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

IFAST Prototyping Activity

REX **R**esonant **EX**traction Improvement

Work Package 5 Task 3

3rd Annual Meeting / 18th April 2024

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

iFAST

Challenge for slow Extraction from Synchrotrons

Slow extraction: Gentle beam excitation at **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 to reach septum for extraction

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

- Change of tune: unintended quadrupole current ripple
- Stochastic amplitude excitation of 'knock-out' extraction

Mitigation research within IFAST-REX:

1. Beam physics:

Reduction of beam sensitivity by non-standard excitation methods

⇒ Extensive simulation of extraction process

2. Technical installations:

- Improved power supplier for magnets
- Novel transverse excitation for knock-out extraction

⇒ Non-standard current measurement and rf-excitation control

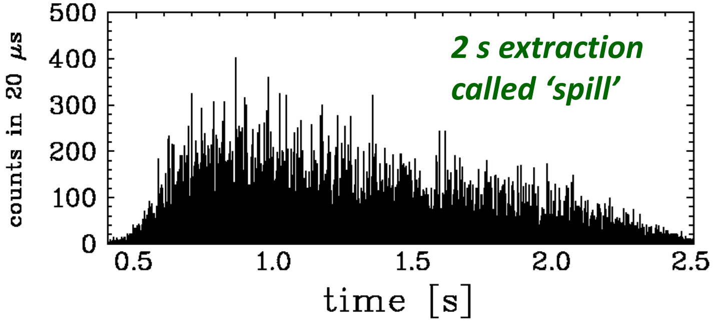
3. Validation:

- Experimental validation at the facilities

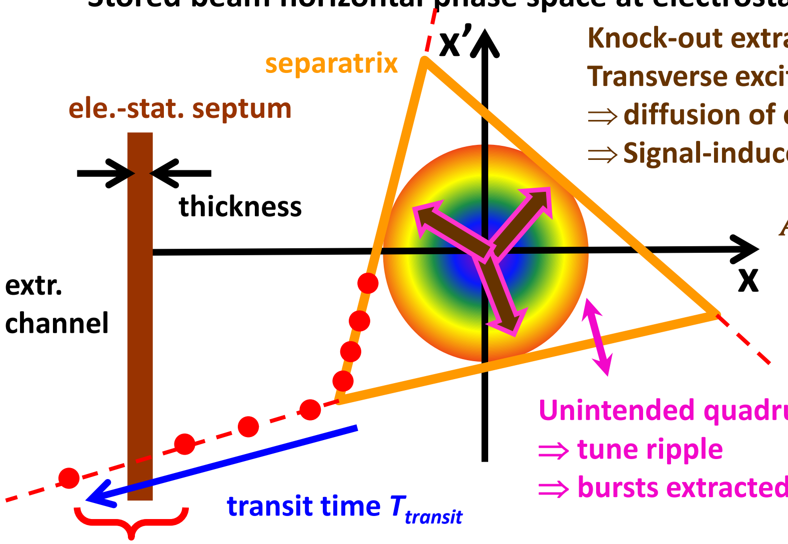
⇒ Tailored improvements for IFAST-REX facilities

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

Quad. scan, un-bunched beam



Stored beam horizontal phase space at electrostatic septum



Knock-out extraction:
Transverse excitation
⇒ diffusion of core to separatrix
⇒ Signal-induced fluctuations

$$A_{stable} \propto \left(\frac{Q_m - Q_{res}}{S}\right)^2 \propto \left(\frac{\epsilon_Q}{S}\right)^2$$

Unintended quadrupole current ripple
⇒ tune ripple
⇒ bursts extracted

last spiral step x_{step}
after 3 turns

Sextupoles: non-linear fields
Ion's amplitude growth per turn
⇔ $T_{transit}$ & x_{step}

Working Groups

Topic: Workshare structure within the entire project:

- **Working Group 1:** Power supplier ripple measurement novel transformer combination
  chair Frank Stulle (Bergoz Instrumentation) → *hardware deliverable, Milestone 20 (month 24) reached*
- **Working Group 2:** Optimized rf-amplifier and control of knock-out extraction
  chair Eike Feldmeier (HIT) → *hardware deliverable, Milestone 20 (month 24) reached*
- **Working Group 3:** Simulation and experimental verification for slow extraction
  chair Francesco Velotti (CERN)
- **Working Group 4:** Innovative detectors and data acquisition for slow extraction
  chair Peter Forck (GSI)

However:

At the advanced project phase, participants collaborate across the WGs to enable success.

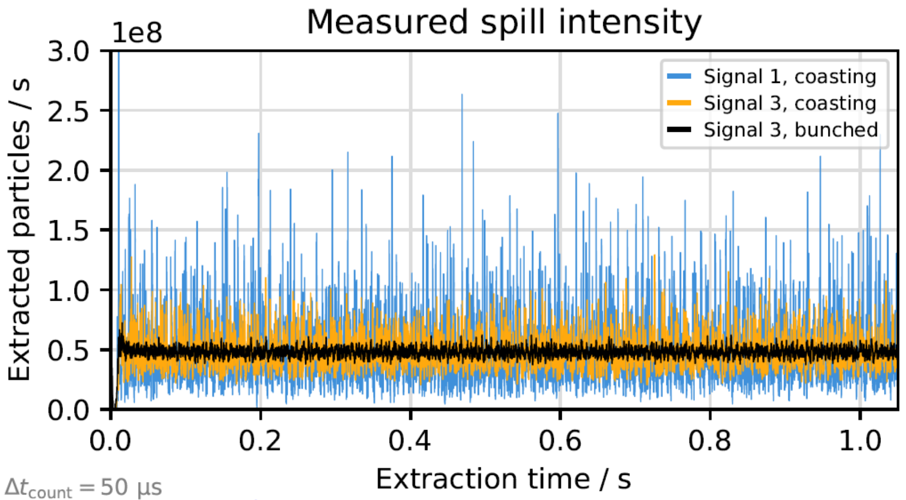
Experiment: Knock-out Extraction Signal Spectrum Dependence

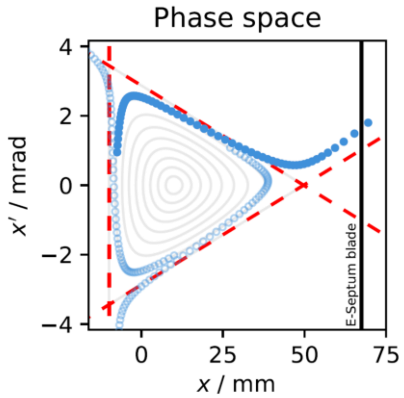
Topic: Spill micro-structure dependence for knock-out extraction

by HIT & GSI with contributions by CERN and MedAustron

Excitation spectrum influences:

- ➢ Separatrix crossing
- ➢ Diffusion from the beam towards core

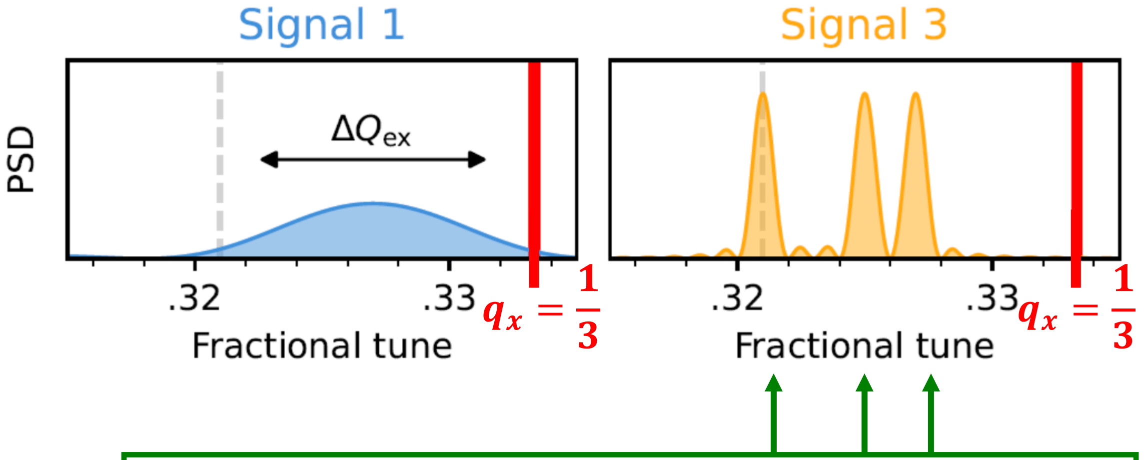




Horizontal tune at HIT Q_x= 1.6789 at end of acceleration

Excitation close to tune & harmonics $f_{ex,i} = Q_{ex,i}\ x f_{rev}$

Signal	$Q_{ex,1}$	$Q_{ex,2}$	$Q_{ex,3}$	ΔQ_{ex}
1	--	0.327	-	0.009
3	0.321	0.327	1.327	0.001



Improvement by multi-band excitation !

Result: Strong dependence on excitation spectra

⇒ **Optimization performed in 2023 (HIT, GSI, MedA)**

- ➢ Versatile signal generation
- ➢ Large power and bandwidth from amplifier

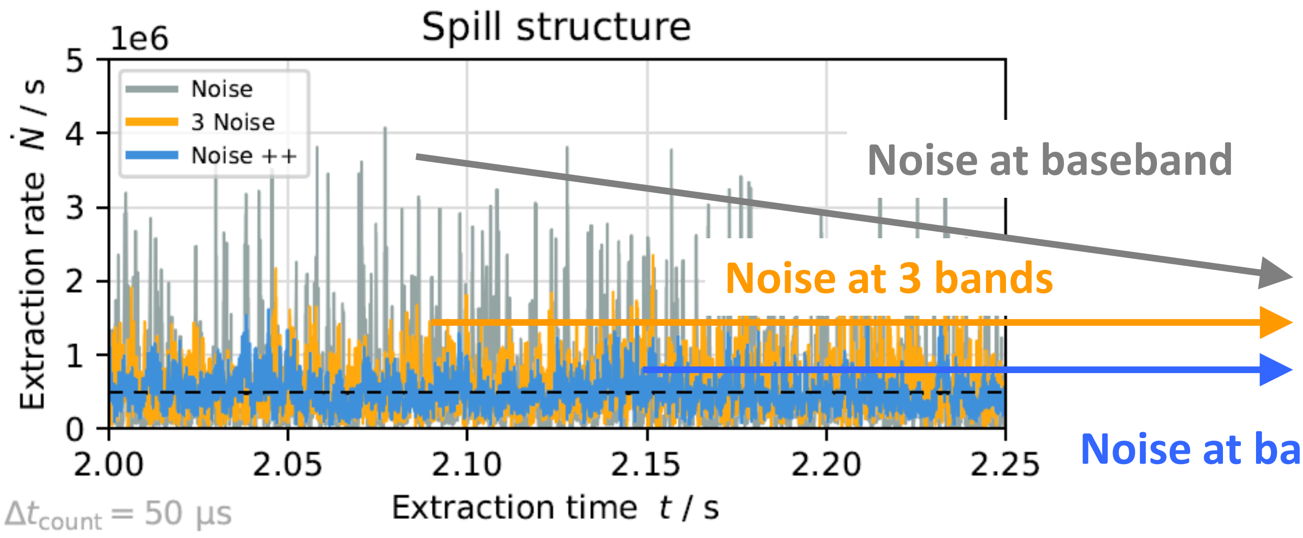
E.C. Cortes Garcia et al. IPAC’22 &
E.C. Cortes Garcia et al. NIM A 167137, 2022
P. Niedermayer el. al. IPAC’23

Experiment: Control of Knock-out Excitation

Topic: Spill micro-structure dependence for knock-out extraction

by GSI with contributions by HIT, CERN and MedAustron

Systematic for excitation types: Tests at COSY (FZ-Jülich) ⇒ Significant influence systematically investigated



Noise at baseband

Noise at 3 bands

	$Q_{\mathrm{ex},1}$	$\Delta Q_{\mathrm{ex},1}$	$Q_{\mathrm{ex},2}$	$\Delta Q_{\mathrm{ex},2}$	$Q_{\mathrm{ex},3}$	$\Delta Q_{\mathrm{ex},3}$	T_{FM}
3 Sine	0.3412		0.6511		1.6530		
Dual FM	0.3412	0.0068					1 ms
RBPSK	0.3362	0.0088					
3 RBPSK	0.3393	0.0020	0.6772	0.0071	1.6782	0.0109	
Noise	0.3380	0.0058					
3 Noise	0.3252	0.0139	0.6760	0.0128	1.6799	0.0034	
Noise ++	0.3387	0.0086	0.6604		1.6611		

Noise at baseband plus sine at two harmonics

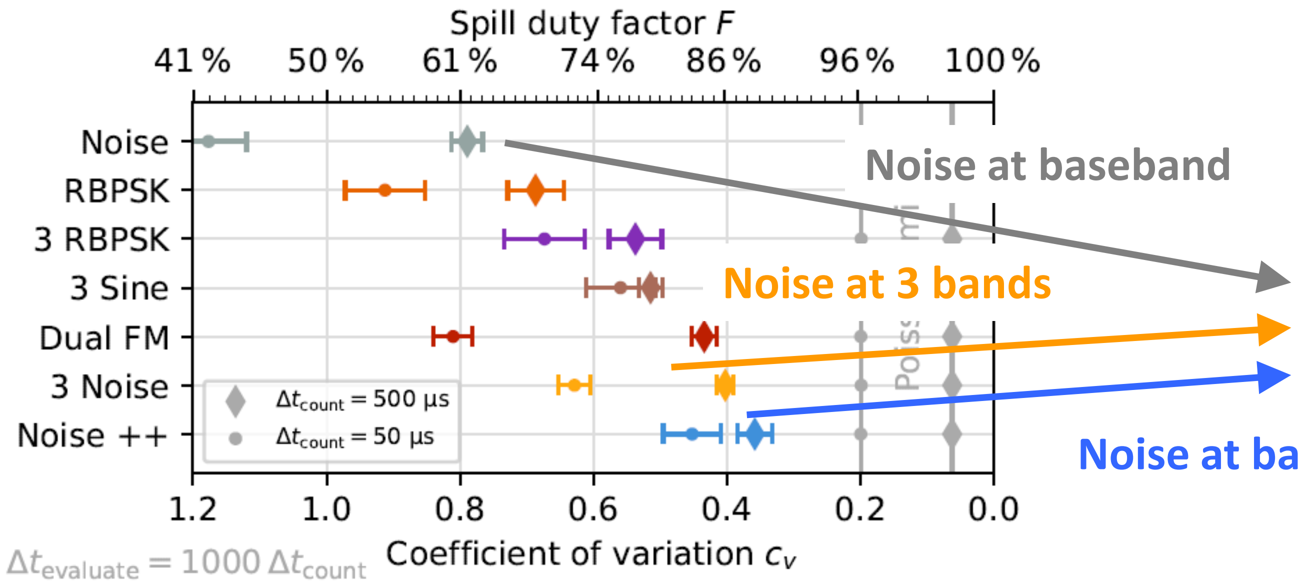
P. Niedermayer, R. Singh.,
Scientific reports, under review

Experiment: Investigation of Extraction Signal Type

Topic: Spill micro-structure dependence for knock-out extraction

by GSI with contributions by HIT, CERN and MedAustron

Systematic for excitation types: Tests at COSY (FZ-Jülich) ⇒ Significant influence <u>systematically</u> investigated



Noise at baseband

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Noise at baseband plus sine at two harmonics

Large fluctuation,
‘bad spill’

small fluctuation,
‘good spill’

Spill characterization via statistical moments:

- Coefficient of variance $c_v = \frac{\sigma}{\mu} = \sqrt{\frac{\langle N^2 \rangle}{\langle N \rangle^2} - 1}$
- Spill duty factor $F = \frac{\langle N \rangle^2}{\langle N^2 \rangle} = \frac{1}{1 + c_v^2}$

Such systematic comparison performed for the first time!

P. Niedermayer, R. Singh.,
Scientific reports, under review

Experiment: Investigation of Extraction Signal Type

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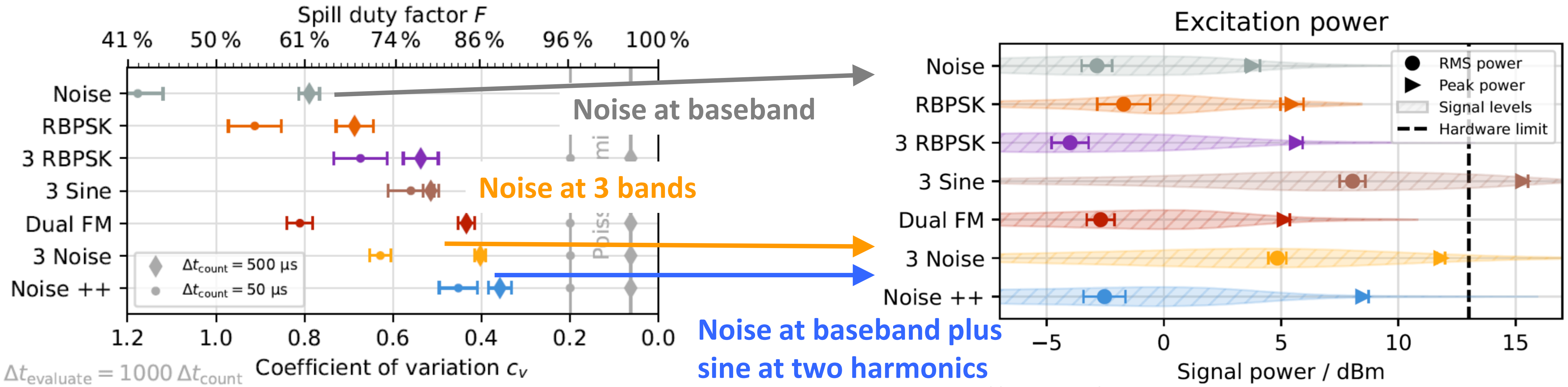


Noise at baseband

Noise at 3 bands

Noise at baseband plus sine at two harmonics

Large fluctuation, ‘bad spill’ → **small fluctuation, ‘good spill’**

However: Different rf excitation power required

⇒ **Noise++ is good compromise**

⇒ **Large power from rf-amplifier (typ. 2x400 W)**, see below

Such systematic comparison performed for the first time!

P. Niedermayer, R. Singh.,
Scientific reports, under review

Simulation: Investigation of Extraction Signal Type

Topic: Spill micro-structure dependence for knock-out extraction

by GSI with contributions by HIT, CERN and MedAustron

Simulations by Xsuite and explanation

Simulation: Single particle tracking (COSY parameters)

Beam dynamics: Non-linear Kobayashi-Hamiltonian as representation of particle transverse energy

Normalization to separatix value H_{sep}

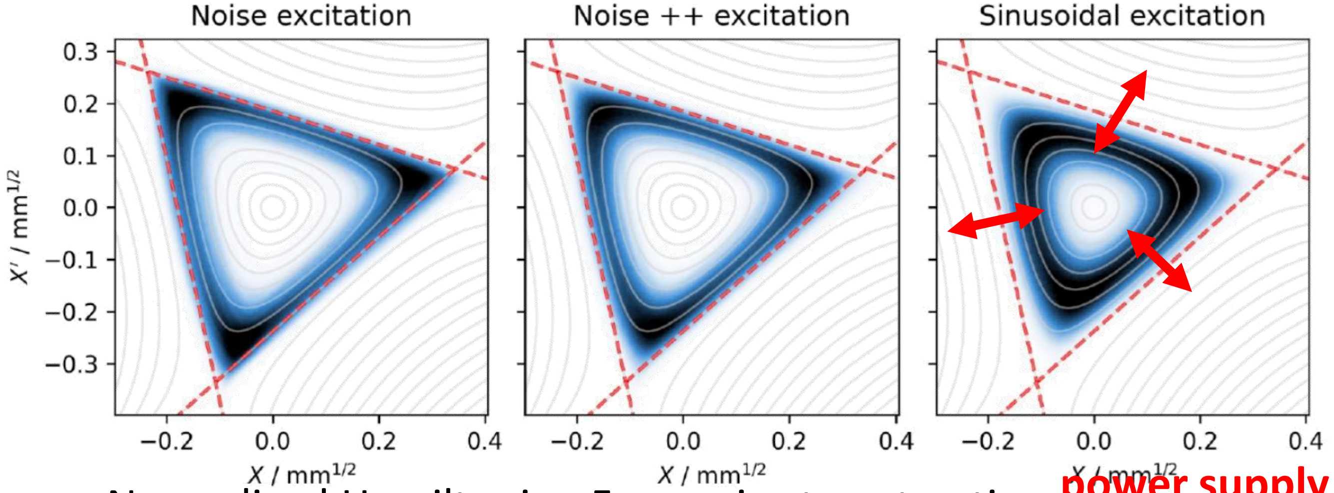
⇒ Distance to separatix and dynamic evolution

Results:

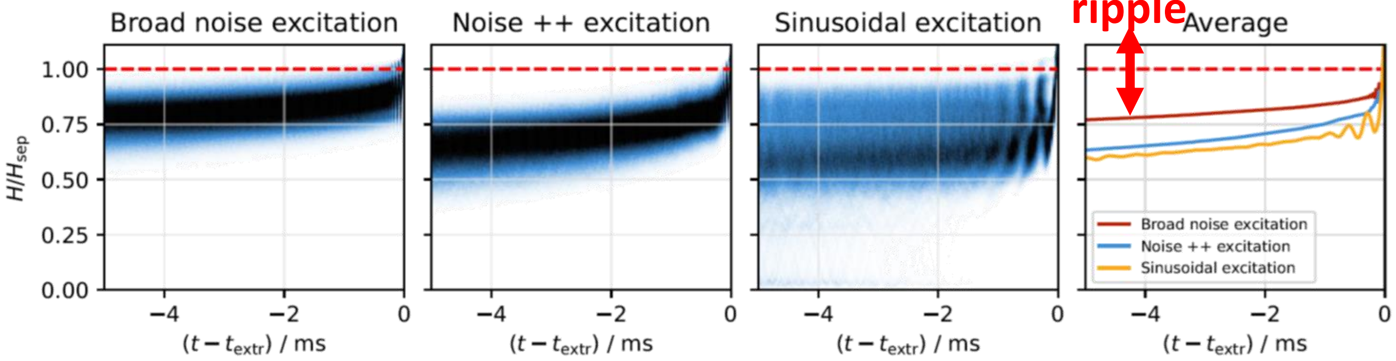
- ➢ Prior to extraction, distance from separatrix varies
- ➢ Crossing separatrix depends on excitation type
- ⇒ Large distance and fast crossing preferred
- ⇒ Less sensitive to separatrix variation
- ⇒ Less sensitive power supply ripple
- ⇒ **Better spill micro-structure achieved**

Normalized horizontal phase space:

Particle density shortly before extraction



Normalized Hamiltonian 5 ms prior to extraction:

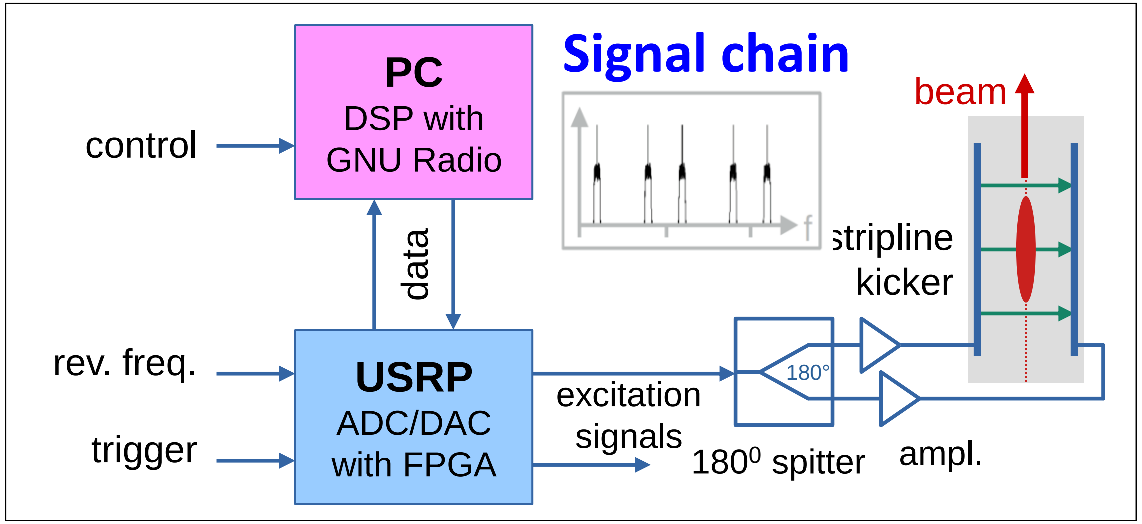


P. Niedermayer, R. Singh.,
Scientific reports, under review

Experiment: Control of Knock-out Excitation

Topic: Technical realization for ko extraction control

by GSI and HIT, with contributions by MedAustron



Control hardware: Universal Software Defined Radio USRP:

- Low-cost commercial hardware
- High performance ADC & DAC
- Highly customizable due to large FPGA

Software:

- Flow-graph design by GNURadio as Open Software

⇒ Very complex signals generation exp. tests with reasonable effort

- Shift of several application to FPGA

⇒ Latency after trigger significantly improved

⇒ Contribution to GNU-based software by GSI

Collaboration efforts at GSI and MedAustron, for test at HIT (due to legal issues)

⇒ **Operational at GSI (& HIT), tests at MedAustron**

⇒ **Milestone for rf-control exceeded** (month 24)

Signal generation (GSI,MedA,HIT)

Universal software defined radio
USDR Ettus X310

- DAC: 16 bit, 200 MS/s
- Analog bandwidth: > 100 MHz
- Max. output voltage 1.8 V
- FPGA: 400k cells, clock rate 200 MHz

P. Niedermayer and R. Singh, IBIC’22 & ‘23

Experiment: Extension for Control of Knock-out Excitation

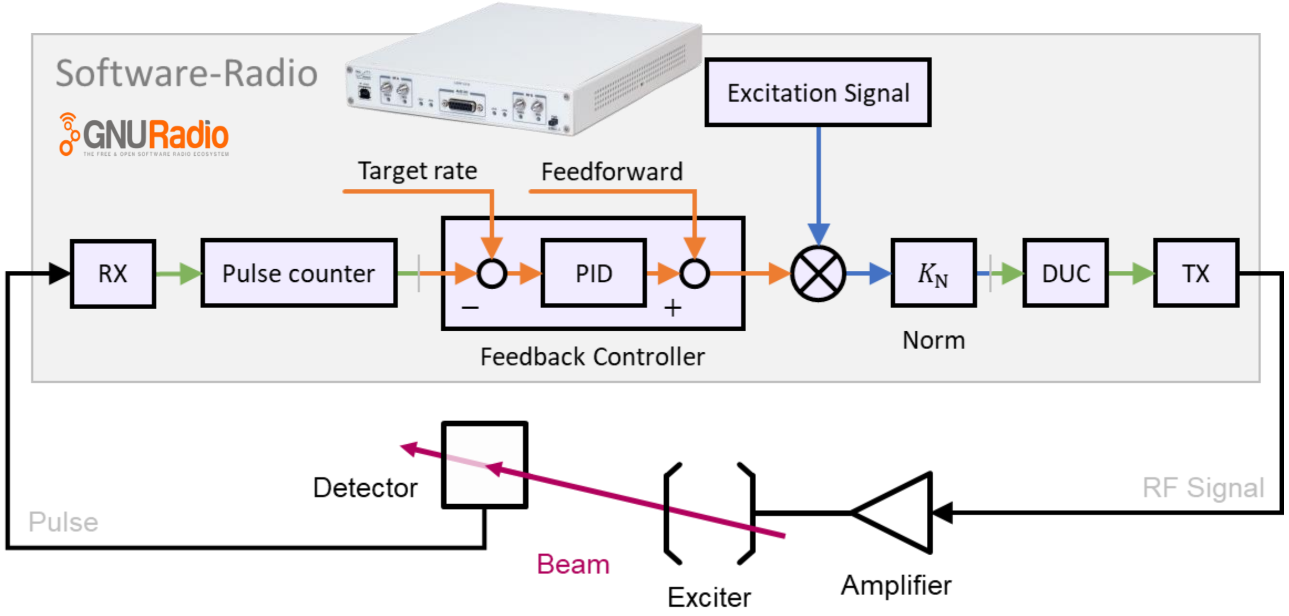
Topic: Feedback for macro-spill improvement

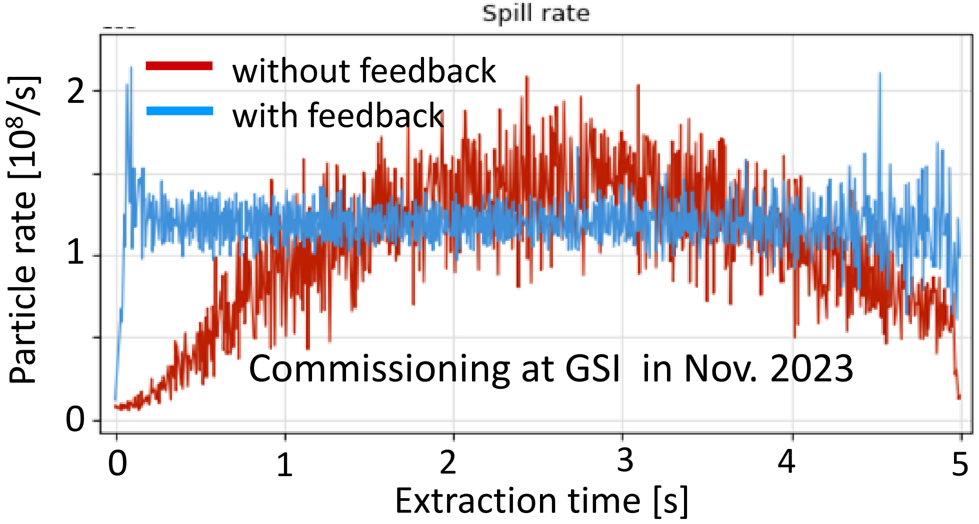
by GSI with contributions by HIT

Technology can be further used for feedback on 1 ms range

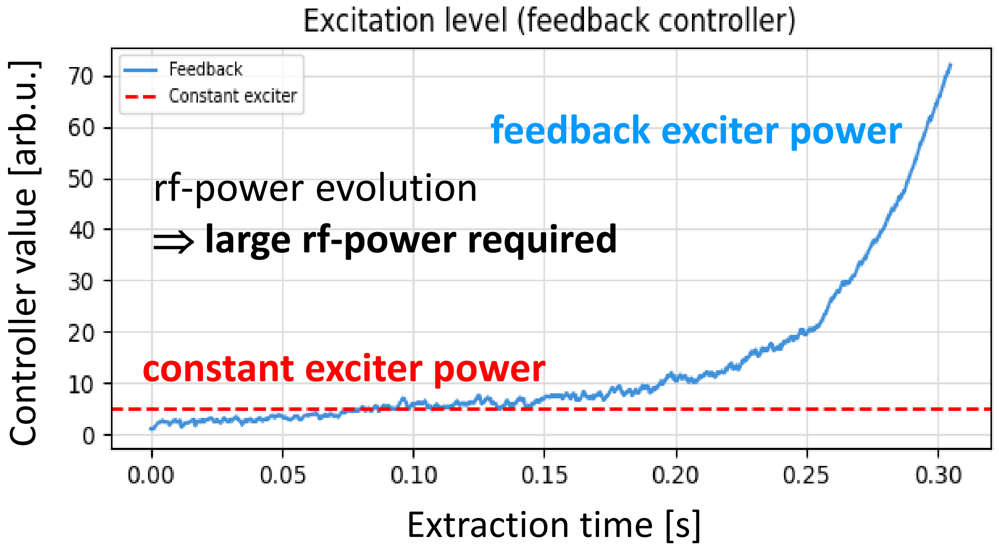
Control hardware & software: Feedback loop on USRP:

- ➢ Shift of several application to FPGA
- ⇒ Latency significantly improved to 30 µs
- ⇒ 300 Hz overall bandwidth **achieved**
- ⇒ Contribution to GNU-based software by GSI





Commissioning at GSI in Nov. 2023



feedback exciter power

rf-power evolution

⇒ **large rf-power required**

constant exciter power

Experiment: Extension for Control of Knock-out Excitation

Topic: Feedback for macro-spill improvement

by GSI with contributions by HIT

Technology can be further used for feedback on 1 ms range

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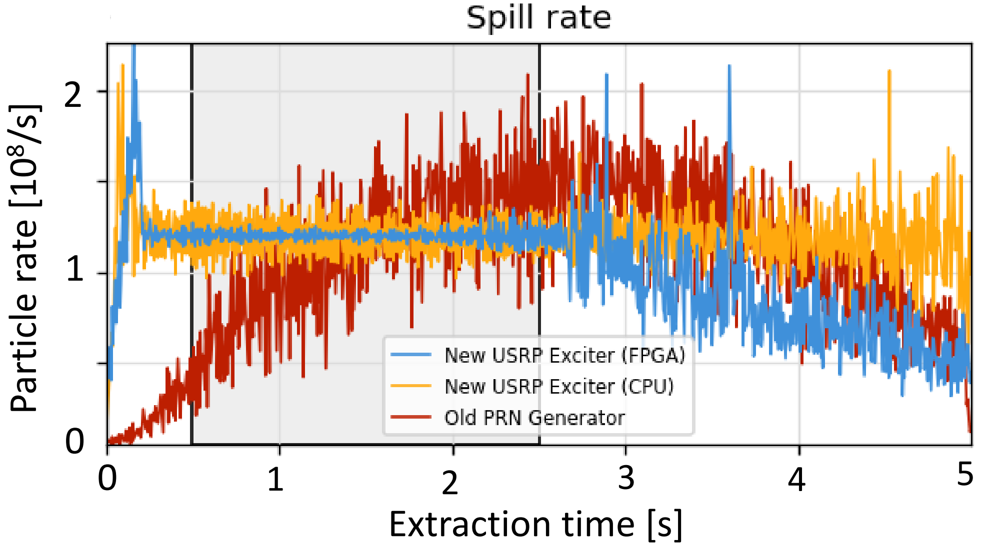
GNURadio



$\Delta t_{count} = 5$ ms

GSI: Feedback plus improved Noise++:

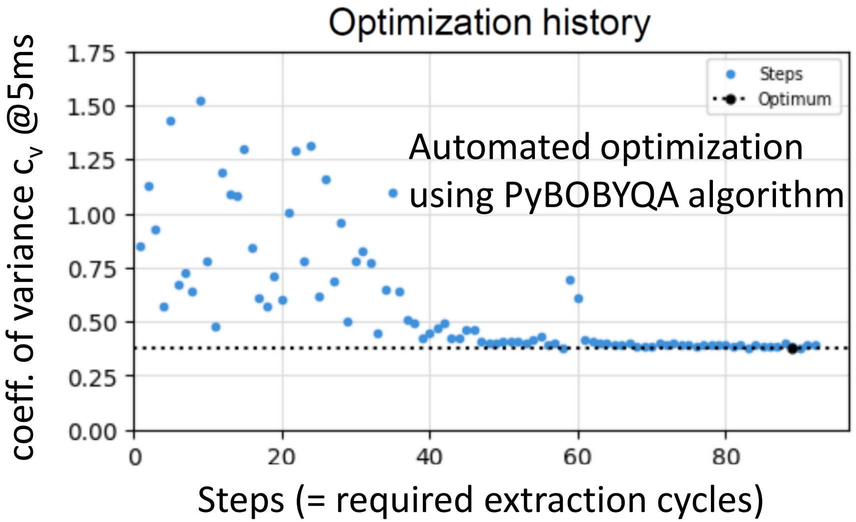
- ⇒ Significant improvement for micro- & macro spill **achieved**
- ⇒ Automated parameter optimization successfully **tested**
- ⇒ In **first operational stage** at GSI now

HIT: Feedback plus improved Phase Shift Keying BPSK:

- ⇒ Comparable system at HIT in **operation**

However, less performant due medical device requirements

⇒ Milestone & deliverable for rf-control exceed



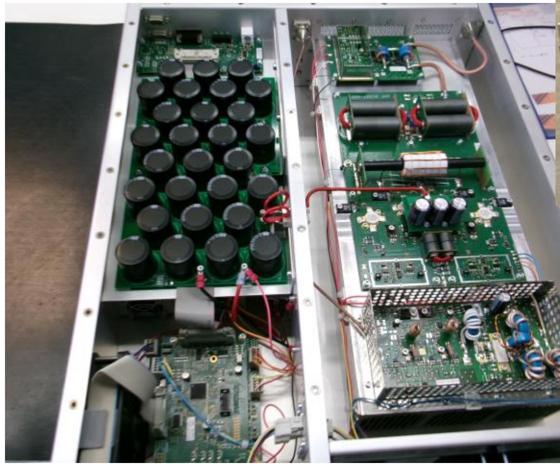
Automated optimization using PyBOBYQA algorithm

RF Power Amplifier (WG 2): Achievements

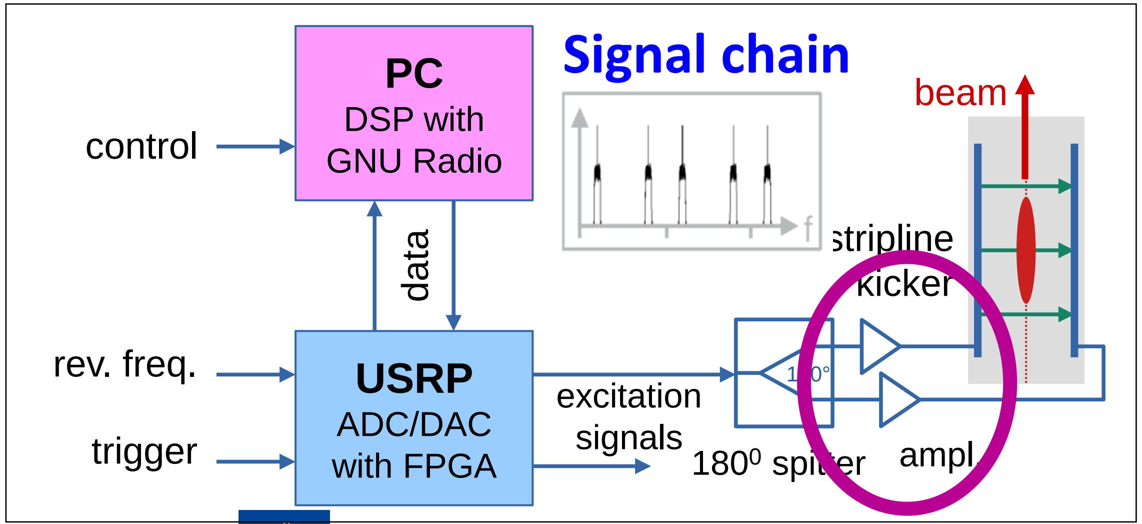
Technical development by company Barthel HF Technik plus GSI & HIT

Topic: Technical realization for knock-out amplifier:

- **High power required** (due to broadband exc. & feedback)
- Higher voltage by pure capacity load (instead 50 Ω)
- **Immunity against reflection for capacitive load**



Achieved parameters	Value	Remark
Frequency range	0.1 … 20 MHz	Broadband !
Output power	500 W	Lager power
Gain	56 … 58 dB	Flatness 2 dB !
Input impedance	50 Ω	
Input reflection VSWR	< 1.2:1	
Output impedance	50 Ω	
Electrode capacitive load	50 pF	Total power reflection
Output reflection VSWR	< 3:1	
Mechanics, cooling	19" rack, air	



RF Power Amplifier (WG 2): Achievements

Technical development by company Barthel HF Technik plus GSI & HIT

Topic: Technical realization for knock-out amplifier

Achievements:

Gain: 57 dB reached for -30 … 0 dBm input, $P_{max} = 500$ W

Gain flatness: < 2 dB for 0.1 … 20 MHz reached

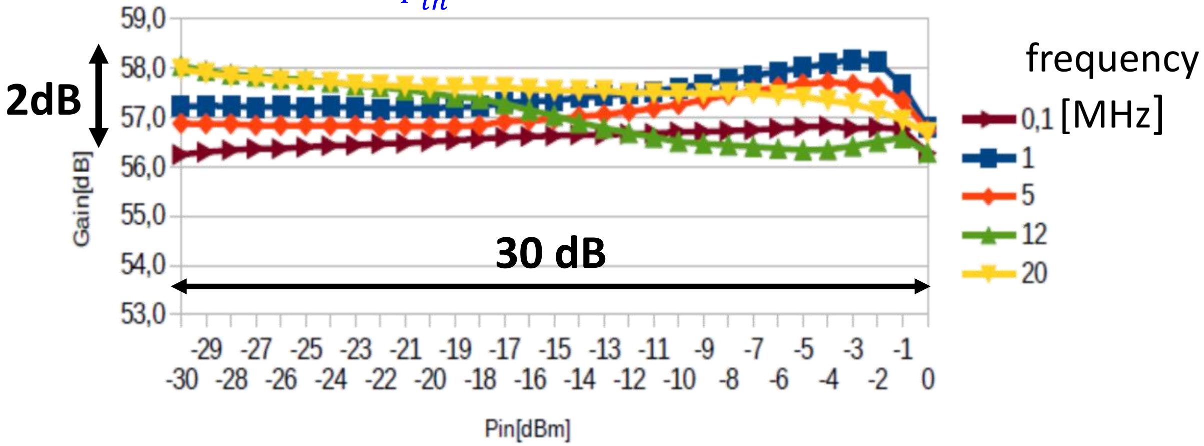
Reflection: Special precautions successfully tested

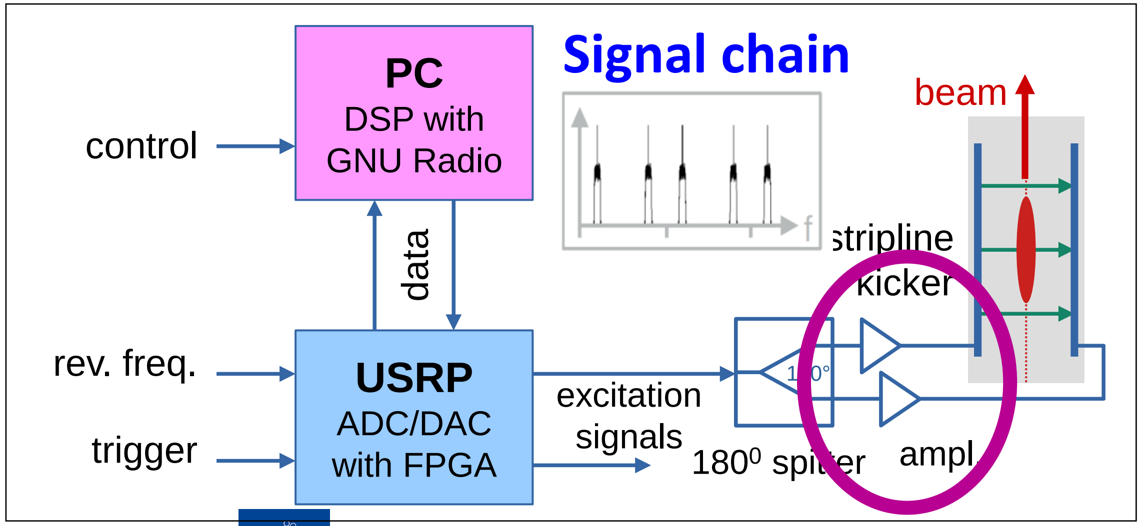
Status:

- Prototype delivered, now under test at HIT
- 2nd amplifier produced in fall 2024
- Actual TRL 6; expected final TRL 7 (only TRL 6 promised)

⇒ **Final milestone D5.3 for month 46 almost reached**

Gain flatness: $\frac{P_{out}}{P_{in}}$ versus P_{in} for 0.1 … 20 MHz





Transformer for Power Supplier (WG 1): Solutions and Achievements

Technical development by company Bergoz Instrumentation plus GSI & CERN

Accelerator physics: Spill fluctuation caused by quadrupole current ripple, i.e. **AC ripples** I_{AC} , bandwidth 10 Hz…40 kHz

Topic: **High dynamic range** current measurement device providing $\frac{\Delta I_{AC}}{I_{DC}} \approx 10^{-7}$ (!) in the presence of $I_{DC} \approx 1$ kA

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

Novelty: **Additional** AC transformer for 10 Hz…40 kHz

Sensitivity for AC part: $\frac{\Delta I_{AC}}{I_{AC}} \approx 10^{-5}$

Challenges: AC-component on strong DC offset

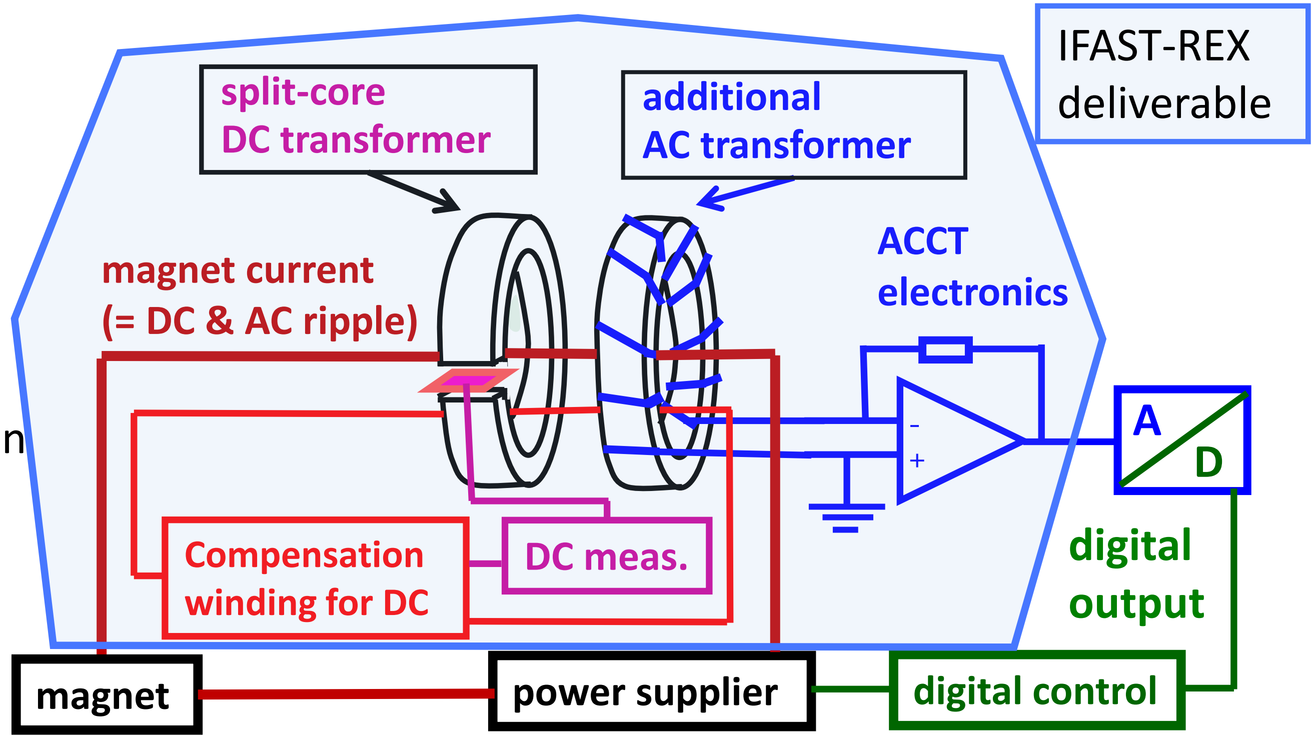
$\Rightarrow$ magnetic core saturation for $I_{DC} \gtrsim 10$ A

Solution: Two transformers

- **DC** transformer measures I_{DC} & used for compensation

  compensation accuracy $\Delta I_{\mathrm{DC}} \approx 1\mathrm{A} \Leftrightarrow \frac{\Delta I_{\mathrm{DC}}}{I_{\mathrm{DC,max}}} \lesssim 10^{-4}$

- **AC transformer for ripple measure** I_{AC}



IFAST-REX deliverable

split-core DC transformer

additional AC transformer

magnet current (= DC & AC ripple)

ACCT electronics

Compensation winding for DC

DC meas.

digital output

magnet

power supplier

digital control

Transformer for Power Supplier (WG 1): Realization

Technical development by company Bergoz Instru. plus GSI & CERN

Development: Prototype by Bergoz as **novel** device

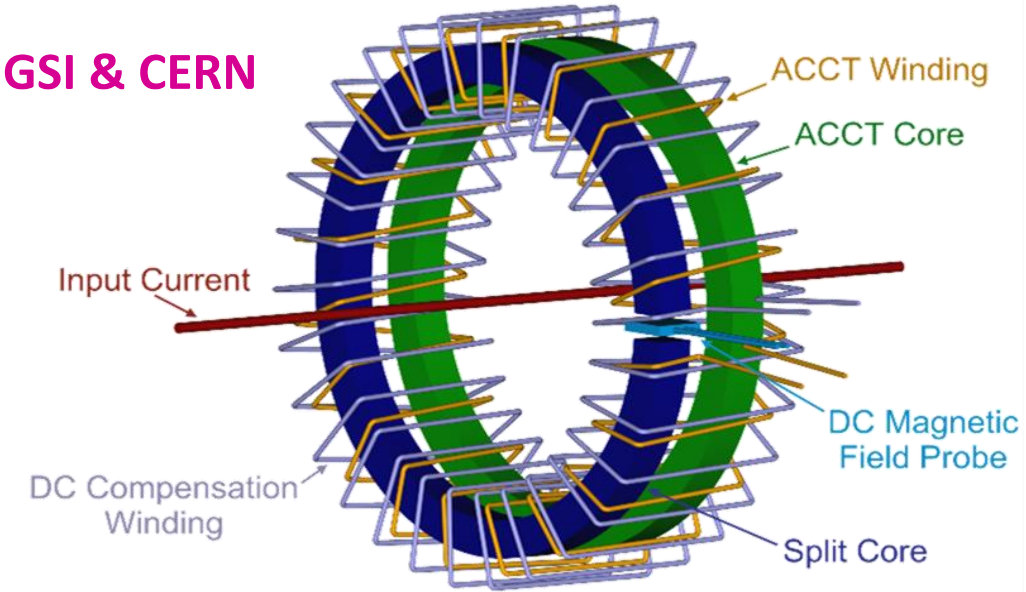
DC part: Split core of 1500 windings

Standard Hall probe Honeywell SS495A1

for AC transformer mag. saturation compensation

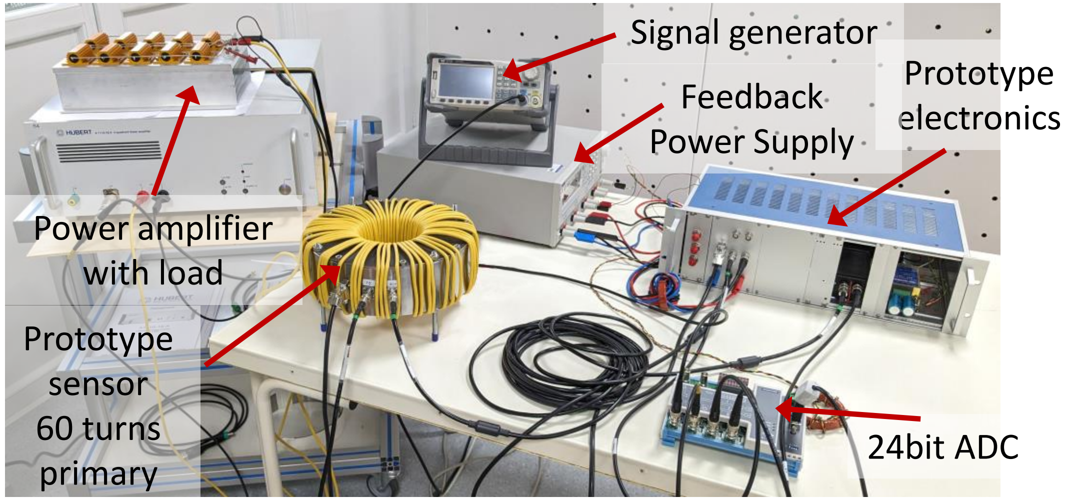
AC part: Core with 1500 windings

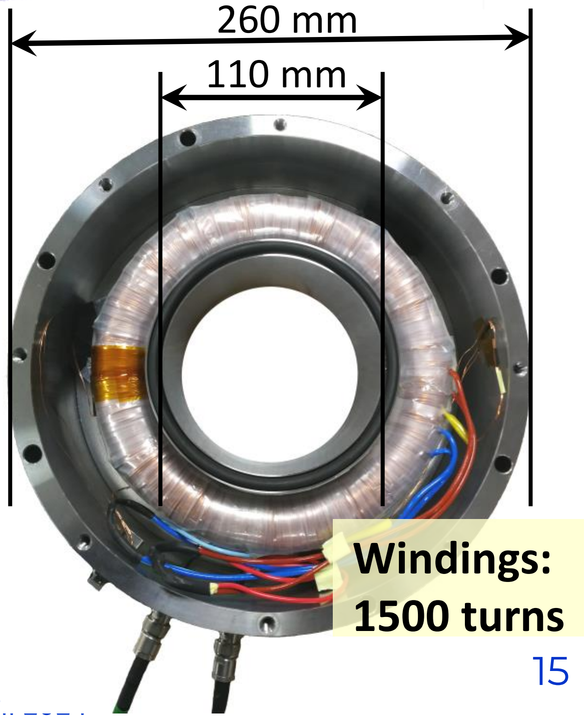
Analogue part comparable to beam current ACCT



Present achievements → prototype design:

- Test at Bergoz:
  up to 400 A_{DC}
  plus ~10^{-3} power supply ripple





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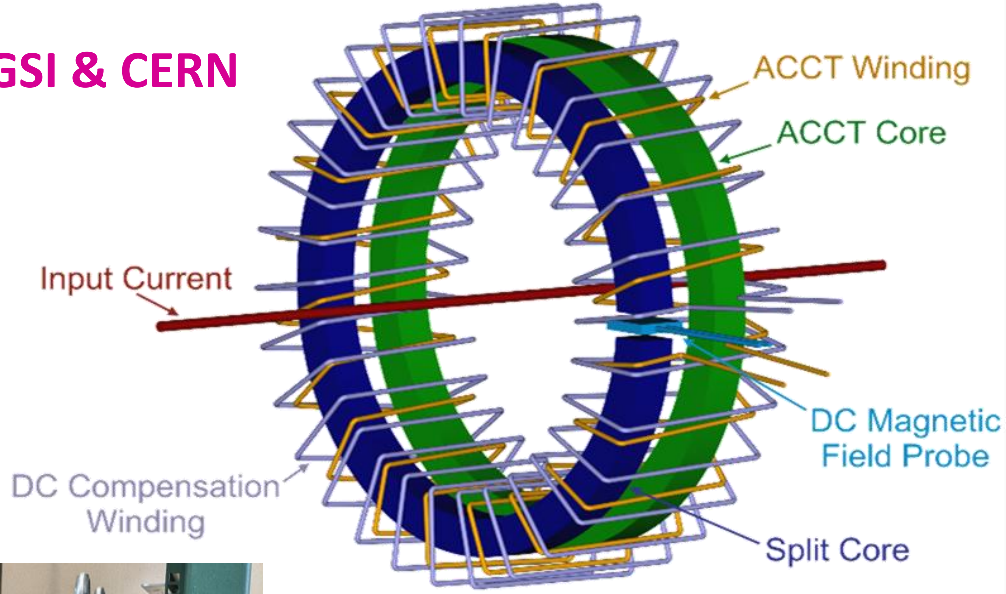
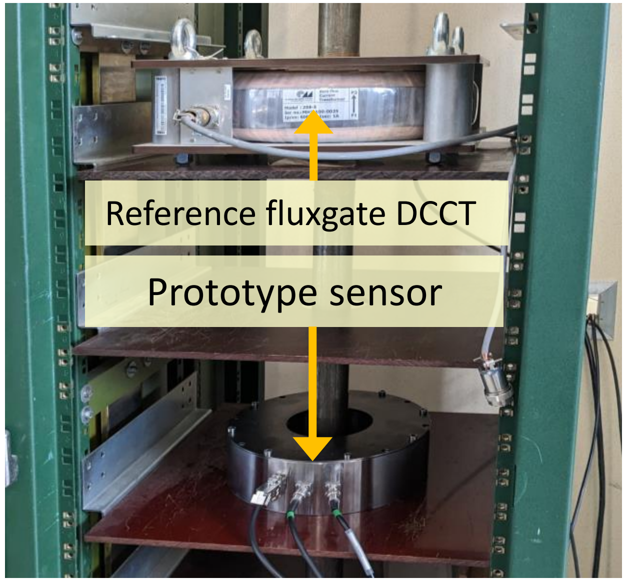


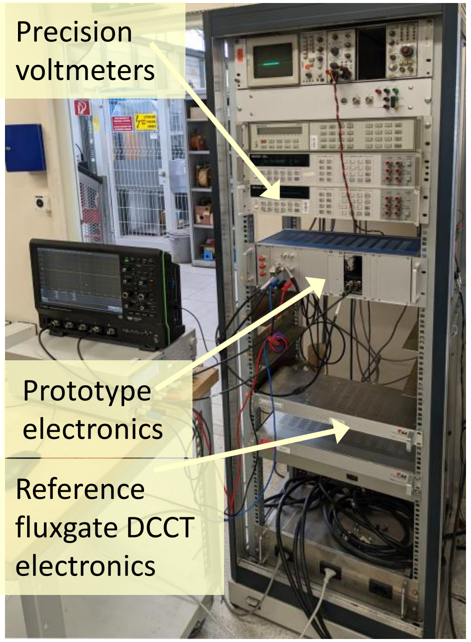
Present achievements → prototype design:

- Test at Bergoz:
  up to 400 A_{DC}
  plus ~10^{-3} power supply ripple

AND

- Test at CERN in 2023:
  up to 5 kA_{DC} with typical power supplier





Transformer for Power Supplier (WG 1): Achievements

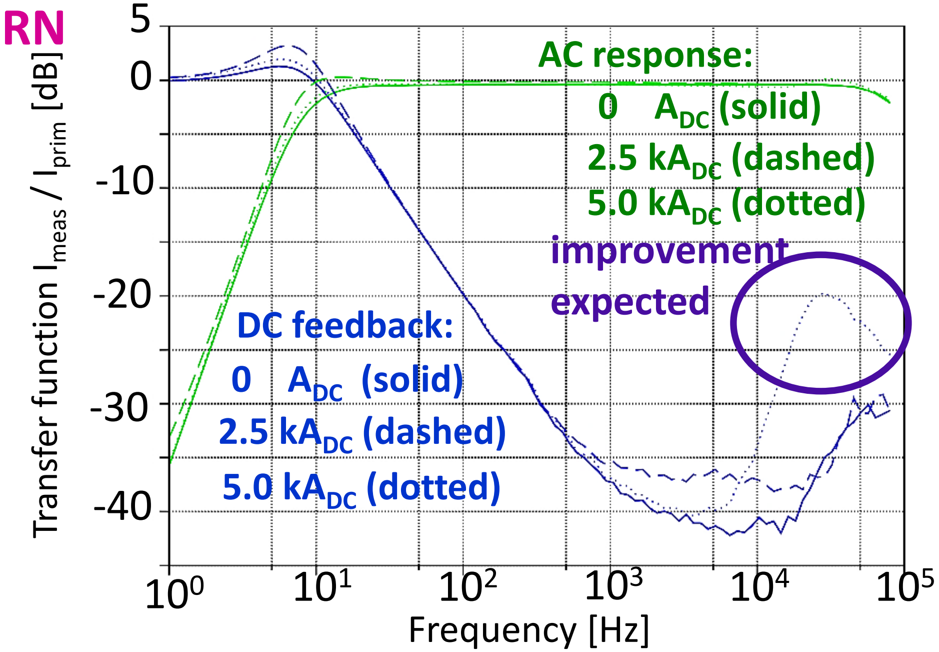
Technical development by company Bergoz Instru. plus GSI & CERN

Achievement:

- Transfer function measurement with compensation for different currents at CERN
- Linearity measurement for feedback 0…5 kA_{DC}
- Further improvements with electronics adjustment
- Achieved AC noise:

$$\frac{\Delta I_{AC,noise}}{I_{AC}} \approx \mathbf{5 \cdot 10^{-5}} \text{ @1MHz and } \frac{\Delta I_{AC,noise}}{I_{AC}} \approx \mathbf{2 \cdot 10^{-5}} \text{ @40kHz}$$

⇒ Proof-of-principle achieved



New electronics: Better DC compensation, expected, test at CERN pending

Status: Functionality proven ⇔ engineering design performed with sufficient bandwidth

Further test at CERN foreseen in June to reach $I_{DC} = 5$ kA

Actual TRL 5 to 6; expected final TRL 6 (as foreseen)

⇒ Final milestone D5.3 for month 46 almost reached

Slow Extraction Workshop 2024

Organized by MedAustron & GSI, sponsored by IFAST

Goal: Expert meeting for all aspects of slow extraction

Frame: International workshop started 2016 at GSI

Date: 11th to 15th Feb. 2024 in Wiener Neustadt, Austria

Subjects: Facility Overview, **Spill Ripples & Beam Quality,**
Hardware and Machine Protection,
Managing Extraction Efficiency, Septa Development,
Optimization & Machine Learning, MedAustron tour

Program: 60 talks, 7 discussions, 1 tutorial, 10 posters

Participants: 63 from Europe, US, Japan, China

Result:

- **<u>All</u>** major experts participated
- Very intense discussion and knowledge transfer
- Recognition of IFAST-REX contribution

Follow-up workshop at BNL mid 2025

5th Slow Extraction Workshop at MedAustron in Wiener Neustadt

11-15 February 2024
TFZ Wiener Neustadt
Europe/Berlin timezone

https://indico.gsi.de/event/18184/

MedAustron in collaboration with GSI supported by iFAST

Following the successes of previous workshops, the 5th Slow Extraction Workshop will be held from the **11th to 14th February 2024**.

The workshop location is Wiener Neustadt in Austria. It is organized by MedAustron with contributions by GSI and some funding by the EU-Project IFAST.

Poster contributions: During the entire workshop, about 20 posters can be presented on boards in the vicinity of the coffee break location. It is an excellent opportunity to present recent results not discussed in detail by the talks. Actual but also posters presented at previous conferences are accepted. No

Status and Summary for IFAST-REX

Novel transformer (WG 1):

- Successful proof-of-principle, specification almost reached, optimization almost finished by industry

Knock-out extraction control and amplifier (WG 2):

- Rf-amplifier manufactured; speciality: broadband gain-flatness & immunity against reflections suited for capacitive load
- Control by versatile capability of SDR implemented, contributions to GNU-based software

Experiments, simulation, and interpretation:

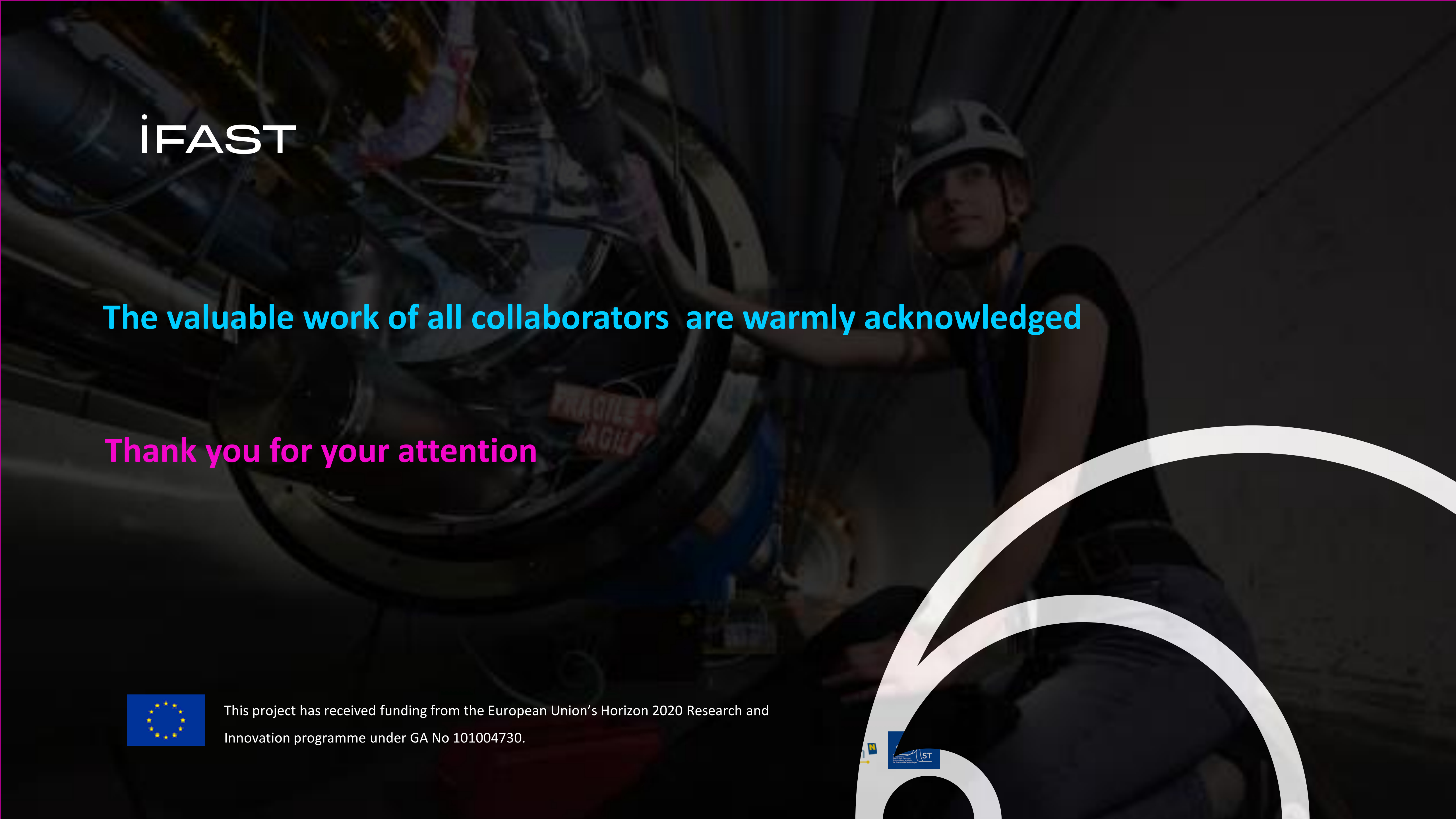
- **Ground-breaking experiments performed with dedicated excitation and feedback & broad to operational usage**
- Further experiments performed at several facilities, significant improvements demonstrated and operational
  e.g. CERN & MedAustron: Empty bucket channelling, COSE, rf-knock-out; CERN & GSI: Diagnostics improvements
- Usage of Xsuite by most members ⇒ advantage for networking
- Network with intensive discussion between participants

Publications with IFAST acknowledgement: 7 conformance proceeding, 3 referred papers in 2023-24

⇒ Milestone MS20 reached and reported in May 2023 (month24)

⇒ On very good track for Deliverable D5.3 in Feb. 2025 (month46)

IFAST-REX contributes significant to technical developments and networking !



iFAST

The valuable work of all collaborators are warmly acknowledged

Thank you for your attention

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Backup slides

Further successful Activities related to Spill Micro-Structure 2023-24

CERN:

- Empty bucket channeling extraction at SPS in operation
- Test of knock-out extraction at SPS
- Improved beam instrumentation at PS and SPS transfer lines

GSI:

- Commissioning of 80 MHz cavity for short bunch generation
- Novel Cryogenic Current Comparator for extracted currents 10 nA < 1 µA with 110 kHz bandwidth
- Tune measurement and simulations for stored beams close to 3rd order resonance

HIT:

- Multiband knock-out excitation for clinical routine operation
- Tune measurement and simulations for stored beams close to 3rd order resonance

MedAustron:

- Test and comparison of various excitation signals for knock-out extraction
- Implementation of empty bucket channeling

SEEIIST:

- Participation in several experiments

Dissemination including IFAST-REX Acknowledgement 2023-24

IPAC 2023:

- P. Forck et al. (**entire IFAST-REX consortium**), '*IFAST-REX: An initiative for the mitigation of beam current fluctuations in slow extraction*'
- J. Yang, P. Forck, R. Singh, S. Sorge (**GSI**), '*Study on spill quality and transit times for slow extraction from SIS18*'
- P. Niedermayer, R. Singh, G. Franchetti, E. Cortés García, E. Feldmeier, T. Haberer (**GSI, HIT**), '*Investigation of micro spill in RF KO extraction using tailored excitation signals*'
- F. Kühteubl et al. (**MedAustron, CERN**), '*Investigating alternative extraction methods at MedAustron*'
- T. Bass, E. Johnson, M. Fraser, Y. Dutheil, P. Arrutia Sota, S. Gibson (**CERN, University Oxford, Royal Holloway London**), '*Benchmarking simulations of slow extraction driven by RF transverse excitation at the CERN Proton Synchrotron*'

IBIC 2023:

- **Contributed Talk**: P. J. Niedermayer, R. Geißler, R. Singh (**GSI**), '*Software Defined Radio Based Feedback System for Transverse Beam Excitation*'

HB 2023:

- **Invited Talk**: E.C. Cortés García, E. Benedetto, E. Feldmeier, T. Haberer, M. Hun, P. Niedermayer, R. Singh, R. Taylor (**HIT, GSI, CERN, SEEIIST**), '*Spectral modification for BTF-based tune measurements close to a 3rd-order resonance*'

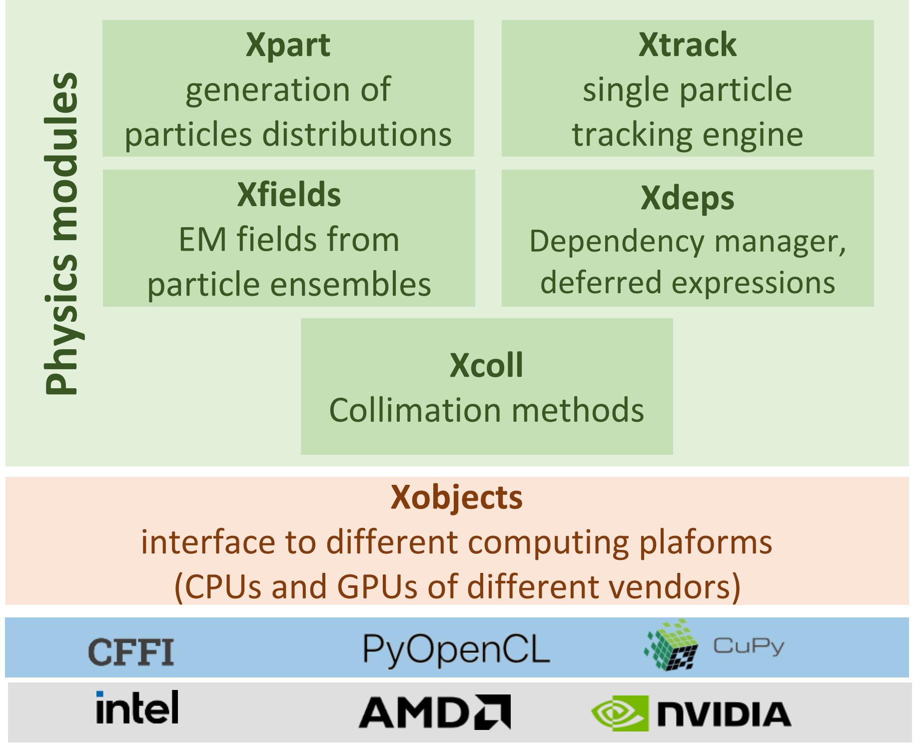
Refereed publications:

- P. Niedermayer, R. Singh (**GSI**), 'Excitation Signal Optimization for Minimizing Fluctuations in Knock Out Slow Extraction', Scientific Reports, under review
- E.C. Cortes Garcia, P. Niedermayer, R. Singh, R. Taylor, E. Benedetto, E. Feldmeier, M. Hun, T. Haberer (**HIT, GSI, CERN, SEEIIST**), '*Interpretation of the horizontal beam response near the third integer resonance*', in preparation for Phys. Rev. Accel. Beams
- Philipp Niedermayer, Rahul Singh (**GSI**), '*Excitation of nonlinear second order betatron sidebands for Knock Out slow extraction at the 1/3 resonance*', in preparation for Phys. Rev. Accel. Beams

Simulation: Usage of Xsuite

Topic: Development at CERN with general purpose applications

Introduction by R. De Maria and G. Iadarola (CERN) for particle tracking



Physics modules

Xpart
generation of particles distributions

Xtrack
single particle tracking engine

Xfields
EM fields from particle ensembles

Xdeps
Dependency manager, deferred expressions

Xcoll
Collimation methods

Xobjects
interface to different computing plaforms
(CPUs and GPUs of different vendors)

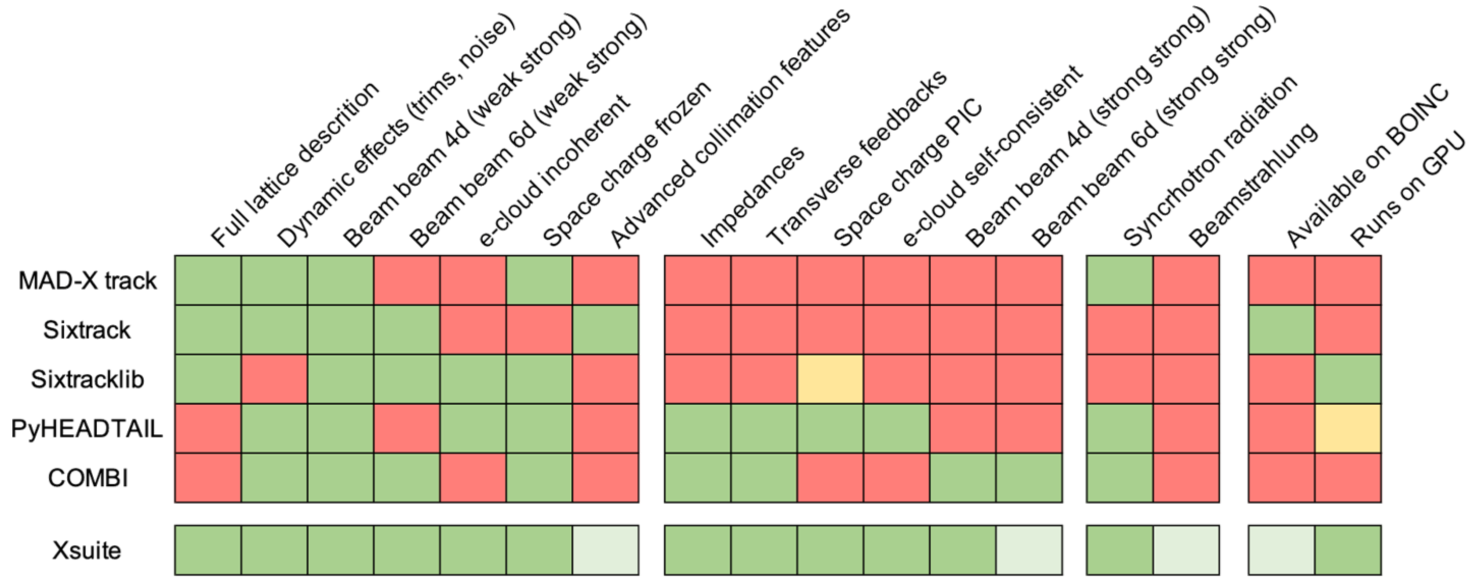
CFFI PyOpenCL CuPy

intel AMD NVIDIA

Lower level libraries

Hardware: CPU & GPU

- 🟩 Available
- ⬜ In development
- 🟥 Not available
- 🟨 Experimental



	Full lattice descrition	Dynamic effects (trims, noise)	Beam beam 4d (weak strong)	Beam beam 6d (weak strong)	e-cloud incoherent	Space charge frozen	Advanced collimation features	Impedances	Transverse feedbacks	Space charge PIC	e-cloud self-consistent	Beam beam 4d (strong strong)	Beam beam 6d (strong strong)	Synchrotron radiation	Beamstrahlung	Available on BOINC	Runs on GPU
MAD-X track	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥
Sixtrack	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥
Sixtracklib	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟩
PyHEADTAIL	🟥	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟨
COMBI	🟥	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟥
Xsuite	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟩	🟩	⬜	🟩	⬜	⬜	🟩

Advantage:

- Combines several tasks
- Input from other codes
- Operated on **G**PUs
- Contribution to additional modules

Nowadays, used almost exclusively for slow extraction simulation

⇒ Intensive exchange between experts

Transformer for Power Supplier (WG1): Specification

Technical development by company Bergoz Instrumentation plus GSI & CERN

Accelerator physics: Spill fluctuation caused by quadrupole current ripple, i.e. **AC ripples** I_{AC} , bandwidth 10 Hz…40 kHz

Topic: Development and integration of **high dynamic range** current measurement device providing $\frac{\Delta I_{AC}}{I_{DC}} \approx 10^{-7}$ (!)

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

Methodology: Test device produced by Bergoz

Parameter for additional control	Main Quad SIS100
Magnet current specification	
DC current min. $I_{DC,min}$ & max. $I_{DC,max}$	1 kA & 10 kA
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
Bandwidth f_{min} … f_{max}	10 Hz … 40 kHz
Total dynamic range I	>120 dB
Measurement resolution flat-top relative $\Delta I_{AC}/I_{DC}$	10^{-7}
Measurement uncertainty U_I	0.1% - 1 %