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

Steering Committee meeting / 16th Nov. 2021

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

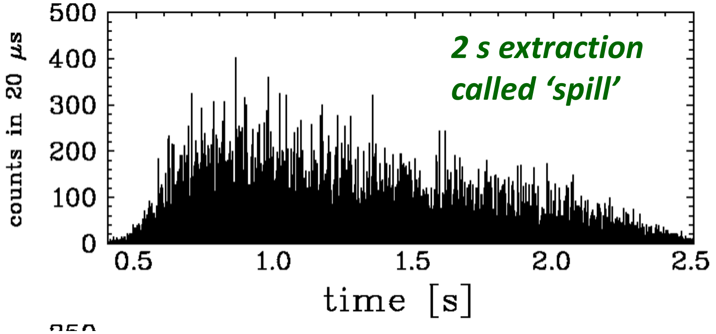
⇒ Non-standard power converter and rf-amplifier control

Validation: Experimental validation at all facilities

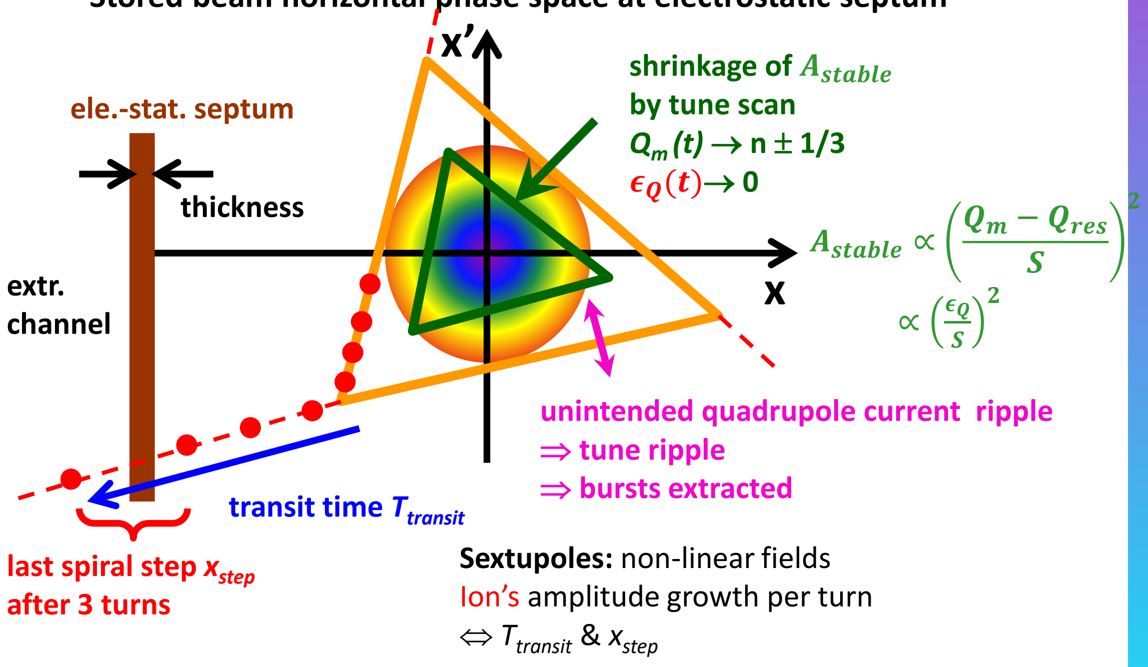
Tailored improvements for IFAST-REX participants

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

Quad. scan, un-bunched beam



Stored beam horizontal phase space at electrostatic septum



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

Time domain characterization:

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

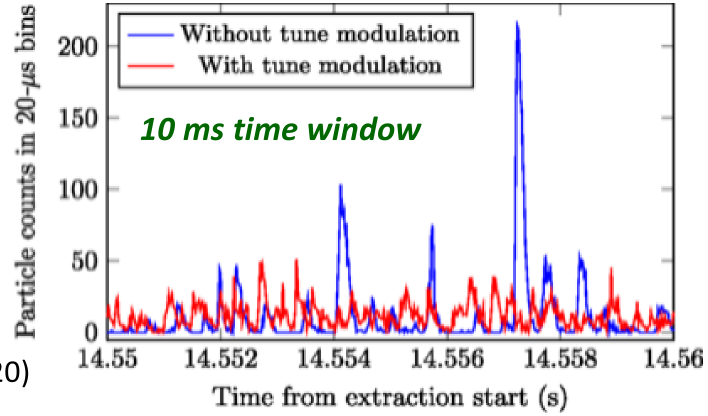
→ Time intervals of e.g. Δt = 10 ms

- ***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:

- Low sextupole strength
- Controlled tune variation

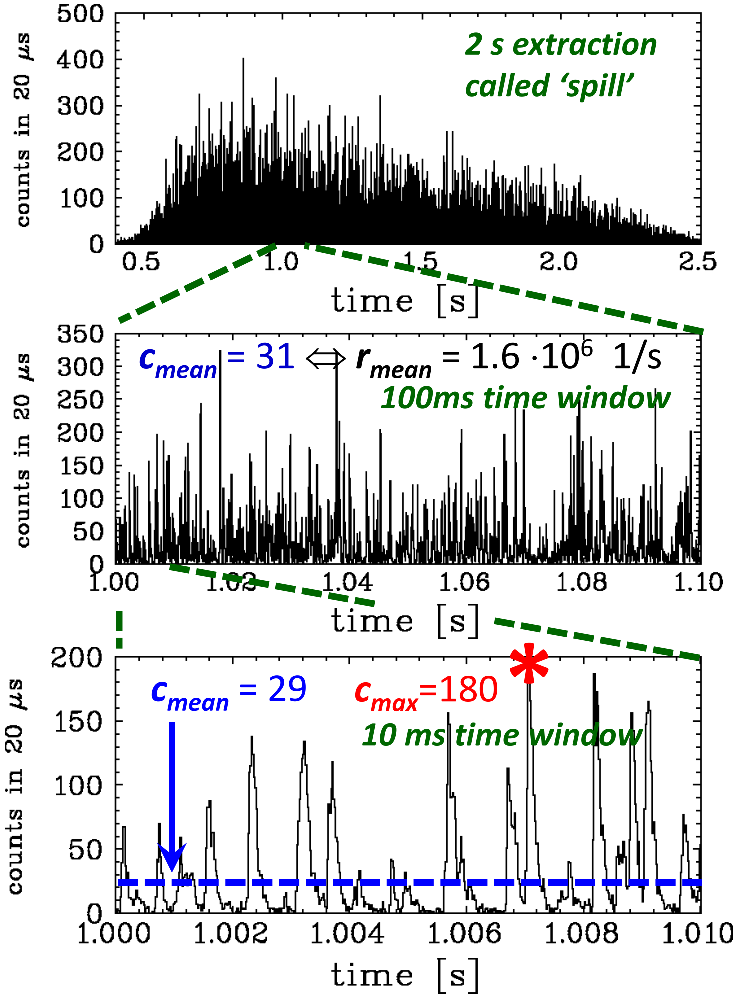
⇒ experimental & theoretical demonstration



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

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

Quad. scan, un-bunched beam



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

IFAST-REX: Survey to compare different Facilities

Performed by MedAustron (Florian Kühteubl et al.)

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 achievements including appropriate scaling e.g. trans. emittance

Status:

- Answers from **all** participants
- Evaluation finished

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 Energy: 300 - 2000	Max: 1e11 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.

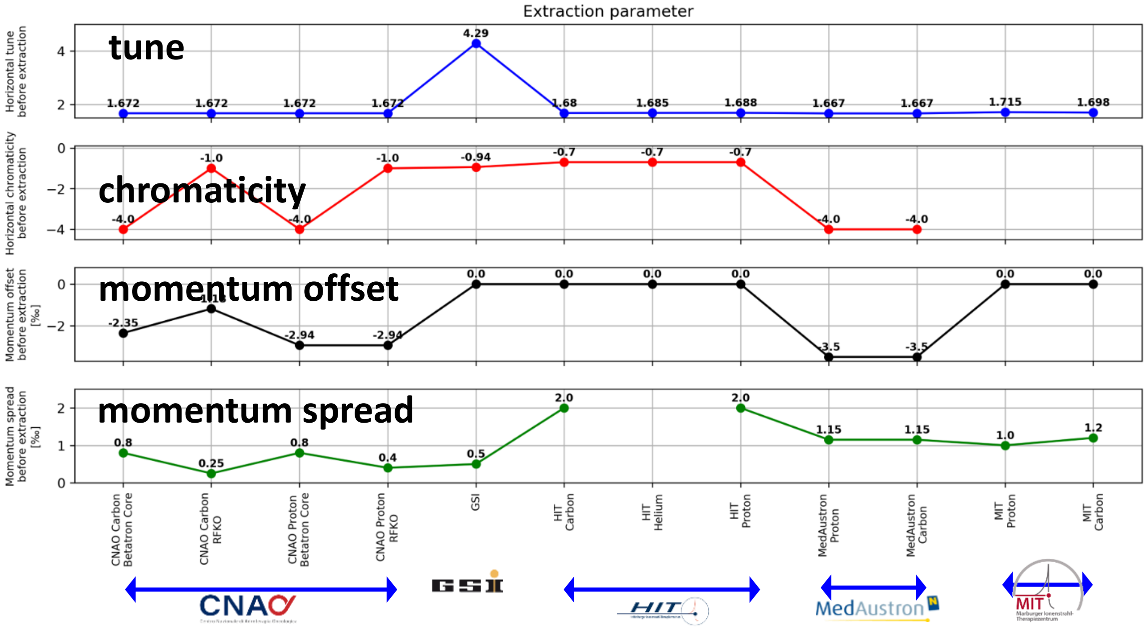
IFAST-REX: Survey to compare different Facilities

Performed by MedAustron (Florian Kühteubl et al.)

Results from questionnaire

Basic synchrotron and bam parameter collected

General beam parameters

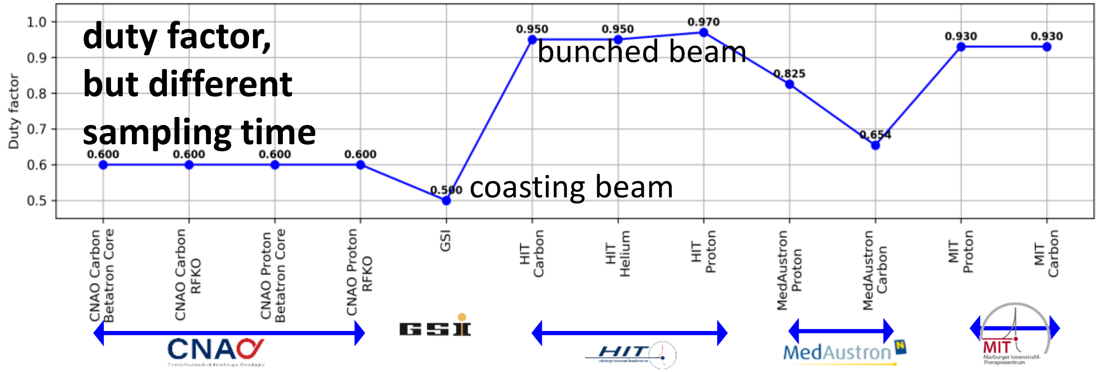


Next step: Data files from all facilities

⇒ comparison of spill quality under comparable conditions

⇒ appropriate scaling, e.g. duty factor for same sampling time, transit time: T_{tr} [turns] & T_{tr} / T_{syn} , long.-trans.: $\frac{\Delta p}{p} \leftrightarrow \frac{\Delta p}{p} / \epsilon_x$ .....

	Method of duty factor measurement	Time resolution of the duty factor measurement
CNAO	duty factor defined as $F = \langle N \rangle^2 / \langle N^2 \rangle$	100µs - 10ms
GSI	Particle counting with plastic scintillators for 1e6/s mean rate; Ionisation chamber for higher rates Beam loss monitors (plastic scintillators) for high currents	data recording with typ. 10µs typ. 10ms for evaluation
HIT	The duty factor has been calculated with the Forck-formula: $F = C^2_{mean}/(C^2_{mean} + C^2_{sigma})$	IC: 50µs Mean intervall: 1ms
MedAustron	spill to cycle period measurement	-
MIT	Evaluation of IC measurement	50µs



Remark: Data from CERN SPS are too different for a common plot

IFAST-REX Working Group Members for initial Phase

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

Bergoz: Frank Stulle
CERN: Diogo Alves, Marek Gasior
CNAO: ---
GSI: Rahul Singh, Andrzej Stafiniak
HIT: --
MedAustron: Claus Schmitzer
MIT: --
SEEIIST: ~~Mariusz Sapinski~~ (resigned) ⇒ Elena Benedetto

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

Barthel: Matthias Barthel
CERN: ---
CNAO: Marco Pullia, Luciano Falbo, Paolo Meliga, Al.Mereghetti
GSI: Rahul Singh
HIT: Eike Feldmeier
MedAustron: Claus Schmitzer, Florian Kühteubl, Dale Prokopovich
MIT: Tobias Blumenschein, Andre Rajan
SEEIIST: Elena Benedetto

3) Slow extraction simulations:

CERN: Verna Kain, Matt. Fraser, Francesca Velotti, Paolo Arrutia
CNAO: Marco Pullia, Luciano Falbo, Paolo Meliga, Al Mereghetti
GSI: Peter Forck, Stefan Sorge
HIT:: Cristopher Cortes, Michael Galsonska
MedAustron: Florian Kühteubl, Alexander Wastl, Dale Prokopovich
MIT: --
SEEIIST: Elena Benedetto, Rebecca Tayor

4) Spill detector development and analysis:

CERN: Federico Roncarolo (maybe Matthew Fraser)
CNAO: Marco Pullia, Luciano Falbo, Paolo Meliga, A. Mereghetti
GSI: Peter Forck, Plamen Boutachkov
HIT: Andreas Peters, Christian Schömers
MedAustron: Dale Prokopovich
MIT: --
SEEIIST: ~~Mariusz Sapinski~~ (resigned) ⇒ Elena Benedetto

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

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
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 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

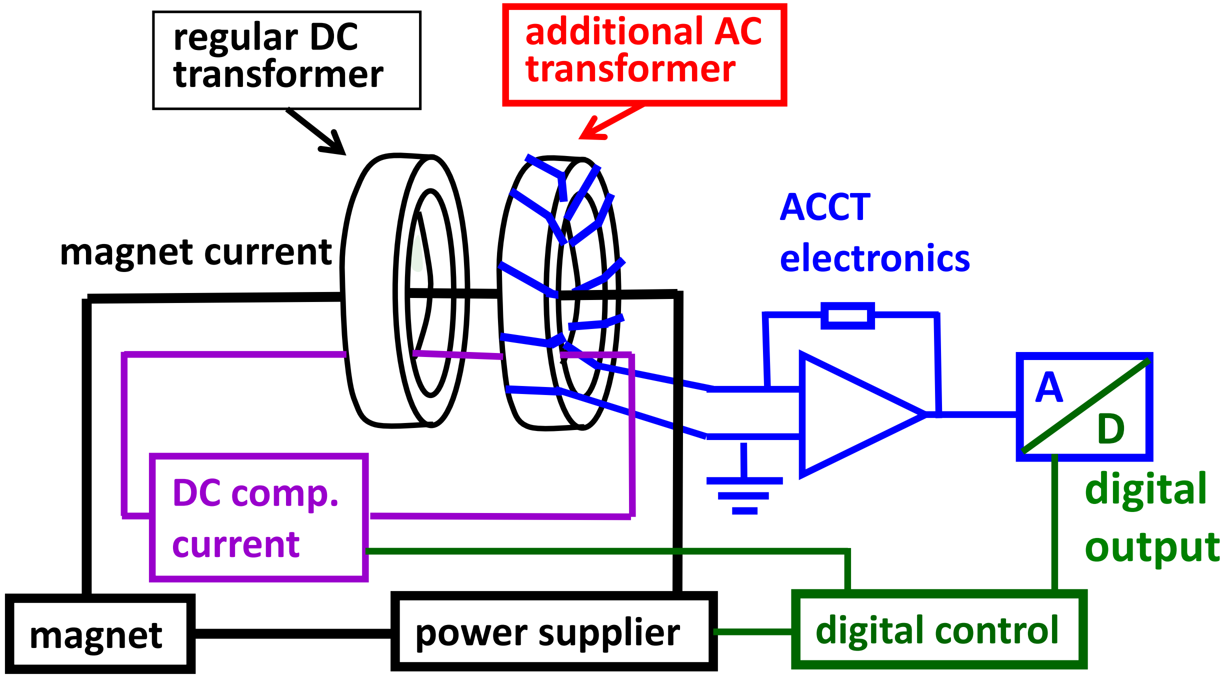
Novelty: **Additional** control of power supplier

Sensitivity: $I_{AC} / I_{DC} < 10^{-5}$

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

Present achievements:

- Layout of AC transformer
- Large bandwidth 1 Hz … 40 kHz achieved
- Integration of DC trans. compensation winding to AC transformer to prevent for core suturation
- Under considerations: Cross talk AC trans. ↔ compensation winding



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 3: Simulation & Experiment

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

Performed by CERN (M. Pari et al.)

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

Goal: Realistic beam simulations by MADX

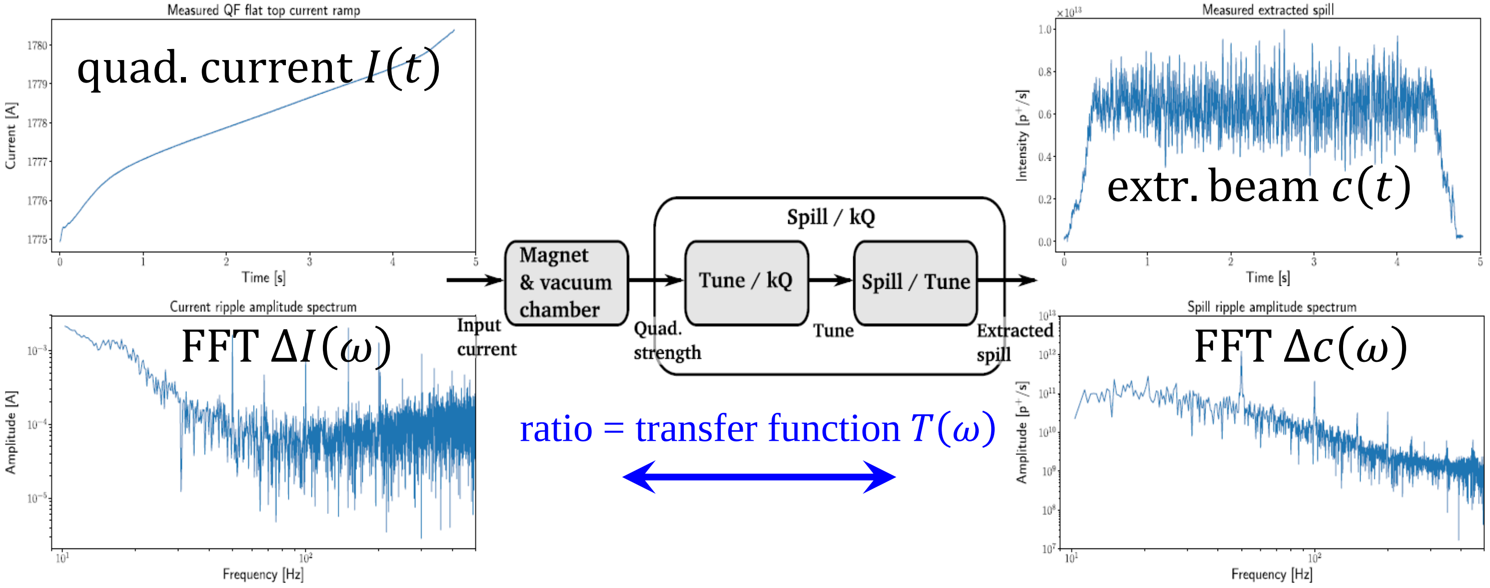
Methodology: Power supplier action to beam

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

with $\Delta c(\omega)$ is Fourier trans. of extracted counts variation

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

using experimental data



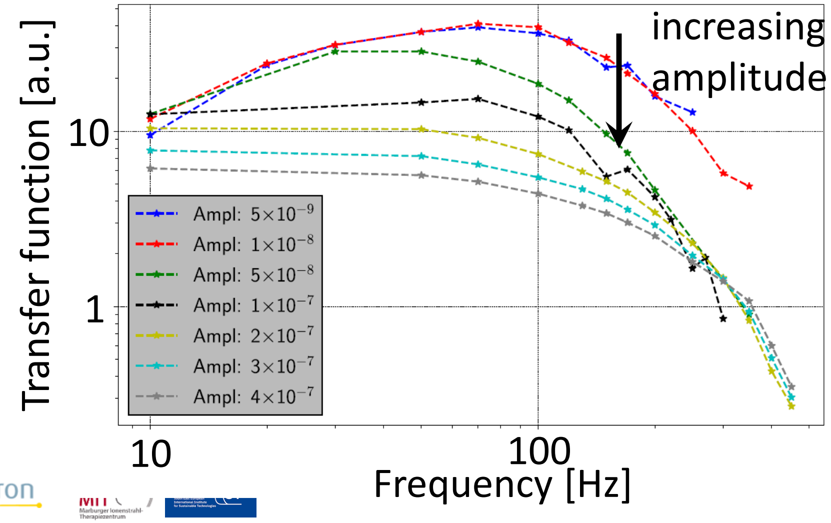
Results:

- ➢ 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)

Status:

- ➢ Results published
- ➢ Application for other facilities possible

Example: MADX simulation for several frequencies



IFAST-REX Working Group 3: Simulation and Experiment

Performed by HIT (Christopher Cortes et al.)

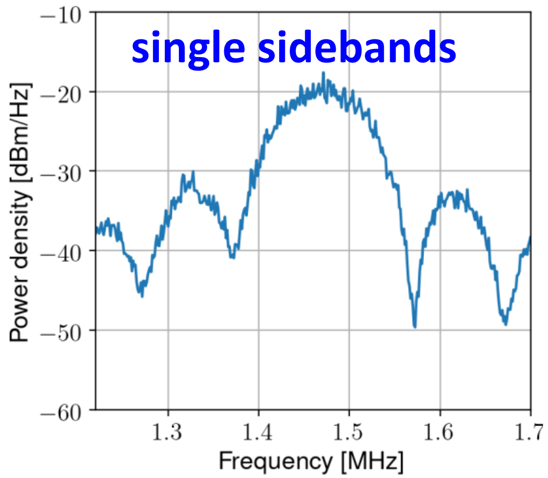
Knock-out extraction: Excitation of betatron amplitudes by transverse rf-noise (used at med. facilities & GSI)

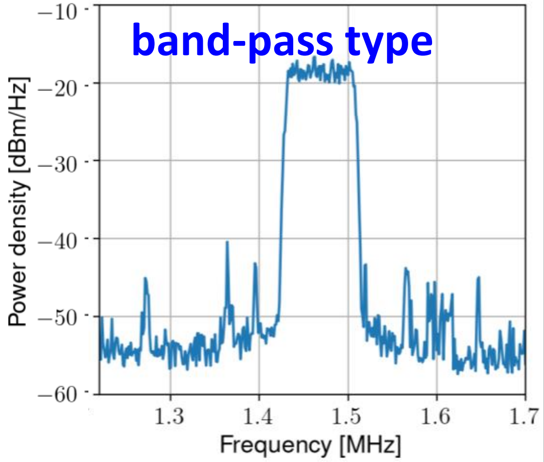
Topic: Beam response to different signal shapes

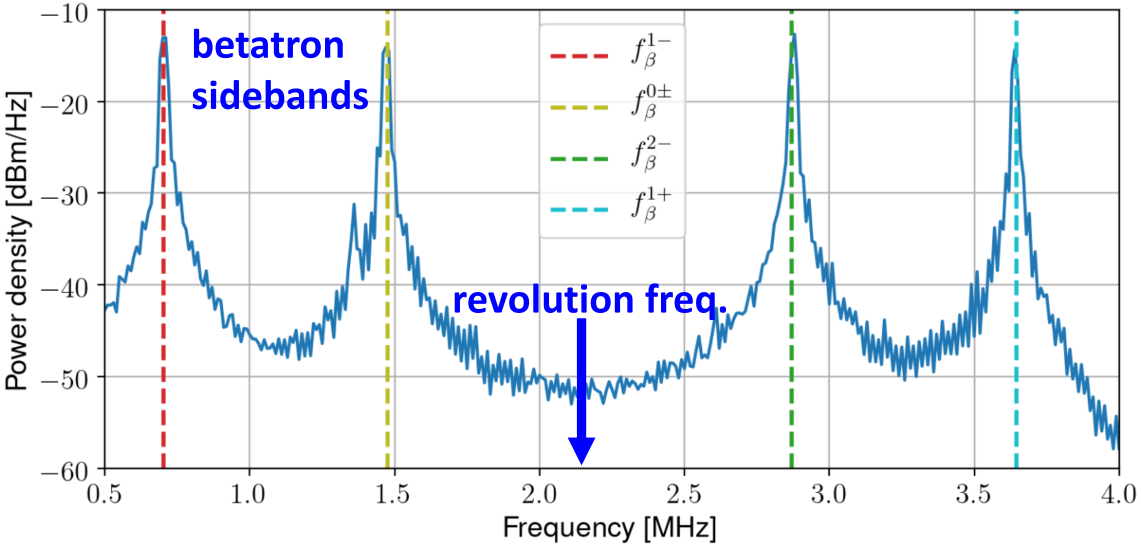
Experiment at HIT:

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

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







IFAST-REX Working Group 3: Simulation and Experiment

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

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

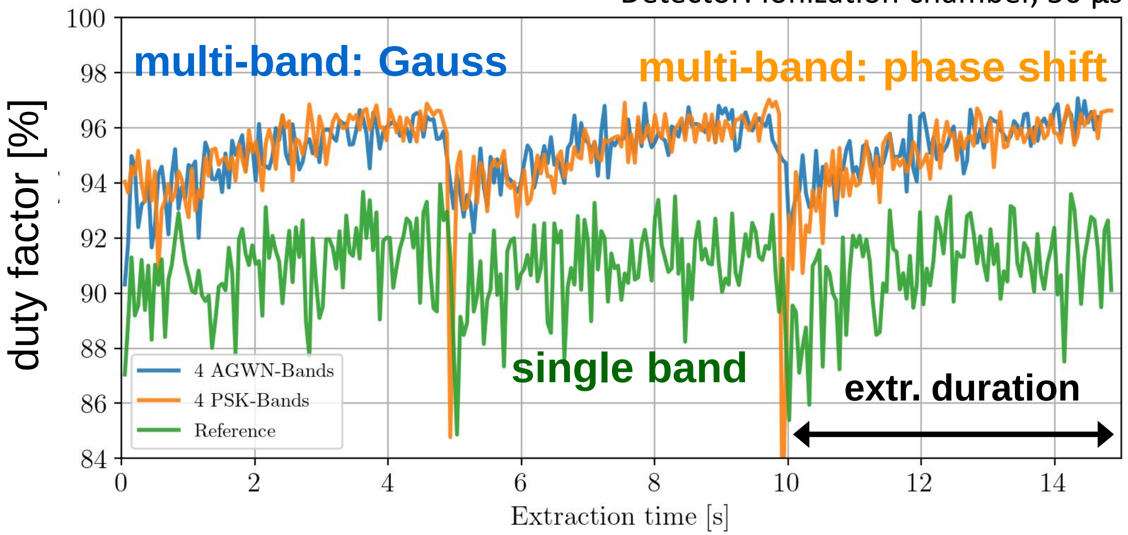
Experimental results at HIT:

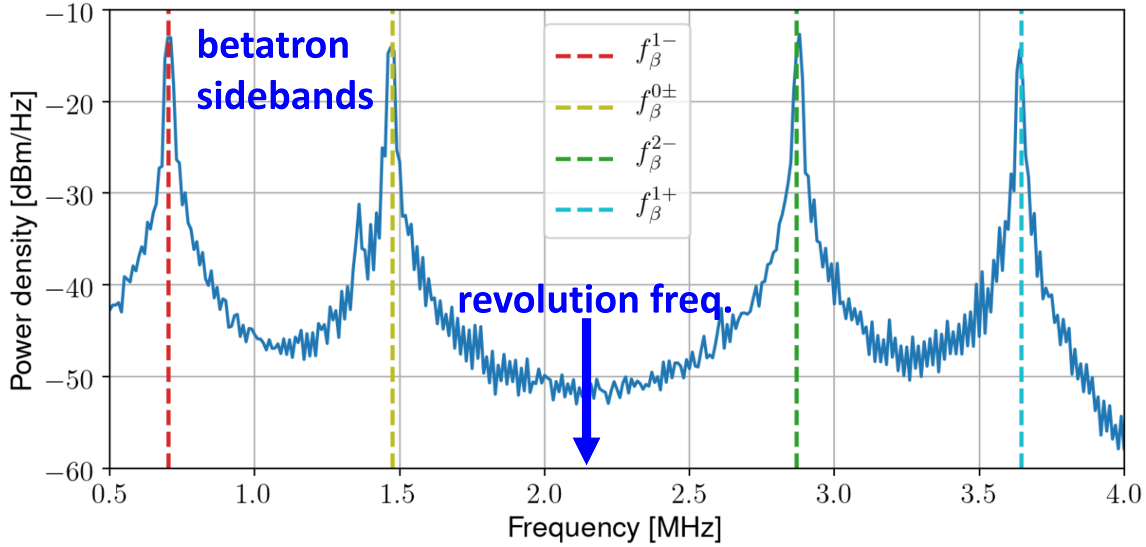
- **Significant increase of beam quality by multi-band**
- Lower influence by noise type
- Technically feasible method of excitation
- Restricted to 4 sidebands due to ***amplifier power***

Micro-structure quality measure → duty factor:

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

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





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

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'
- Additional variable gain amplifier required

$\Rightarrow$ matched solution with good flexibility

HIT: Signal generation

Universal software radio:

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

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

$\Rightarrow$ rigorous requirements

Status: First design considerations,
waiting for more detailed specifications

IFAST-REX Working Group 4: Spill Detector Development and Analysis

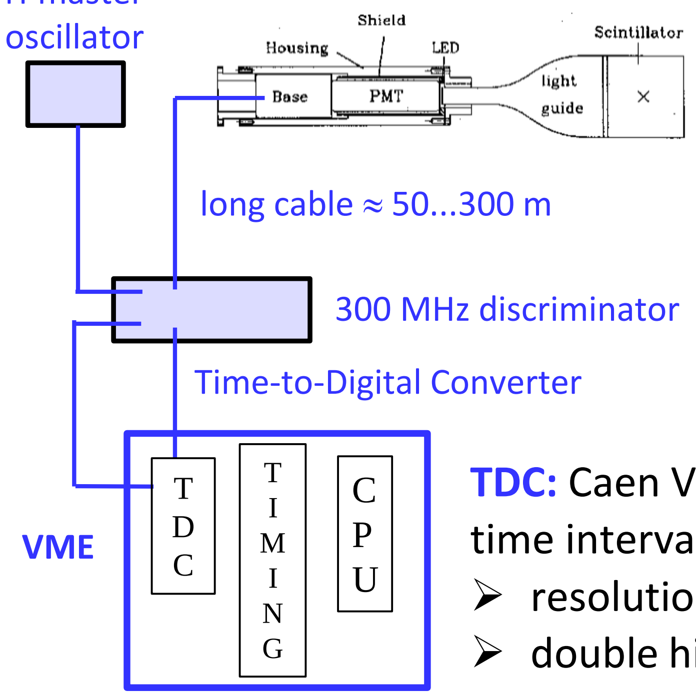
Performed by GSI (R. Singh, T. Milosic et al.)

Topic: Fast particle detectors and versatile data acquisition

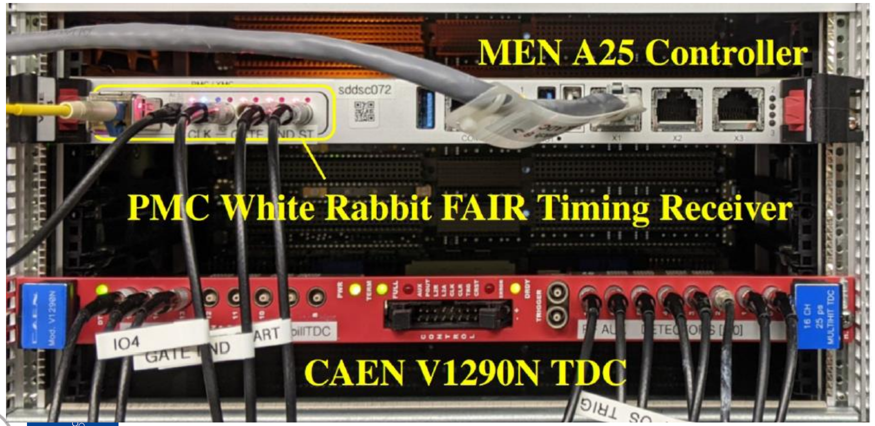
Goal:
- Spill characterization down to µs resolution
- For bunched beam extr.:
  arrival time at detector = 'bunches' , ns resolution
- High count rate
- Versatile data acquisition
- Usable at all facilities

Status:
- TDC-based DAQ operational at GSI with excellent performance
- Scaler-based DAQ at GSI must be refurbished
- Presently: Fixed to GSI IT infrastructure (as FESA-based)
- Offline method of data analysis must be discussed
- Further on: Development of fast inorganic scintillators progressing at GSI with superior radiation hardness

Analog and digital chain:



TDC: Caen V1290N
time interval counter
- resolution σ_{rms}= √2*35 ps ~ 50 ps
- double hit discrimination 5 ns



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

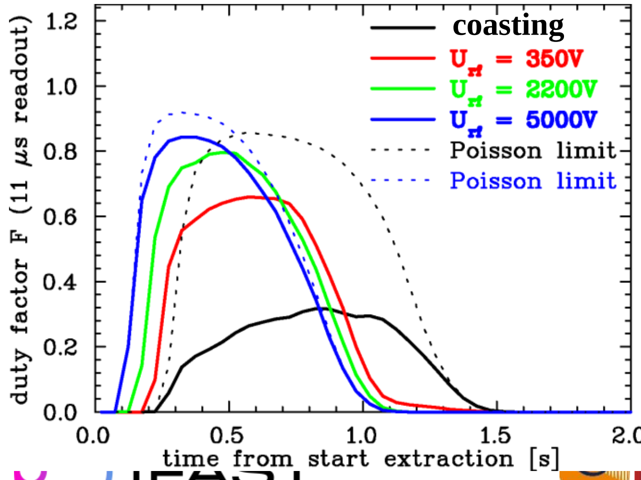
IFAST-REX Working Group 4: Spill detector development and analysis

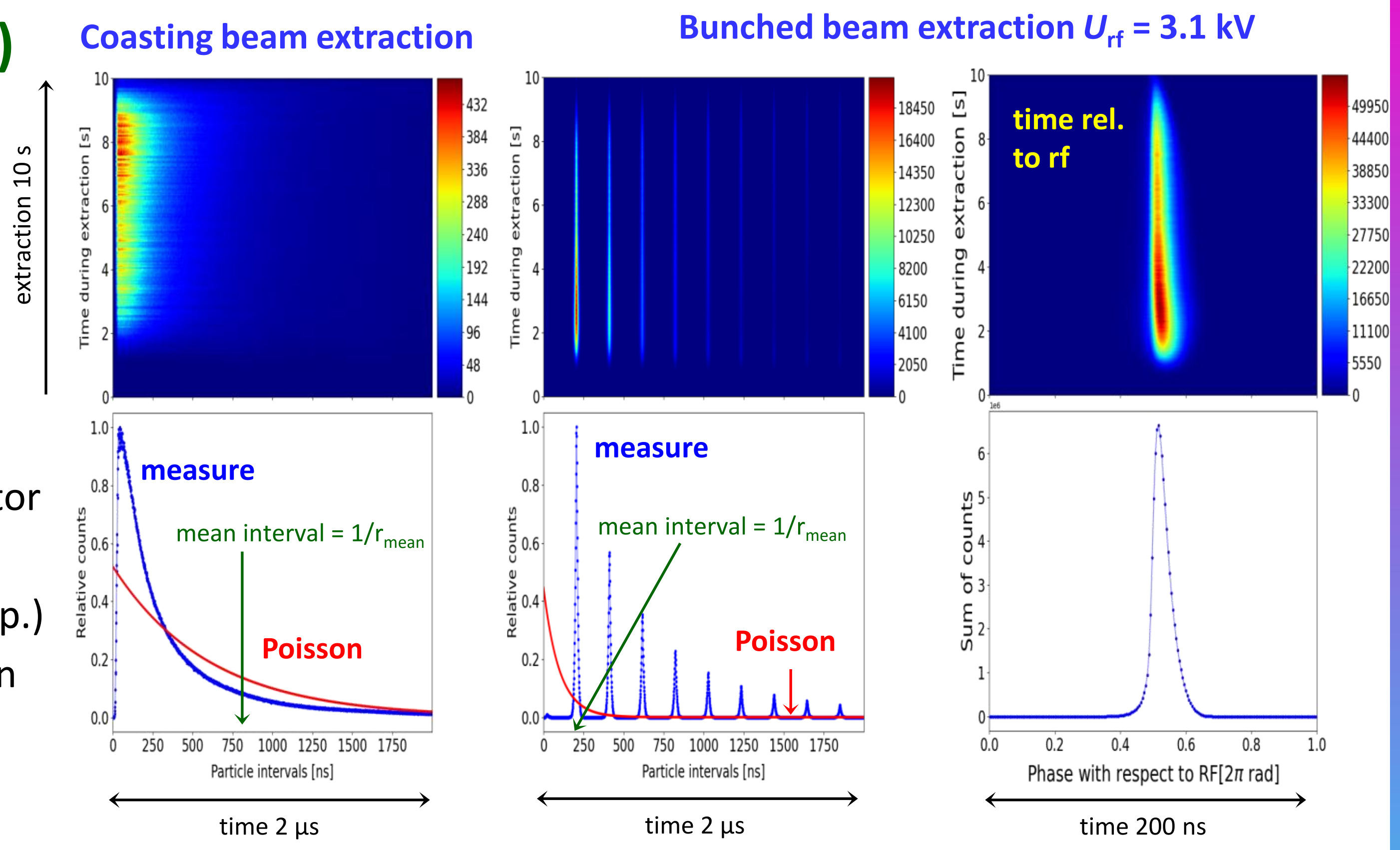
Performed by GSI (R. Singh, T. Milosic et al.)

Topic: Fast particle detectors and data acquisition

Results: Measurement of ion arrival versus rf &
Ion ↔ ion time interval:

- Detection with plastic scintillators
- DAQ fulfills all requirements
- Costing beam: Quite 'non-Poisson'
- Bunched beam: wider interval distrib. ⇔ better duty factor
- Bunched beam: Short 'bunches', ≈ 1/3 of stored bunch (acceptable for med. facilities, but not at GSI fix target exp.)
- Longitudinal width variation center shift during extraction





Beam: f_{rf} = 4.96 MHz

Coasting and bunched beam extraction:
Beam: Bi^{68+} with 300 MeV/u, with f_{rf} = 3.62 MHz

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Conclusion:

- Collaboration established
- Work Group content determined
- WG 1 (novel transformer combination): Significant progress
- WG 2 (knock-out amplifier & control): Technical development started
- WG 3 (simulation & experiment): Various investigations performed
- WG 4 (detectors & DAQ): Progress (but presently DAQ usable at GSI only)
- Coordination should be improved

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.