HEIDELBERG UNIVERSITY HOSPITAL

Heidelberg Ion-Beam Therapy Centre

Slow extraction @HIT – Experiences and Developments

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Kick-off Meeting for I.FAST-REX / Resonance Extraction Improvement, Virtual Meeting, 8th/9th February 2021

UK HD

OUTLINE

- Introduction
- RF-KO system at HIT and motivations for enhancements
- Intensity feedback loop (“DIC”)
- Further Upgrade: Intensity-modulated spill
- Summary and Outlook
- Acknowledgements

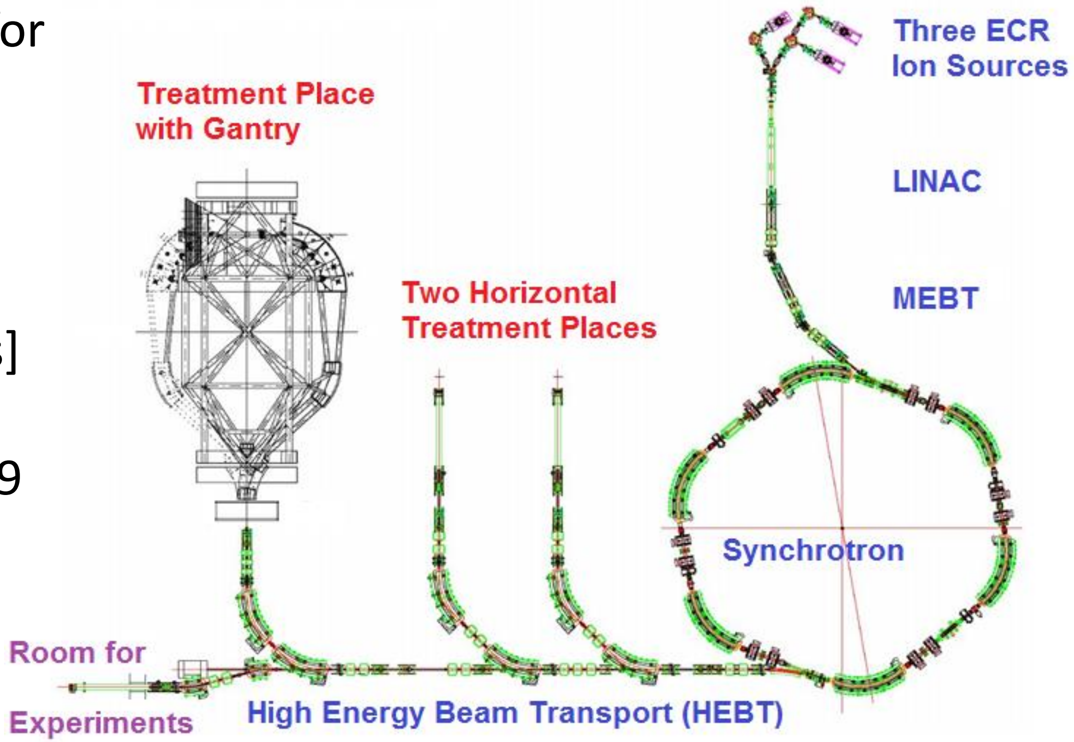
Introduction - The **H**eidelberg **I**onbeam **T**herapy facility

Dedicated Accelerator complex for tumor treatment with:

- p and He beams up to 230 MeV/u
- C beams up to 430 MeV/u

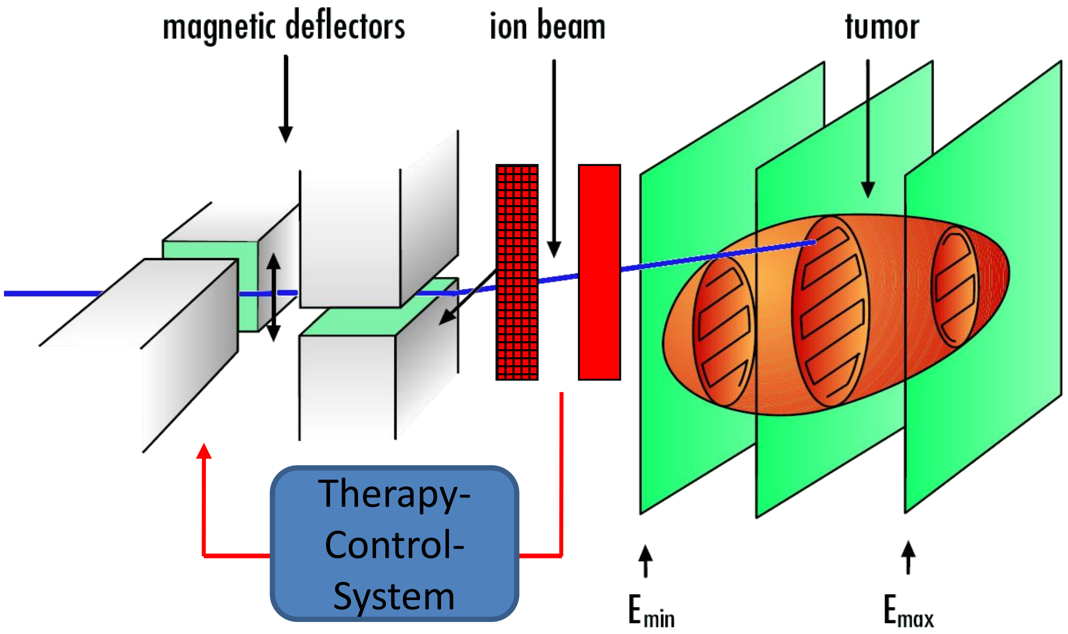
[higher energies for experiments]

Patient treatment started in 2009 (Gantry: 2012)
Currently ~ 700 patients/year
(> 600 patients in 2020)
Total: > 6500 patients treated



Introduction - Dose delivery by raster scan method

- At HIT the *raster scan* method is used
- Tumor is irradiated slice-by-slice and spot-by-spot
- Scanning process needs ~milliseconds per spot
- Beam spill of several seconds is needed
- Position and intensity is measured, the scanning velocity is adapted



Introduction – the beam "wish list"

- Beam position: ± 0.5 mm
- Beam spot: 2D-Gaussian ± 15% FWHM
- Intensity:
  - „well-tempered"
  - triggered extraction for breath hold dose delivery
  - spill pause function
  - dynamic intensity control ~ 1 ms
  - higher intensities: ~10^{12} (p), ~10^{10} (C) per spill for radiosurgery and multi-energy and/or breath hold dose delivery

From: T. Haberer, Slow Extraction Workshop, 2016, Darmstadt, Germany

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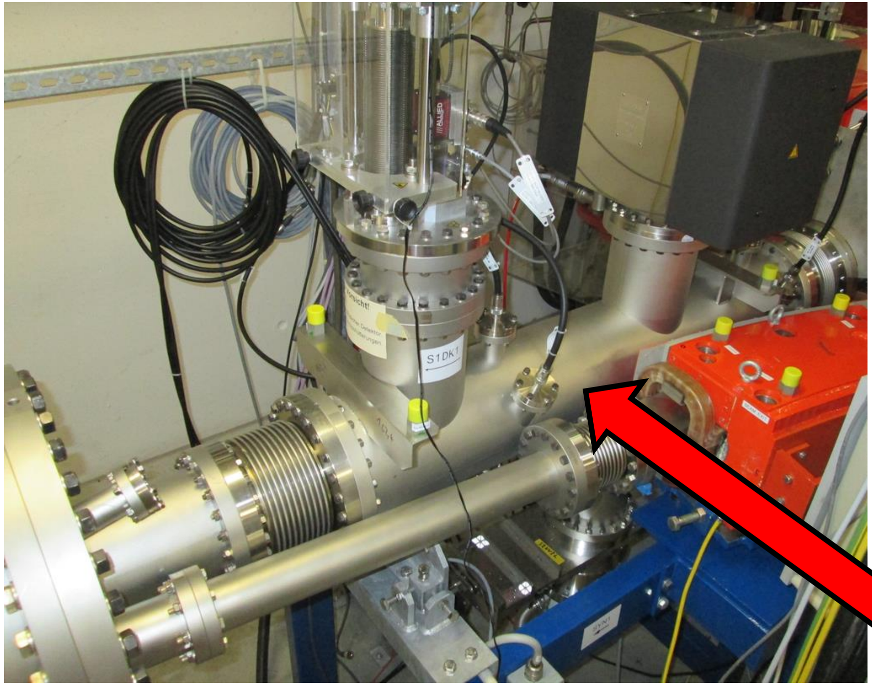
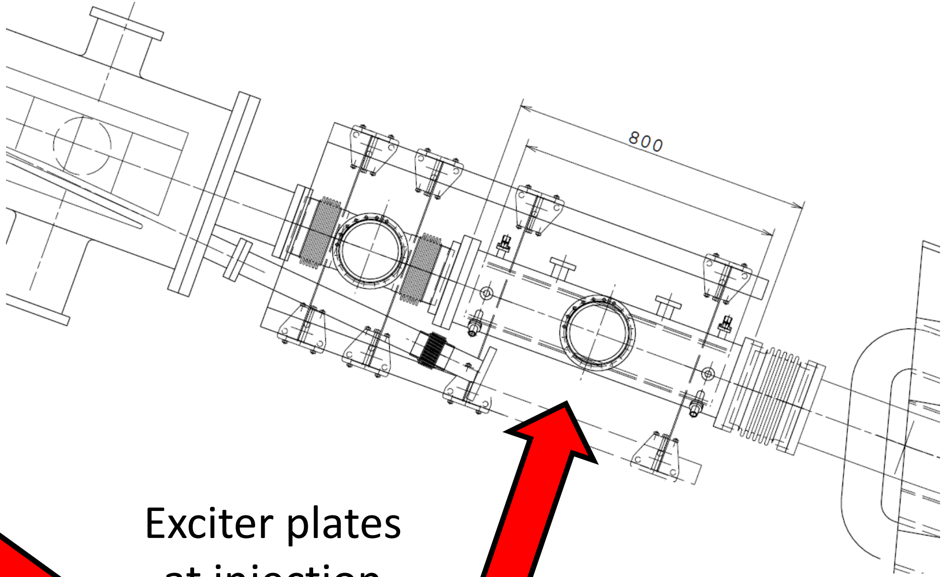
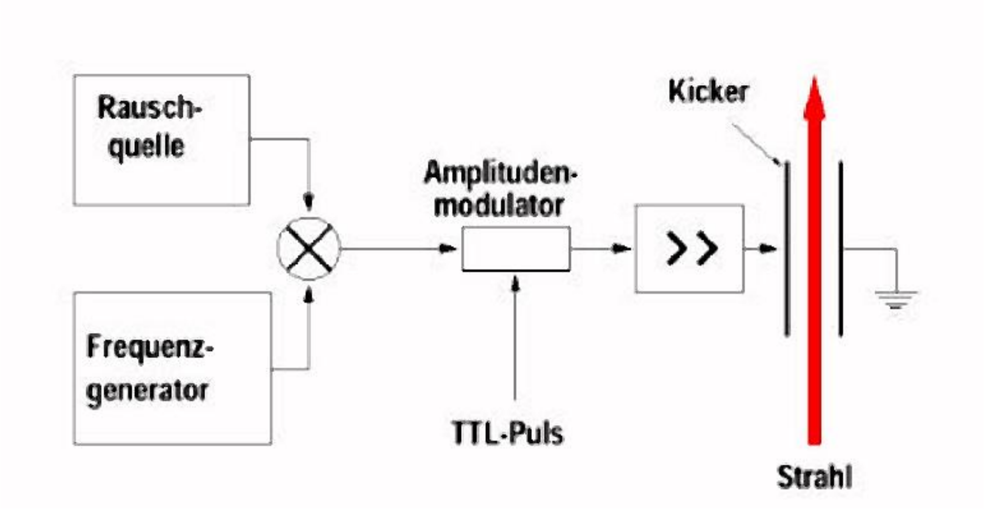
RF-KO system at HIT – mechanical installation

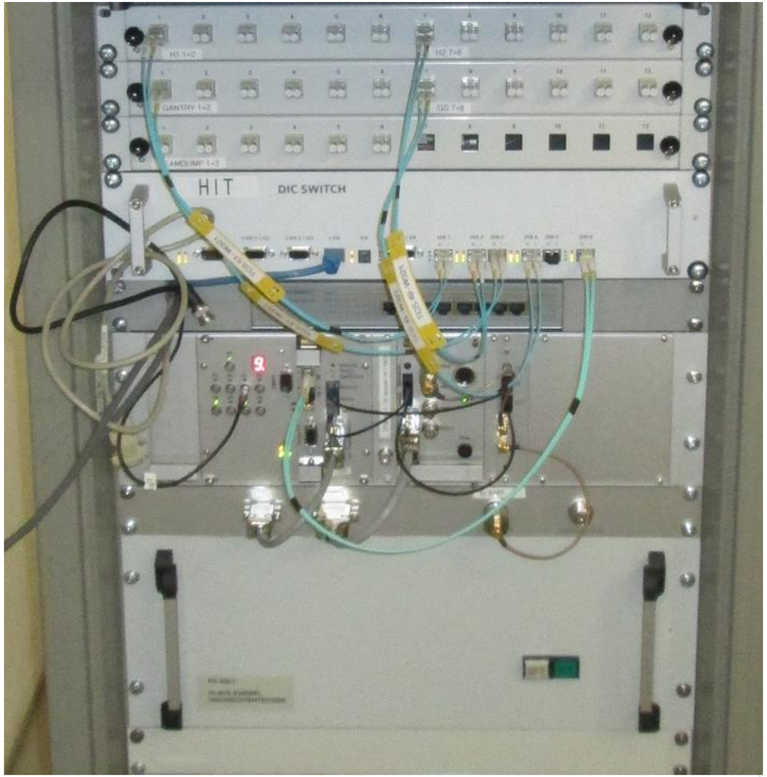




Exciter plates at injection section

RF-KO system at HIT – RF amplifier & control

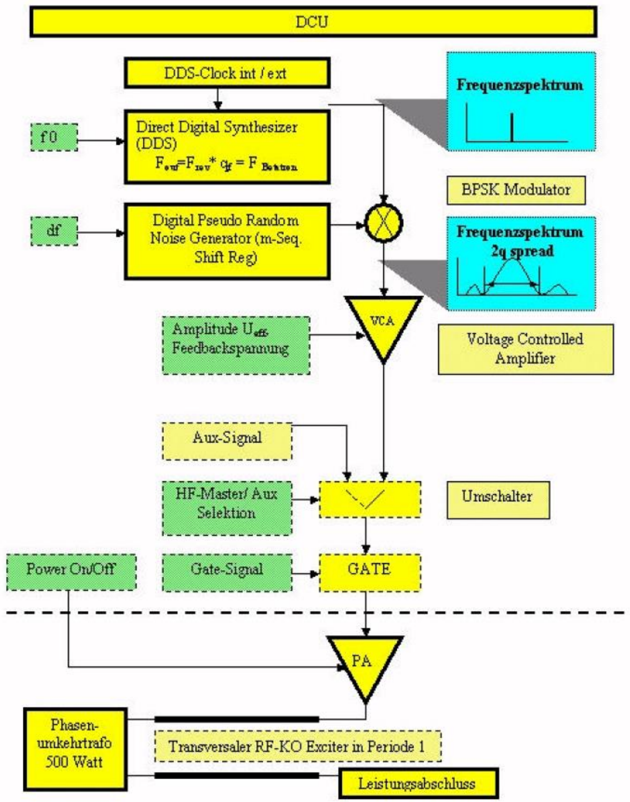




RF-KO system at HIT – signal generation in detail

Flowchart of signal generation:

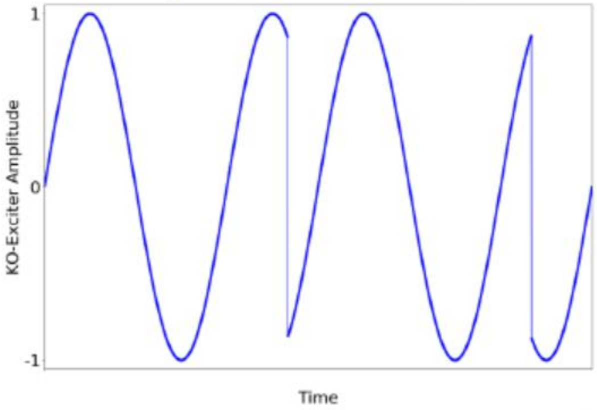
- DCU sets parameters generated by the *data supply model*
- Direct Digital Synthesizer providing a *Pseudo random binary phase shift keying (PRBPSK)* signal
- Power amplifier
- Passive electronic elements in the tunnel



RF-KO system at HIT – used frequency spectrum

Excitation method: Pseudo random binary phase shift keying (PRBPSK)

Exemplary excitation signal

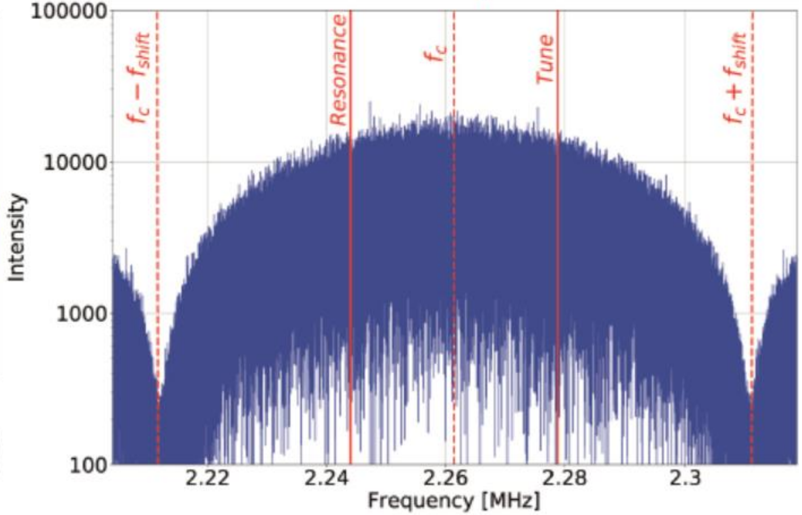


$$V_{KO}(t) = \widehat{V}_{KO} \cdot sin\left(2\pi f_c t + \phi_{shift}\right)$$

$$\phi'_{shift} = \phi_{shift} + \begin{cases} 0, & n_{random} \leq 0.5 \\ \pi, & n_{random} > 0.5 \end{cases}$$

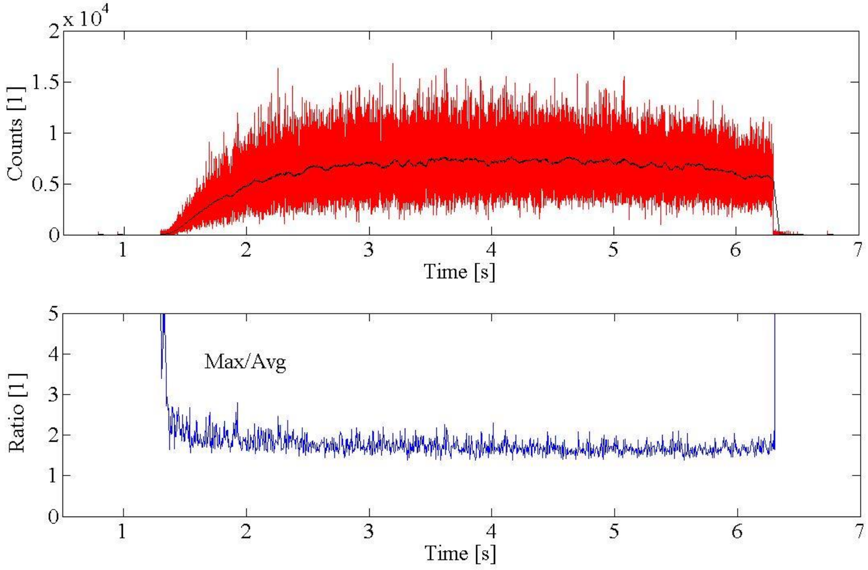
$$n_{random} \in (0,1) \; with \; f_{shift}$$

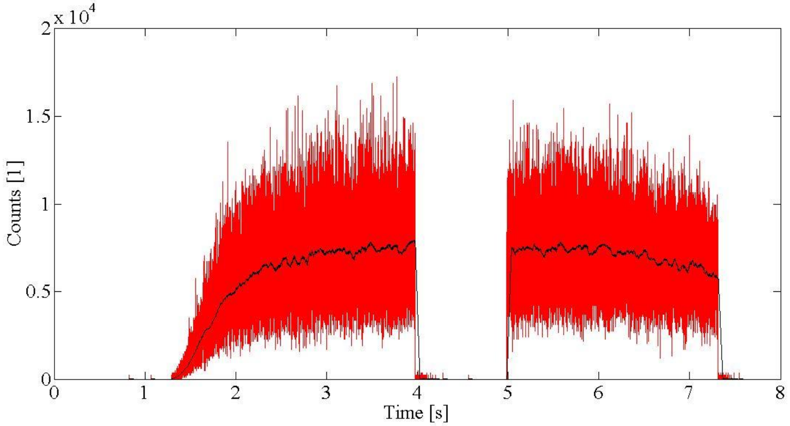
Excitation spectrum



From: F. Faber, SEW 2019, Fermilab

Typical spill with RF-KO extraction (2008)

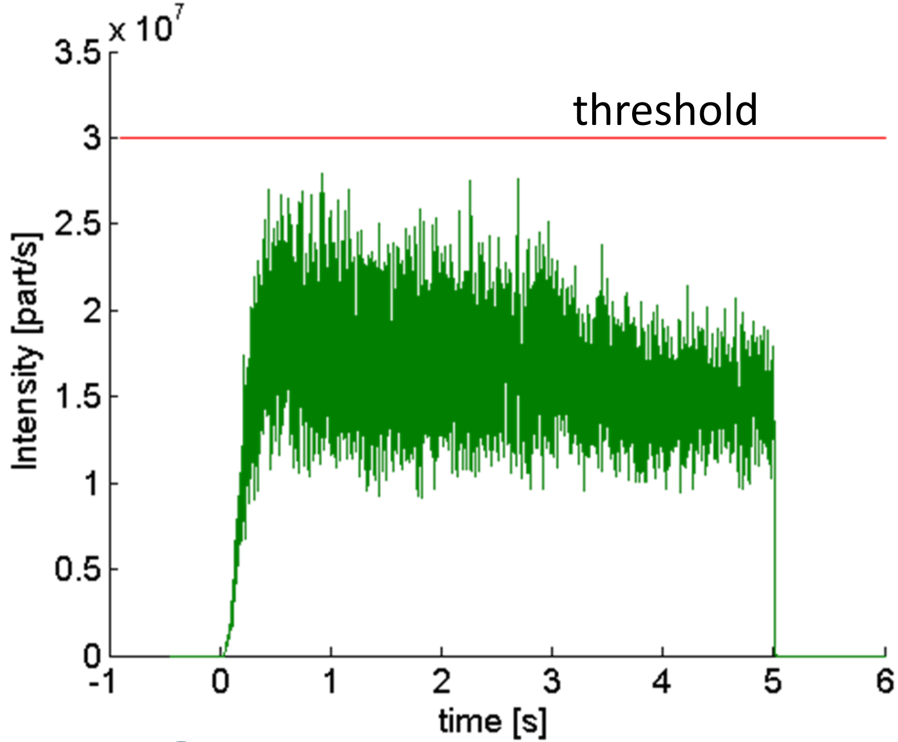




From: A. Peters et al., EPAC 2008

Spill structure measurements after synchrotron/HEBT commissioning in 2007 / 2008 using an ionization chamber

Motivation for enhancements



- Typical spill structure achieved with RF knock-out.
- Ideally as high as possible
- Reality: Scanning velocity is lower than desired.
- Spill-quality is essential for the treatment time! Spikes (above threshold) lead to interlocks!

C. Schömers et al., NIM A 795 (2015) 92-99

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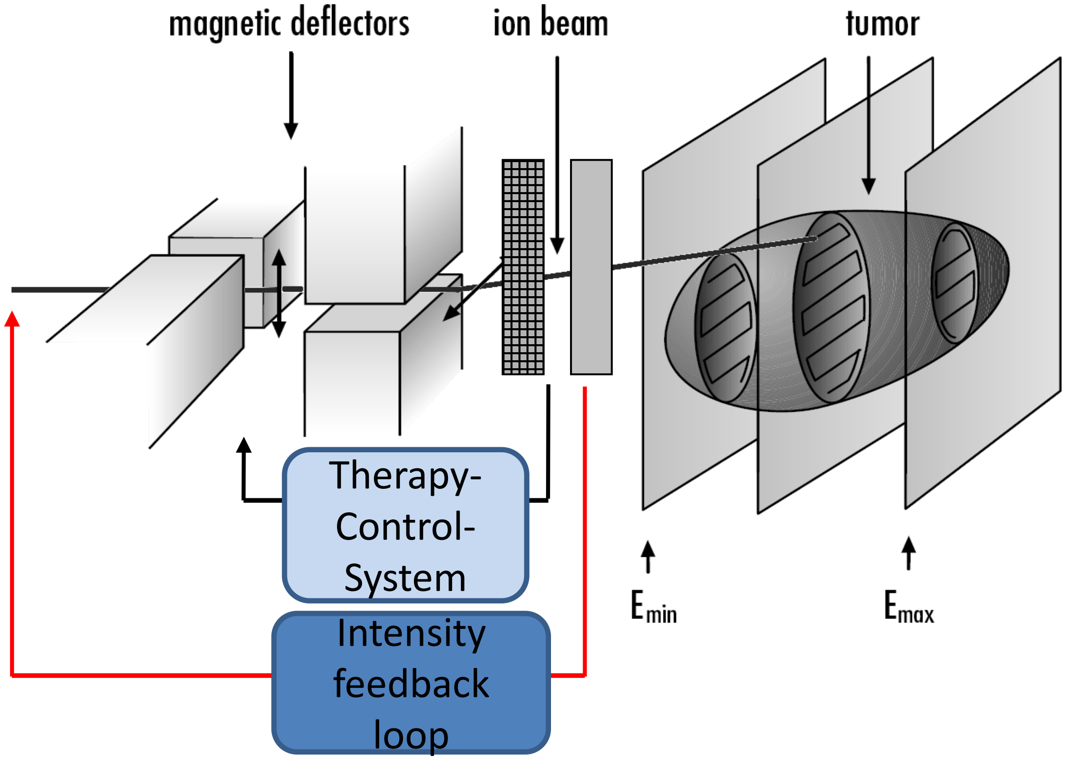
Intensity feedback loop - principle

- Use intensity signal
- Add feedback loop
- Position and intensity is measured, the scanning velocity and the intensity is adapted
- Coupling the *medical product* with the *industrial product* accelerator



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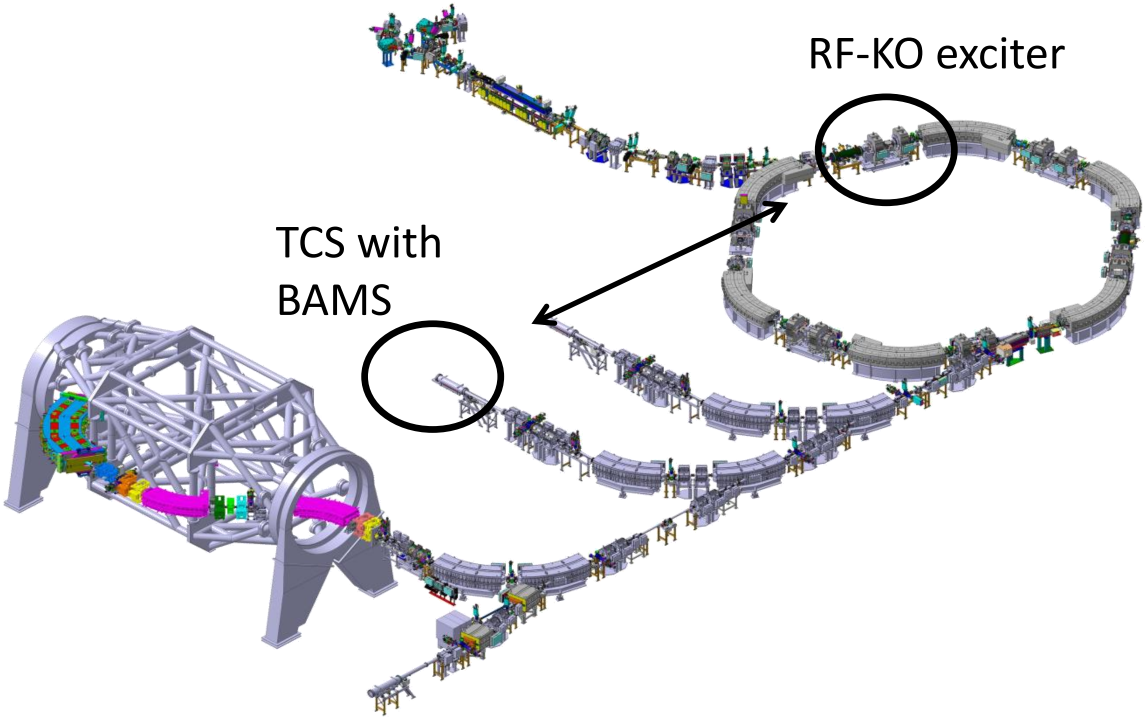
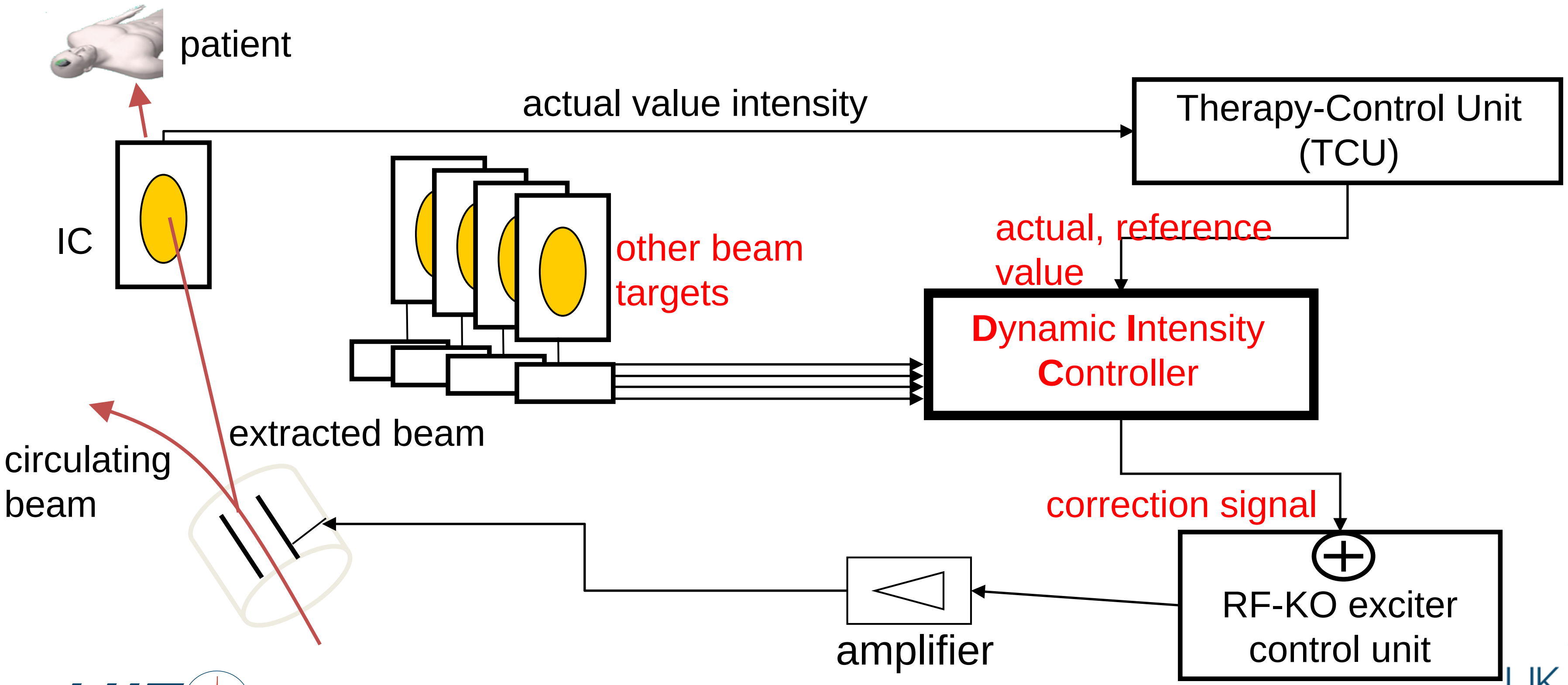


Intensity feedback loop – technical realization

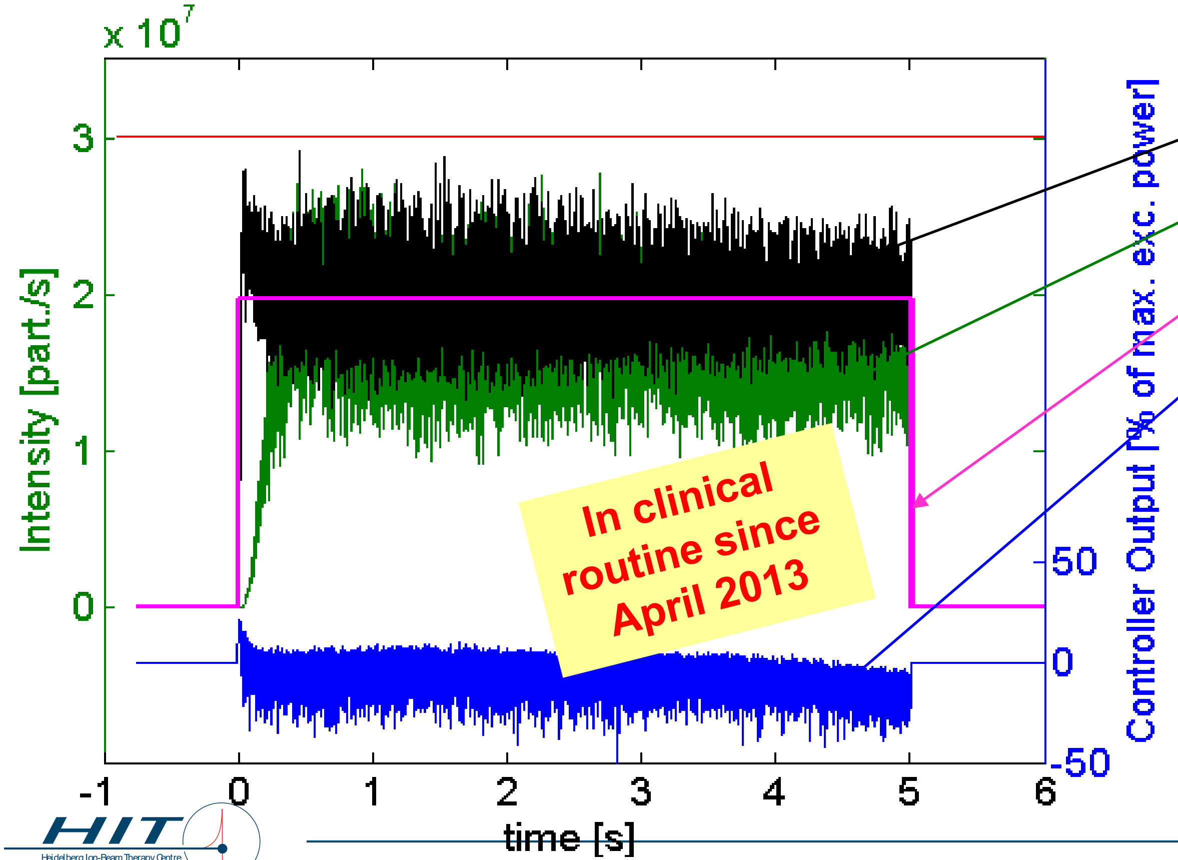
C. Schömers et al., NIM A 795 (2015) 92-99



Intensity controller details

- PID controller
  - "P" for a fast response
  - "I" for no remaining control deviation
  - "D" optional and currently deactivated
- PID-parameters as a function of (ion, energy, intensity)
  - ≈ 5000 combinations
  - 1% was defined in commissioning, than interpolated and tested
- Additional features:
  - Mechanism to mitigate intensity overshoot
  - "Early abort" – controller realizes when synchrotron is empty
  - …

Results of the feedback loop implementation



- Spill shape
  - With feedback
  - Without feedback
  - Reference value
  - Controller output
- Higher average intensity (15 %!)
- Faster irradiation
- Less machine tuning

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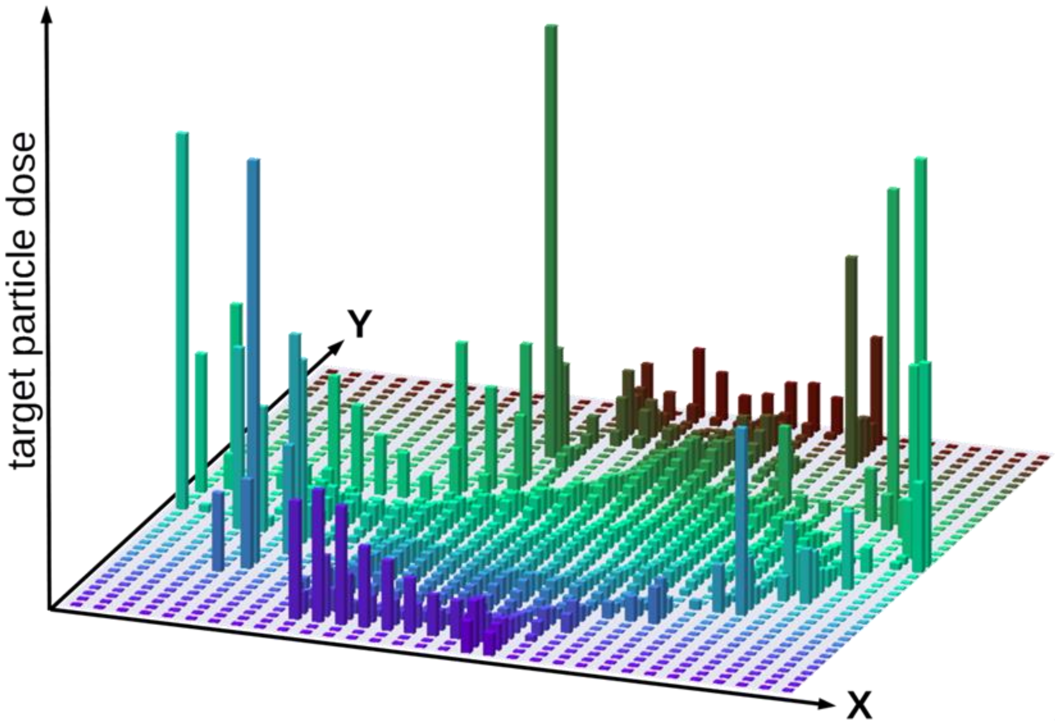
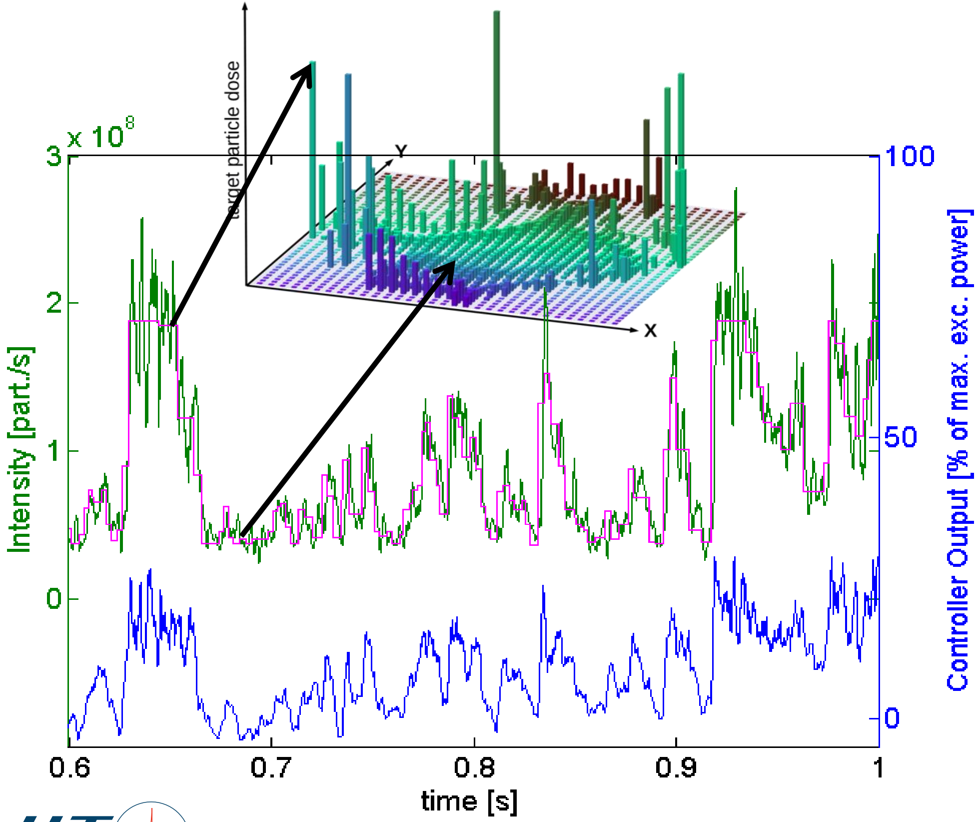
Typical dose distribution (one slice)

- Example of dose distribution of one slice shows high intensity dynamics
- Lowest particle fluence determines intensity for whole slice
- Fixed intensity: irradiation time per raster point can vary by a factor of 2000!



Further Upgrade: Intensity-modulated spill



- Rasterpoint individual reference value
- Feedback loop adapts the actual intensity
- Beam-on time can again be reduced by ≈45%!

In clinical routine since April 2014

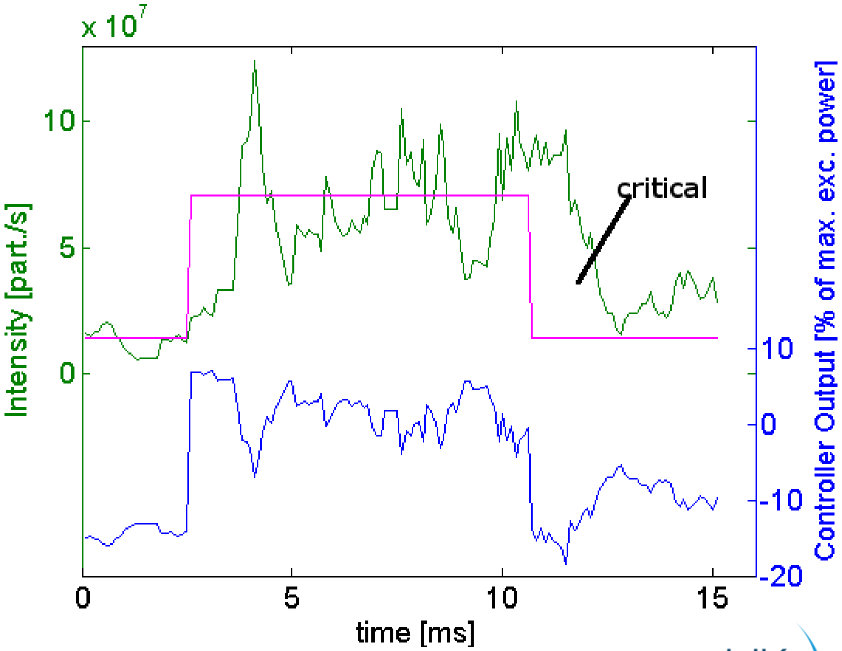
C. Schömers et al., NIM A 795 (2015) 92-99

Challenges and limitations

- Limits of the feedback loop due to dead times
  - Signal detection, ionization chamber ~ 150µs
  - Particle excitation ~ 0 - 600µs
  - Latencies in digital transmission ~ 100µs

- Irradiating too fast leads to interlocks and must be avoided!

- Reference value pattern must be defined in an intelligent way!



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HIT RF-KO system enhancements – Summary

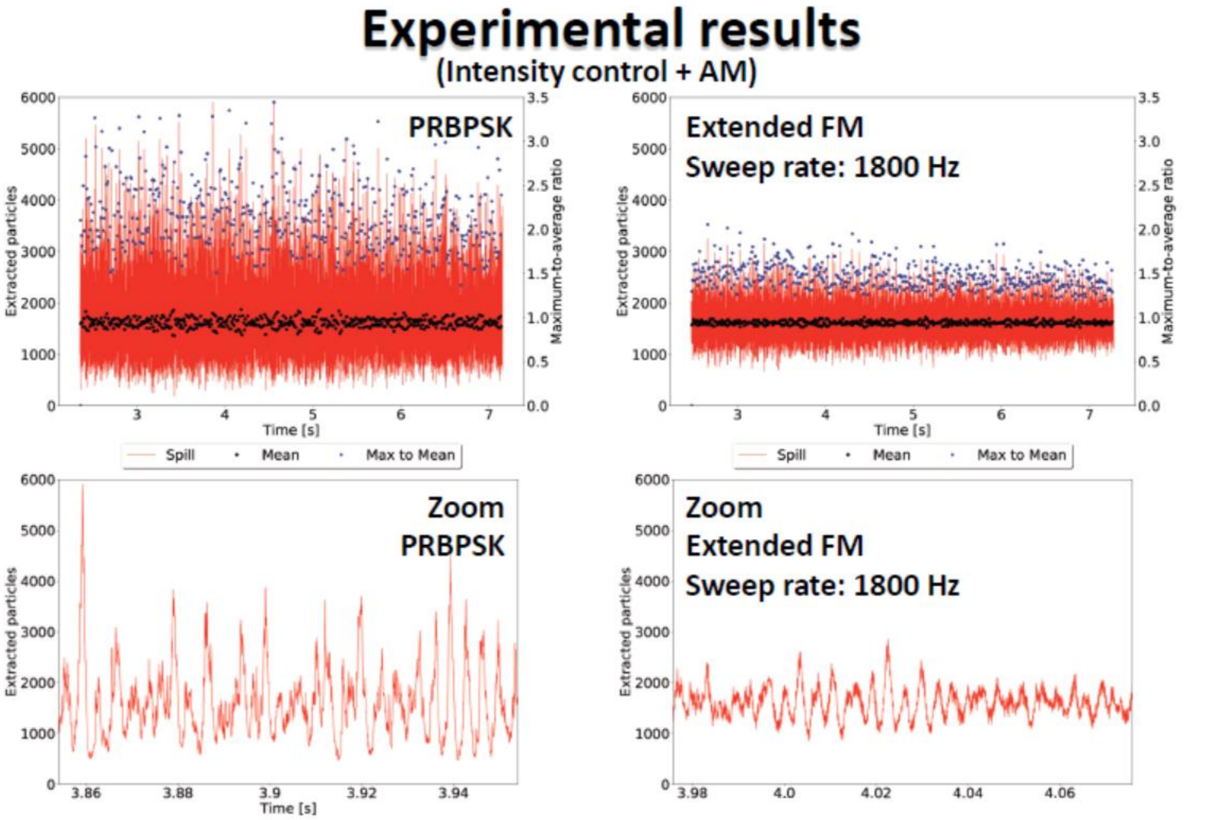
- Dynamic Intensity Control system completely implemented, used in standard operation of the HIT facility
- Available for all combinations of beam parameters provided by the HIT accelerator
- Detailed safety aspects implemented with regard to risk management of the therapy facility
- Further upgrade: Intensity variation on a millisecond scale according to the patient-specific pattern
- Overall patient treatment time was reduced by 10%!

Outlook: Investigations with extended FM excitation

Simulations inspired by HIMAC papers led to an extended FM excitation scheme.

First experiments using a $^{12}C^{6+}$ beam with max. energy of 430 MeV/u showed promising results →

Investigations restarted now!



From: F. Faber, SEW 2019, Fermilab

Thank you for your attention!

Thanks to the following persons providing material for this talk:
Christian Schömers and a lot of other colleagues at HIT,
Fiona Faber (TU Darmstadt)

… and now the second HIT part by Eike Feldmeier!

RF-KO system at HIT – EU sponsored initiative

I.FAST - Innovation Fostering in Accelerator Science and Technology (official start:1st May 2021)

Task 5.3: Improvement of **R**esonant slow **EX**traction spill quality (REX)

- Mitigate intensity fluctuations of slowly extracted beam from synchrotrons by means of detailed parameter simulations, related experimental verifications, and active beam control.
- Produce a prototype of improved hardware for power supply control to achieve a current stability in the range of $\Delta I / I < 10^{-6}$.
- Design and produce a high-performance RF-amplifier with versatile control for knock-out extraction.
- Main proposer: Peter Forck, GSI and HIT, MIT, CNAO, MedAustron, CERN,SEEIIST; Companies: Barthel, Bergoz

Slow Extraction Workshops

2016: GSI, Darmstadt, Germany, https://indico.gsi.de/event/4496/

2017: CERN, Geneva, Switzerland, https://indico.cern.ch/event/639766/

2019: Fermilab, Batavia, USA, https://indico.fnal.gov/event/20260/