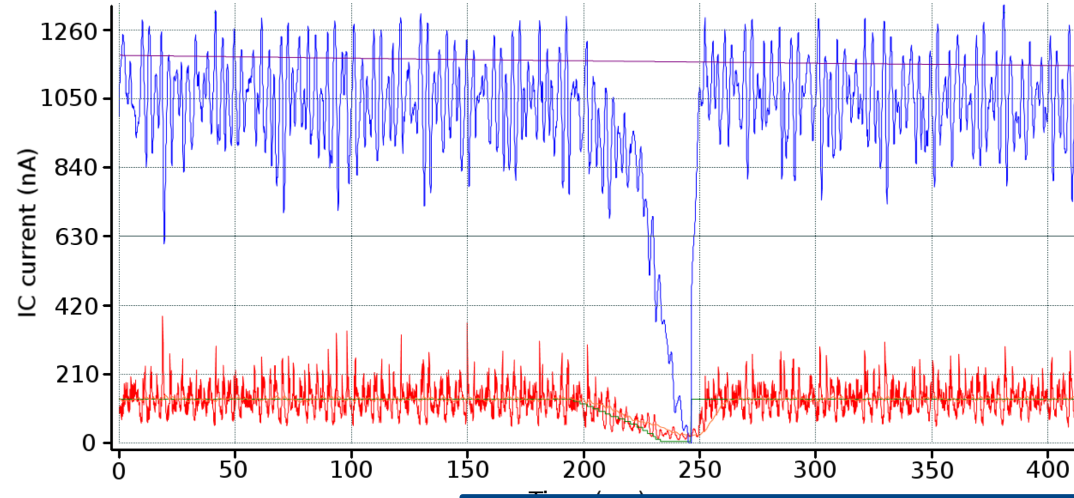
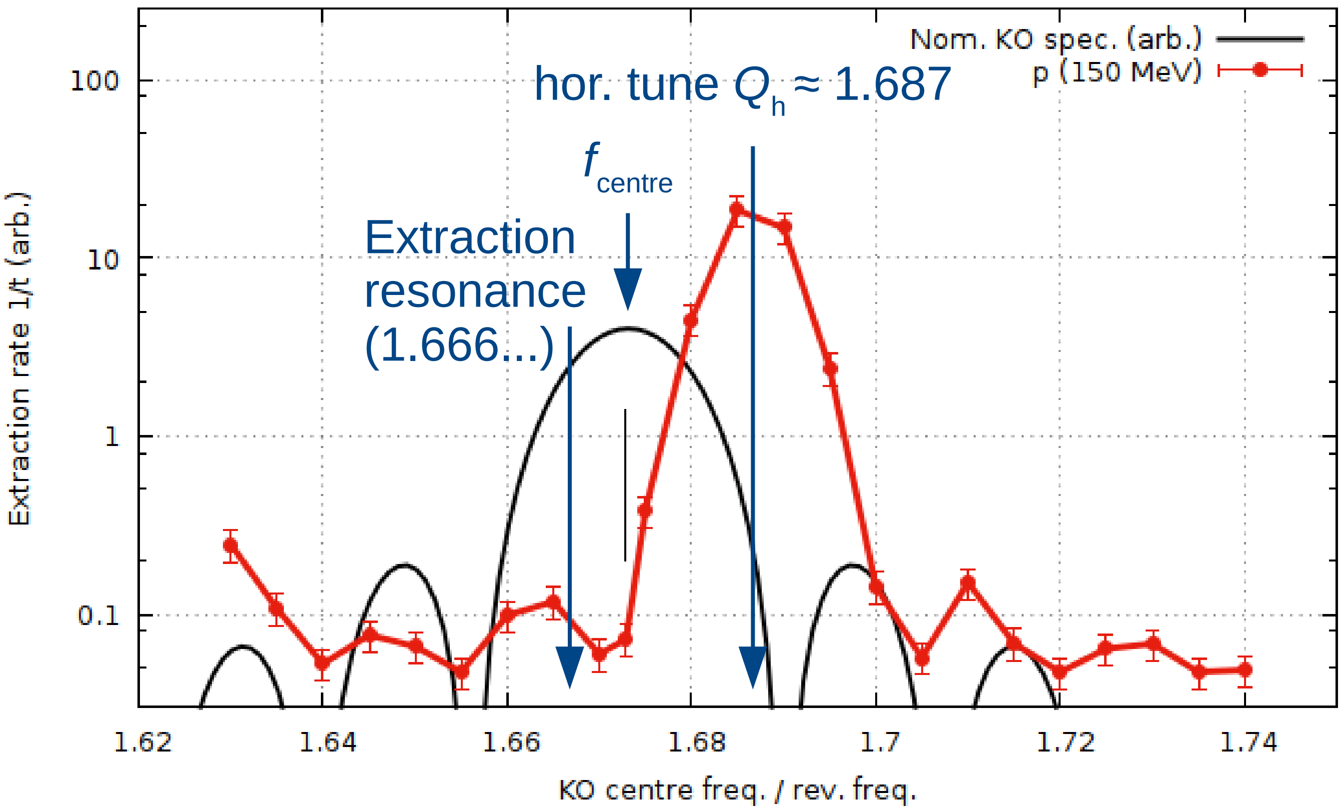
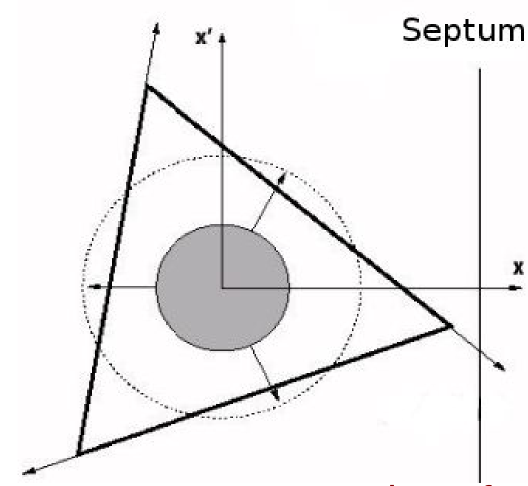




Explanation:

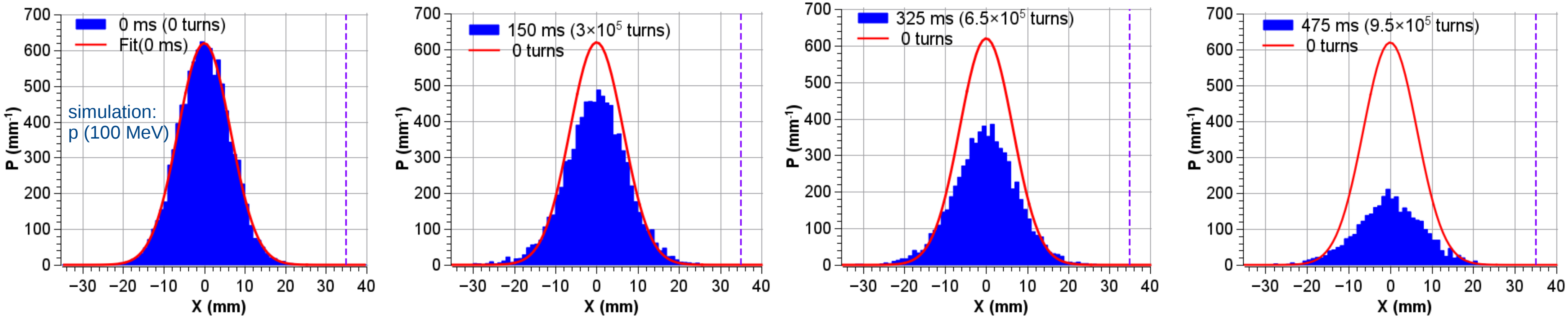
Excite particles at large amplitudes first.



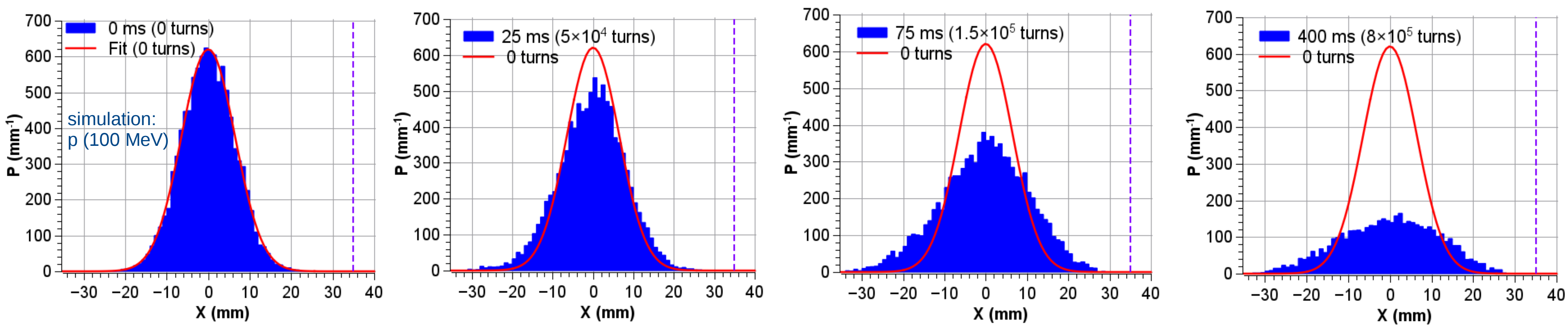
→ Prevents creation of “unnecessary” beam halo.

Simulations (2): Exciter frequency

KO centre freq. "detuned": Particles in halo are rapidly extracted, beam core keeps its shape.
→ Expect good down-ramping behaviour of spill rate **:-)**



KO centre freq. = particle tune: Beam core is excited, large unstable halo.
→ Spill goes on even when KO exciter is switched off. **:-(**



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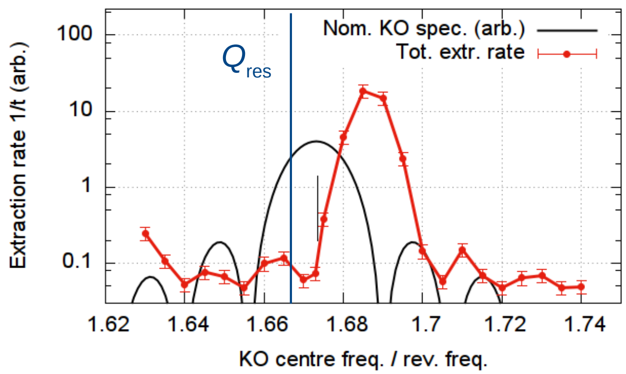
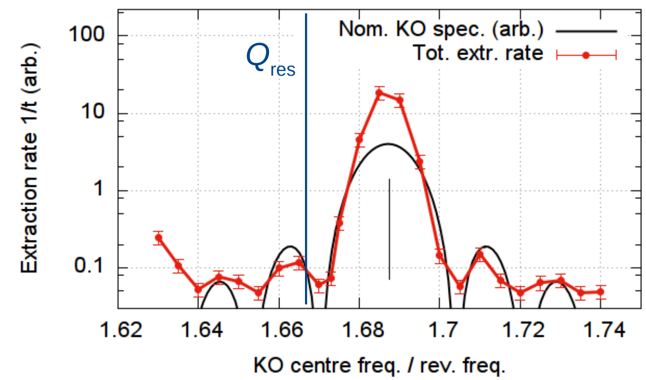
Simulations (2): Exciter frequency



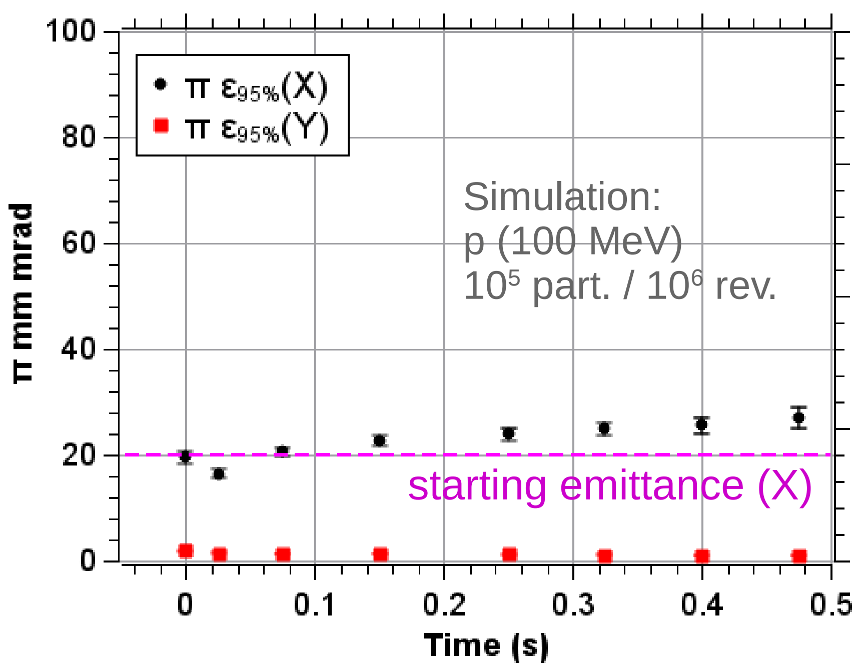


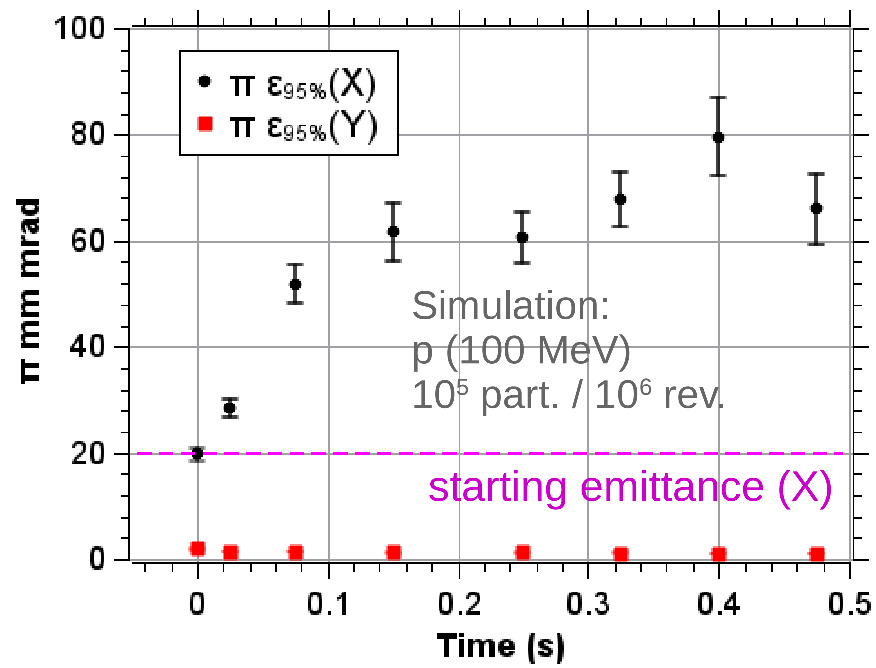
Noise centre freq. "detuned"

→ Weak horizontal emittance growth.

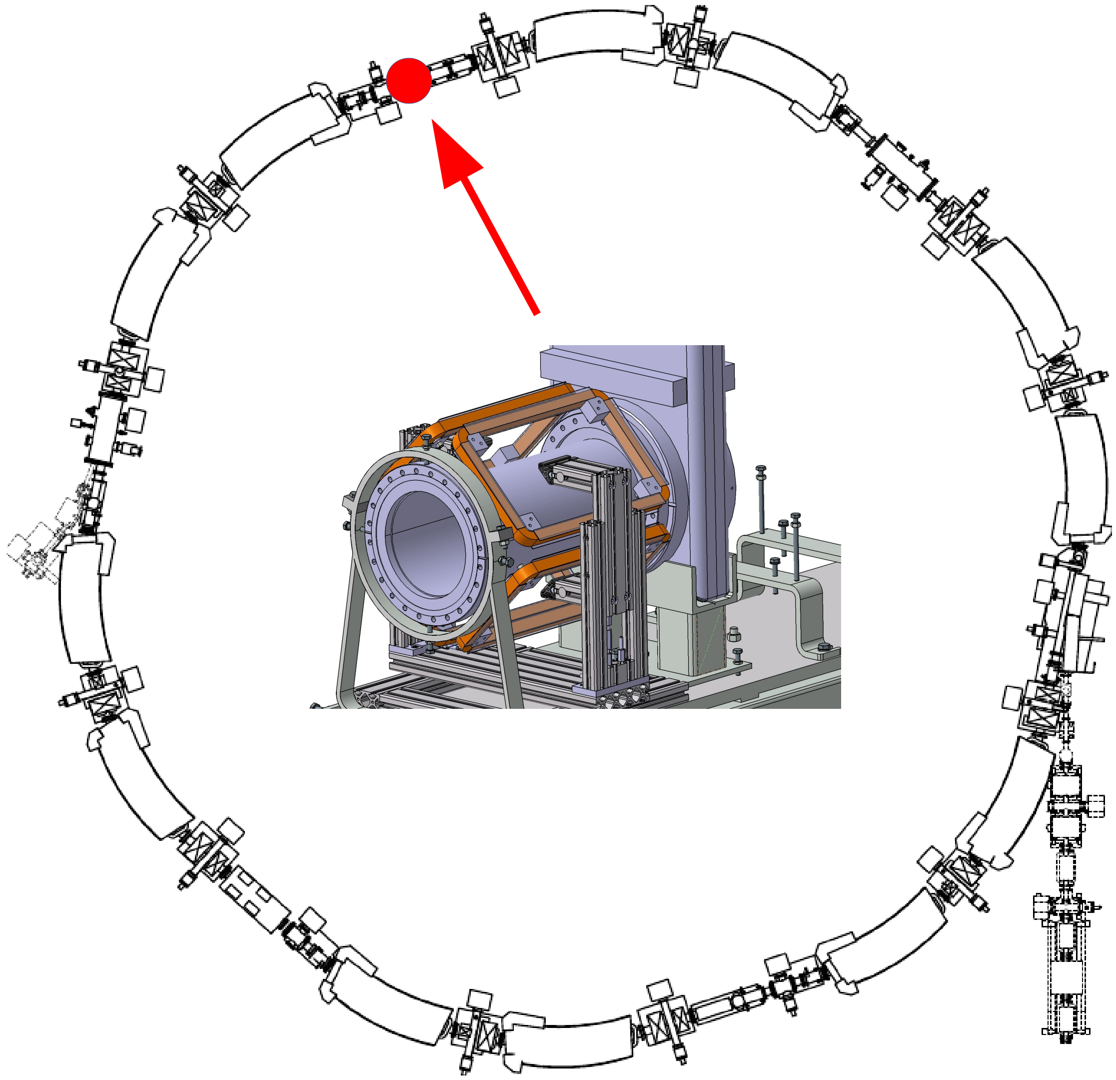
Noise centre freq. = particle tune

→ Strong horizontal emittance growth.

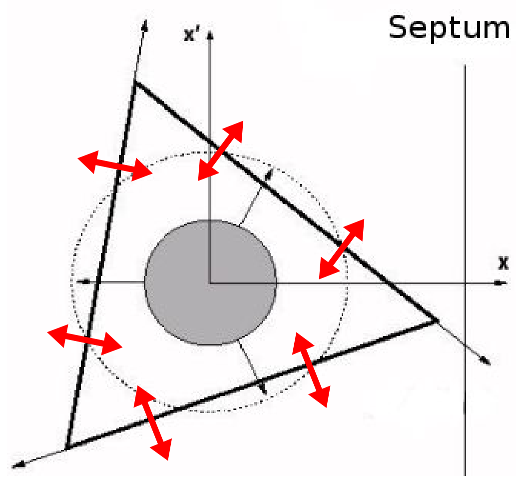




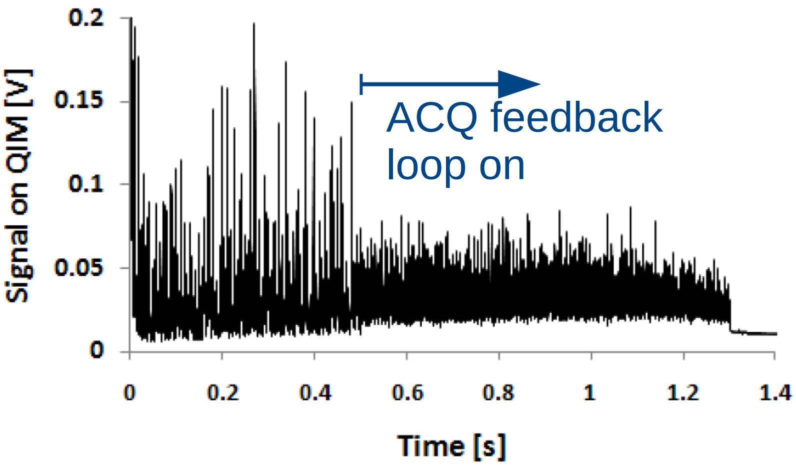
Outlook: Fast tune variations



Air-core quadrupole (ACQ)
for fast (< ms) tune modulations.



Good previous experience at CNAO:



Cracciolo et al., Proc IPAC 2011

Thanks to M. Pullia for sharing technical information!!

MIT
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Outlook: Fast tune variations

Designed for tune shifts

$\delta Q_h \sim 10^{-3} \ldots 10^{-2}$

at rigidity of C / p therapy beams.

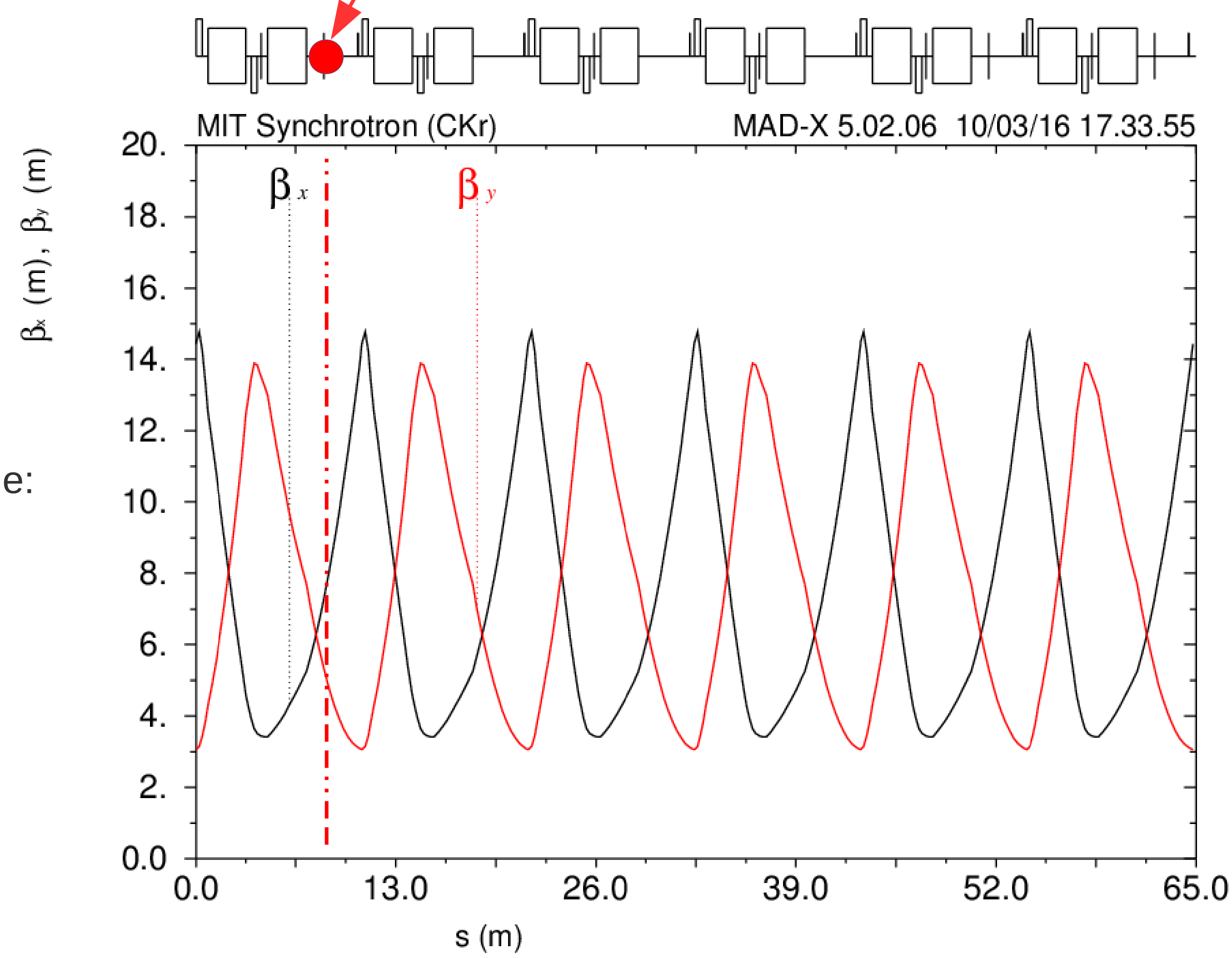
Due to spatial constraints vertical tune shift at MIT is almost as large as horizontal one:

MIT: $\beta_h / \beta_v \sim 1.5$

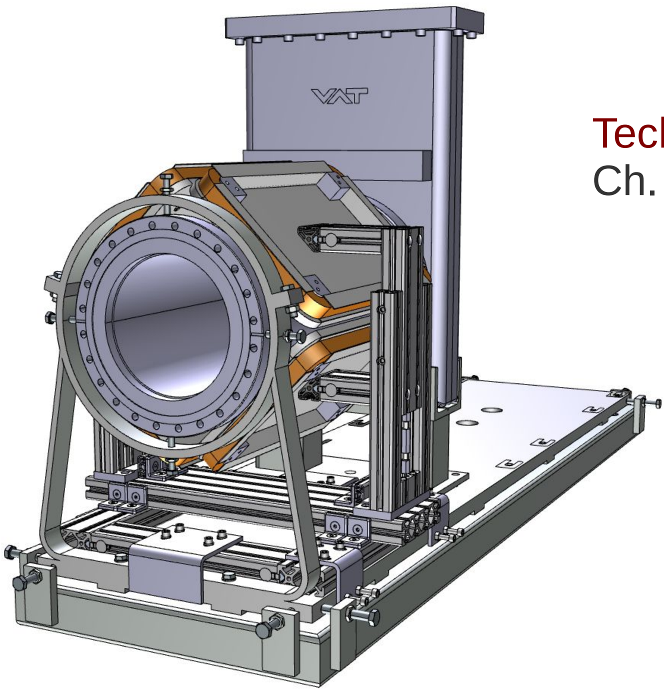
ACQ magnet will also be compatible with Heidelberg (HIT) synchrotron.

HIT: $\beta_h / \beta_v \sim 3$

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



Outlook: Fast tune variations



Technical design:
Ch. Dorn (GSI/HIT)

Current amplifier
(HIFI, off-the-shelf)
→ I_{peak} > 10 A into 4 Ω up to 40 kHz

Magnet assembly now starting …

… first experiments planned for 2018

- Quantify effects of tune ripple injection.
- Smoothing of spill by separatrix "blurring"?
- Interplay of ACQ and KO-excitation.
- Active feedback/-forward loops.
- …

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U. Scheeler, C. K., B. Kröck,
A. Weber, M. Witt,
Th. Haberer

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

Thank You for your Attention.

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