This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

IFAST Prototyping Activity **REX**

Resonant **EX**traction Improvement

Work Package 5 Task 3

1st Annual Meeting / 5th May 2022

Peter Forck & Rahul Singh (GSI) on behalf of the consortium

iFAST

Challenges for slow Extraction form Synchrotrons

Slow extraction: Gentle excitation of a beam **third** order resonance

Beam physics: Extraction as ‘slow losses’ for 1 … 10 s

- Particle crosses stability boarder sequentially
- Exponential amplitude growth during ‘transit time’
  ≈ 50 … 1000 turns reaching septum and is extracted

Problem: Sensitivity to any **unintended** resonance condition, e.g.:

- Change of tune: unintended quadrupole current ripple
- Change of excitation strength: sextupole current ripple
- Stochastic amplitude excitation of ‘knock-out’ extraction

Mitigation research within IFAST-REX:

Beam physics: Methods for beam sensitivity reduction

Proposal of non-standard excitation methods

⇒ Extensive simulation of extraction process

Technical installations: Improved power supplier for magnets

Improved transverse particle excitation for knock-out extraction

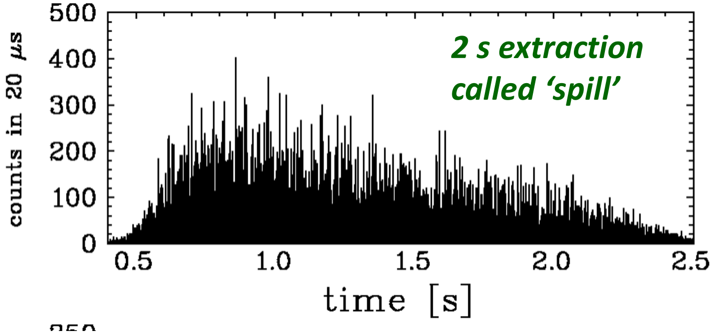
⇒ Non-standard power converter and rf-amplifier control

Validation: Experimental validation at all facilities

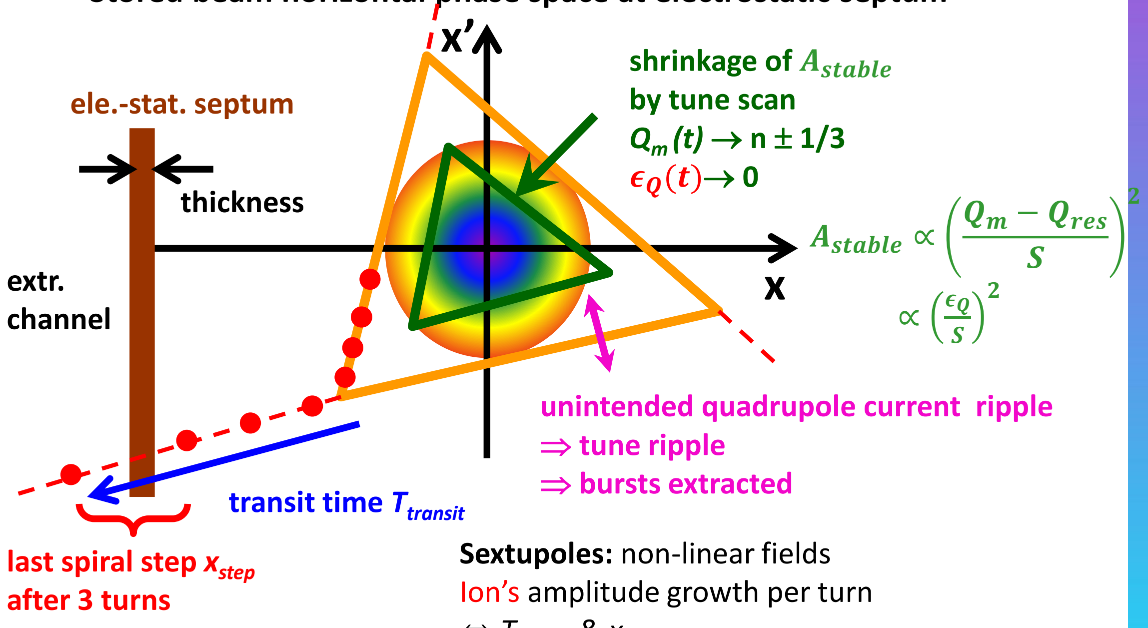
Tailored improvements for IFAST-REX participants

Example: C^{6+} at 300 MeV/u at GSI

Quad. scan, un-bunched beam



Stored beam horizontal phase space at electrostatic septum



Sextupoles: non-linear fields

Ion’s amplitude growth per turn

⇔ $T_{transit}$ & x_{step}

iFAST

barthel HF-Technik, bergoz Instrumentation, CERN, CNAO, GSI, HIT, MedAustron, MIT, SEEIIST

Example for 'Spill Micro-Structure' for a coasting Beam

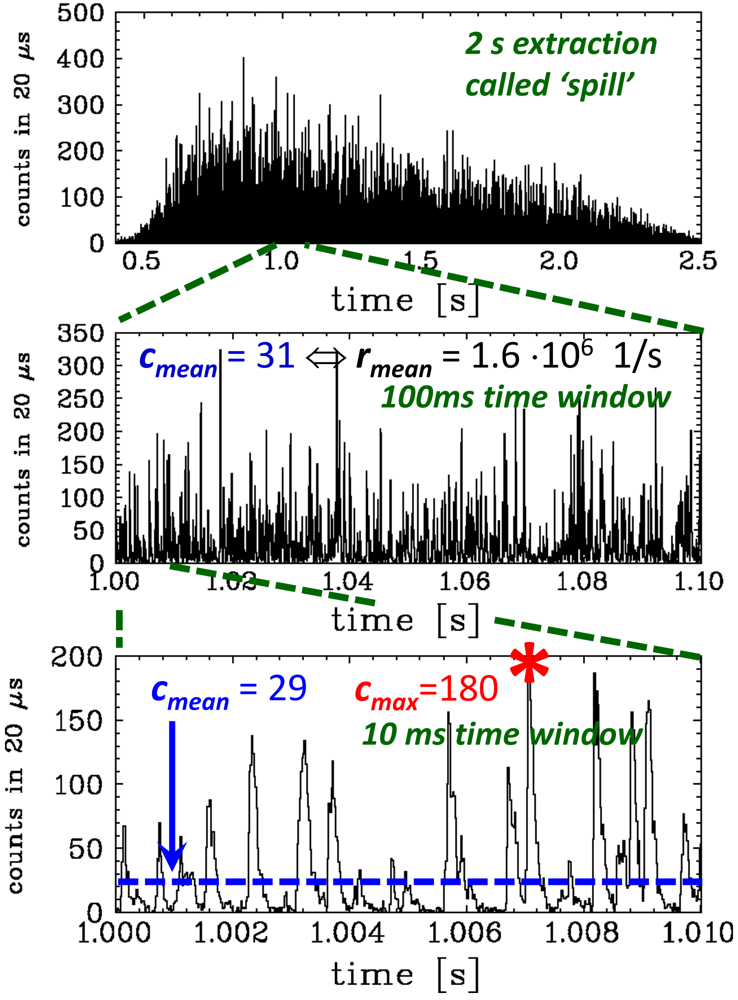
Slow extraction: Gentle Excitation of a beam **third** order resonance

Beam physics: Extraction as 'slow losses' for 1 … 10 s

- Particle crosses stability boarder sequentially
- Exponential amplitude growth during 'transit time' ≈ 50 … 1000 turns reaching septum and is extracted

Problem: Sensitivity to any disturbance of resonance condition

Example: C^{6+} at 300 MeV/u at GSI
Quad. scan, un-bunched beam



Time domain characterization:

Spill characterization readout time $t_{read} = 20\ \mu s$

→ Time intervals of e.g. Δt = 10 ms

- ***Max.-to-aver.*** $r_{\Delta t} = c_{max} / c_{mean}$
- ***Duty factor, i.e. normalized fluctuations*** $F_{\Delta t} \equiv \frac{c_{mean}^2}{c_{mean}^2 + \sigma_c^2} \equiv \frac{\langle c \rangle^2}{\langle c^2 \rangle}$

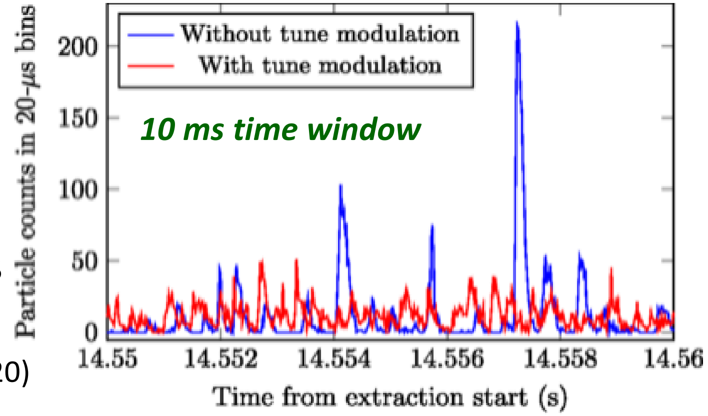
Improvement possible:

(here: Controlled tune variation)

⇒ Beam dynamics simulation

⇒ Experimental demonstration

⇒ Application at several facilities



R. Singh et al., Phys. Rev. Applied **13,044076** (2020)

duty factor $F_{20\mu s} \approx 0.4$

iFAST

barthel HF-Technik, bergoz INSTRUMENTATION, CERN, CNAO, GSI, HIT, MedAustron, MIT, SEEIIST

IFAST-REX Work-Package Collaboration Meeting

2nd Collaboration Meeting 17th of February, 40 attendees

See https://indico.gsi.de/event/14171/

Contributions to the work-packages:

1) High dynamic range current measurement device
   chair F. Stulle (Bergoz)
2) KO signal generation and amplification
   chair Eike Feldmeier (HIT)
3) Slow extraction simulation and experiments
   chair Francesco Velotti (CERN)
4) Spill detector development and analysis
   chair Peter Forck (GSI)

General workshop on slow extraction issues

Online organized by KEK (Japan) with 89 attendees
at https://conference-indico.kek.jp/event/163/
One major subject related to micro-structure

Contributions from IFAST-REX participants!

Forthcoming face-to-face workshop planned for end of 2023 in Wiener Neustadt
to be organized by MedAustron & GSI in the frame of **IFAST-REX**

IFAST-REX Working Group 3 (Simulation&Experiment): Survey to compare different Facilities

Performed by Florian Kühteubl et al.(MedAustron)

Questionnaire of 3 pages related to:

- General beam parameters
  - ⇒ appropriate scaling
- Type of slow extraction
  - ⇒ comparison of different methods
- Typical quality and its measurement
  - ⇒ experiences of improvements
- **Comparison of typical extraction data**

Goal: achievements including

appropriate scaling e.g. wrt. trans. emittance

Status:

- Evaluation finished
- Typical data from all participants evaluated

iFAST-REX
Slow Extraction Survey

Please fill out the survey separately for all available extraction methods and/or particle types!

In case of any questions or uncertainties, please contact Florian Kühteubl (florian.kuehteubl@medaustron.at).

General	
Institution:	GSI
Machine:	SIS-18
Circumference of the accelerator [m]:	216.72 m

Beam parameter			
Particle type:	protons and all ions until Uranium		
Energy [MeV/u]:	Min: 11.4	Max: 2000 (protons)	
Revolution frequency [MHz]:	Min: 0.2	Max: 1.2 (dep. q/m)	
Number of particles at flat top + corresponding energy [MeV/u]:	Min: 1e5	Max: 1e11	
	Energy: 300 - 2000	Energy: 300 - 2000	
How is the number of particles/current circulating in the ring measured? What is the sensitivity of the measurement?	DCCT : Maximum bandwidth is 20 kHz. Sensitivity of measurement is approximately 1 uA. (number of particles for 1 µA depend on charge-to-mass ratio from H+ to U73+)		
Normalized beam emittance of the circulating beam before extraction [π mm mrad]:	Horizontal:	30 mm-mrad	
	Vertical:	5 mm-mrad	
	Method of measurement:	Ionization profile monitor inside synchrotron, vertical profile with screen measurement in transfer	

Efficiency & Quality			
Number of particles/spill in the extraction line:	Min: 1e4/s	Max: 1e11/s	
How is the number of extracted particles measured? What is the sensitivity of the measurement?	Plastic scrintillators (up to 1e6/s mean rate) Ionization chambers (lower boarder 1e4 for heavy ions e.g. U73+ to 1e5/s for proton; upper boarder 1e8/s for U73+ and 1e11/s for protons) Secondary electron monitors (lower boarder 1e6/s for U73+ and 1e10/s for protons). A cryogenic current comparator is also under		
Extraction efficiency [%]: *w.r.t the number of particles at flat top*	60-90% (depending on beam emittance)		
Beam losses at the septum [%]: *w.r.t the number of particles at flat top*	10-30% (depending on beam emittance)		
Duty factor:	Typical value:	0.5	
	Method of measurement:	Particle counting with plastic scri	
	Time resolution:	typ. 10 ms for evaluation; data re	

Notes & Comments

1) Bunched beam extraction and tune wobbling are used for mitigation of spill modulation caused due to power supply ripples
2) A slow multicyle feedbacksystem is used to control the shape of macropulse. The output of detectors over multiple cycles are used to correct the macropulse.

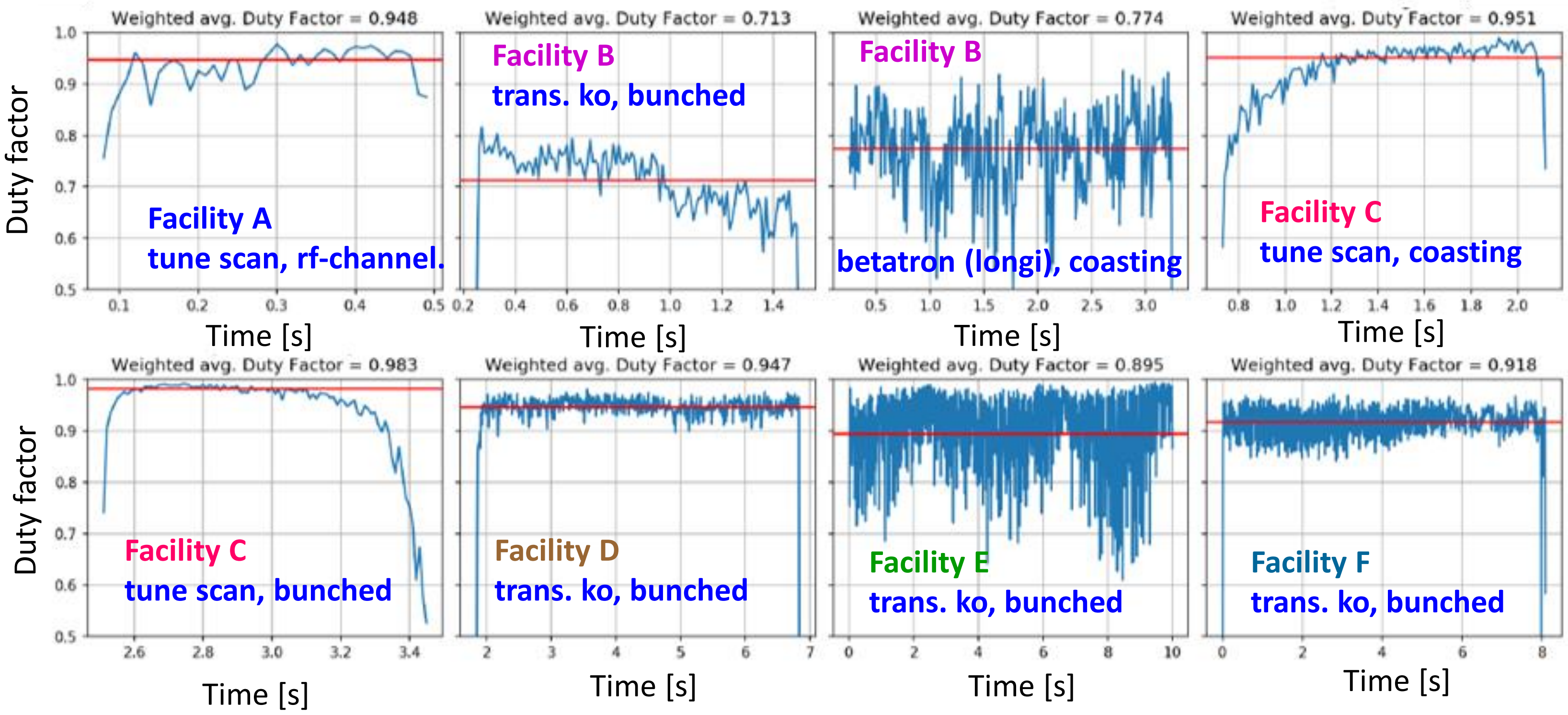
Facilities:

- European medical synchrotrons
- CERN-SPS & GSI

IFAST-REX WG 3: Typical Duty Factor for different Facilities for operational Parameters

Performed by Florian Kühteubl et al. (MedAustron) for same sample period of 10 ms (but different extr. duration)

Duty factor $F_{\Delta t} \equiv \frac{c_{mean}^2}{c_{mean}^2 + \sigma_c^2} \equiv \frac{\langle c \rangle^2}{\langle c^2 \rangle}$ **describes normalized fluctuations ⇒ the larger the duty factor the better the beam**



Facility	Ex. meth.	Beam	Improve ment	Duty fac. $F_{\Delta t}$
A	Tune scan	coasting	Rf-chan.	0.948
B	Trans. ko	Bunched	Air-core quad	0.713
	Betatron,	Coasting	Rf-chan	0.774
C	Tune scan	Coasting	Tune wobble	0.951
	Tune scan	Bunched	-	0.983
D	Trans. ko	Bunched	-	0.947
E	Trans. ko	Bunched	Rf-chan.	0.895
F	Trans. ko	Bunched	Air-core quad.	0.918

Result: - Different beam quality caused by power supplier quality

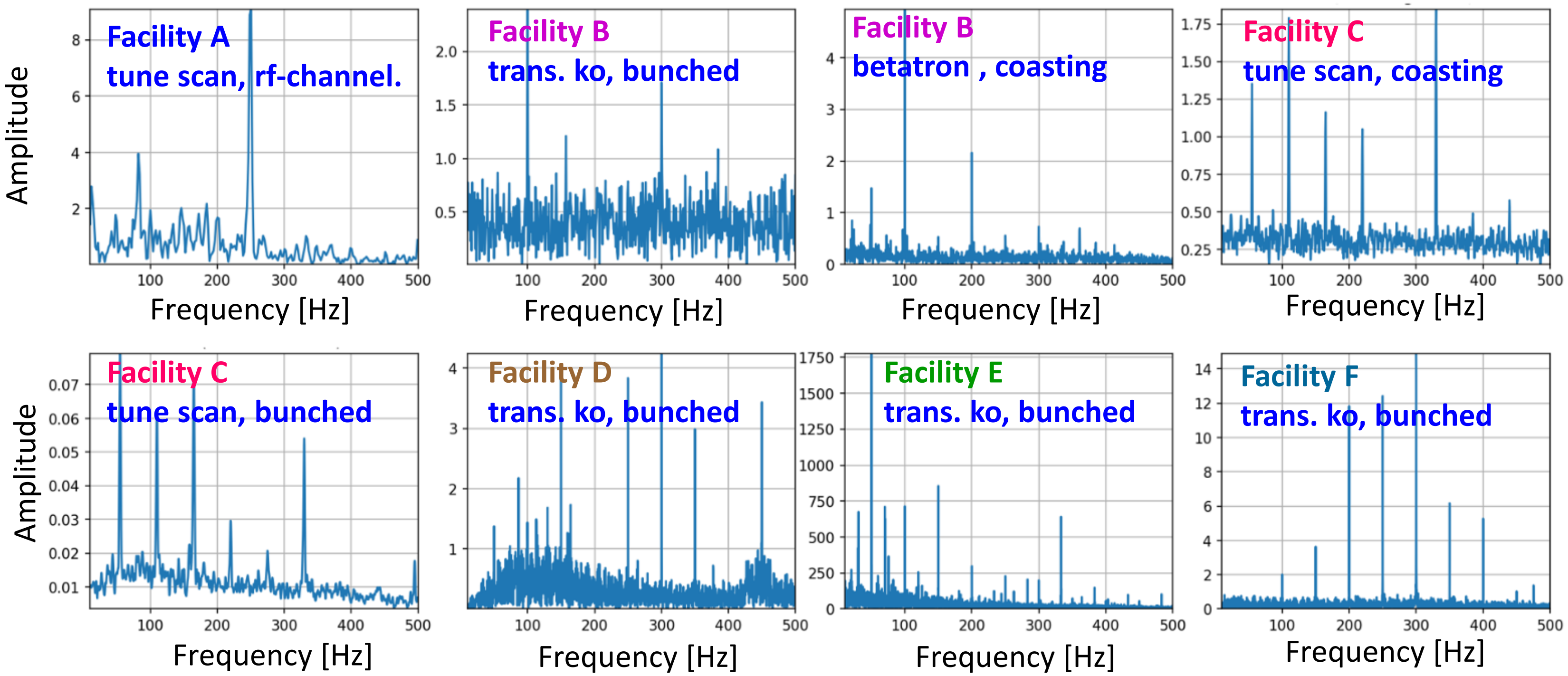
- Various active beam stabilizations in operation and under test

IFAST-REX WG 3: Typ. Frequency Spectrum for different Facilities for operational Parameters

Performed by Florian Kühteubl et al. (MedAustron) for same sample period of 10 ms

Comparison different facilities with same sample rate: Frequency spectrum 0…500 Hz

→ Characterization of power supplier quality and beam reaction for typical (= user-defined) conditions



Results:

- 50 Hz related lines; depends strongly on power supplier type
- Different beam reaction (broadband)
- Differences (expected)

  coasting ↔ bunched beam

⇒ Beam characterization for simulation

⇒ Requirements & methods of counteraction

IFAST-REX Working Group 3 (Simulation&Experiment): Beam Response Simulation

M. Pari et al., Phys. Rev. Accel. Beams 24, 083501 (2021)

Example: CERN (F. Velotti, M. Pari et al.)

Topic: Modelling power supplier action to **SPS** beam

Goal: Realistic beam simulations by MADX

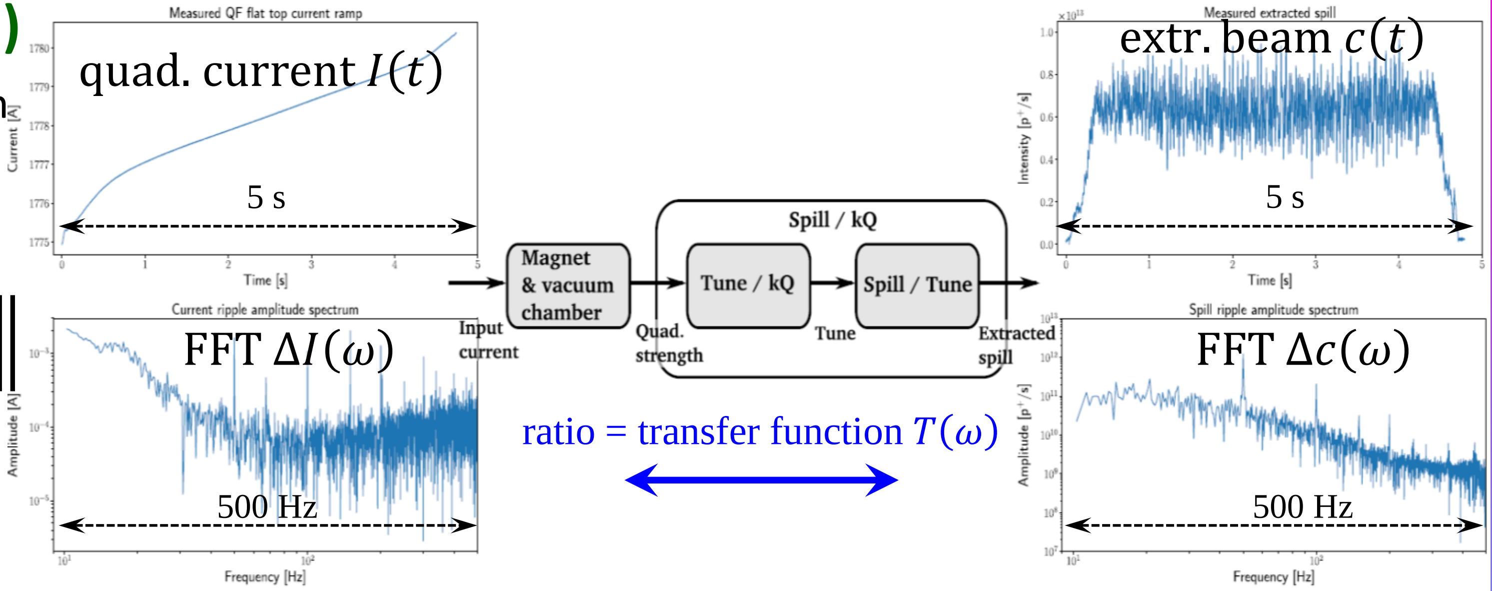
Methodology: Power supplier action to beam

described by **transfer function** $T(\omega) = \left\| \frac{\Delta c(\omega)}{\Delta I(\omega)} \right\|$

$\Delta c(\omega)$ is Fourier trans. of extracted beam

$\Delta I(\omega)$ is Fourier trans. of power supplier variation

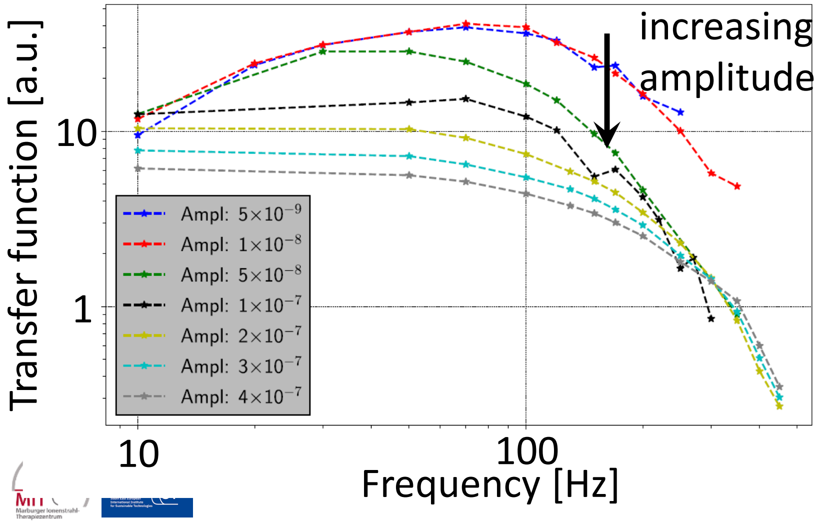
using experimental data



Results:

- Excellent correspondence to exp. data
- Amplitude dependence i.e. non-linear behavior
- Detailed simulations executed to explain dependencies
- Related to transit time (description e.g. preferred by GSI)

Example: MADX simulation for several frequencies



Status:

- Results published
- Application for other facilities possible

Highlight talk by Francesco Velotti on Friday

IFAST-REX Working Group 3 (Simulation & Experiment): Improvements

Topic: Visualization & optimization of complex process

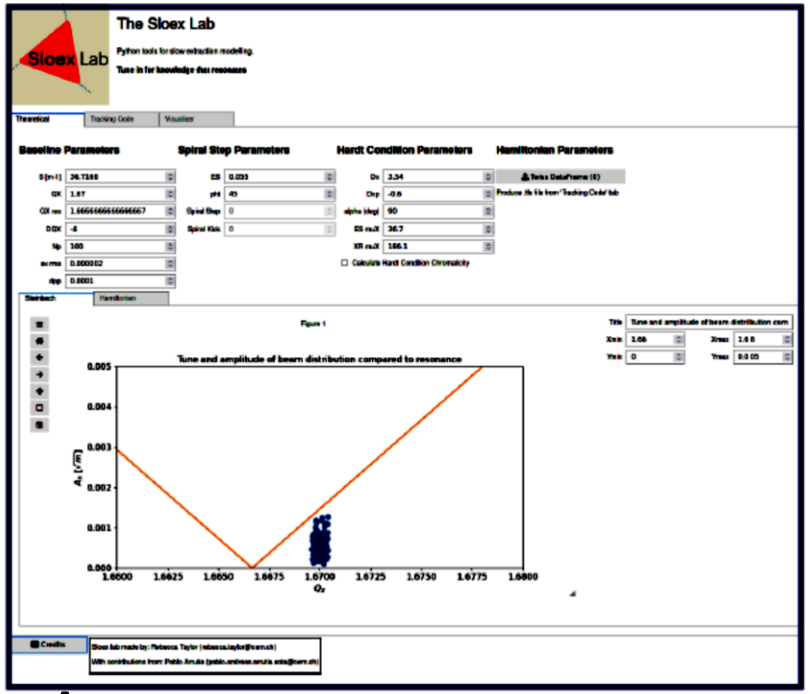
Example: SEEIIST & CERN (R. Taylor et al.)

Goal: General understand of important processes

Methodology: MAD-X simulations and MAPTRACK with Python-based GUI

Status:

- Improving modelling
- Code optimization (common effort for all facilities)
- Application for other facilities possible

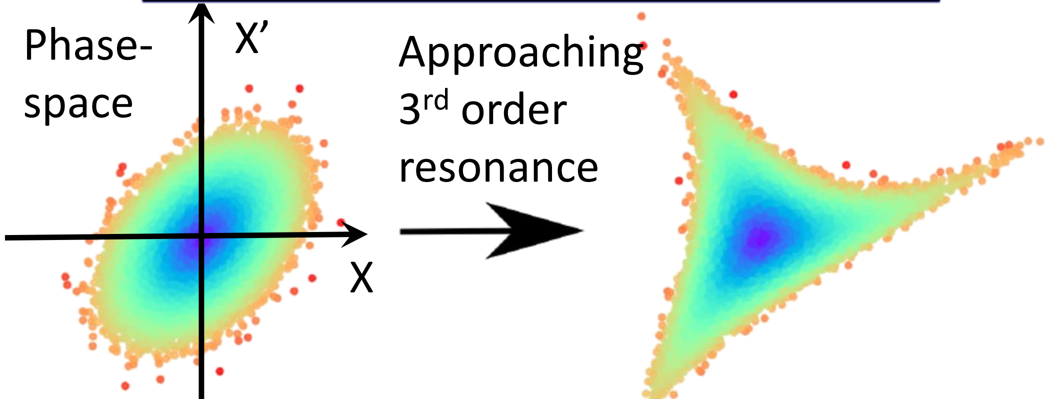


Example: HIT (Ch. Cortes et al.)

Goal: Optimization of knock-out extraction caused fluctuations

Methodology: Simulation for HIT & comparison to dedicated experiments

Experiment: Tune determination close to 3rd order resonance



IFAST-REX Working Group 3 (Simulation&Experiment): Tune measurement at HIT & GSI

Topic: Tune measurement for beams shortly before extraction

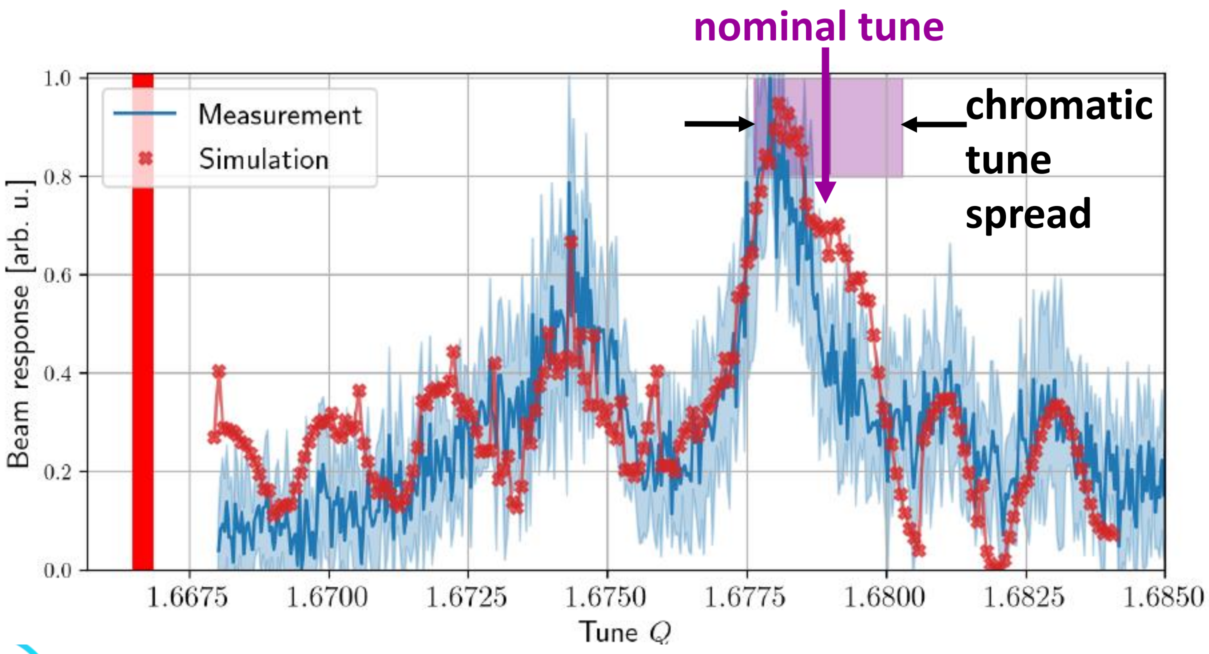
by C. Cortes (HIT), R. Singh (GSI), R. Taylor (CERN&SEEIIST)

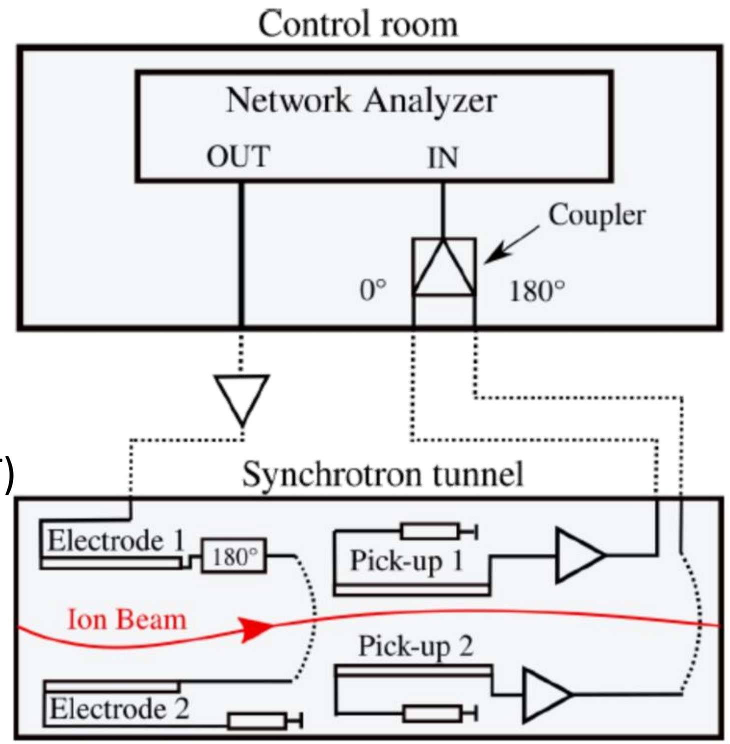
Goal: Modeling non-linear beam parameter close to 3rd order resonance

$\Rightarrow$ optimized knock-out extraction spectrum

Methodology: Beam Transfer Function measurement & comparison to MAD-X simulation

Status: Work in progress, Interpretation under intense discussion (HIT, GSI, CERN&SEEIIST)





Remark:

- Single peak expected for a stable stored beam, i.e. without resonance driving terms by sextuples
- BFT measurement seldom (never?) performed under unstable conditions

IFAST-REX WG 3: (Simulation&Experiment): Optimized Excitation Spectrum

Performed by HIT (Christopher Cortes et al.)

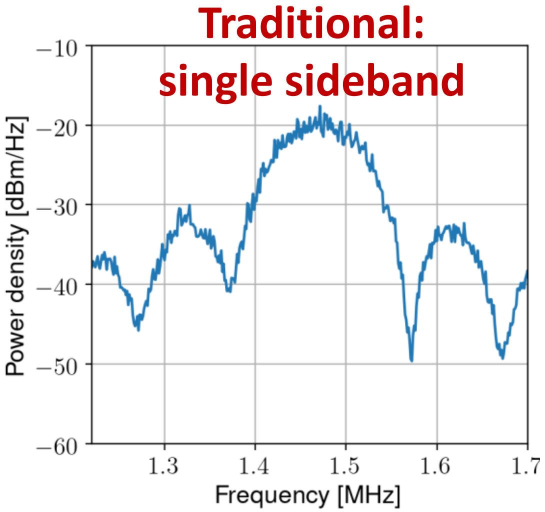
Knock-out extraction: Excitation of betatron amplitudes by transverse rf-noise (used at med. facilities & GSI)

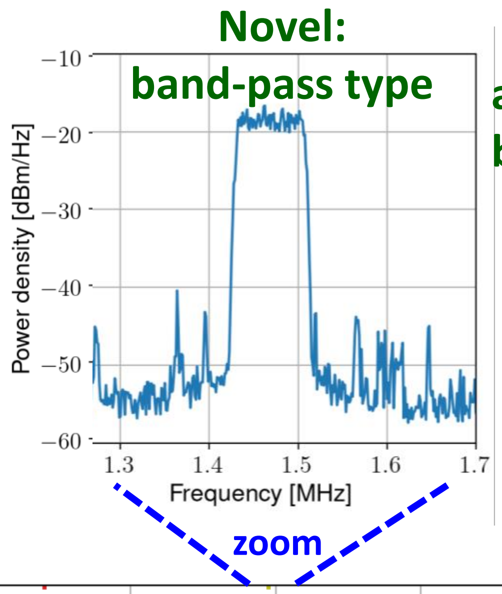
Topic: Beam response to different signal shapes

Experiment at HIT:

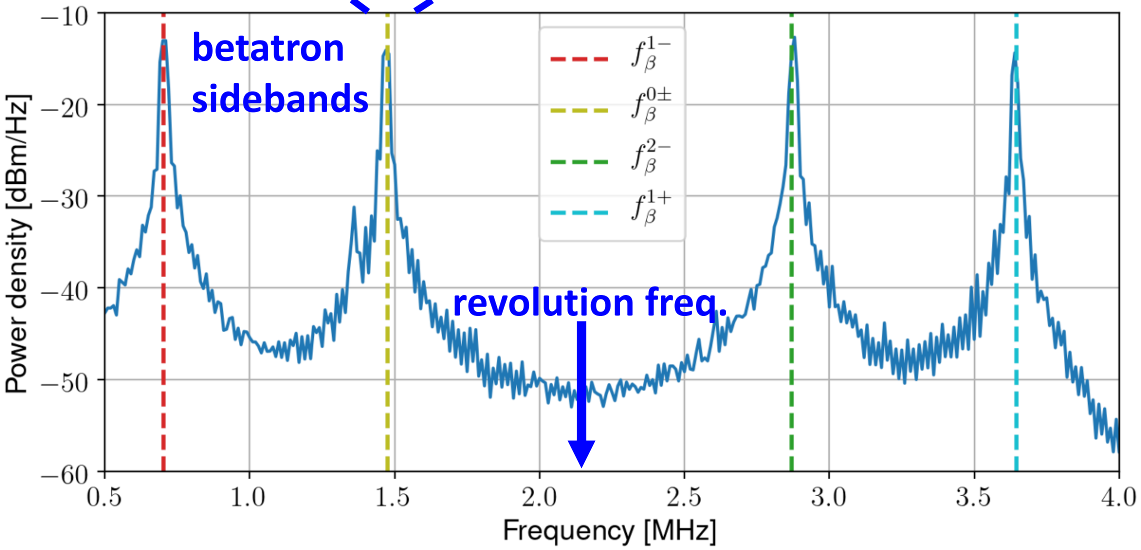
Traditional: **Single** band excitation with sinc-shaped noise function by 'random phase shift keying'

Novel: **Multi** band excitation with flat bands





at several harmonics of betatron frequencies



iFAST

barthel HF-Technik, bergoz INSTRUMENTATION, CERN, CNAO, GSI, HIT, MedAustron, MIT, SEEIIST

IFAST-REX Working Group 3: Simulation and Experiment

Performed by HIT (Christopher Cortes et al.)

Knock-out extraction: Excitation of betatron amplitudes by transverse rf-noise (used at med. facilities & GSI)

Topic: Beam response to different signal shapes

Experimental results at HIT:

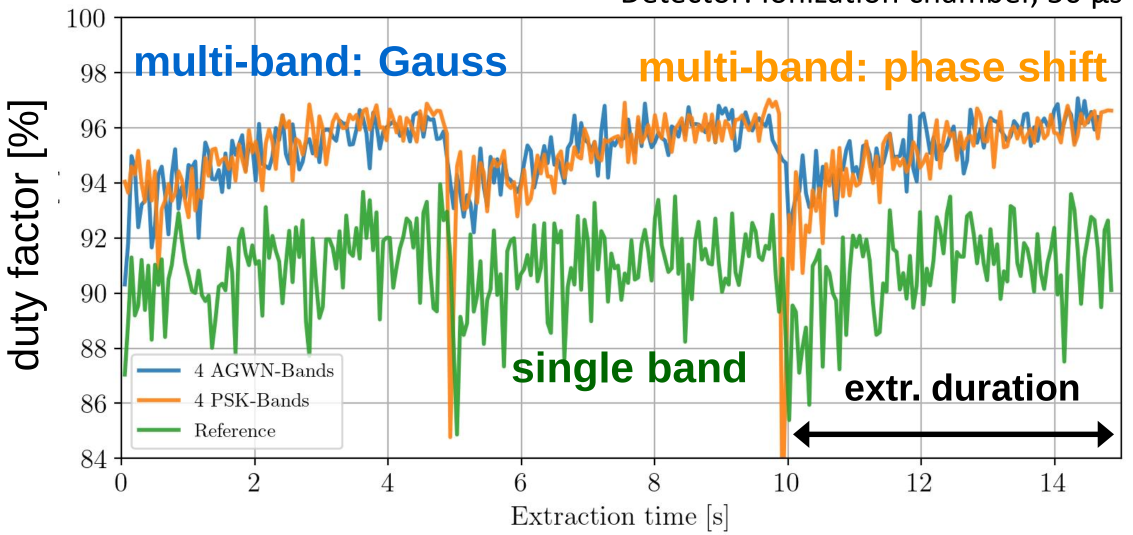
- **Significant increase of beam quality by multi-band**
- Lower influence by noise type
- Technically feasible method of excitation
- Restricted to 4 sidebands due to ***amplifier power***

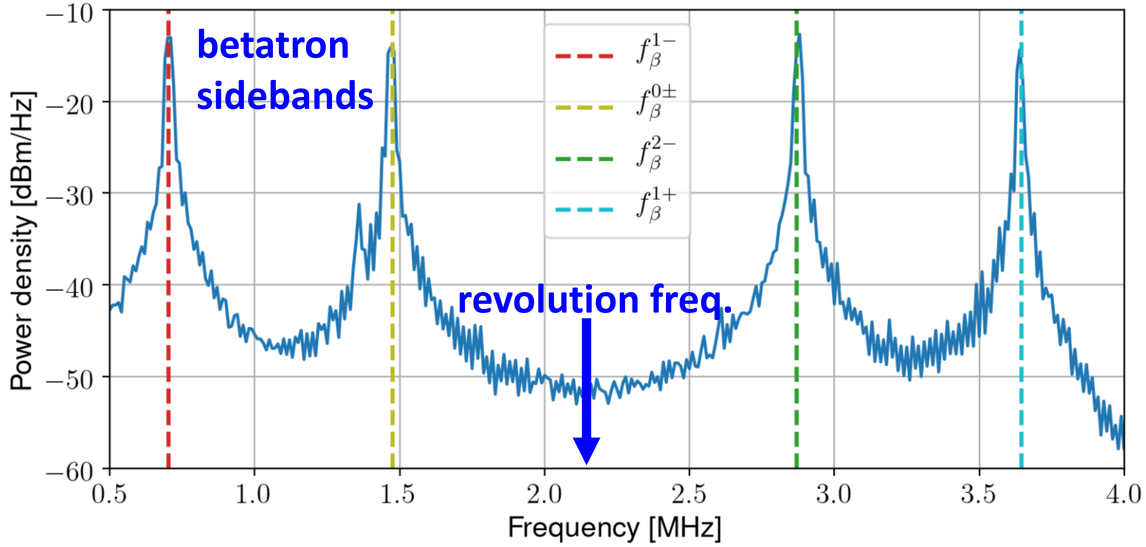
Micro-structure quality measure → duty factor:

$F_{\Delta t} = \frac{\langle c \rangle^2}{\langle c^2 \rangle}$ i.e. inverse normalized fluctuations

at HIT readout time $\Delta t = 50\ \mu s$ (e.g. at GSI $\Delta t = 10\ \mu s$)

Beam: C^{6+} 124 MeV/u, 8e7 ions, tune $Q_x = 1.68$
Detector: Ionization chamber, 50 µs readout





IFAST-REX Working Group 2: Knock-out Extraction Signal Generation and Amplification

Performed by HIT (Eike Feldmeier et al.) & company Barthel

Knock-out extraction: Excitation of betatron amplitudes by transverse rf-noise (used at med. facilities & GSI)

Topic: Technical realization for knock-out extr. amplifier

Digital signal generation by 'Software Radio':

- Performant commercial DAC board
- Control by freeware 'GNU Radio'
- Detailed programming optimization at HIT & GSI
  e.g. adaption of latency required

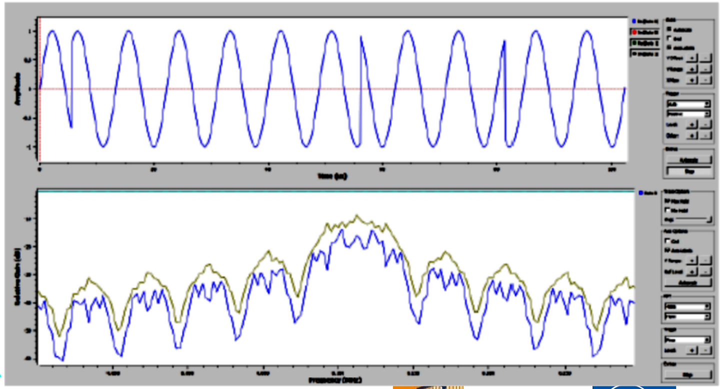
⇒ matched solution with good flexibility

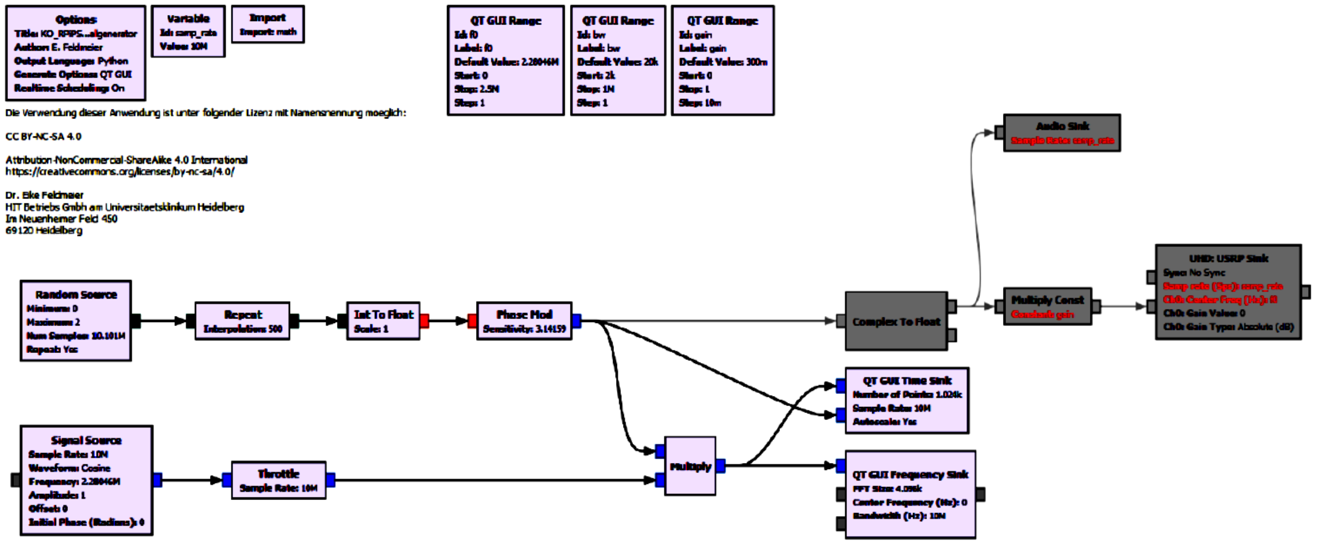
Status: Specification achieved, good tool for beam studies

Signal generation (HIT, GSI)

Universal software radio:

- DAC: 16 bit, 400 MS/s
- Analog bandwidth: > 100 MHz
- Max. output voltage 1.8 V





IFAST-REX Working Group 2: Knock-out Extraction Signal Generation and Amplification

Performed by HIT (Eike Feldmeier et al.) & company Barthel

Knock-out extraction: Excitation of betatron amplitudes by transverse rf-noise (used at med. facilities & GSI)

Topic: Technical realization for knock-out extr. amplifier

Power amplifier (beneficiary company Barthel):

- Bandwidth: 0.1 … 20 MHz (or higher)
- Power: 1 kW@50Ω or higher for multi-bands
- Matching network required, efficient voltage generation rigorous requirements

Status: Specification from HIT give to Barthels

Waiting for detailed specifications from other facilities

Milestone MS20 in month 24 expected:

'Engineering design of improved power supply current measurement and RF-amplifier layout'

IFAST-REX Working Group 1: Specification for power Supplier Stabilization

Performed by company Bergoz (Frank Stulle et al.)

Accelerator physics: Spill fluctuation main caused by quadrupole current ripple; experimentally confirmed

Topic: Development and integration of **high dynamic range** current measurement device proving $\frac{\Delta I}{I_{DC}} \approx 10^{-7}$

Goal: Production of large dynamic range AC current measurement device by company Bergoz

Methodology: Detailed specification table produced as steered by GSI and Bergoz

Status: Agreement on most items for GSI quadrupoles
pending: spec. other facilities, but comparable

Challenges: AC-component at $I_{AC,min}/I_{DC} = 10^{-4}$ level on strong DC offset

Development: First design consideration by Bergoz

Parameter for additional control	Main Quad SIS100
Magnet current specification	
DC current min. $I_{DC,min}$ & max. $I_{DC,max}$	1 kA & 11 kA
DC current polarity	pos, neg
DC current ramp gradient r_I	6000 A/s
Ramp time Δt	0.1 … 1 s
AC modulation rel. min. $I_{AC,min}/I_{DC}$ & max. $I_{AC,max}/I_{DC}$	10^{-4} & 10^{-2}
AC modulation absolute min. $I_{AC,min}$ max. $I_{AC,max}$	0.1 & 100 A
Measurement requirements	
Measurement duration t_{tot}	20 s
Measurement bandwidth f_{min} … f_{max}	10 Hz … 40 kHz
Measurement dynamic range total	>120 dB
Measurement dynamic range per range setting	>100 dB
Measurement resolution flat-top relative $\sigma_{I,FT}/I_{DC}$	10^{-7}
Measurement uncertainty u_I	0.1% - 1 %
Temperature coefficient c_T	NN %/K

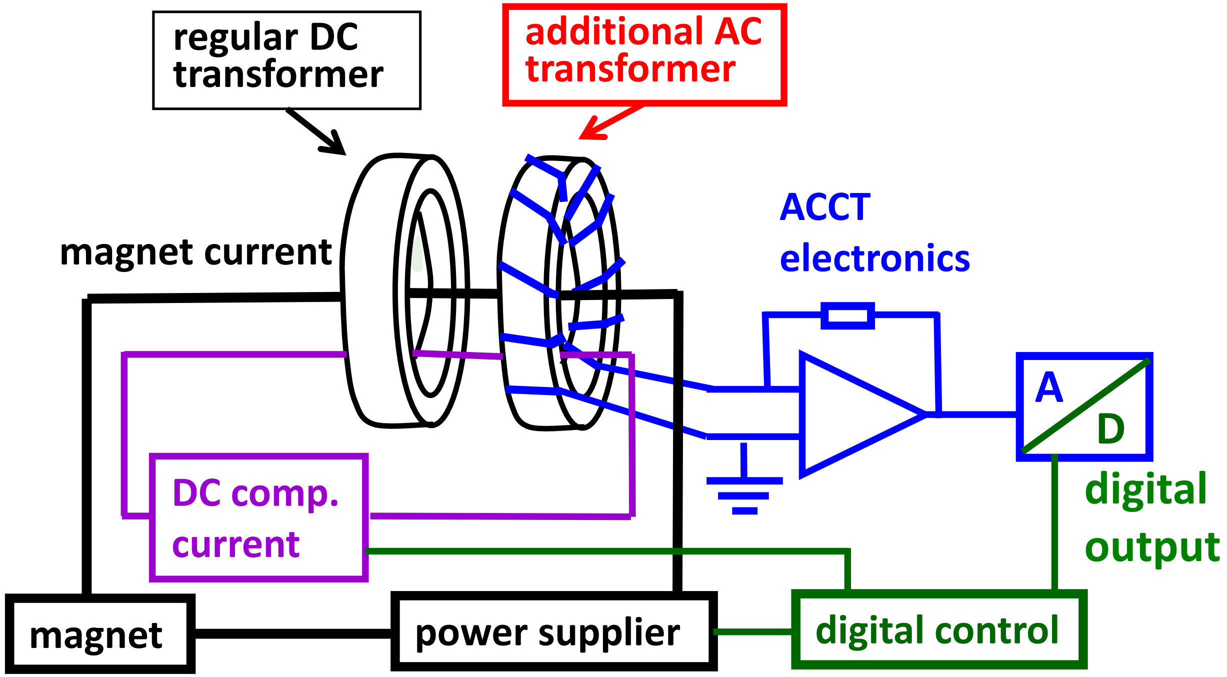
IFAST-REX Working Group 1: Design for AC Current Measurement

Performed by company Bergoz (Frank Stulle)

Topic: Development and integration of
high dynamic range current measurement device

Novelty: Additional control of power supplier
Sensitivity: $I_{AC} / I_{DC} < 10^{-5}$

Development: First layout by Bergoz as **novel** device



Parameter of transformer core and electronics	Main Quad SIS100
Diameter *D*	100 mm
Outer Length *L*	≤ 20 cm
Outer Width *W*	≤ 20 cm
Outer Hight *H*	≤ 20 cm
Weight *M*	NN
ADC sample rate	≥ 100 kSa/s
ADC eff. bits ENOB	≥ 17 bit

IFAST-REX Working Group 1: Realization for AC Current Measurement

Performed by company Bergoz (Frank Stulle)

Topic: Development and integration of
high dynamic range current measurement device

Novelty: **Additional** control of power supplier
Sensitivity: $I_{AC} / I_{DC} < 10^{-5}$

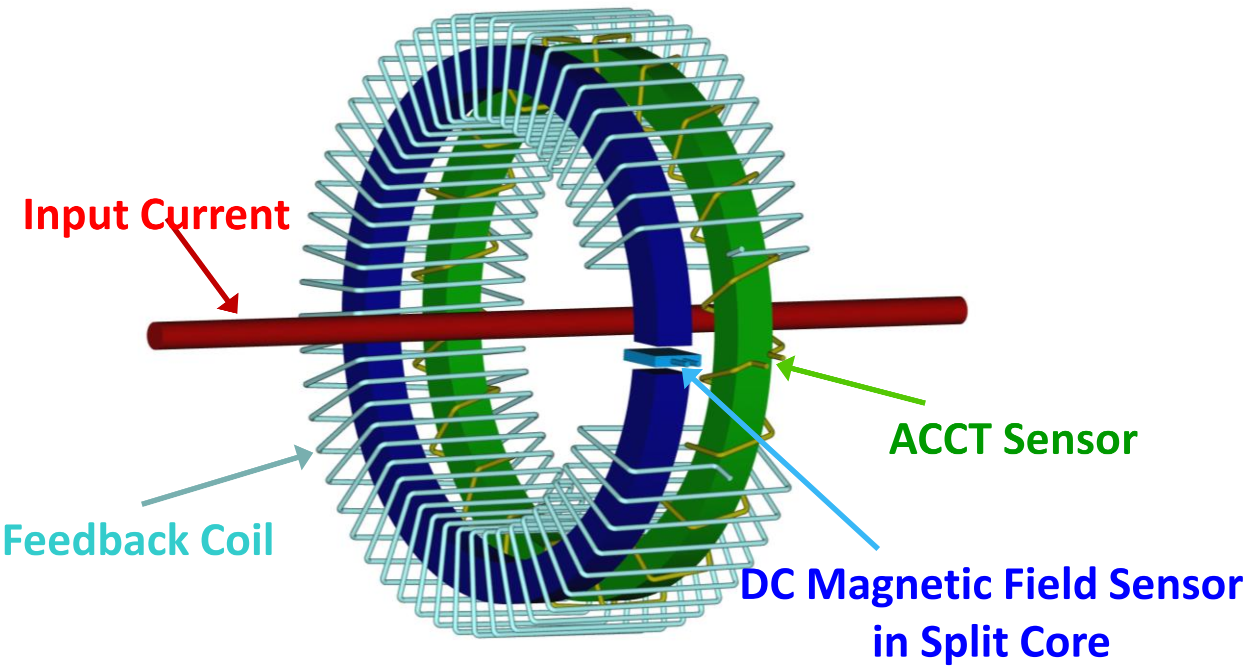
Development: First layout by Bergoz as **novel** device

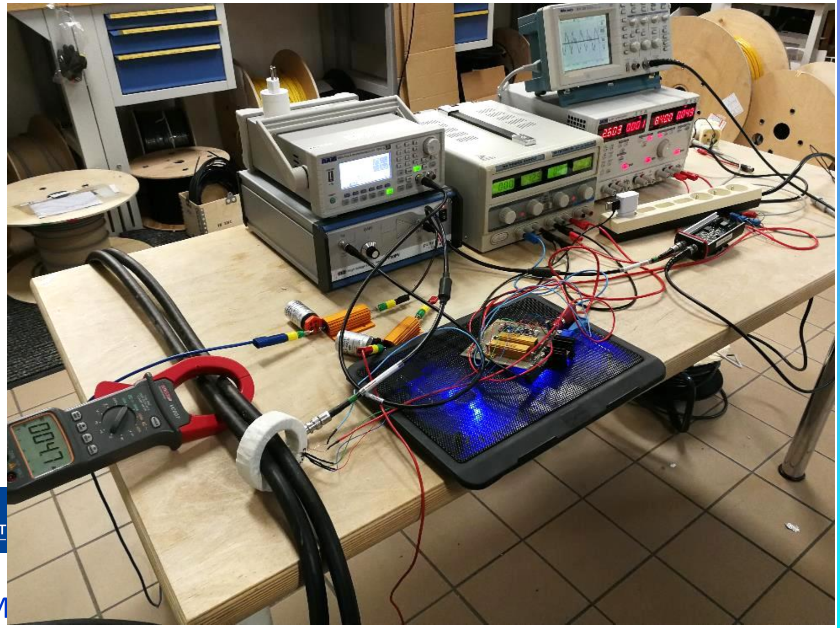
Present achievements → proof-of-principle achieved:

- Test with up to 400 A_{dc} plus ~10^{-3} power supply ripple
- Large bandwidth 1 Hz … 40 kHz achieved
- Integration of DC trans. compensation winding to AC transformer to prevent for core saturation
- Under considerations: Improvement of AC resolution, Cross talk AC trans. ↔ compensation winding

Specification from different labs must be collected

Status: Work in good progress





IFAST-REX WG 4 (Detector Development): Radiation-hard inorganic ZnO:In Scintillator

Performed by GSI (P. Boutachkov et al.)

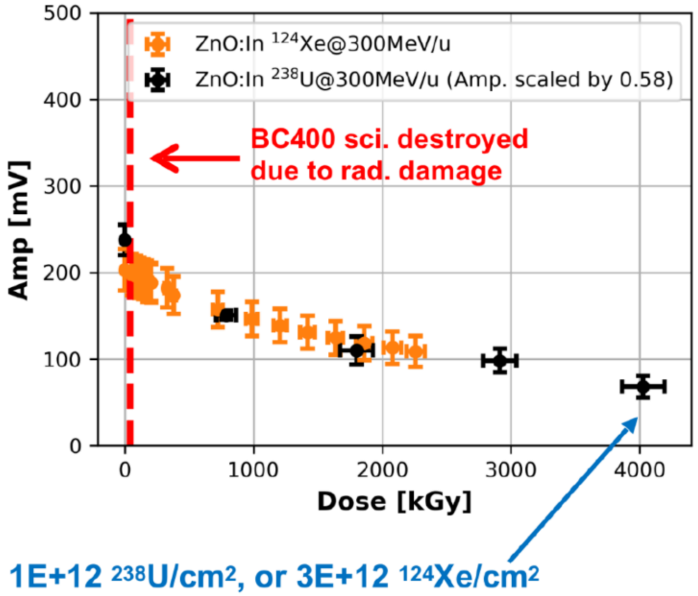
Topic: Alternative to plastic scintillator

$\rightarrow$ Radiation-hard particle counter by inorganic scintillators

Example: Beam: : U and Xe at 300 MeV/u

IBIC-2019, P. Boutachkov et. al.

https://doi.org/10.18429/JACoW-IBIC2019-MOPP005

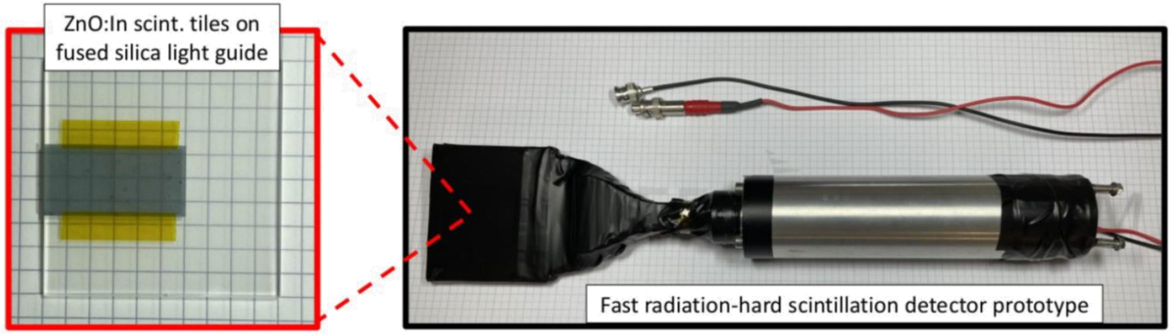


Development:

- ➢ Large area 50x50 mm^2 needed
- ➢ Compilation of e.g. 15 mm^2 tiles

Two scintillator tiles detector,

detector active area 30x15 mm^2



Preliminary: ^{78}Kr @ 300 MeV/u, 98% efficiency compare to BC400

Advantage:

- ➢ Much higher radiation hardness
- ➢ Fast counting with r_{aver} = 10^7 1/s
- ➢ Can be used as detector for spill characterization

Development: Large area detector possible!

Possible restriction: Too low output for protons and light ions (?)

iFAST

Conclusion:

- Collaboration established and in good swing
- WG 1 (novel transformer combination): Proof-of-principle achieved, significant progress
- WG 2 (knock-out amplifier & control): Realization of signal generation achieved, amplifier design started
- WG 3 (simulation & experiment): Various investigations performed, common exteriments and discussion
- WG 4 (detectors & DAQ): Progress for radiation-hard scintillators and DAQ
- Coordination ongoing, common investigations by CERN, GSI, HIT, SEEIIST

The valuable work of all collaborators are warmly acknowledged

Thank you for your attention

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

IFAST-REX Work-package Members for initial Phase

1) Development and integration of high dynamic range current measurement device:

Bergoz: **Frank Stulle (chair)**
CERN: Miguel Cerqueira Bastos
CNAO: ---
GSI: Rahul Singh, Andrzej Stafiniak, Peter Forck
HIT: Andreas Peters
MedAustron: Claus Schmitzer, Dale Prokopovich
MIT: --
SEEIIST:---

2) Specification and contribution for KO signal generation, exciter and amplifier design:

Barthel: Matthias Barthel
CERN: Wolfgang Hofle
CNAO: Marco Pullia, Alessio Mereghetti, Paolo Meliga
GSI: Rahul Singh, Philipp Niedermayer, Stefan Sorge (o), Peter Forck (o)
HIT: **Eike Feldmeier (chair)**
MedAustron: Claus Schmitzer, Florian Kühteubl, Dale Prokopovich
MIT: Tobias Blumenschein, Andre Rojan
SEEIIST: Elena Benedetto

3) Slow extraction simulations:

CERN: V. Kain, **Matt. Fraser (co-chair)**, **F. Velotti (chair)**, P. Arrutia
CNAO: Marco Pullia, Luciano Falbo, Alessio Mereghetti, Paolo Meliga
GSI: Peter Forck, Stefan Sorge, Jiangyan Yang, Rahul Singh, Björn Galnander
HIT: Cristopher Cortes, Michael Galonska
MedAustron: Florian Kühteubl, Alexander Wastl, Dale Prokopovich
MIT: --
SEEIIST: Elena Benedetto, Rebecca Taylor (see CERN)

4) Spill detector development and analysis:

CERN: Federico Roncarolo, Inaki Ortega (maybe Matt. Fraser)
CNAO: Marco Pullia, Luciano Falbo, Alessio Mereghetti, Paolo Meliga
GSI: **Peter Forck (chair)**, Plamen Boutachkov
HIT: Andreas Peters, Christian Schömers
MedAustron: Dale Prokopovich
MIT: --
SEEIIST: Elena Benedetto (o)

All mentioned people contribute significantly to the progress!