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Heidelberg Ion-Beam Therapy Centre

Review of spill structure enhancements at HIT and other ion therapy facilities

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Accelerator Seminar, GSI Darmstadt, 3rd December 2020

UK
HD

Abstract:

Ion beam therapy facilities are mostly based on synchrotrons and different slow extraction methods are used to produce a "DC-like" beam feeding the raster scan systems to apply the pre-planned dose distributions to the patients. At HIT the RF knockout method developed by HIMAC in Japan was installed and continuously enhanced since the patient treatment started in 2009. Several steps like the "Dynamic Intensity Control" based on feedback mechanism will be reviewed. In addition, the developments at other ion beam facilities - CNAO in Italy, MIT in Marburg and MedAustron in Austria - will be described, partly based on the Betatron method proposed in the PIMMS study twenty years ago. The experiences after more than ten years of operation as well as the next development steps planned within the EU funded IFAST initiative will be reported.

OUTLINE

- Introduction
- A short view back into history
- A little bit of slow extraction theory
- RF-KO system at HIT, Intensity feedback loop ("DIC") and further enhancements under investigation
- Betatron core implementation at CNAO including extensions
- Comparison
- Acknowledgements

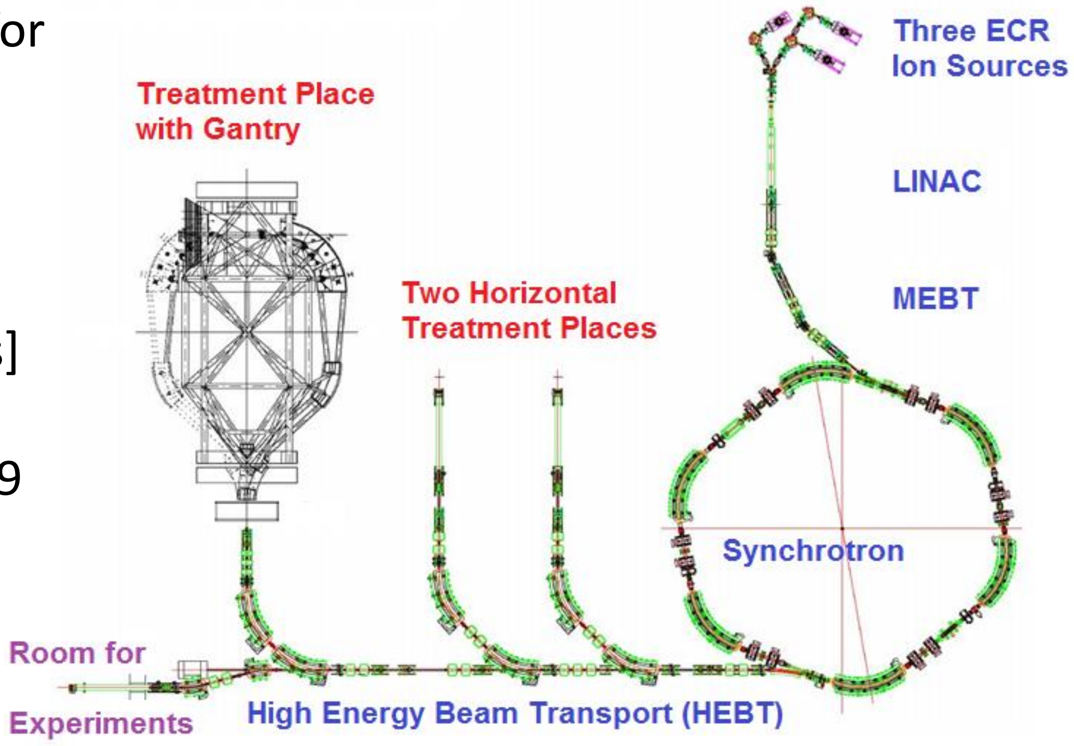
Introduction - The **H**eidelberg **I**onbeam **T**herapy facility

Dedicated Accelerator complex for tumor treatment with:

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

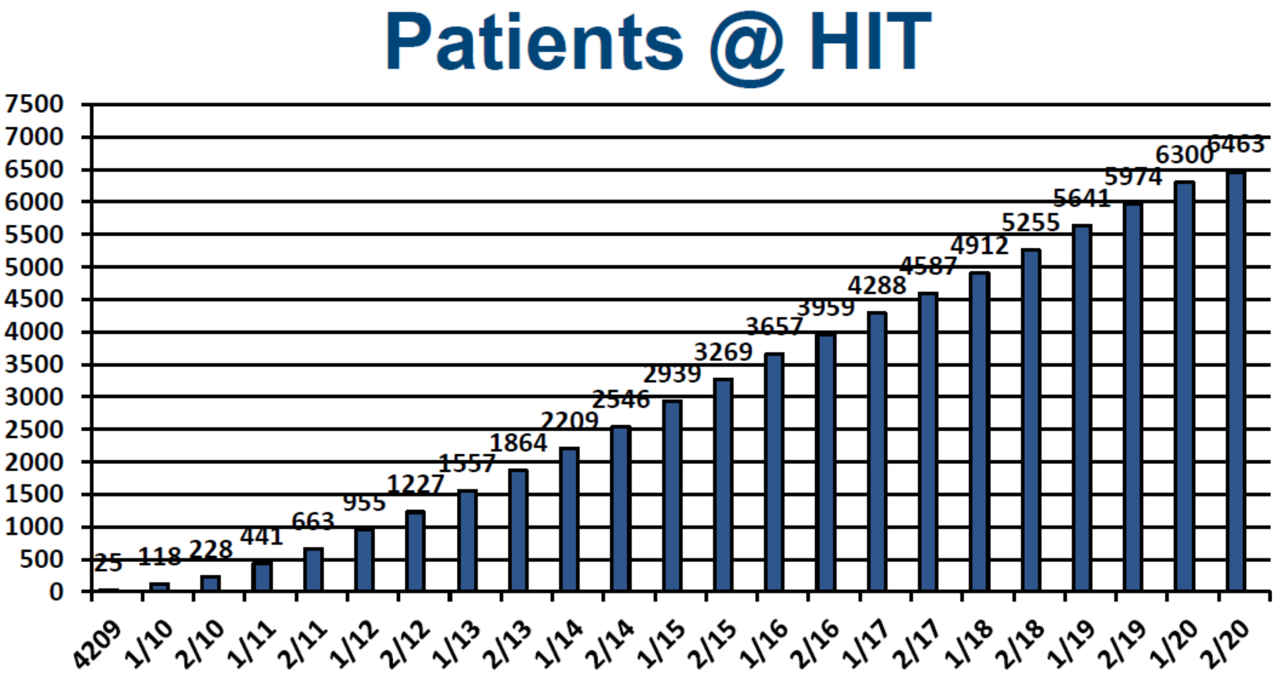
[higher energies for experiments]

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



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

Long-term Statistics

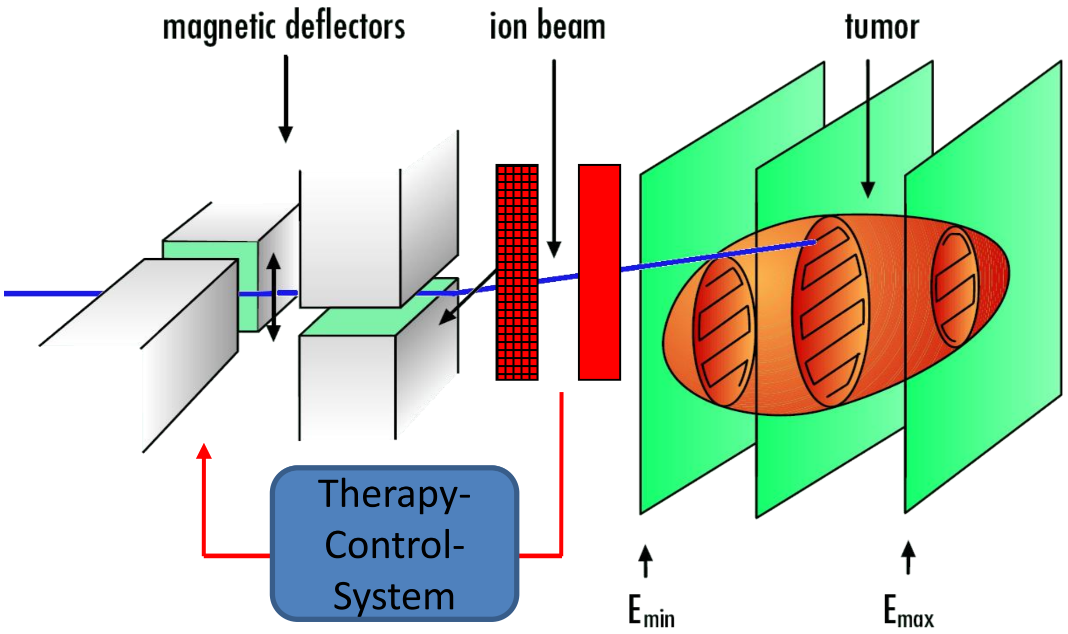


2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
14	214	435	570	637	676	723	690	628	668	719	489*

* bis 30.09.2020

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: $\sim 10^{12}$ (p), $\sim 10^{10}$ (C) per spill for radiosurgery and multi-energy and/or breath hold dose delivery

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

Introduction – Challenges for a medical application

- Medical application!
  - ➢ High reliability
  - ➢ Integration into the medical product
  - ➢ Risk management

- Be faster – and keep the accuracy!

→Check before any new implementation:

- ✓ Beam position and width
- ✓ 2D dose homogeneity (radiographic films)
- ✓ 3D dose distribution (patient plan verification)
- ✓ No. of interlocks during treatment

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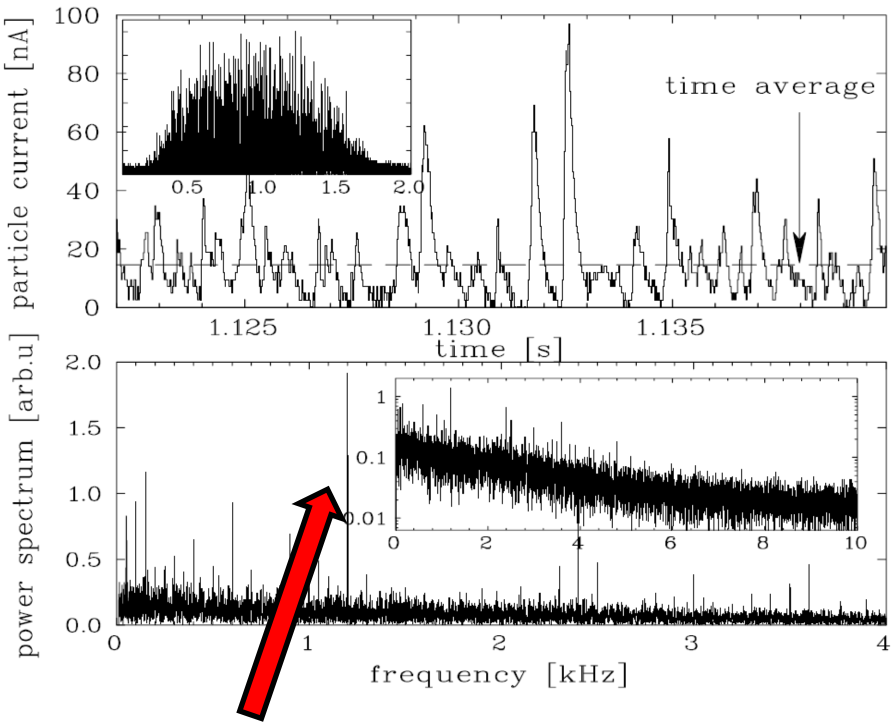
A view back into history – SIS18 in the 90ies



Early measurements done at SIS18 using the CCC detector with high current Neon beams showing strong spill modulations by power supply ripples (before major modi-fications by Breitenberger et al. short time later) –

Max/Avg. > 6!

Slow extraction method: fast quadrupole – driving the beam in the 3rd order resonance

From: A. Peters et al., BIW 1998, Stanford, USA

A view back into history – SIS18 in the 90ies

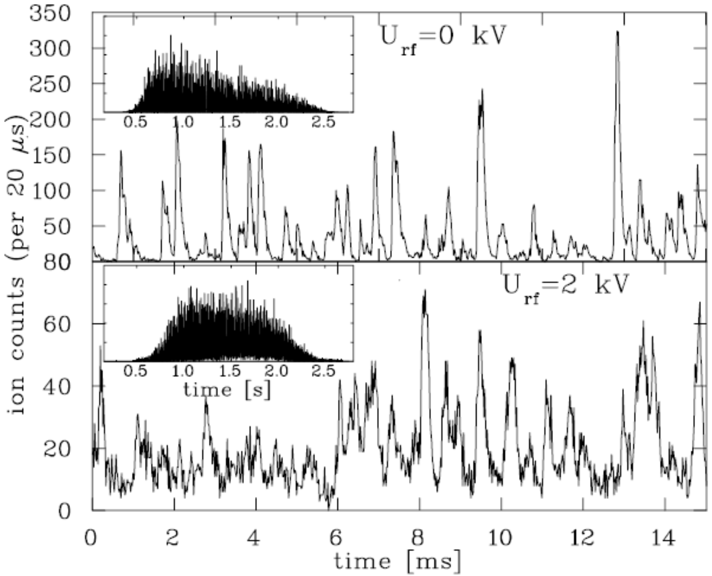


Figure 1: Typical time structure of a spill extracted by tune variation without bunching (top) and improvement by a 2 kV bunching voltage (bottom). The full spill-signal of the 300 MeV/u C^{6+} beam is drawn in the insert.

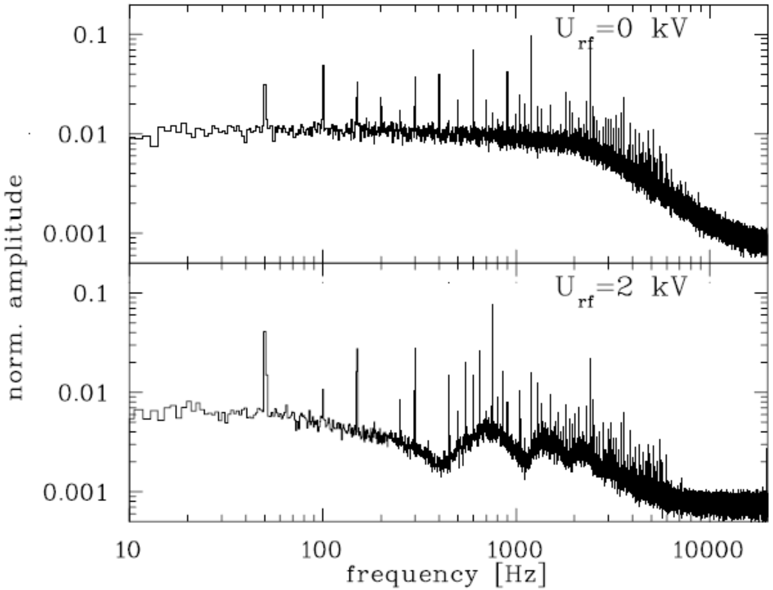


Figure 2: Fourier transformation of of the signals displayed in Fig.1 averaged over 10 Spills; without bunching (top) and with bunching (bottom).

From: P. Forck, H. Eickhoff, A. Peters, A. Dolinskii, Paper at EPAC 2000, Vienna, Austria

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A little bit of theory - introduction

Slow extraction methods:

- Moving the resonance
  - Probably the first method ever used. The tune of the machine is changed by a quadrupole so as to move the resonance across the beam. ("not recommended") **– A –**
- Moving the beam
  - Constant ion optics in the synchrotron
  - Amplitude driven, constant separatrix → the beam is excited by transverse stochastic noise, so that its betatron amplitudes grow. ("quick to respond") **– B –**
  - Momentum-driven → the beam is accelerated towards the stationary resonance e.g. by a betatron core ("having a large inductance it is not ultra-fast to respond") **– C –**

From: P. Bryant, CAS 2017, Erice, Italy

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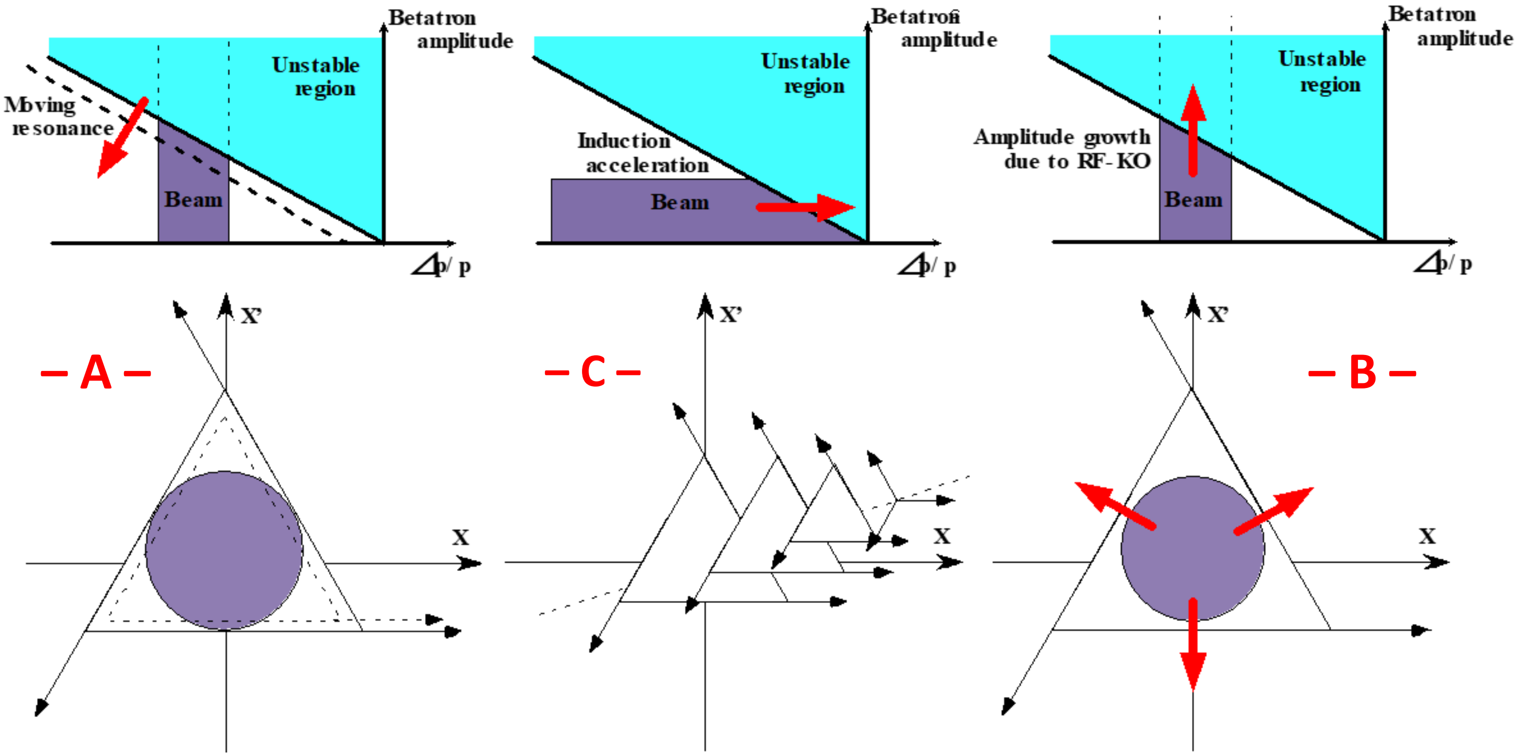
A little bit of theory - introduction

Steinbach diagrams

Separatrix view



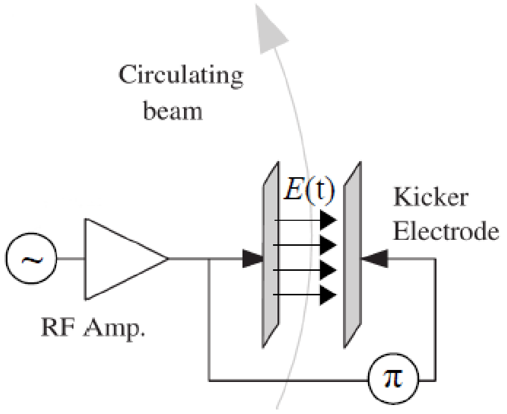
From: K. Noda, NIM A 374 (1996)

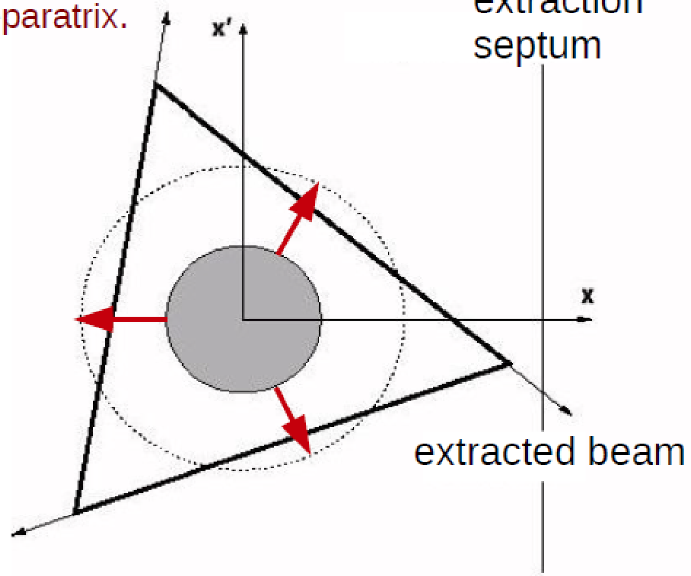
A little bit of theory – RF-KO method

(Transverse) RF-Knock-Out method:

Excite horizontal betatron motion

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





Albrecht, PhD, 1996

From: C. Krantz, this seminar, April 2019

A little bit of theory – betatron core extraction

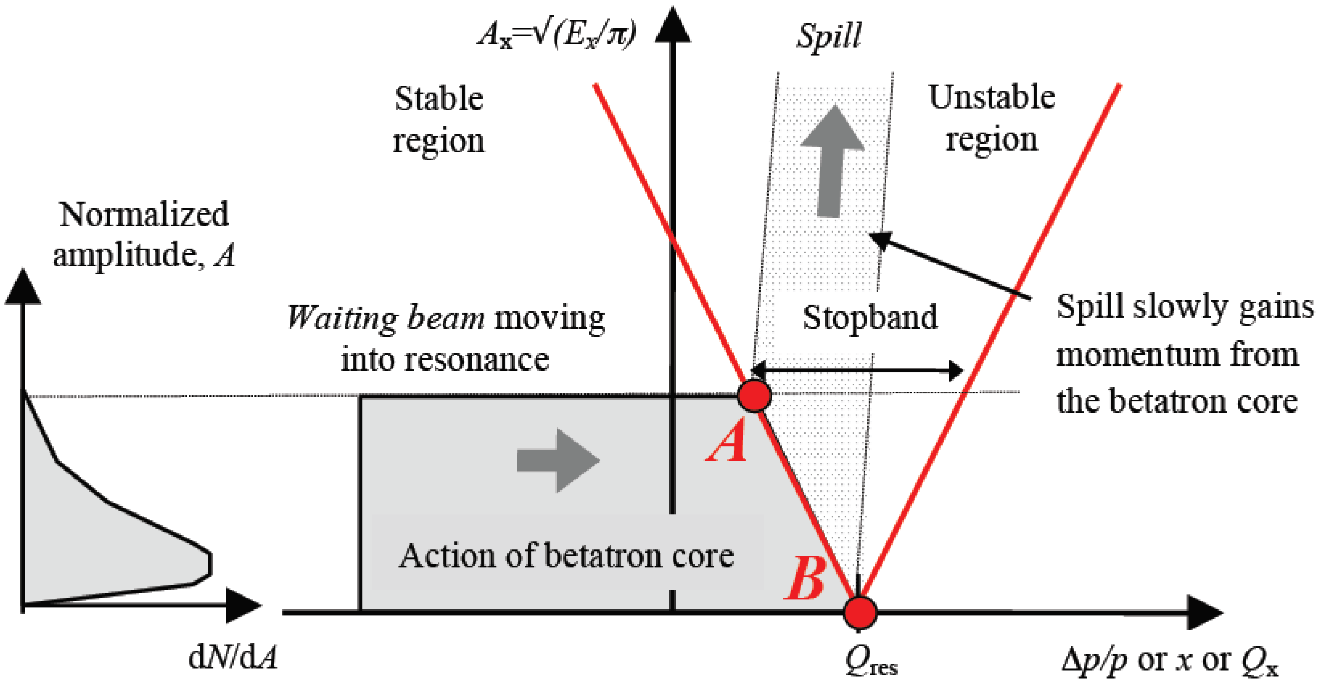


Fig. 3: An example of a Steinbach diagram for a momentum-driven slow extraction

From: P. Bryant, CAS 2017, Erice, Italy

A little bit of theory – betatron core extraction

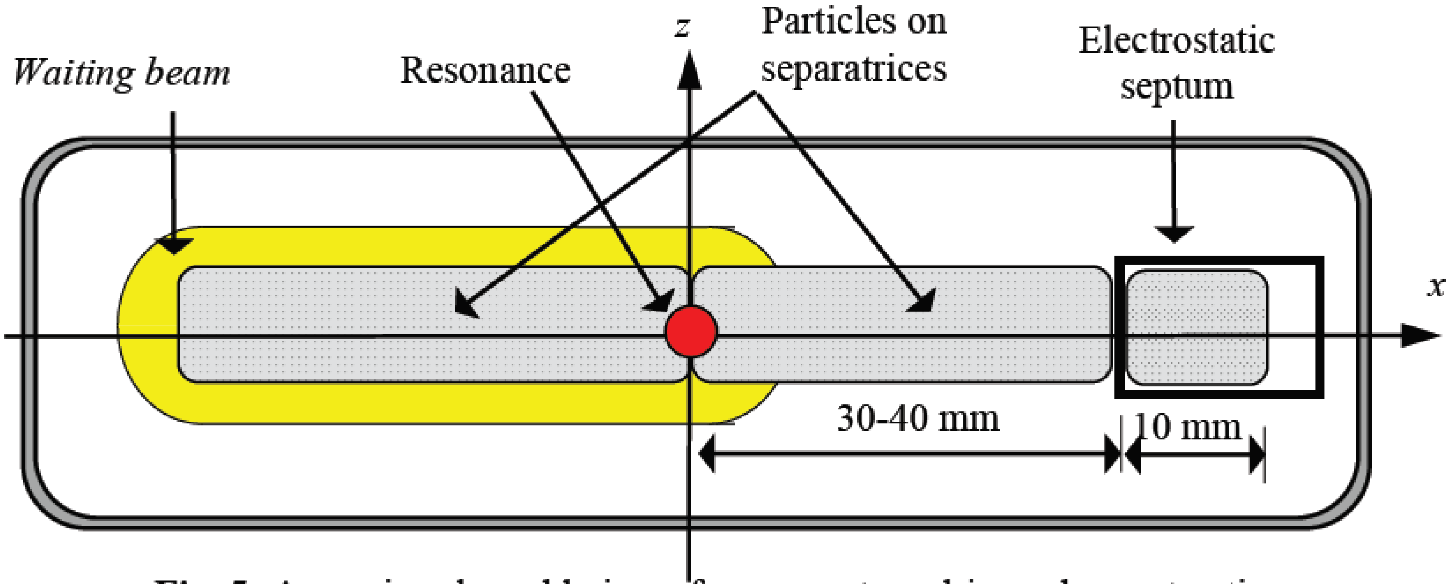


Fig. 5: A quasi-real-world view of a momentum-driven slow extraction

From: P. Bryant, CAS 2017, Erice, Italy

A little bit of theory – betatron core extraction

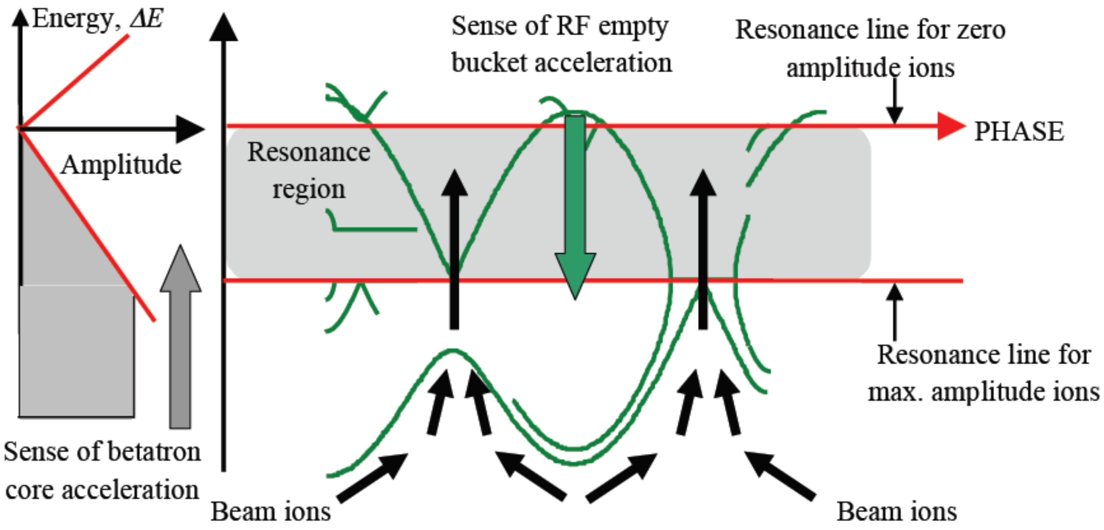
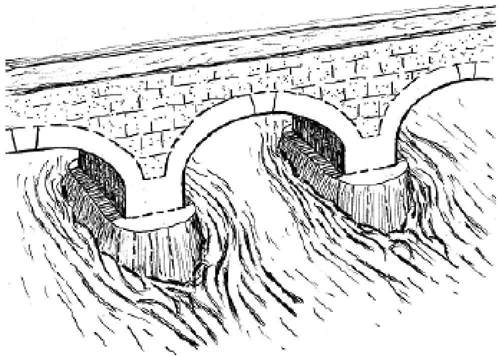


Fig. 26: Empty-bucket channelling



The bridge analogy to empty-bucket channelling

From: P. Bryant, CAS 2017, Erice, Italy

Precision beams for hadron therapy

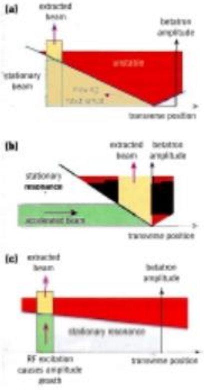


Fig. 1 – *how a particle beam can be moved into the unstable region of a resonance for extraction.*

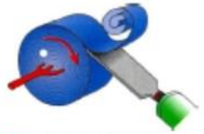


Fig. 2 – *the quadrupole-driven extraction of figure 1(a) is analogous to turning a piece of wood on a lathe.*

Fig. 3 – *the acceleration-driven extraction of figure 1(b) is analogous to a different kind of wood turning, with shavings from all radii.*

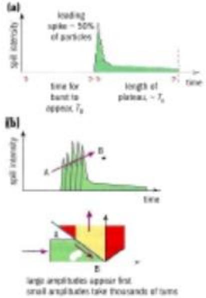


Fig. 4 – *acceleration-driven extraction mixes different initial amplitudes, the spikes becoming blurred and the resultant beam more smooth.*

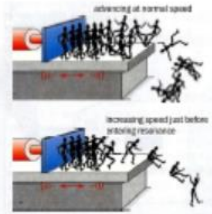


Fig. 5 – *illustrating the technique of "front-end acceleration". Victims on a shaking cliff being slowly pushed towards the edge by a ram will fall randomly, but if ordered to take a running jump, their increase in velocity compared to the floor movement makes their lemming-like exodus more uniform.*

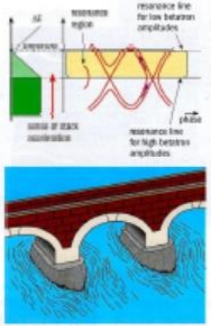


Fig. 6 – *if the longitudinal phase space between resonance and beam is partially blocked by radio-frequency "buckets" (stable areas in phase space), then the beam must dodge round them, rather as the water in a river rushes more quickly past the piers of a bridge.*

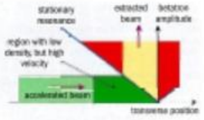


Fig. 7 – *a suitably modified version of the extraction scheme of figure 1(b).*

CERN is host to the Proton-Ion Medical Machine Study (PIMMS), a multinational collaboration that is looking at how particle physics can benefit medical treatment.

Increased life expectancy goes hand in hand with support from science. At present, about one in three of us will have an encounter with cancer and, in developed countries, about one in eight will have this treated by a linear accelerator.

Conventional accelerator-based treatments use spread-out photon or proton beams collimated to the tumour shape. However, some tumours are more radio-resistant while others have complex shapes and are lodged around vital organs such as the optic nerve.

For these requirements of higher radiobiological efficiency and higher precision, the next generation of hadron therapy accelerators are arming themselves with light ions (probably carbon) and high-precision voxel (volume pixel) or raster scanning techniques that maintain millimetre precision over complex volumes.

The expertise of accelerator labs like CERN helps point the way to further progress in this fast-growing applications area of particle physics. For example, the accelerator has to deliver the beam smoothly and controllably. Resonant slow extraction can be used from a synchrotron, but how can the legendary sensitivity of the spill be stabilized?

Figure 1 shows how a beam can be moved into the unstable region of a resonance for extraction. Scenario (a) is the classic quadrupole-driven extraction that "pushes" the resonance across the beam. Scenario (b) shows the acceleration-driven extraction (used successfully at CERN's LEAR low-energy antiproton ring) that instead moves the beam across the resonance. Finally, scenario (c) (from Japan) blows up the oscillation amplitudes until the particles reach the resonance.

The quadrupole-driven extraction (a) is analogous to turning a piece of wood on a lathe, as illustrated in figure 2. However, in particle extraction the "wood" shaving is more important than the remaining wood. The wood turns about one million times to complete the extraction and the resultant wafer-thin shaving is easily destroyed by the slightest vibration.

With this classic technique, a sharp movement between the beam and the resonance for particles with a given amplitude leads to a burst of particles in the spill with a leading peak and a flat plateau. The time needed for this burst to appear depends on the initial oscillation amplitude. The first remedial step is to adopt acceleration-driven extraction, illustrated in figure 3 by analogy to a different kind of wood turning. In this case, the shaving is composed of wood from all radii. By mixing different initial amplitudes, the spikes are blurred. Figure 4 shows the resultant smoothing effect.

The next remedial step – "front-end acceleration" – is more active. Imagine a crowd on a shaking cliff being slowly pushed towards the edge by a ram (figure 5). The victims will fall randomly, but if ordered to take a running jump, their increase in velocity compared to the floor movement would stabilize them and the lemming-like exodus would be more uniform.

This can be done with a slow extraction and has been demonstrated in the CERN proton synchrotron. If the longitudinal phase space between resonance and beam is partially blocked by radio-frequency "buckets" (stable areas in phase space), then the beam must dodge round them, rather as the water in a river rushes more quickly past the piers of a bridge (figure 6).

To accelerate the beam, a betatron core is an ideal choice for a smooth spill and has the great advantage that all other parameters in the machine can be kept constant during the extraction. These refinements modify the extraction of figure 1(c) into figure 7.

CERN is hosting and supporting PIMMS (Proton-Ion Medical Machine Study), where these and other ideas are being developed. PIMMS is a fruitful collaboration between the national organizations Med-AUSTRON in Austria, Onkologie 2000 in the Czech Republic and the TERA Foundation in Italy. The study group has also benefited from close contacts with the GSI laboratory, Darmstadt, where beams of carbon ions are already being used for therapy.

Philip Bryant, CERN.

From: P. Bryant, CERN Courier, Oct. 1998

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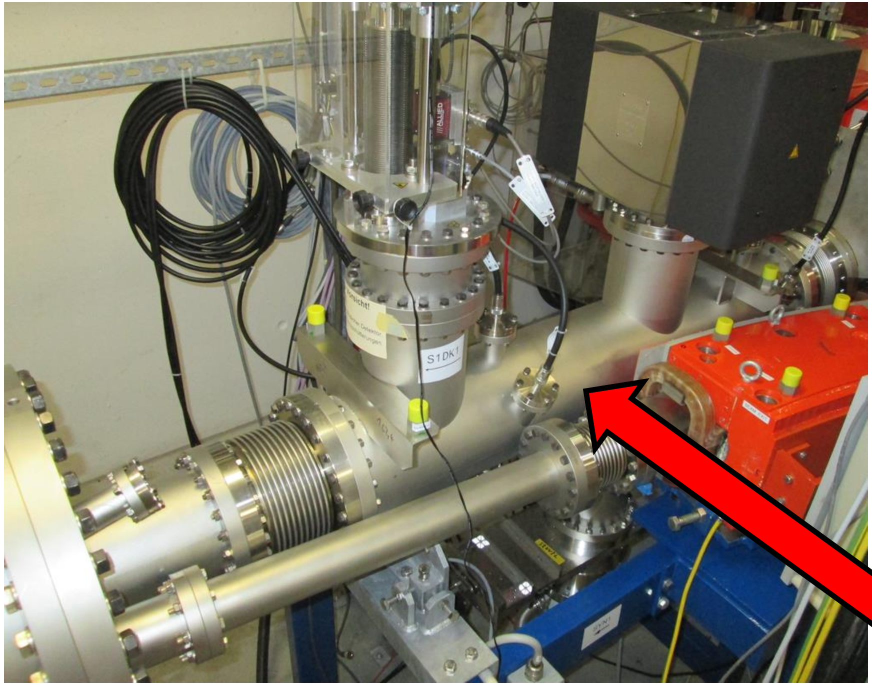
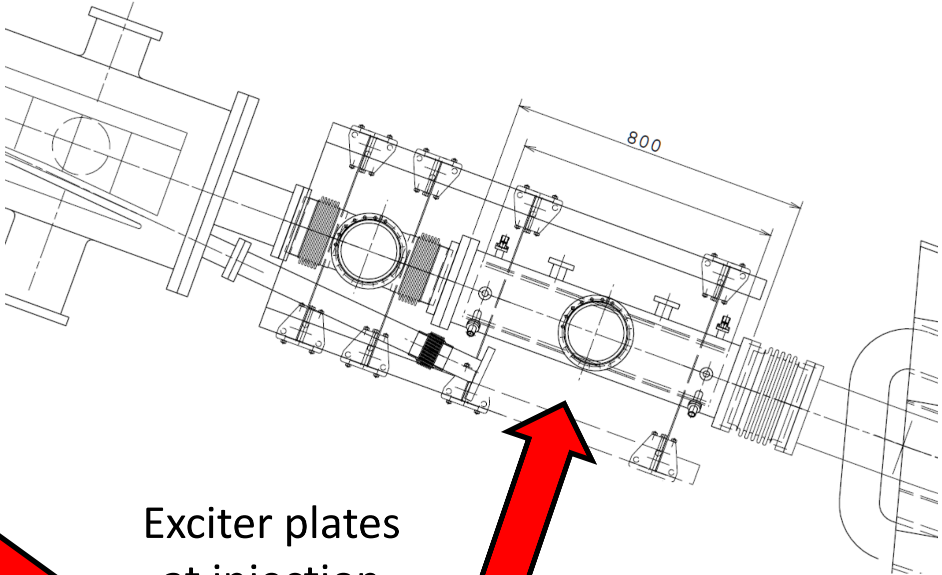
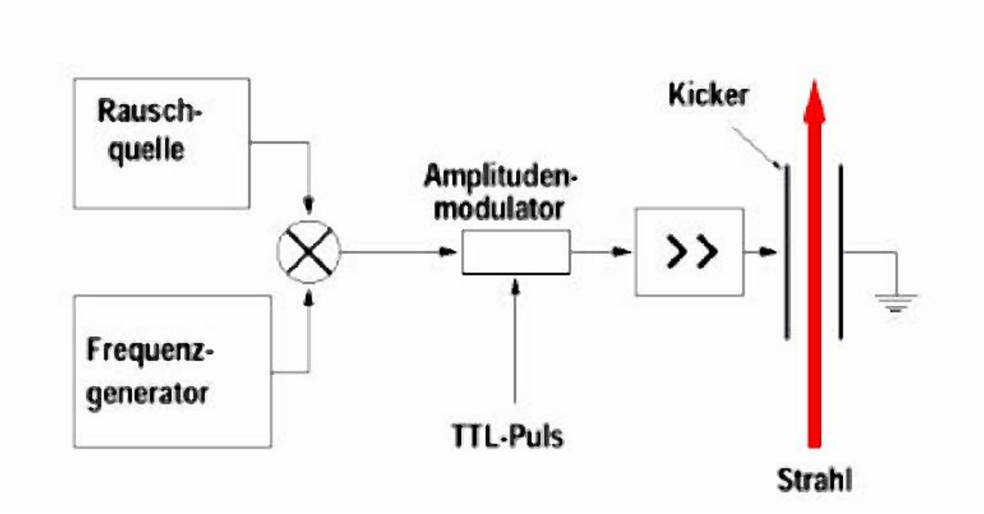
RF-KO system at HIT – mechanical installation

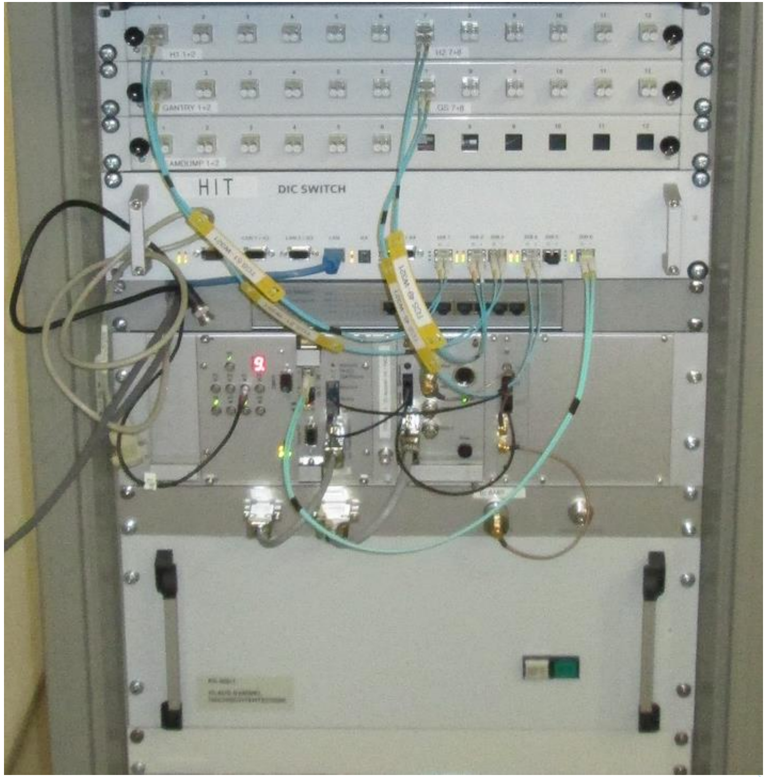




Exciter plates at injection section

RF-KO system at HIT – RF amplifier & control

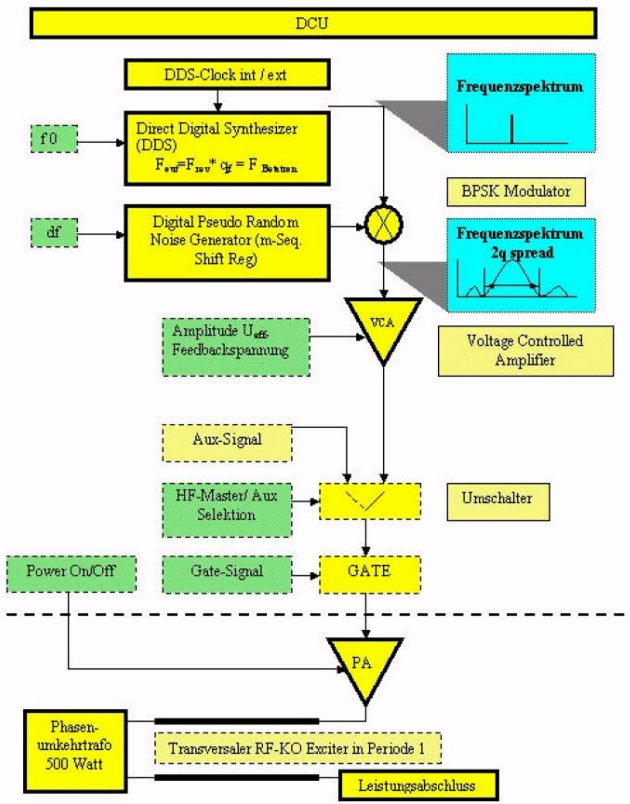




RF-KO system at HIT – signal generation in detail

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

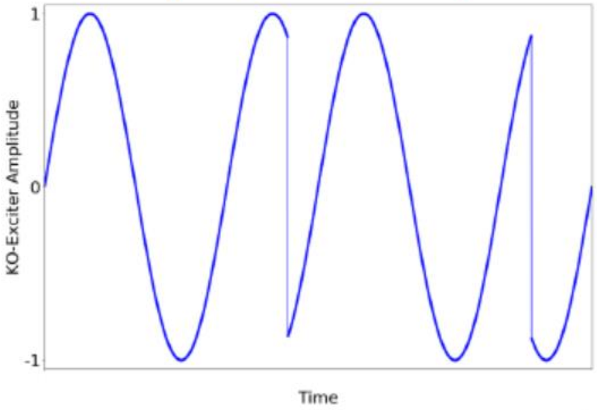


RF-KO system at HIT – used frequency spectrum

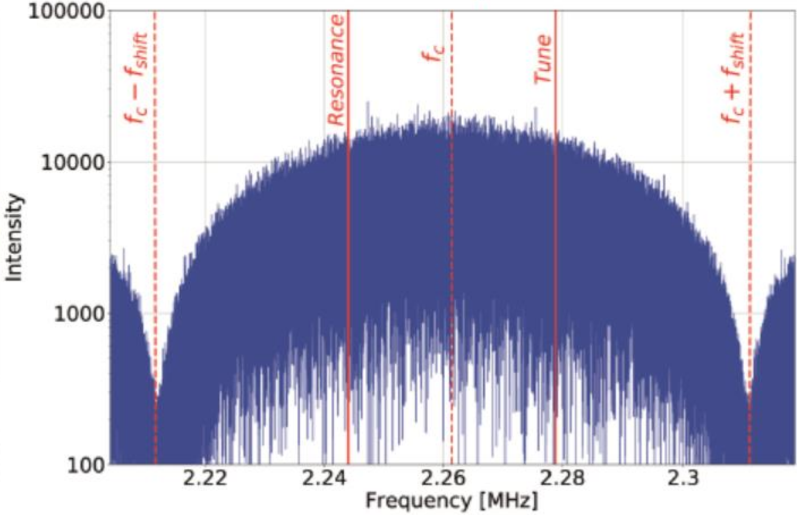
From: F. Faber, SEW 2019, Fermilab

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

Exemplary excitation signal



Excitation spectrum

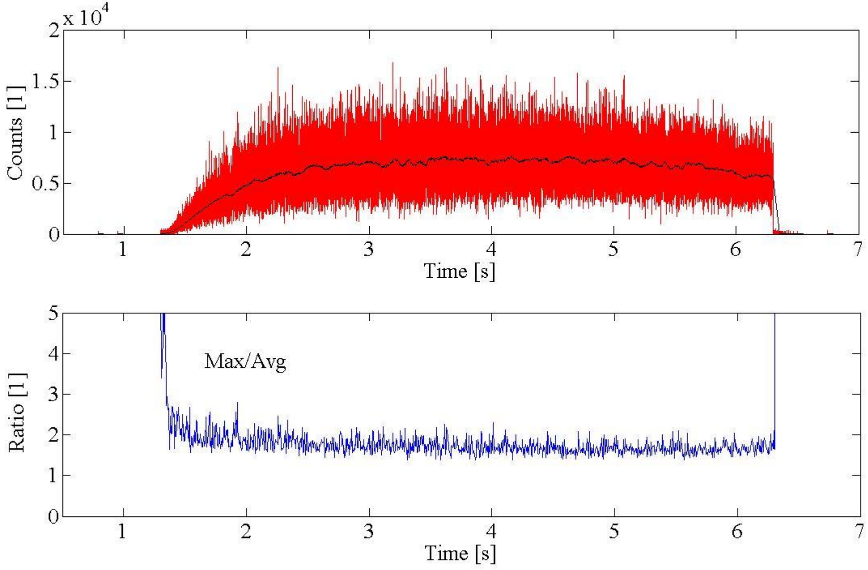


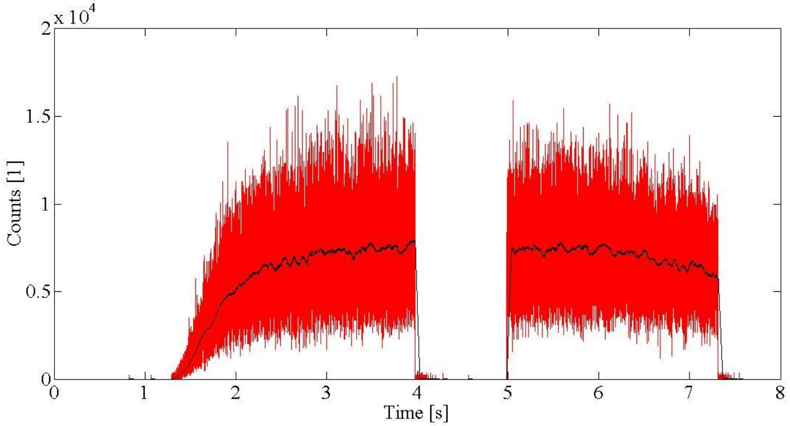
$$V_{KO}(t) = \widehat{V}_{KO} \cdot sin\left(2\pi f_c t + \phi_{shift}\right)$$

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

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

Typical spill with RF-KO extraction (2008)

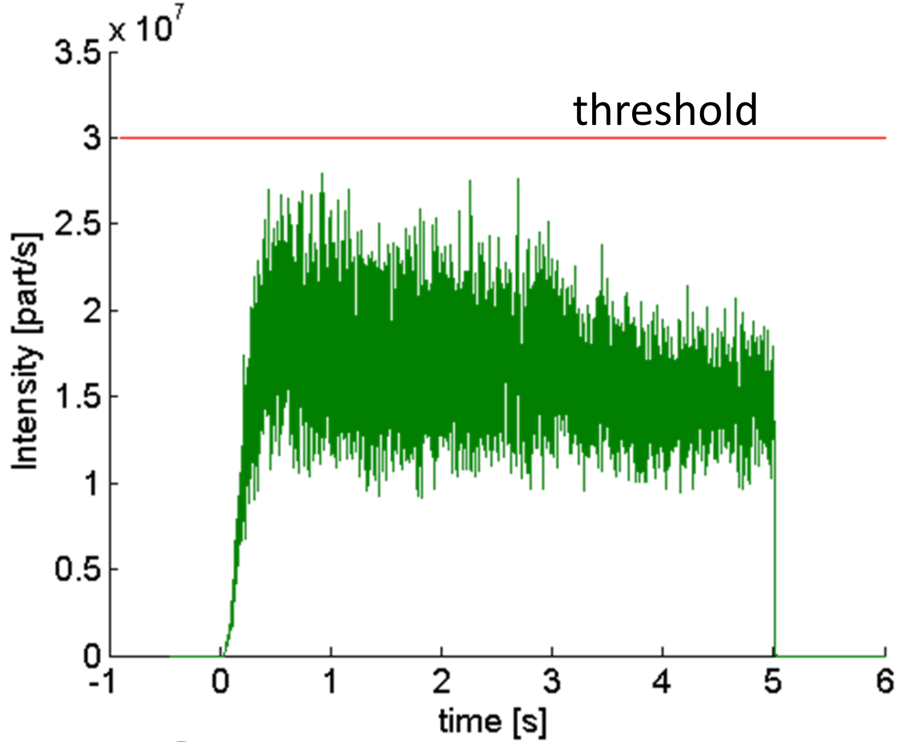




From: A. Peters et al., EPAC 2008

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

Motivation for enhancements

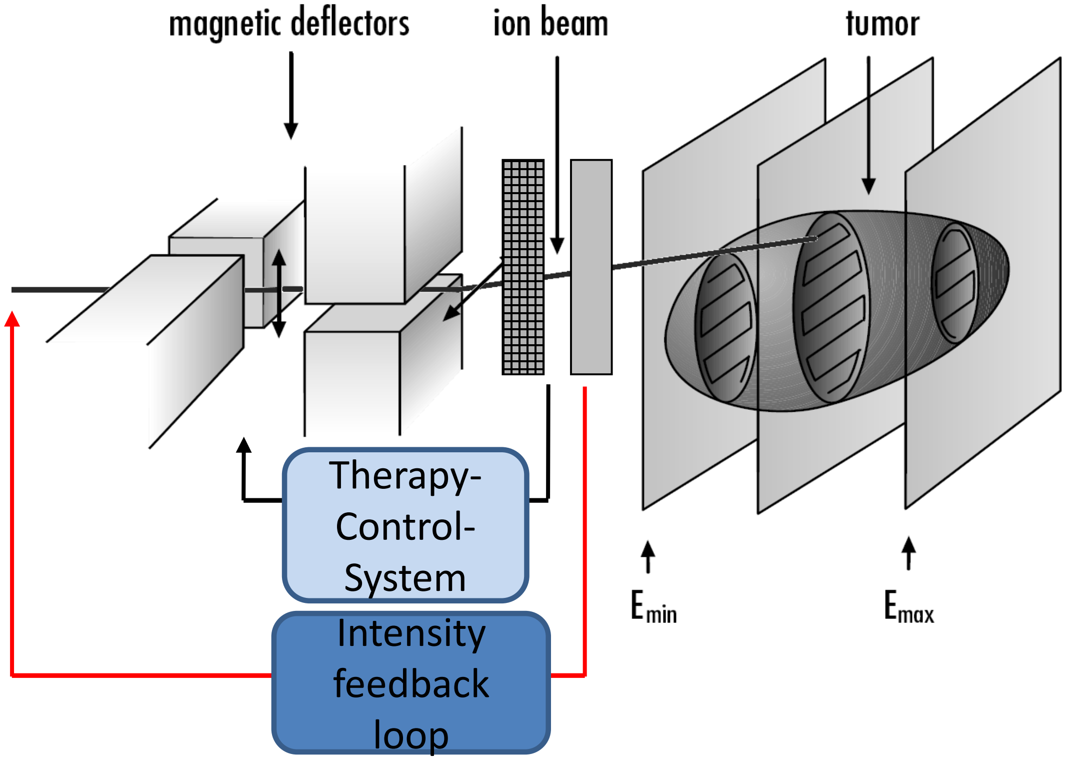
Therapy works fine – why do we need higher performance?

Reasons for the reduction of individual treatment time are:

- Higher patient comfort (locally immobilized!)
- More patients can be treated
- Economic facility operation
- Higher dose conformity

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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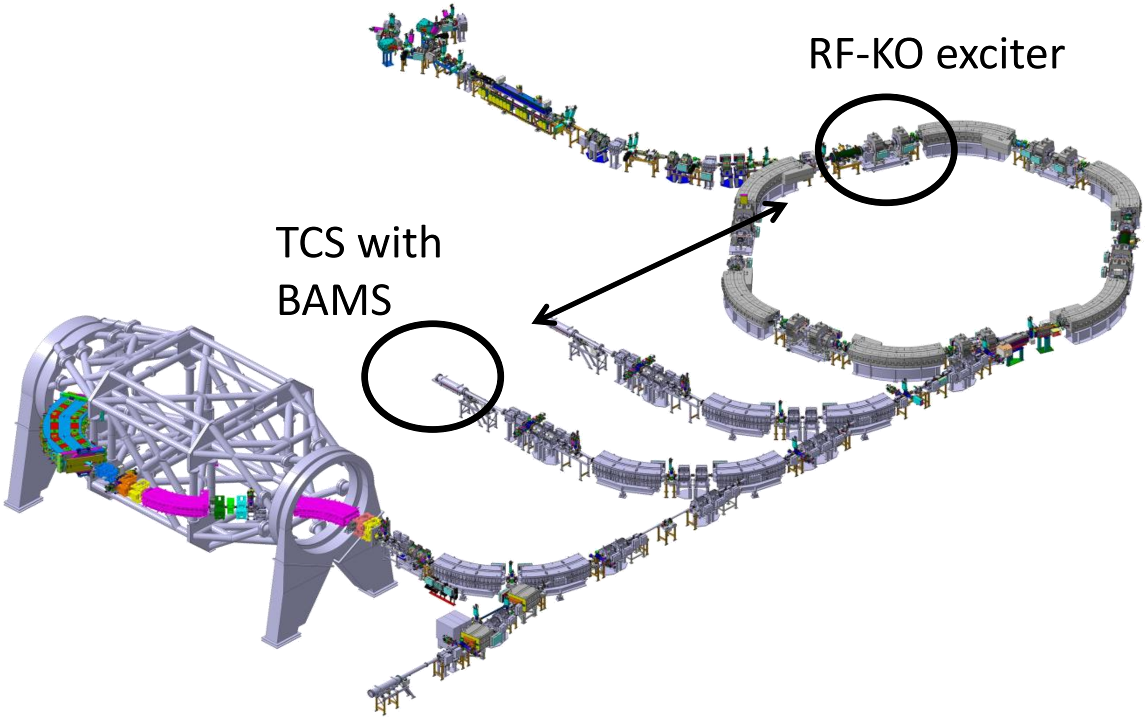
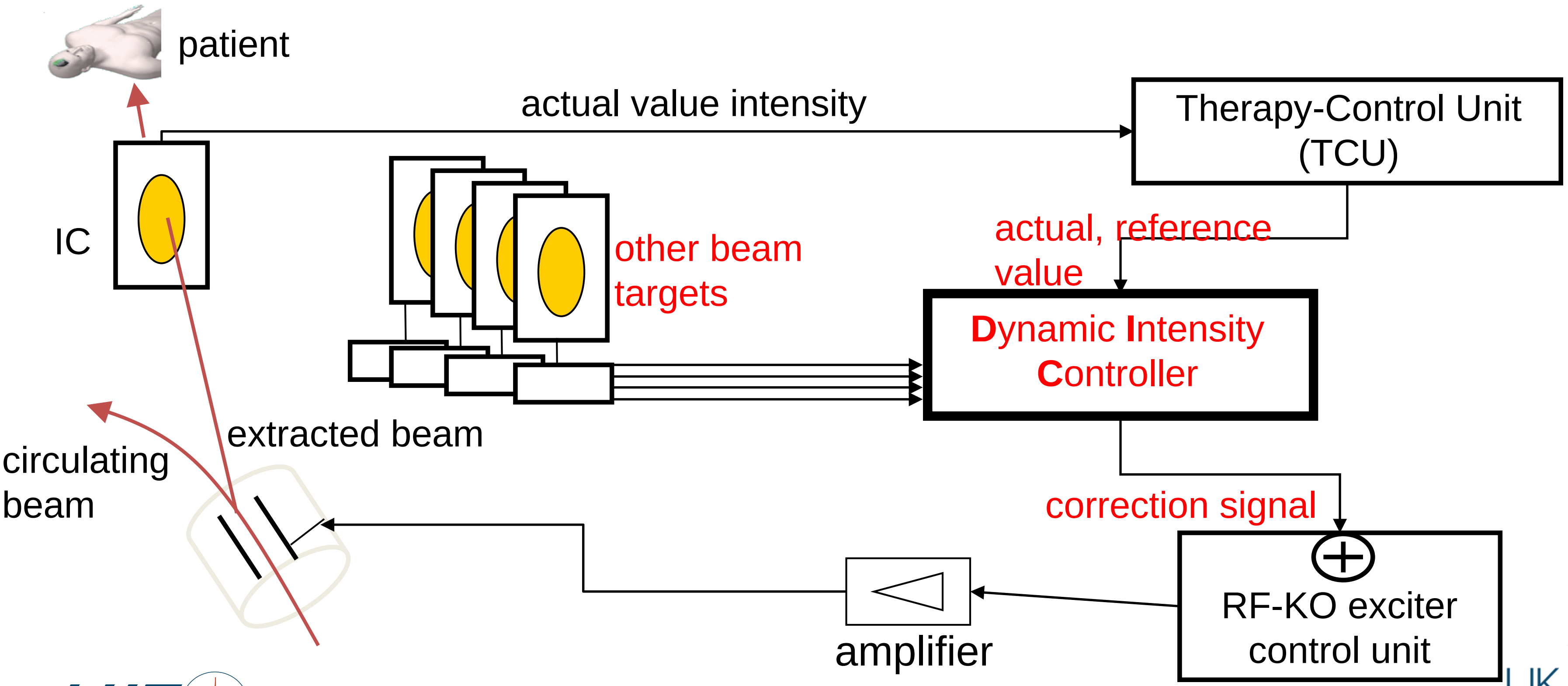


Intensity feedback loop – technical realization

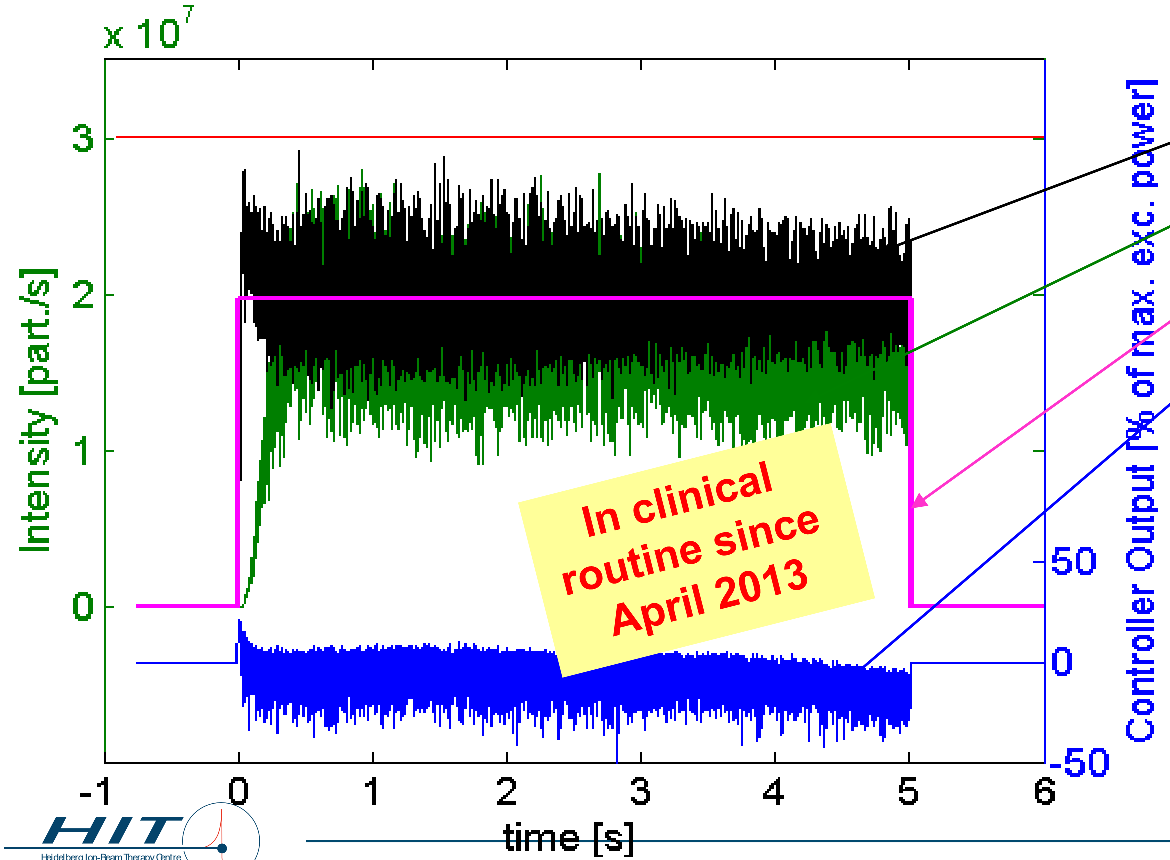


C. Schömers et al., NIM A 795 (2015) 92-99

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
  - …

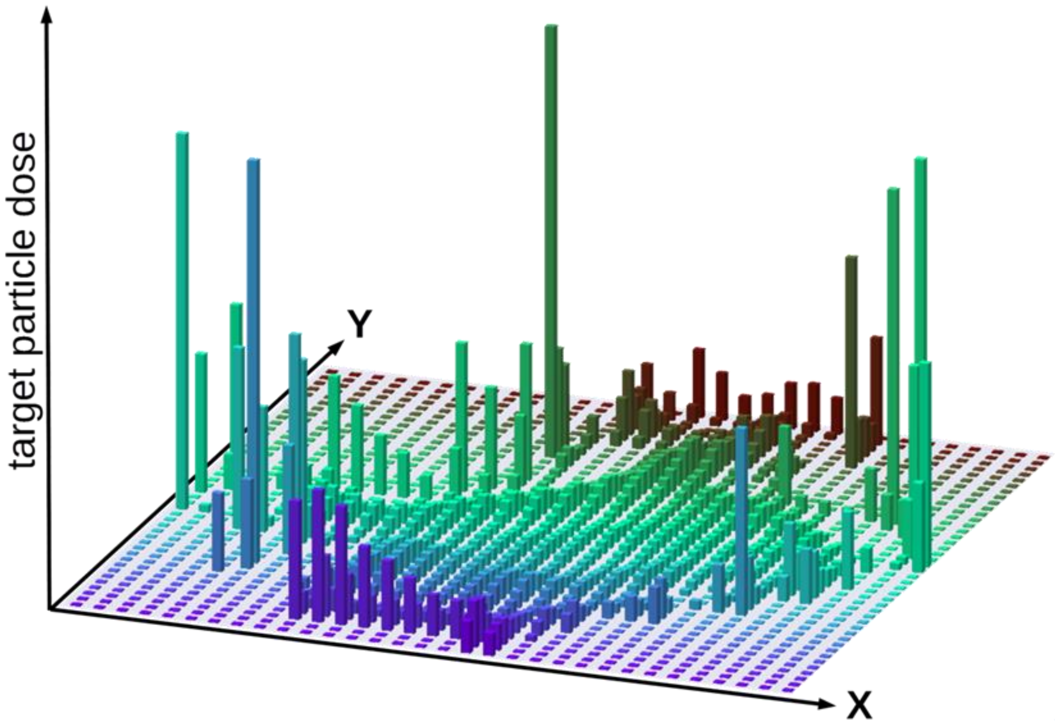
Results of the feedback loop implementation



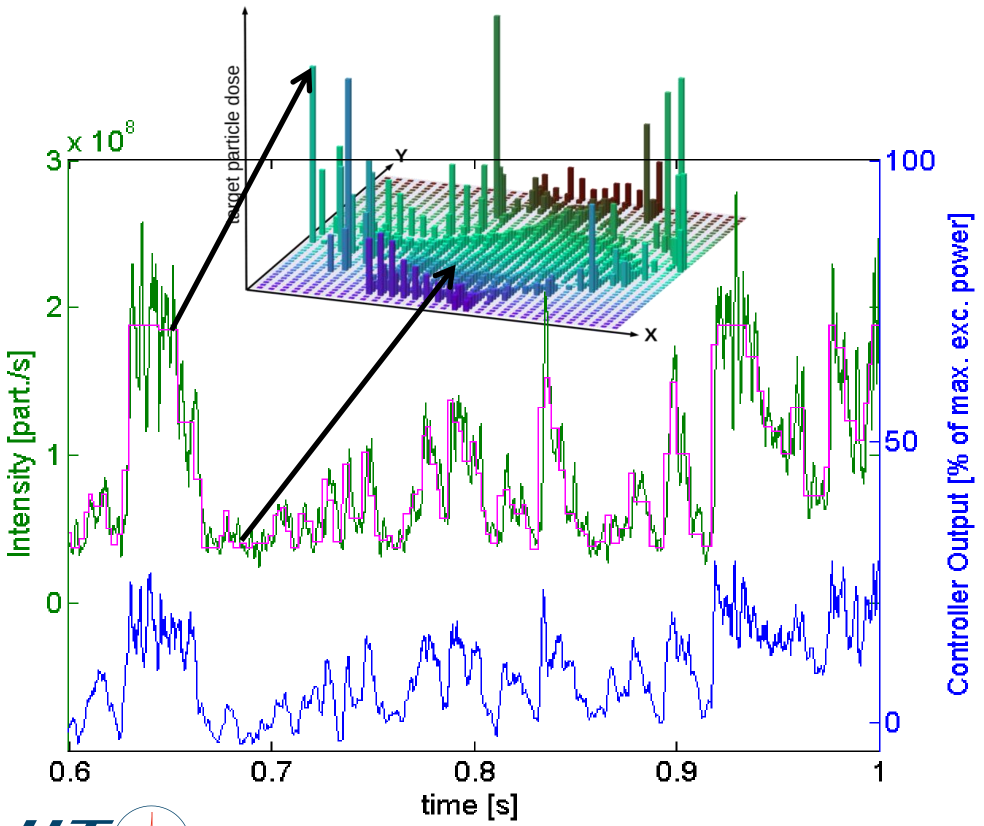
- Spill shape
  - With feedback
  - Without feedback
  - Reference value
  - Controller output
- Higher average intensity (15 %!)
- Faster irradiation
- Less machine tuning

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



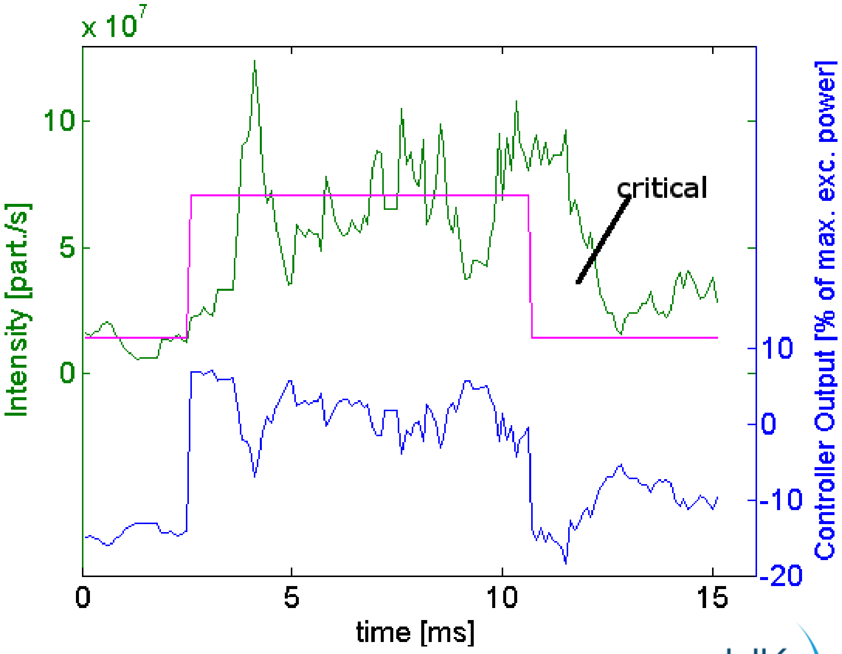
- Rasterpoint individual reference value
- Feedback loop adapts the actual intensity
- Beam-on time can again be reduced by ≈45%!

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!

HIT RF-KO system enhancements – Summary

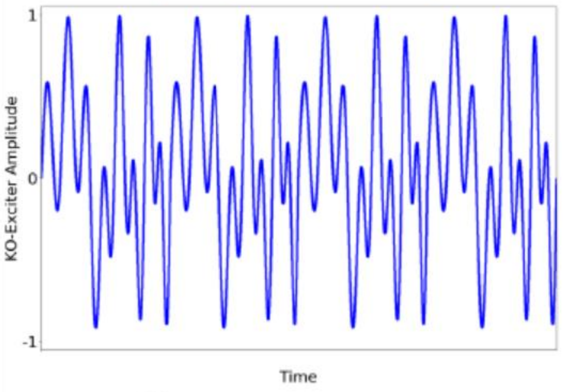
- Dynamic Intensity Control system completely implemented, used in standard operation of the HIT facility
- Available for all combinations of beam parameters provided by the HIT accelerator
- Detailed safety aspects implemented with regard to risk management of the therapy facility
- Intensity variation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

RF-KO system at HIT – upgrade investigations

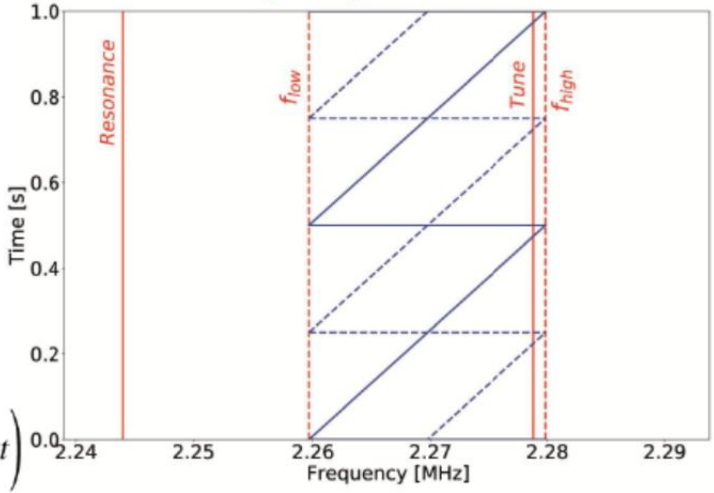
Simulations inspired by HIMAC papers

Excitation method: Dual frequency modulation (FM)

Exemplary excitation signal



Frequency modulation



$$V_{KO}(t) = \frac{\widehat{V}_{KO}}{2}\left[\sin\left(\left[f_{low} + \frac{f_{high} - f_{low}}{T_{sweep}}t\right]2\pi t\right) + \sin\left(\left[\frac{f_{high} + f_{low}}{2} + \frac{f_{high} - f_{low}}{T_{sweep}}t\right]2\pi t\right)\right]$$

$$t \in (0, T_{sweep}/2)$$

Idea by K. Noda et al., Nucl. Instr. and Meth. A 492 (2002), pp. 253 - 263

From: F. Faber, SEW 2019, Fermilab

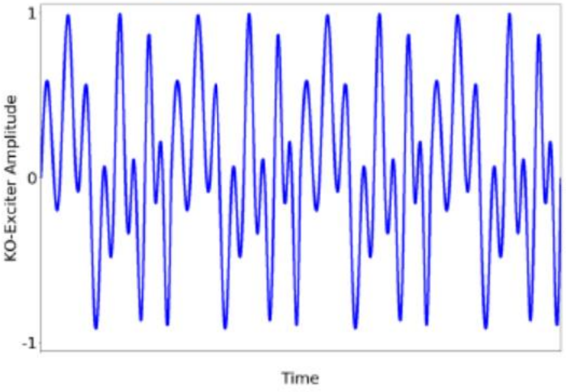
RF-KO system at HIT – upgrade investigations

From: F. Faber, SEW 2019, Fermilab

Simulations inspired by HIMAC papers

Excitation method: Dual frequency modulation (FM)

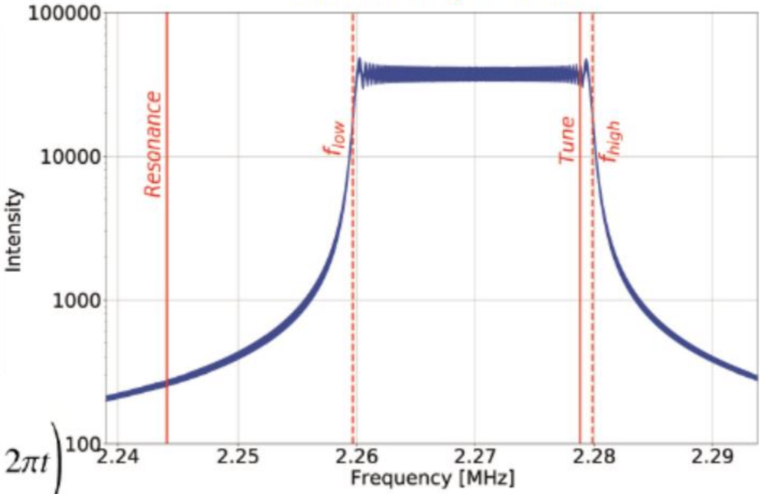
Exemplary excitation signal



$$V_{KO}(t) = \frac{\widehat{V}_{KO}}{2}\left[\sin\left(\left[f_{low} + \frac{f_{high}-f_{low}}{T_{sweep}}t\right]2\pi t\right) + \sin\left(\left[\frac{f_{high}+f_{low}}{2} + \frac{f_{high}-f_{low}}{T_{sweep}}t\right]2\pi t\right)\right]$$

$$t \in \left(0, T_{sweep}/2\right)$$

Excitation spectrum



Idea by K. Noda et al., Nucl. Instr. and Meth. A 492 (2002), pp. 253 - 263

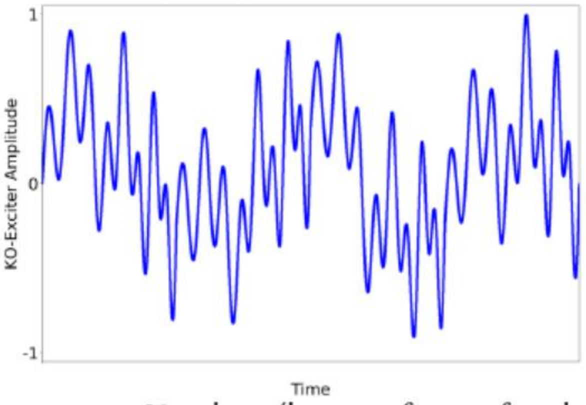
RF-KO system at HIT – upgrade investigations

From: F. Faber, SEW 2019, Fermilab

Excitation method: Extended frequency modulation (FM)

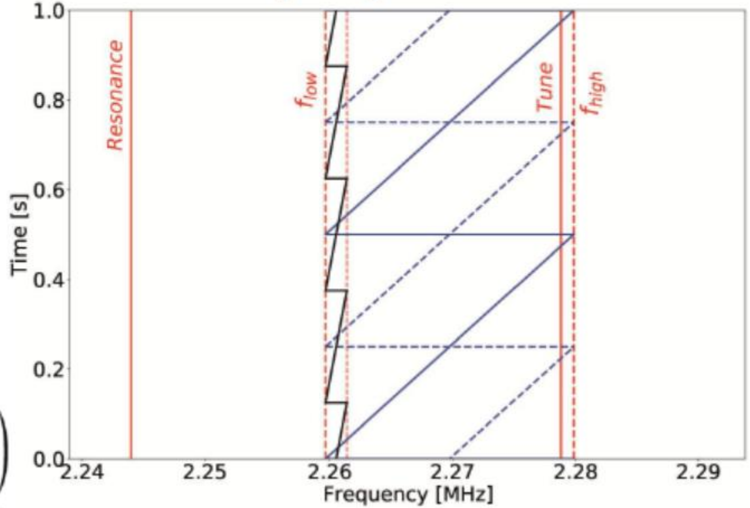
Simulations led to an extended FM method

Exemplary excitation signal



$$V_{KO}(t) = \frac{V_{KO}}{3}\left[\sin\left(\left[f_{low} + \frac{f_{high} - f_{low}}{T_{sweep}}t\right]2\pi t\right) + \sin\left(\left[\frac{f_{high} + f_{low}}{2} + \frac{f_{high} - f_{low}}{T_{sweep}}t\right]2\pi t\right) + \sin\left(\left[f_0^{add} + \frac{2(f_{high}^{add} - f_{low})}{T_{sweep}}t\right]2\pi t\right)\right]$$

Frequency modulation



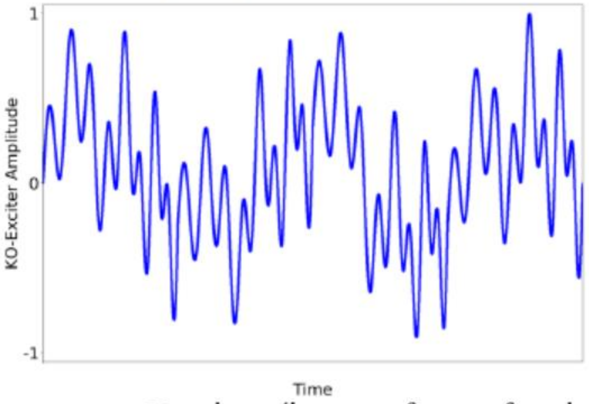
$$f_0^{add} = \begin{cases} \frac{f_{high}^{add} + f_{low}}{2}, & t \in \left(0, T_{sweep}/4\right) \\ f_{low} - \frac{(f_{high}^{add} - f_{low})}{2}, & t \in \left(T_{sweep}/4, T_{sweep}/2\right) \end{cases}$$

RF-KO system at HIT – upgrade investigations

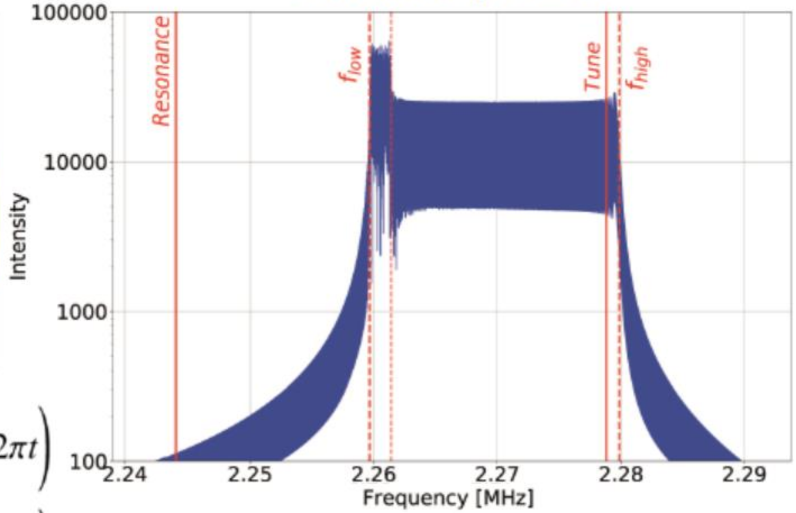
Excitation method: Extended frequency modulation (FM)

Simulations led to an extended FM method

Exemplary excitation signal



Excitation spectrum



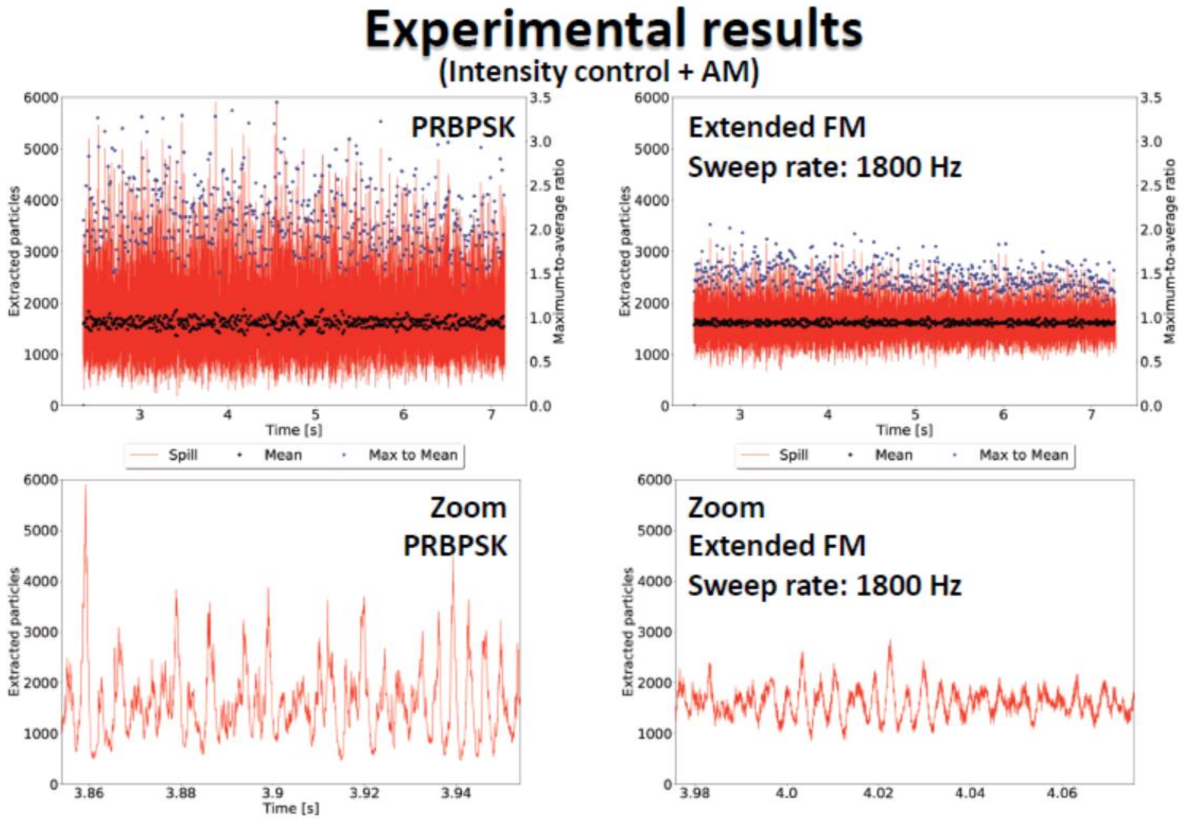
$$V_{KO}(t) = \frac{V_{KO}}{3}\left[\sin\left(\left[f_{low} + \frac{f_{high} - f_{low}}{T_{sweep}} t\right] 2\pi t\right) + \sin\left(\left[\frac{f_{high} + f_{low}}{2} + \frac{f_{high} - f_{low}}{T_{sweep}} t\right] 2\pi t\right) + \sin\left(\left[f_0^{add} + \frac{2(f_{high}^{add} - f_{low})}{T_{sweep}} t\right] 2\pi t\right)\right]$$

$$f_0^{add} = \begin{cases} \frac{f_{high}^{add} + f_{low}}{2}, & t \in \left(0, T_{sweep}/4\right) \\ f_{low} - \frac{(f_{high}^{add} - f_{low})}{2}, & t \in \left(T_{sweep}/4, T_{sweep}/2\right) \end{cases}$$

From: F. Faber, SEW 2019, Fermilab

RF-KO system at HIT – upgrade investigations

Experiments using a $^{12}C^{6+}$ beam with max. energy of 430 MeV/u (still not completely optimized!)



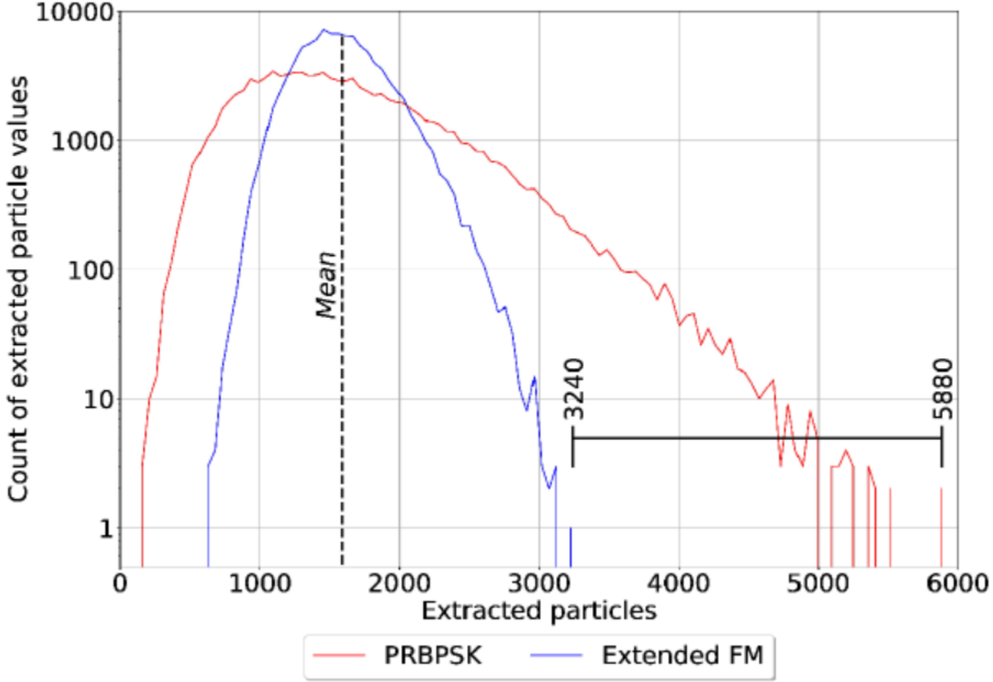
From: F. Faber, SEW 2019, Fermilab

RF-KO system at HIT – upgrade investigations

Experiments using a $^{12}C^{6+}$ beam with max. energy of 430 MeV/u:

→ More RF power needed

→ New flexible synthesizer, now under development



From: F. Faber, SEW 2019, Fermilab

RF-KO system at HIT – EU sponsored initiative

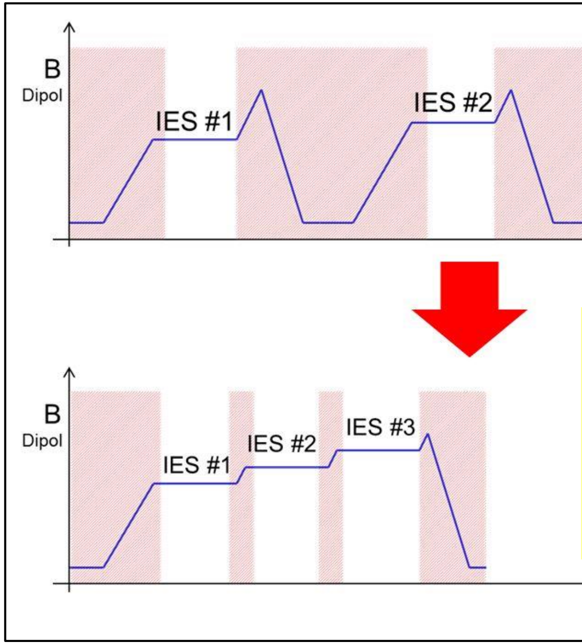
I.FAST - Innovation Fostering in Accelerator Science and Technology (official start:1st May 2021)

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

Further enhancements under investigation - MEB

(1) More and more ACS components get obsolete, new DCU generation necessary
(2) New functionalities for higher efficiency of the facility needed – so-called “multiple energy operation” (in German: MEB) scheme → This will cause higher complexity of the ACS, but a huge potential for shortening irradiation times.
(3) For the RF-KO system at HIT the new acceleration scheme is nearly transparent, no major changes necessary, only adjustment of parameter settings.



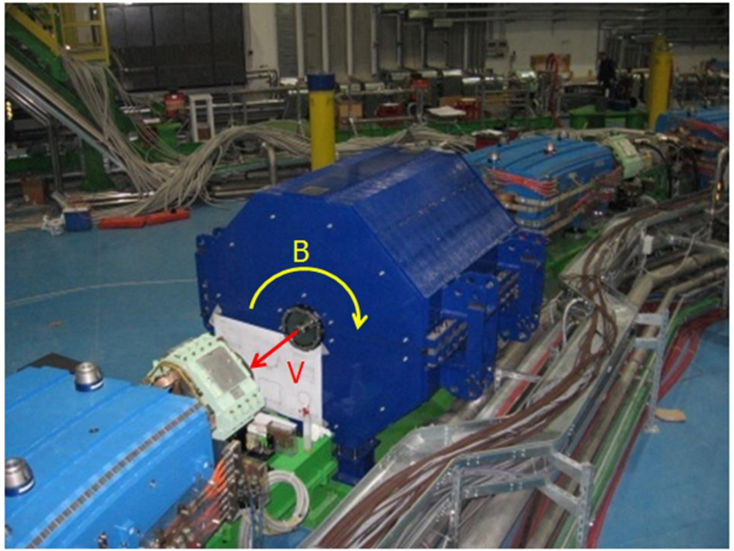
Cycle time reduction using post-acceleration

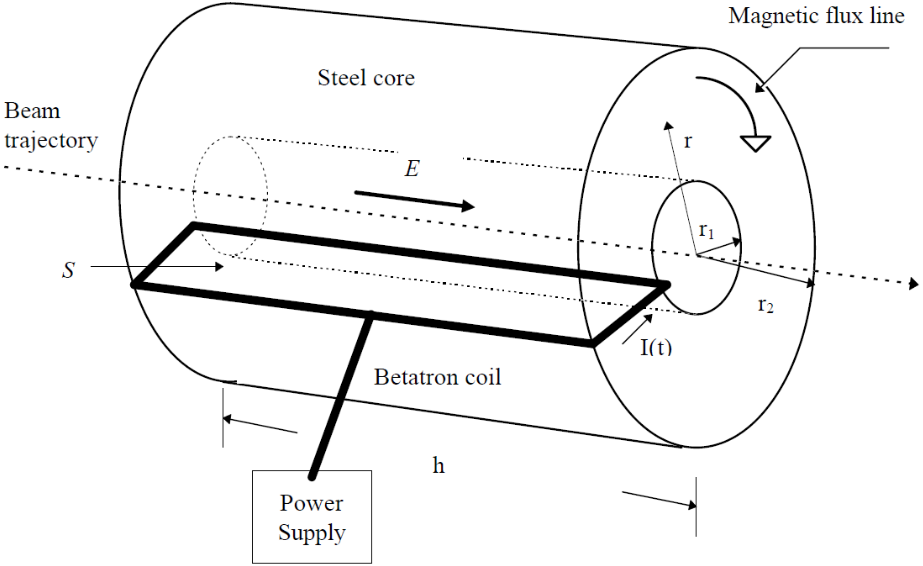
OUTLINE

- Introduction
- A short view back into history
- A little bit of slow extraction theory
- RF-KO system at HIT, Intensity feedback loop (“DIC”) and further enhancements under investigation
- Betatron core implementation at CNAO including extensions
- Comparison
- Acknowledgements

Betatron core at CNAO

From: L. Badano, S. Rossi, Report PS-97-019, CERN





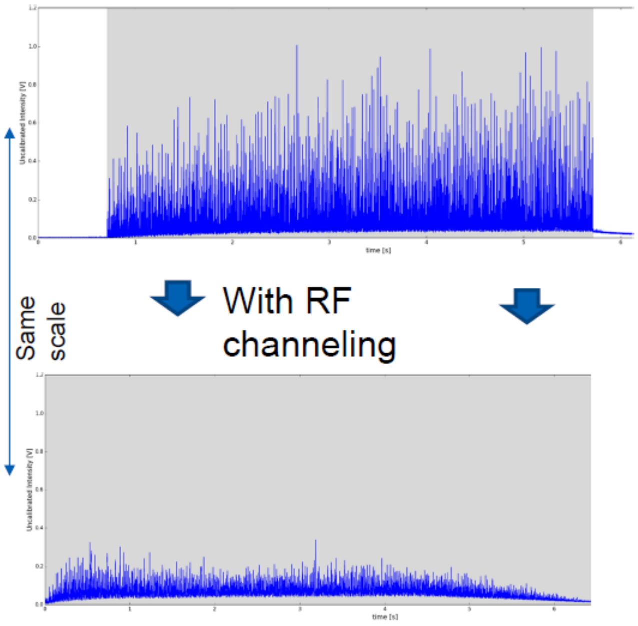
Length (h) [m]	1.5
Internal radius (r_1) [m]	0.08
External radius (r_2) [m]	0.75
Area of a section perpendicular to the magnetic field lines (S) [m^2]	1.005
Lamination thickness [mm]	0.5
Steel density [kg/m^3]	7870
Steel mass (m_s) [kg]	2.062×10^4

Betatron core at CNAO

RF-Channeling spill smoothening

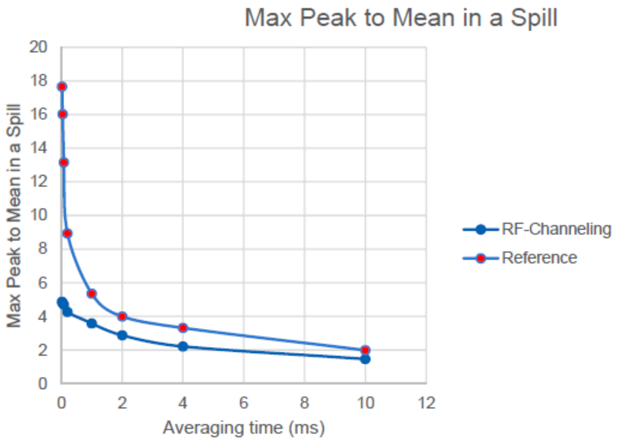
Spill shape only by betraton core extraction

...and with RF channeling



Spill time structure (50kHz)

Change Spot Sizes!!!
→ Re-commissioning



En:62.4 MeV - F_{rev}: 1.33 MHz.
ΔF_{ch}:15kHz – 1500V
Negligible losses

A. De Franco,
C. Schmitzer

From: M. Pullia, SEW 2019 at Fermilab

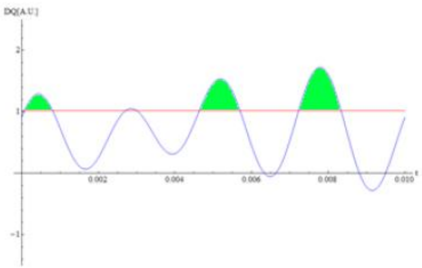
HIT Heidelberg Ion-Beam Therapy Centre

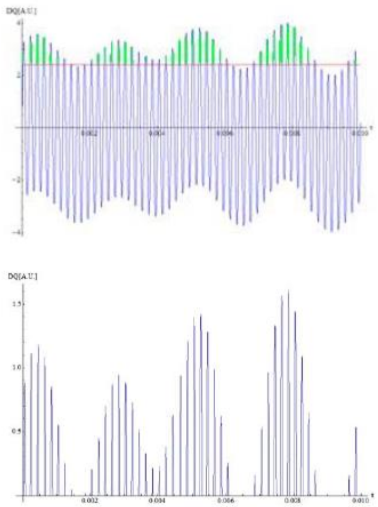
UK HD

Betatron core at CNAO

High Frquency Ripple Injection

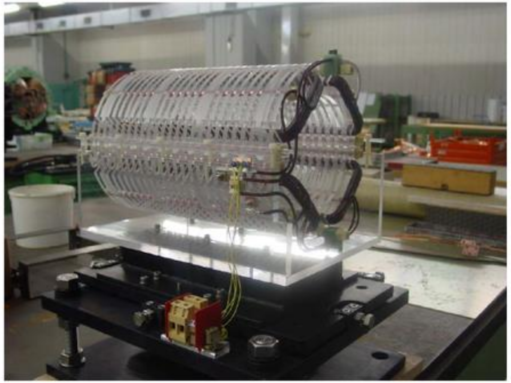
Inject a large ripple with a frequency higher than the one you are interested in





The amount of extracted beam depends only on the betatron, thus an apparently more homegeneous spill is obtained.

Air core quadrupole



From: M. Pullia, SEW 2019 at Fermilab

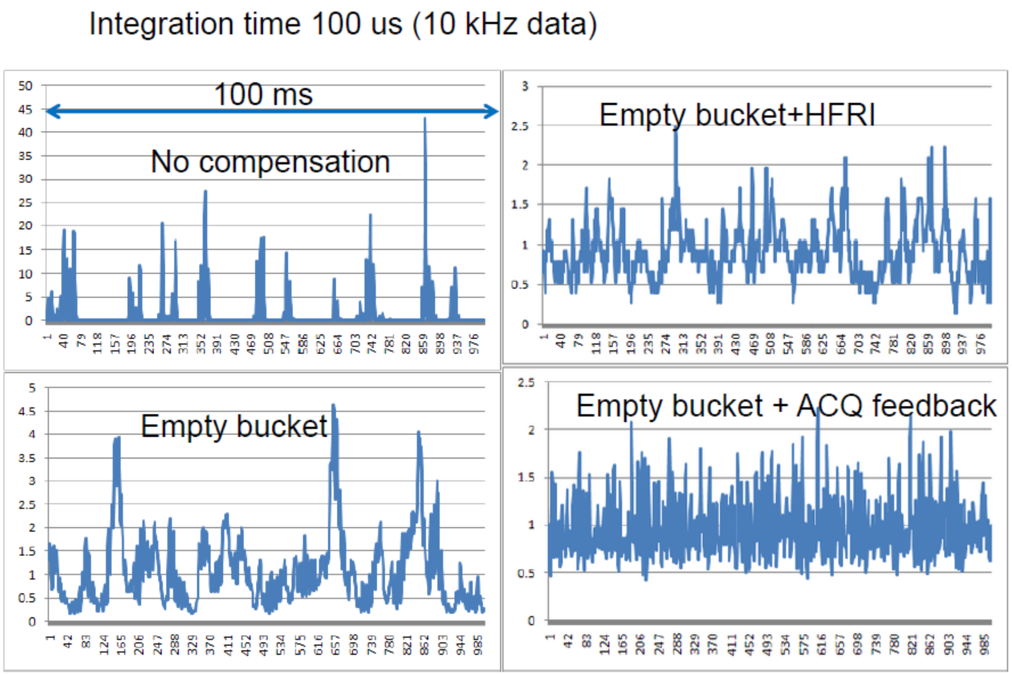
Betatron core at CNAO

Adding more and more active systems leads to beam smoothening, but operation is getting more complex!

(ACQ active in real operation?)

Behavior at CNAO and Medaustron different due to diverse power supplies!

Ripple compensation



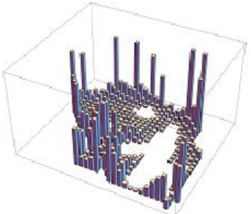
From: M. Pullia, SEW 2019 at Fermilab

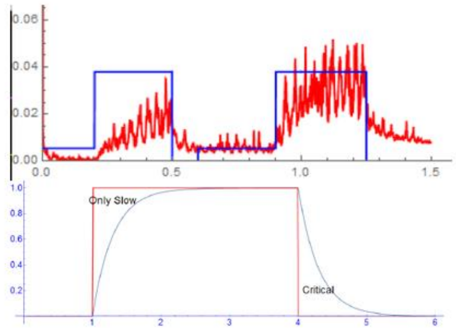
Betatron core at CNAO

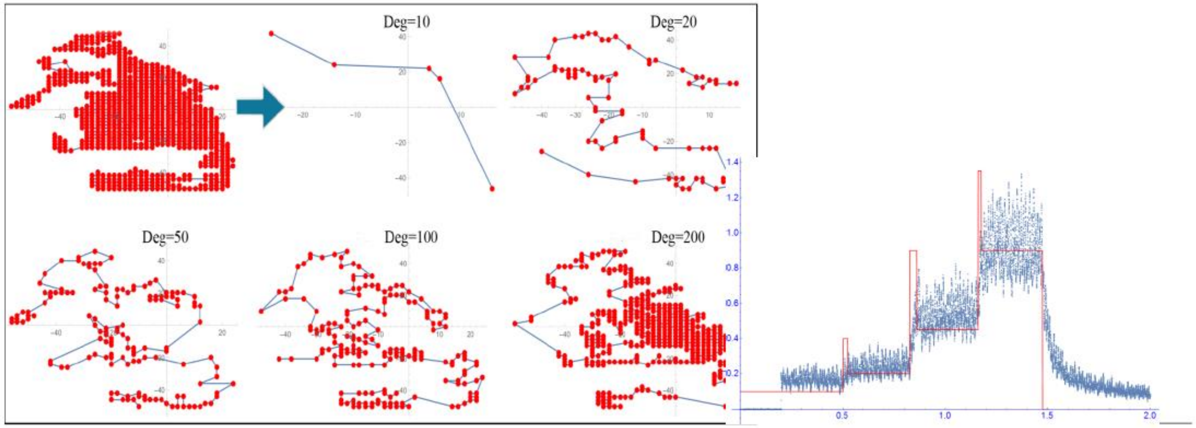
The betatron core reaction speed is lower (upper right) than RF-KO, therefore dynamic intensity control is severely restricted → usage of clever sorting algorithm.

Intensity modulation

Subdivide slice in classes and re-sort in order to treat spots with increasing intensity.







From: M. Pullia, SEW 2019 at Fermilab

RF-KO implemented at CNAO

As an alternative to the betatron core CNAO build its own RF KO system → view inside the vacuum chamber showing exciter plates.

Photo presented at 6th EITOC-Meeting@HIT, 2018

The exciter installed in the CNAO synchrotron – *commissioning is still ongoing.*

From: M. Pullia, SEW 2019 at Fermilab

O U T L I N E

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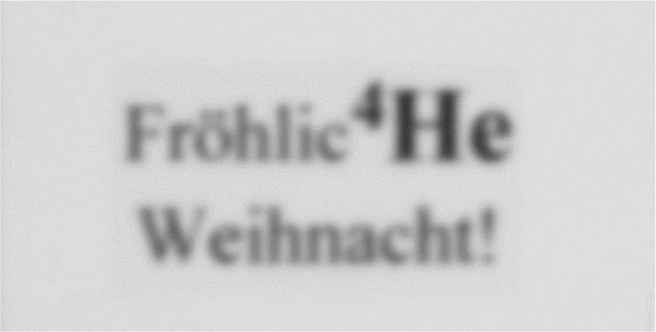
Comparison (my personal view)

Property	RF-KO system	Betatron core system
Mechanics and space needed	Simple / < 1m	Heavy / > 1.5m
System costs	moderate	high
Spill quality /with extensions	Good / excellent	Moderate / good
Feedback compatibility	Excellent	Poor (Bandwidth too small)
Multiple energy operation Compatible	compatible	difficult - impossible

Thank you for your attention!



Thanks to the following persons providing material for this talk:
Christian Schömers et al. (HIT), Peter Forck et al. (GSI),
Fiona Faber (TU Darmstadt), Claude Krantz et al. (MIT, now GSI),
Koji Noda (HIMAC), Marco Pullia et al. (CNAO), Phil Bryant (CERN)
and others

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/