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

2nd Annual Meeting / 20th April 2023

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

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
- Improved transverse excitation for knock-out extraction

⇒ Non-standard current measurement and rf-excitation control

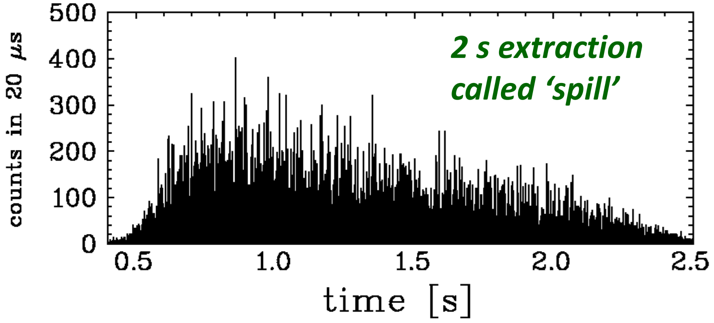
3. Validation:

- Experimental validation at the facilities

⇒ Tailored improvements for IFAST-REX facilities

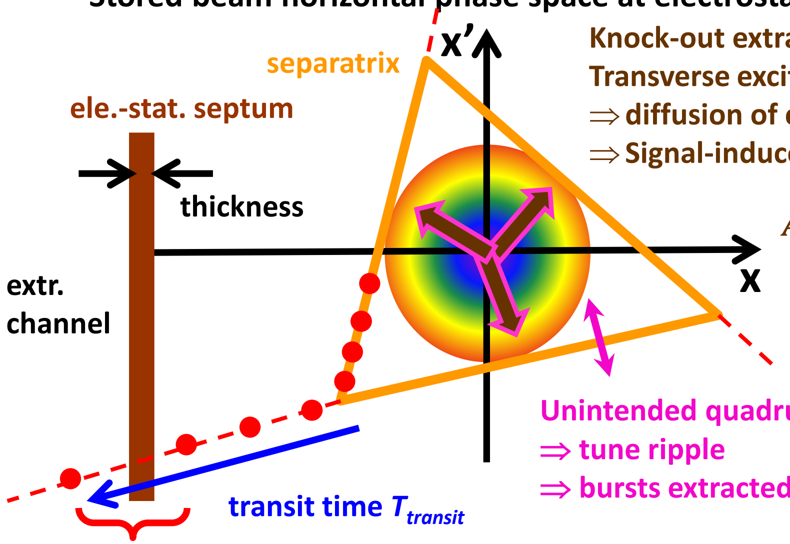
Example: C^{6+} at 300 MeV/u at GSI

Quad. scan, un-bunched beam



2 s extraction called 'spill'

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

transit time $T_{transit}$

last spiral step x_{step} after 3 turns

Sextupoles: non-linear fields

Ion's amplitude growth per turn

⇔ $T_{transit}$ & x_{step}

IFAST-REX Structure: Working Groups

Topic: Workshare structure within the entire project

- **Working Group 1:** Power supplier ripple measurement novel transformer combination
  chair Frank Stulle (Bergoz Instrumentation)
- **Working Group 2:** Optimized rf-amplifier and control of knock-out extraction
  chair Eike Feldmeier (HIT)
- **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)

IFAST-REX Working Group 3 (Simulation & Experiment): Network concerning Simulations

Topic: Slow extraction simulation ⇒ particle tracking with non- linearities

Contributions by CERN, CNAO, GSI, HIT, MedAustron, SEEIIST

Methodology: Network chaired by **Francesco Velotti** CERN

Status:

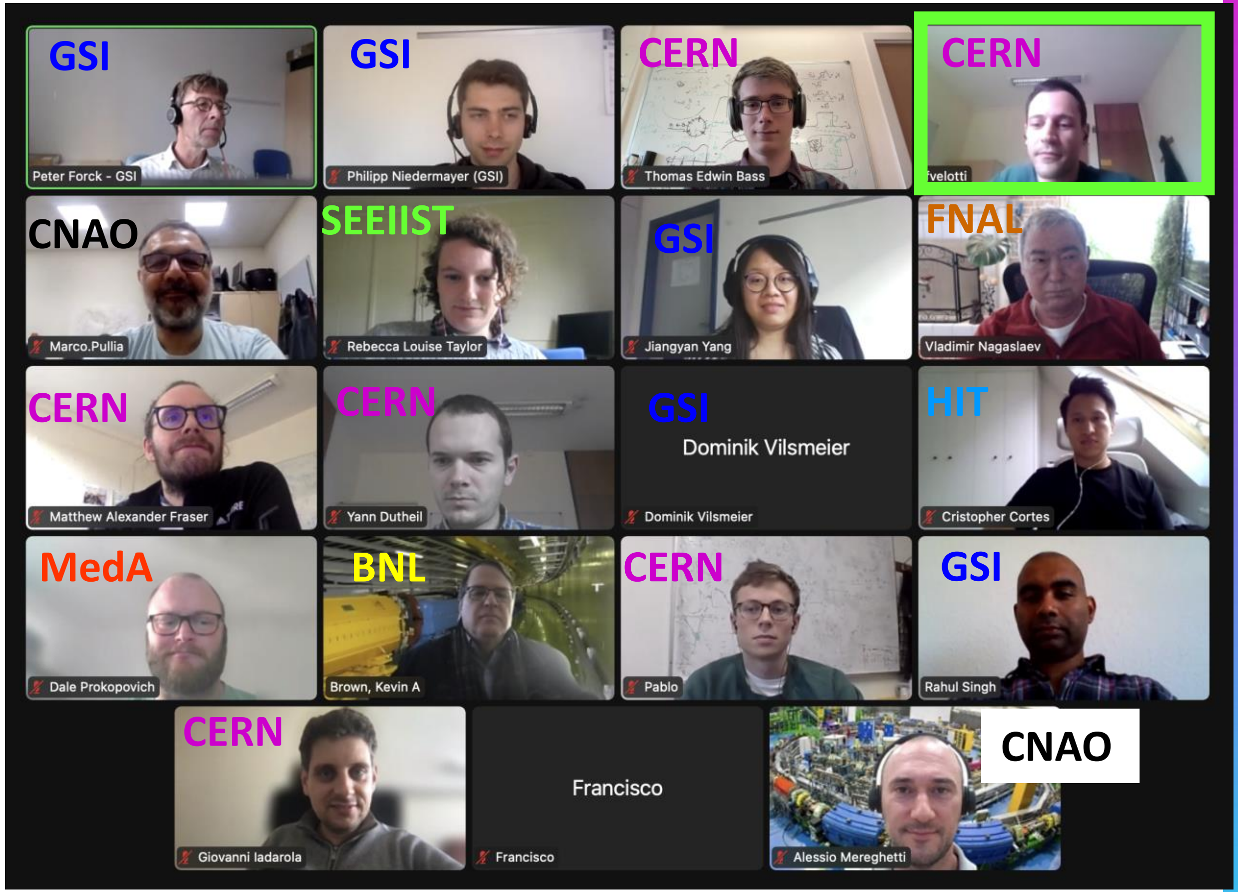
- Quatrely collaboration meeting
- Intensive personal discussion

⇒ Network established

Subjects:

- Support for simulation techniques
- Presentation and discussion of results
- Introduction to Xsuite

⇒ Very fruitful collaboration; in particular, between PhD students



IFAST-REX Working Group 3 (Simulation & Experiment): Usage of Xsuite

Topic: Development at CERN with general purpose applications

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

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

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

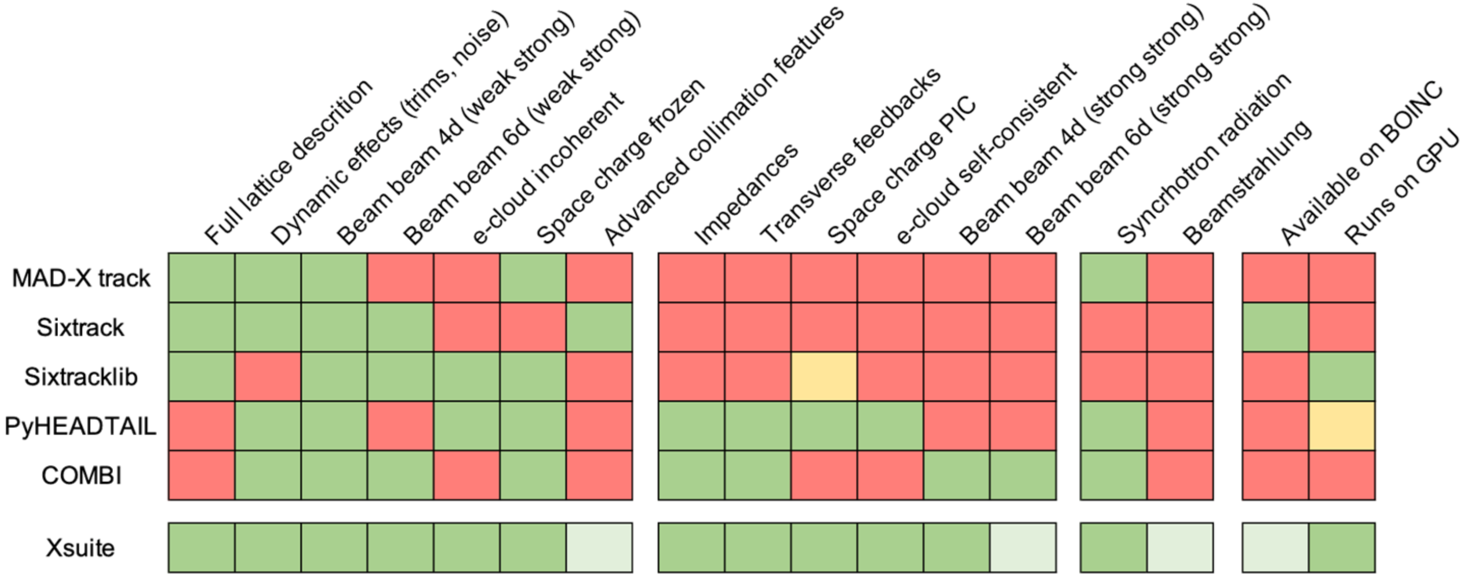
Xobjects
interface to different computing plaforms
(CPUs and GPUs of different vendors)

CFFI PyOpenCL CuPy

Lower level libraries
(external, open source)

intel AMD NVIDIA

Hardware: CPU & GPU



	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 <u>G</u>PUs
- ➢ Additional module possible

GitHub

iFAST

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

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

Topic: Tune spectrum for beams shortly before extraction

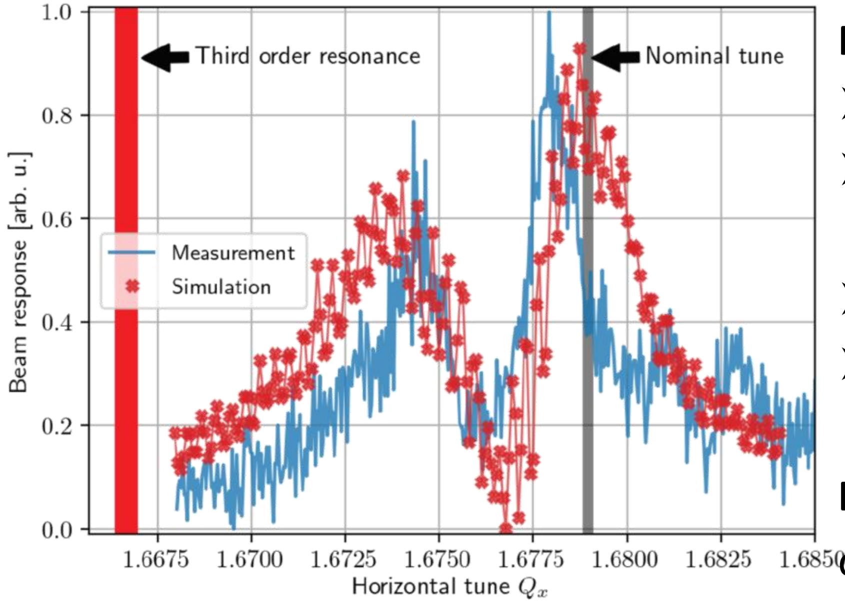
by C. Cortes, E. Feldmeier (HIT), P. Niedermayer R. Singh (GSI), R. Taylor (CERN&SEEIIST)

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

⇒ optimized **knock-out extraction** spectrum

Methodology: chirped tune **measurement** & comparison to simulation

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



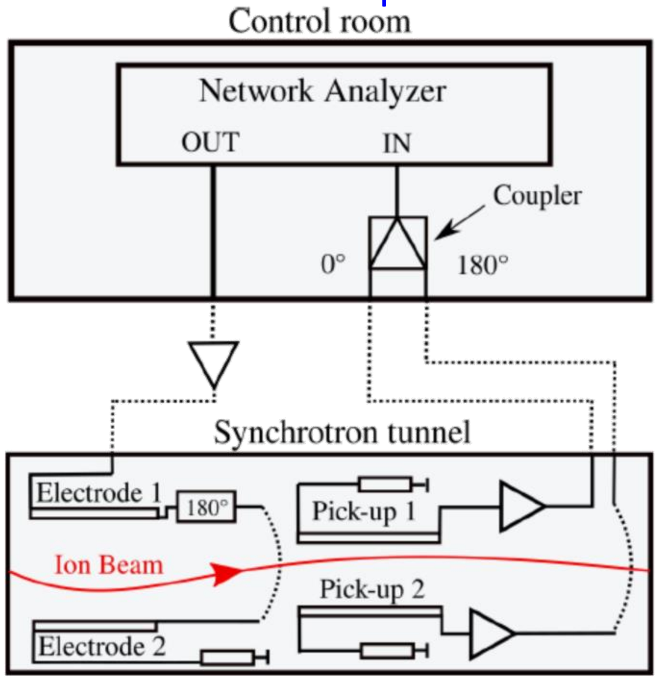
E.C. Cortes Garcia et al. IPAC’22 & NIM A 167137, 2022

Parameter at HIT:

- C^{6+} 124 MeV/u
- ≈ 10^7 particles,
  i.e. no space charge
- Frequency chirp
- Single peak for
  stable beam conditions

But: Several peaks measured close to non-linear resonance

Beam Transfer Function measurement setup at HIT:



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⇒ optimized **knock-out extraction** spectrum

Methodology: chirped tune measurement & **comparison** to simulation

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

Model for acc. physics interpretation:

Simulation in Xsuite with simplified lattice

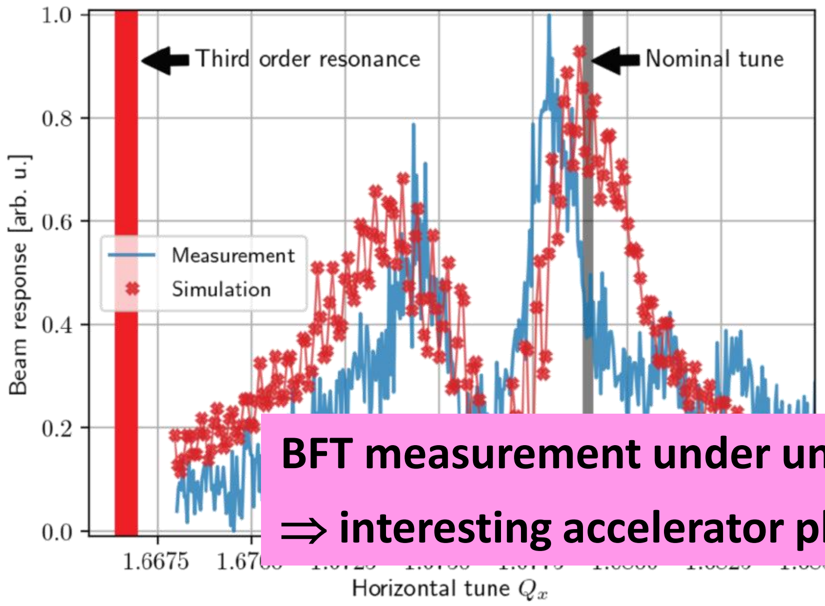
Beating between $f_\beta = Q_{nom} f_{rev}$ and f_{excite}

⇒ beam excitation

Non-linearity by sextupoles

⇒ frequency spread

Status: Extensive simulations ongoing



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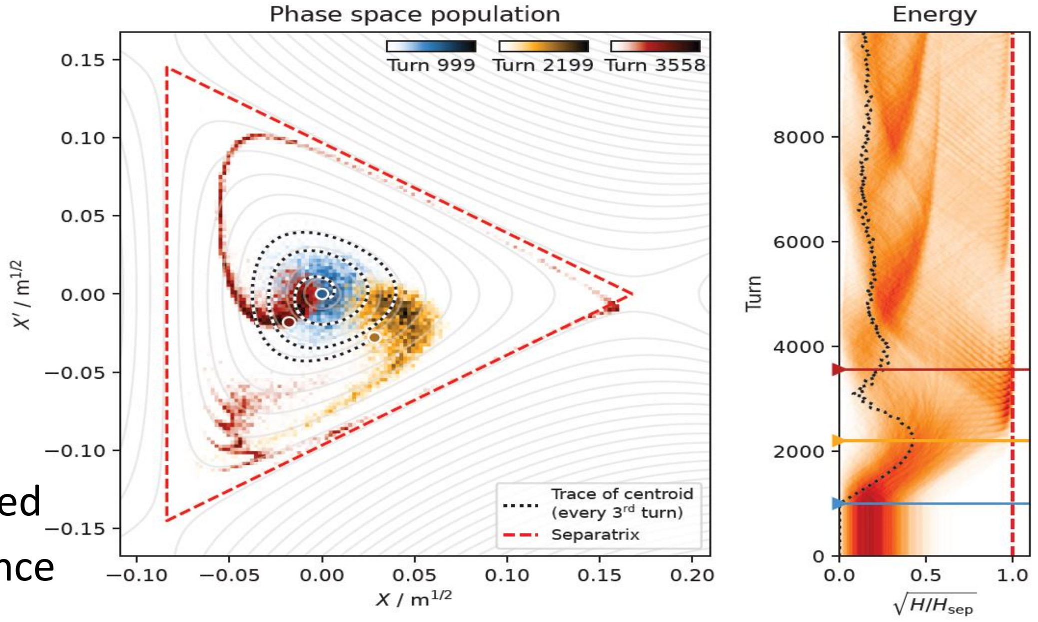
  i.e. no space charge
- Frequency chirp
- Single peak for
  ions
  asured
  close to non-linear resonance

BFT measurement under unstable conditions

⇒ interesting accelerator physics



E.C. Cortes Garcia et al. IPAC'22 & NIM A 167137, 2022

P. Niedermayer and R. Singh IPAC'22

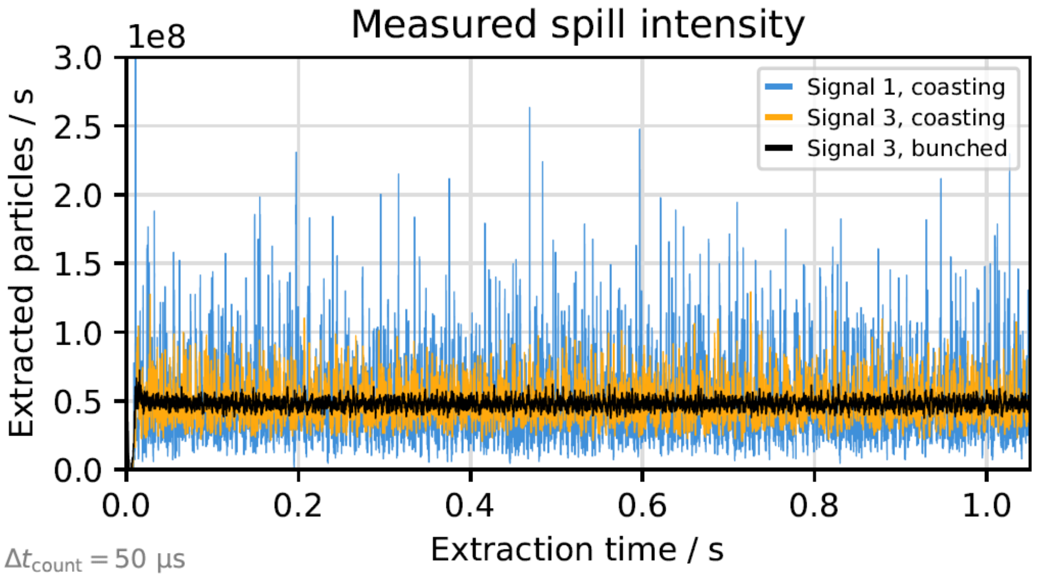
IFAST-REX Working Group 3 (Simulation & Experiment): Signal Spectrum Dependence

Topic: Excitation spectrum dependence of spill micro-structure for knock-out extraction

by C. Cortes, E. Feldmeier (HIT), P. Niedermayer R. Singh (GSI)

Excitation spectrum influences

- Diffusion from the beam core towards
- Separatrix crossing

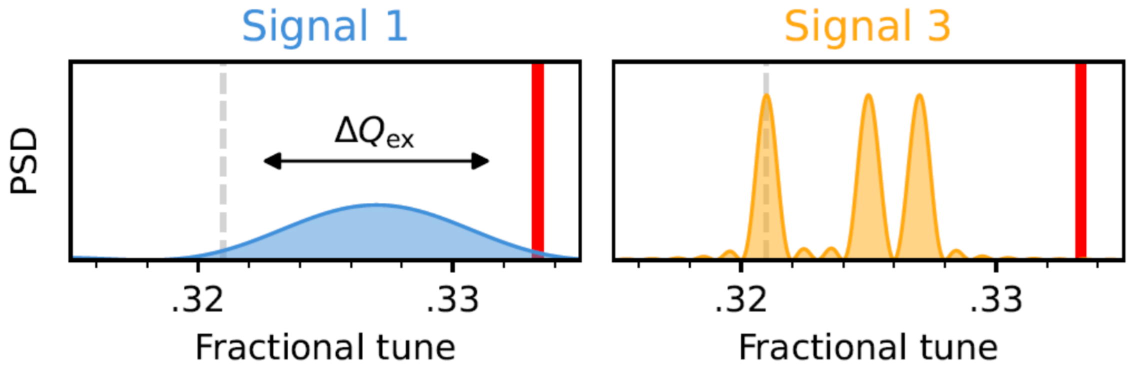


Result: Strong dependence on excitation spectra

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
2	0.321	0.327	1.327	0.009
3	0.321	0.327	1.327	0.001



- Noise by random phase-shift keying
- Further signal spectra applied

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

IFAST-REX Working Group 3 (Simulation & Experiment): Signal Spectrum Dependence

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- ➢ Diffusion from the beam core towards
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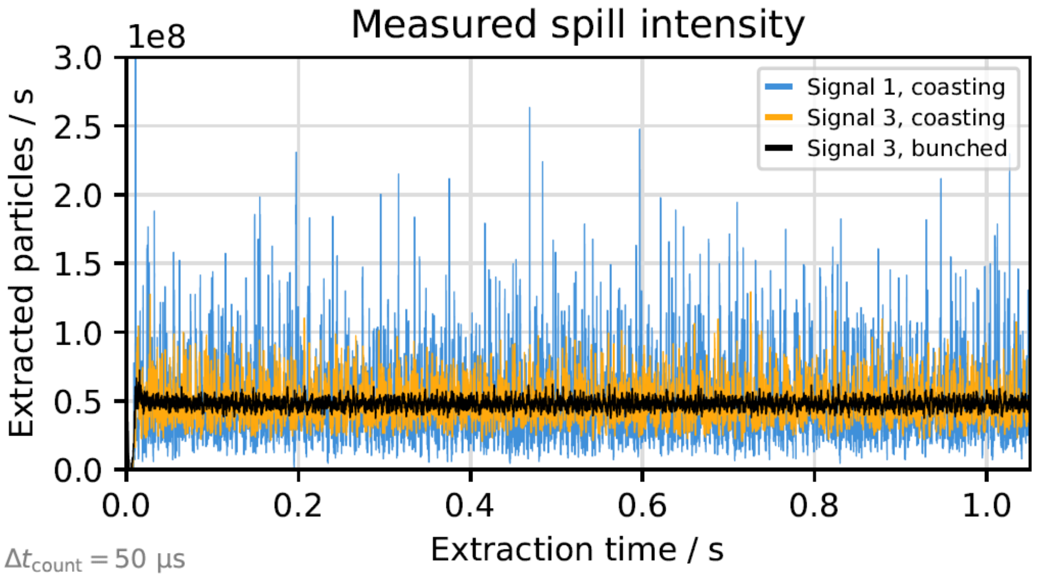

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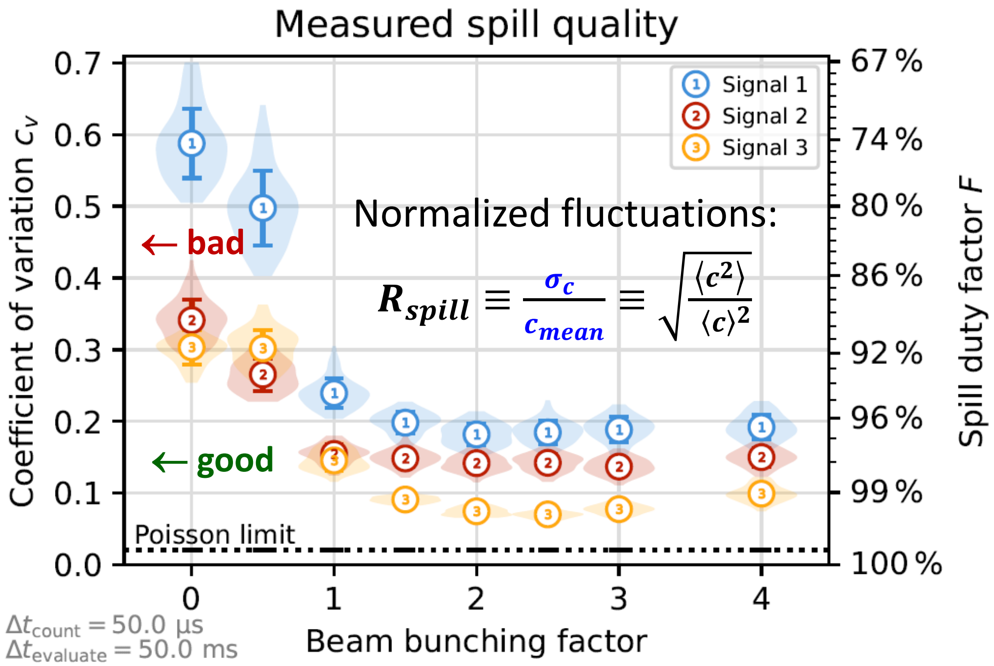


Results:

- ➢ Significant improvement for **coasting & bunched** beams
- ➢ Confirmed by simulations
- ➢ Multi-band excitation preferred
- ➢ Higher frequencies required

One consequence: Mod. of initial specification of rf power 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

IFAST-REX Working Group 2 (Knock-out Excitation): Control of Knock-out Excitation

Technical development by GSI, HIT and MedAustron

Tune measurement & control of knock-out excitation spectrum:

USRP hardware and GNU-Radio software:

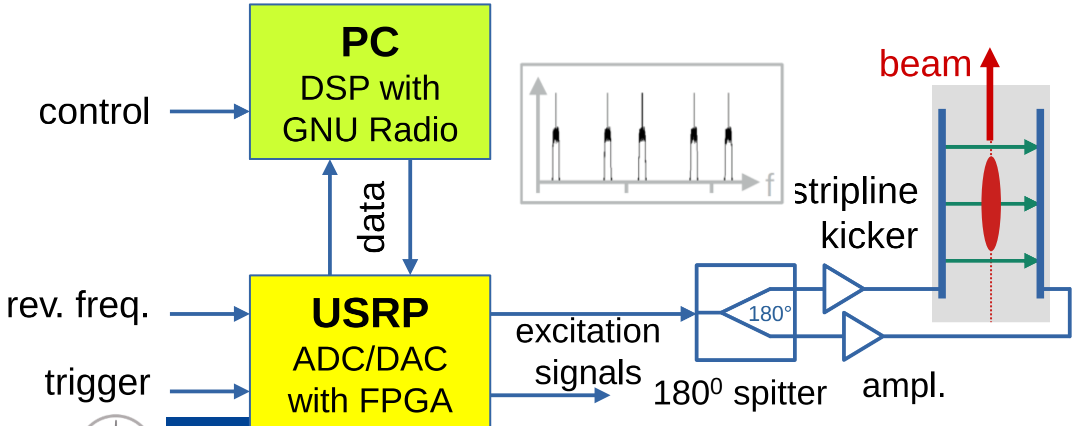
- Highly customizable, low cost signal generation
- Flow-graph design by GNURadio as Open Software
- Further applications: Tune measurement, tune wobbling etc.

Signal generation (HIT, GSI,MedA)

Universal software defined radio USDR Ettus N210

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

Improved version: Ettus x310



control

PC
DSP with
GNU Radio

data

rev. freq.

trigger

USRP
ADC/DAC
with FPGA

excitation
signals

180°

180^0 spitter

ampl.

stripline
kicker

beam

f

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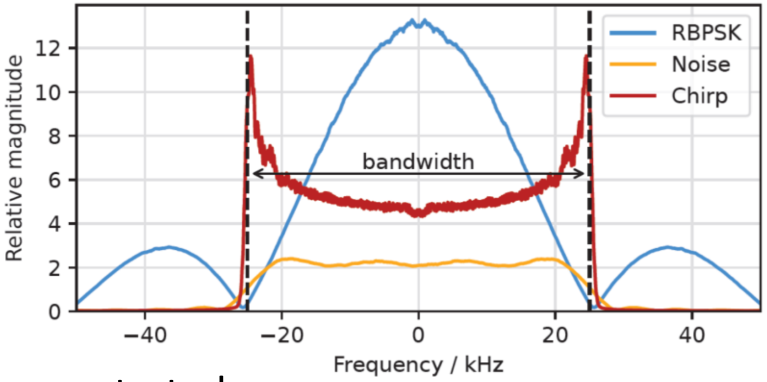
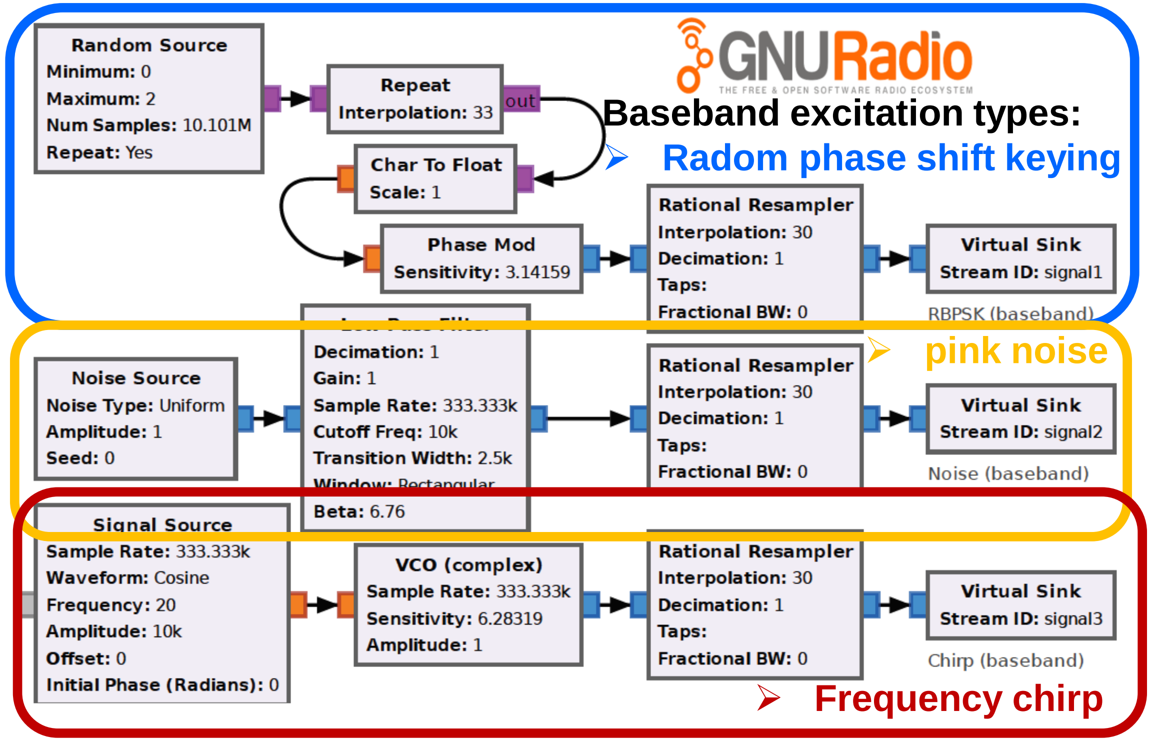




GNURadio

Baseband excitation types:

- ➢ Radom phase shift keying
- ➢ pink noise
- ➢ Frequency chirp

Random Source
Minimum: 0
Maximum: 2
Num Samples: 10.101M
Repeat: Yes

Repeat
Interpolation: 33

Char To Float
Scale: 1

Phase Mod
Sensitivity: 3.14159

Rational Resampler
Interpolation: 30
Decimation: 1
Taps:
Fractional BW: 0

Virtual Sink
Stream ID: signal1

RBPSK (baseband)

Noise Source
Noise Type: Uniform
Amplitude: 1
Seed: 0

Decimation: 1
Gain: 1
Sample Rate: 333.333k
Cutoff Freq: 10k
Transition Width: 2.5k
Window: Rectangular
Beta: 6.76

Rational Resampler
Interpolation: 30
Decimation: 1
Taps:
Fractional BW: 0

Virtual Sink
Stream ID: signal2

Noise (baseband)

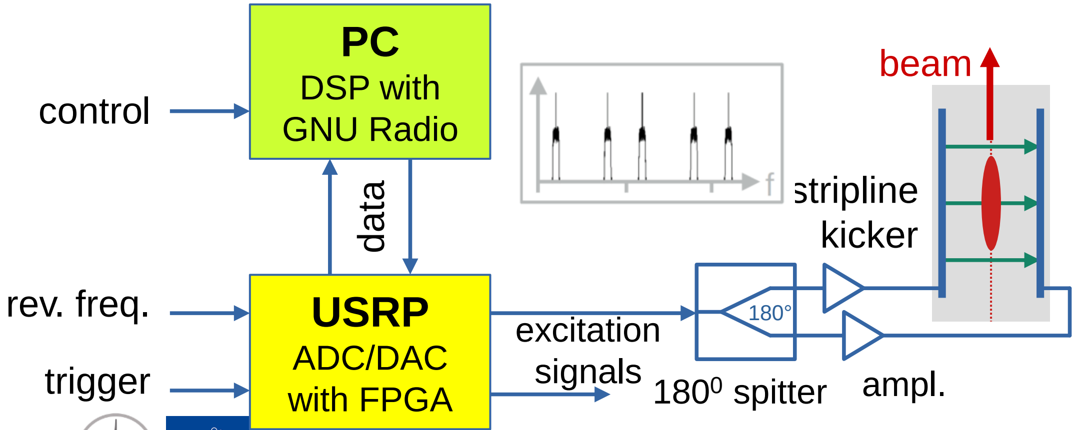
Signal Source
Sample Rate: 333.333k
Waveform: Cosine
Frequency: 20
Amplitude: 10k
Offset: 0
Initial Phase (Radians): 0

VCO (complex)
Sample Rate: 333.333k
Sensitivity: 6.28319
Amplitude: 1

Rational Resampler
Interpolation: 30
Decimation: 1
Taps:
Fractional BW: 0

Virtual Sink
Stream ID: signal3

Chirp (baseband)



control

PC
DSP with
GNU Radio

data

rev. freq.

trigger

USRP
ADC/DAC
with FPGA

excitation
signals

180⁰ spitter

ampl.

stripline
kicker

beam

Status:

- ➢ Functionality demonstrated
- ➢ Latency after trigger significantly improved
- ➢ Additional module added to GNURadio software
- ➢ Documentation at GIT https://git.gsi.de/p.niedermayer/exciter

⇒ **Milestone for rf-amplifier control reached** (month 24)

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

IFAST-REX Working Group 2 (Knock-out Excitation): rf Power Amplifier & Matching Network

Performed by company Barthel HF Technik

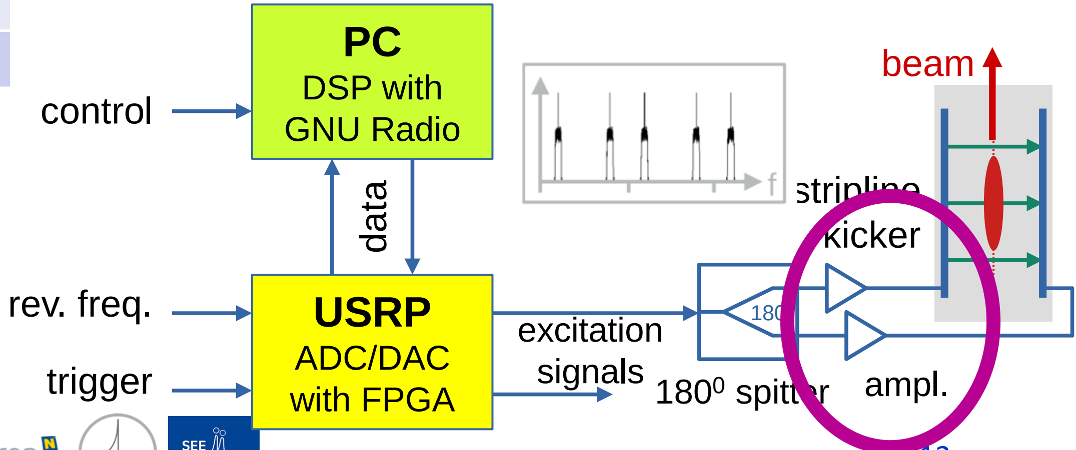
Topic: Technical realization for knock-out amplifier & matching

Basic specification for power amplifier:

Parameter	Value	Remark
Frequency range	0.5 … 15 MHz	
Output power	1 kW	500 W for GSI, HIT
Gain	57 … 60 dB	
Input impedance	50 Ω	
Input reflection VSWR	< 1.2:1	
Amplifier output impedance	50 Ω	
Electrode capacitive load	50 pF	1: 5 matching network req.
Output reflection VSWR	< 3:1	
Mechanics, cooling	19" rack, air	

Challenges:

- Large bandwidth with good gain flatness
- Reflected power suppression
- Matching network to increase voltage on kicker electrodes



IFAST-REX Working Group 2 (Knock-out Excitation): rf Power Amplifier & Matching Network

Performed by company Barthel HF Technik

Topic: Technical realization for knock-out amplifier & matching

Results from comparable amplifier with Z = 50 Ω load:

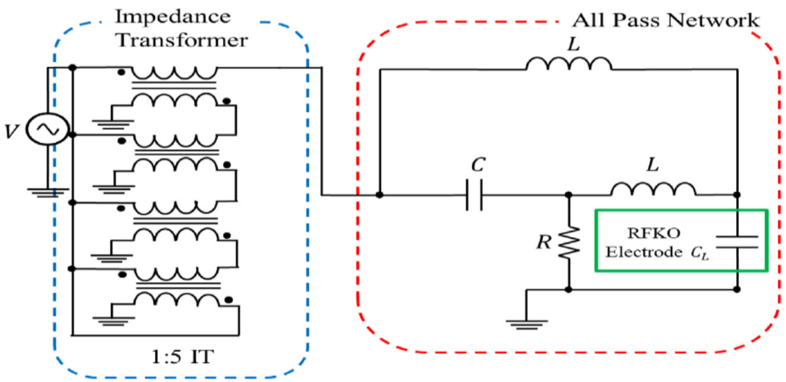
Gain linearity: 2 dB reached for -20 … 0 dBm input

Gain flatness: ≈ 1 dB for 0.5 … 8 MHz reached, optimization ongoing

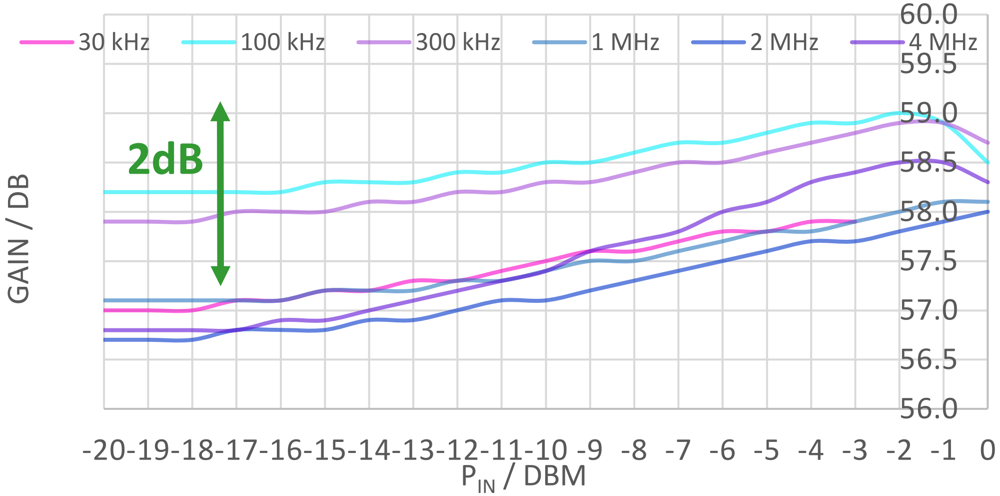
Matching network to increase the electrodes voltage

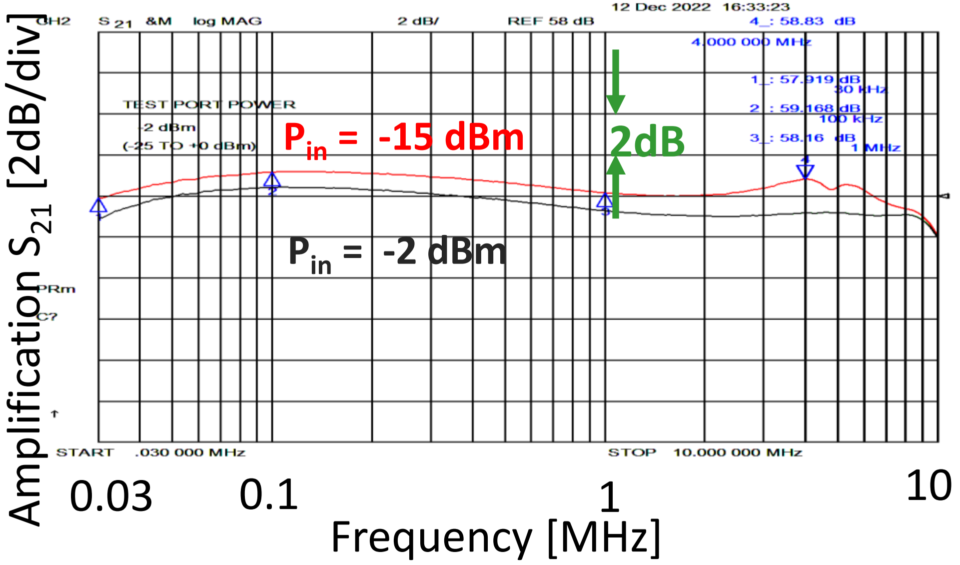
Transformer chain with matching to electrodes

Care concerning reflections and electrode coupling



Gain versus P_{in}, frequency





Status: Specification now established

Design started

Courtesy T. Shiokawa et al., NIM A1010, 165560, 2021

IFAST-REX Working Group 1 (Power Supplier Measure.): Requirements & Specification

Performed by company Bergoz Instrumentation (Frank Stulle et al.)

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

Detailed specification steered by GSI & 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 %

IFAST-REX Working Group 1 (Power Supplier Measure.): Solution

Performed by company Bergoz Instrumentation (Frank Stulle et al.)

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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

Detailed specification steered by GSI & Bergoz

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

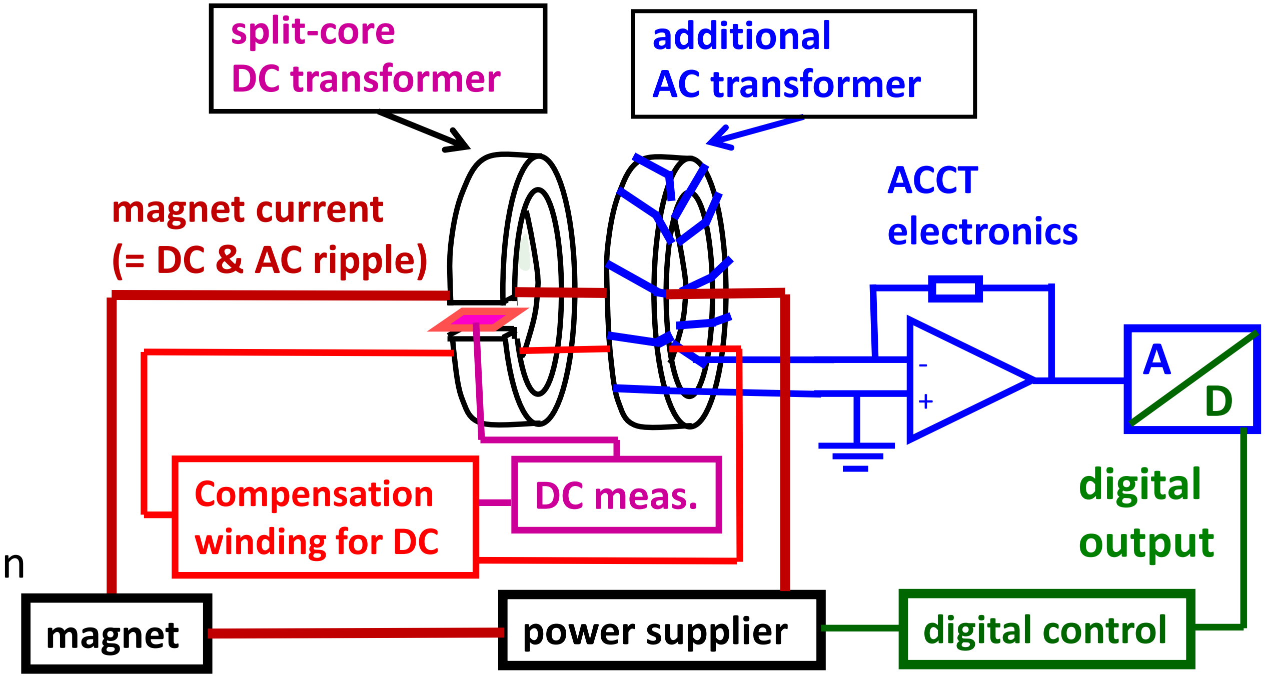
Sensitivity for AC part: $\frac{\Delta I_{AC}}{I_{AC}} \approx 10^{-5}$

Challenges: AC-component on strong DC offset

$\Rightarrow$ magnetic saturation of core

Solution: Two transformers

- DC transformer measures I_{DC} & used for compensation
- AC transformer for ripple measure I_{AC}



IFAST-REX Working Group 1 (PS Current Measure.): Realization for AC Measurement

Performed by company Bergoz Instrumentation

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

DC part: Split core of 1500 windings

Hall probe Honeywell SS495A1

AC part: Core with 1500 windings

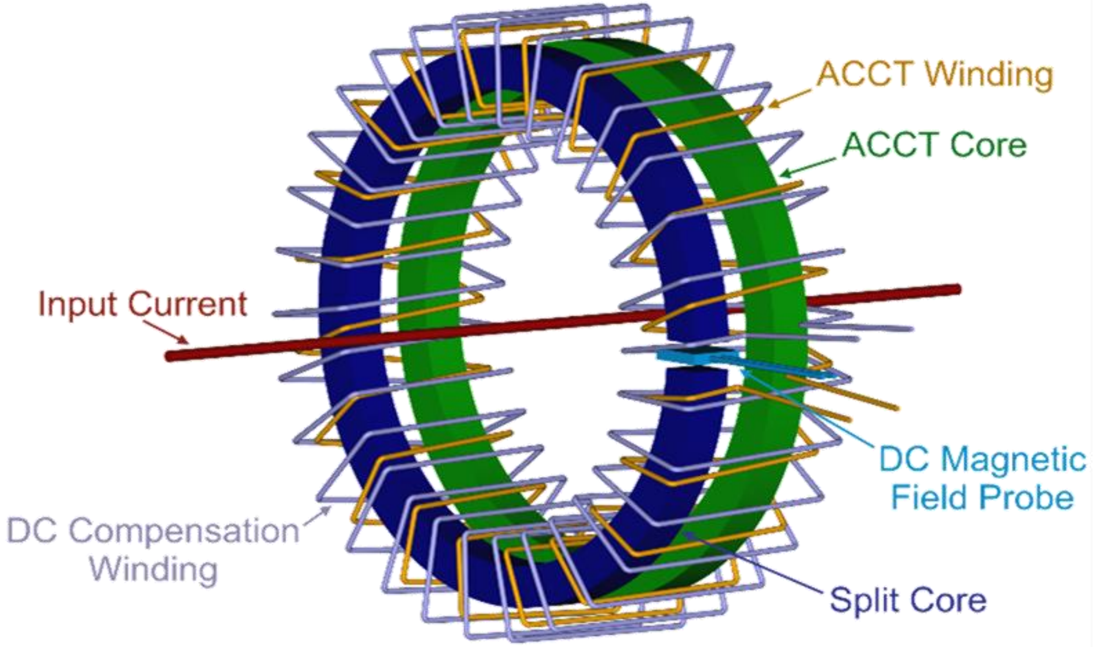
Analogue part comparable to beam current ACCT

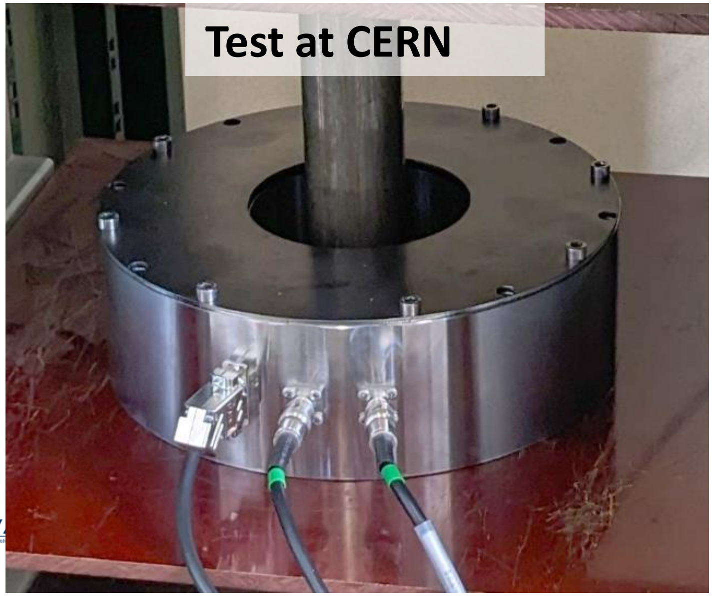
Present achievements → prototype design:

- Integration of DC trans. compensation winding to AC transformer to prevent for core saturation
- Test at Bergoz:
  up to 400 A_{DC} plus ~10^{-3} power supply ripple
- Test at CERN:
  up to 5000 A_{DC}

⇒ DC compensation achieved

⇒ AC measurement with $\frac{\Delta I_{AC}}{I_{AC}} \approx 5\,x\,10^{-5}$ achieved




Test at CERN


Test at Bergoz

IFAST-REX Working Group 1 (PS Current Measure.): Realization for AC Measurement

Performed by company Bergoz Instrumentation

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

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: $\frac{\Delta I_{AC,noise}}{I_{AC}} \approx 5 \cdot 10^{-5}$

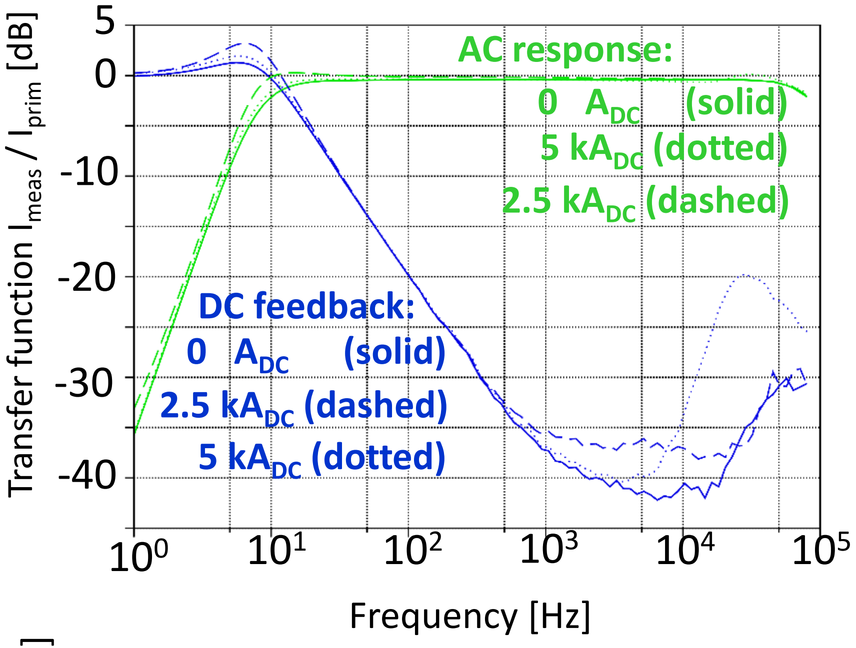
improvement possible by reduction of ele-mag. interference

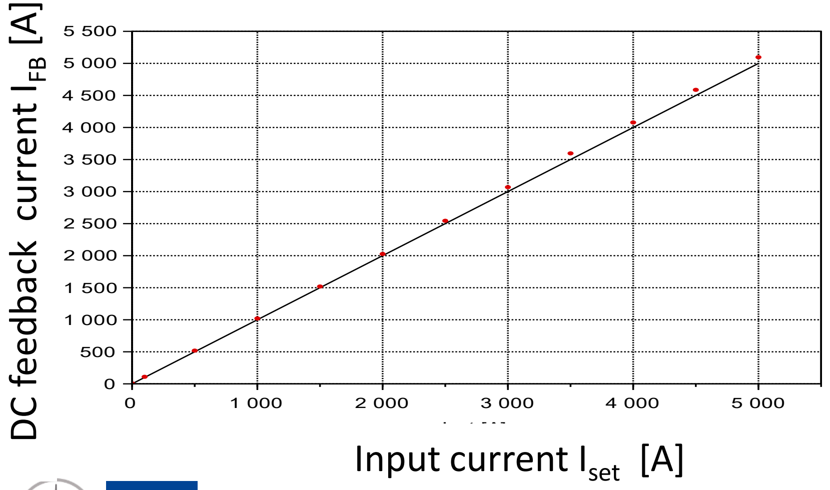
⇒ **Proof-of-principle**

Status: Functionality proven

⇒ engineering design performed

⇒ **Milestone for sensitive AC $\frac{\Delta I_{AC}}{I_{AC}} \approx 5 \cdot 10^{-5}$ reached** (month 24)





IFAST-REX Structure: Status and Summary

WG 1 (Novel transformer combination):

- Successful proof-of-principle, specification almost reached, optimization ongoing

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

- Ground-breaking experiments performed, rf-amplifier and matching network specification now fixed
- Control by versatile capability of SDR implemented
- Technical design of rf-amplifier & network ongoing (slightly delayed due to specification verification)

WG 3 (Simulation & experiments):

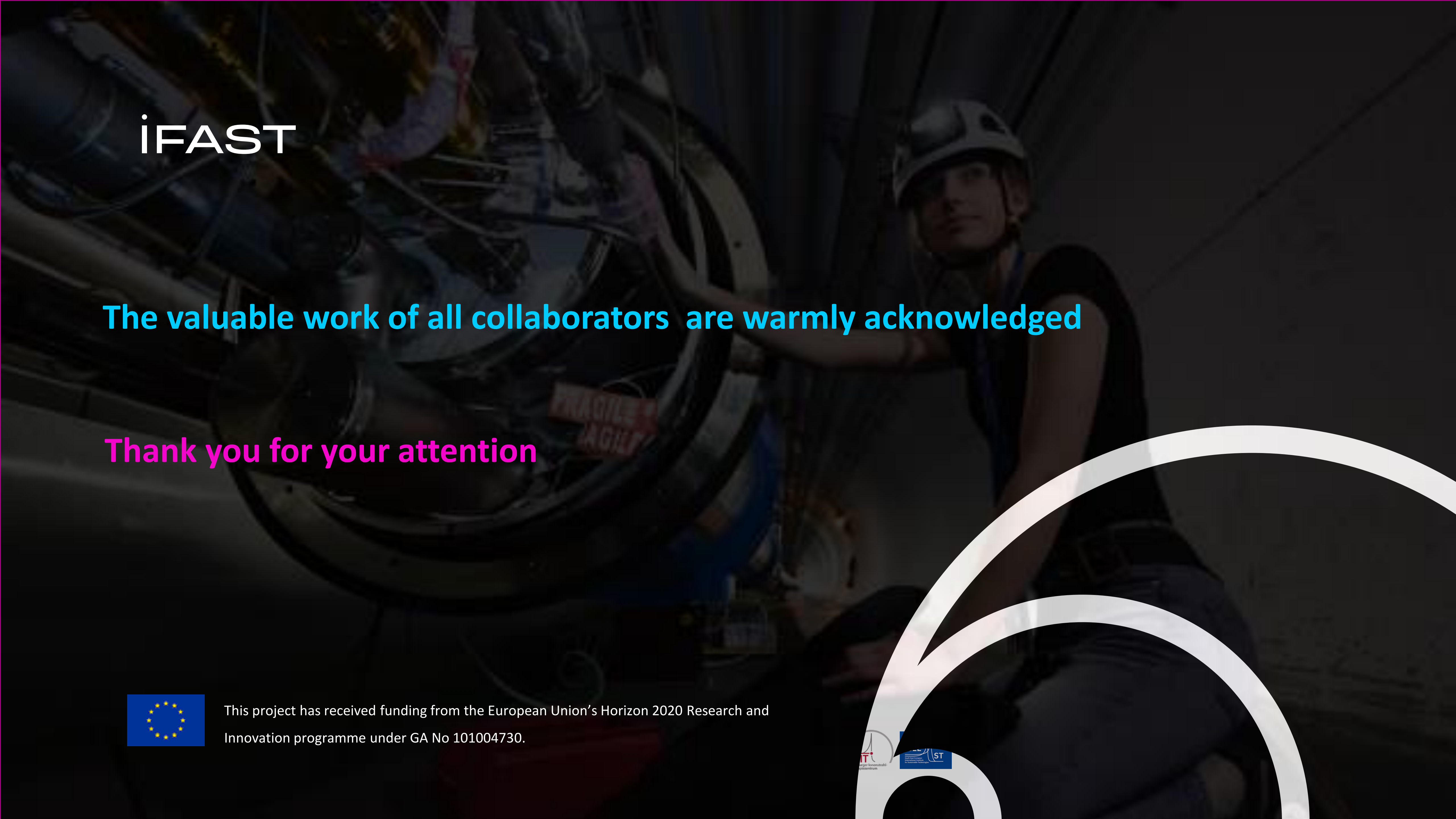
- Network with intensive discussion between participants; usage of Xsuite by most members
- Experiments performed at several facilities, e.g. for specification of knock-out rf-chain

WG 4 (Detectors for slow extraction):

- Fast particle detectors at CERN (time resolved OTR monitor) & GSI (rad-hard scintillators)

⇒ Milestone 20 reached on time (end of April 2023)

IPAC’23: 8 related poster presentations by CERN, GSI & MedAustron



iFAST

The valuable work of all collaborators are warmly acknowledged

Thank you for your attention

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Backup slides

IFAST-REX Working Group 4 (Detectors for diagnostics): Fast Spill Characterization

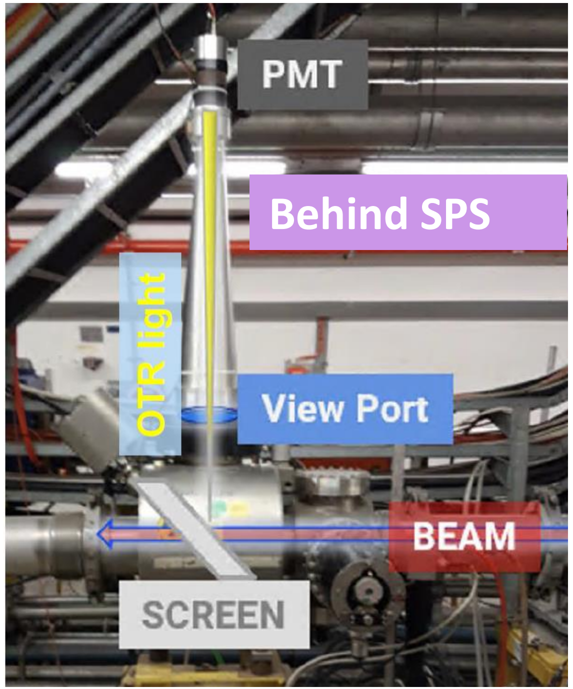
Performed by CERN (F. Roncarolo et al.)

Topic: Time resolved Optical Transition Radiation

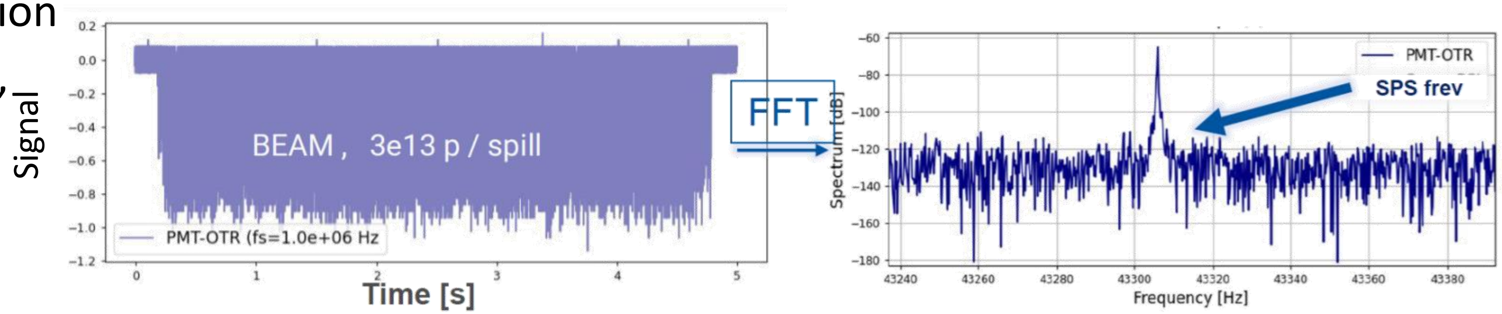
Detector: OTR screen read by photomultiplier, Refurbished monitor behind SPS

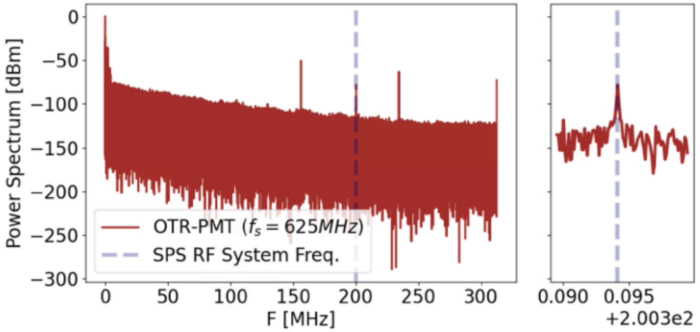
bandwidth DC…300 MHz

(OTR is prompt process)

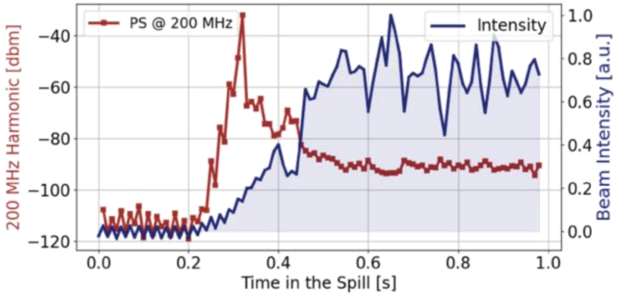


One application: Frequency component evolution during spill





(a) Left: Harmonics calculated over a 10 ms time window. Right: zoom around the SPS RF frequency at 200 MHz



(b) Evolution of the beam power measured at 200 MHz during the first part of the spill with the relative beam intensity extracted from the total PMT signal amplitude. Each point corresponds to a 10 ms integration time.

Topic: Alternative to plastic scintillator performed by GSI (P. Boutachkov et al.)

→ Radiation-hard particle counter by ZnO inorganic scintillators

→ Discussed at Annual Meeting 2022

F. Roncarolo et al. , IBIC'22

IPAC 2023: 8 Posters related to Slow Extraction from IFAST-REX Participants

CERN:

P. A. Arrutia Sota et al.: Benchmarking Simulations of Slow Extraction Driven By RF Transverse Excitation at the CERN Proton Synchrotron

P. A. Arrutia Sota et al.: RF techniques for spill quality improvement in the SPS

R. Taylor et al. (also SEEIIST): Flexible and Dynamic Slow Extraction Simulations with Maptrack

GSI:

J. Yang et al.: Simulation of tune sweep slow extraction improvement via transverse emittance exchange at GSI SIS18

P. Forck et al.: IFAST-REX: An initiative for the mitigation of beam current fluctuations in slow extraction

P. Niedermayer et al.: Investigation of micro spill in RF KO extraction using tailored excitation signals

MedAustron:

F. Kühteubl et al.: Investigating Alternative Extraction Methods at MedAustron

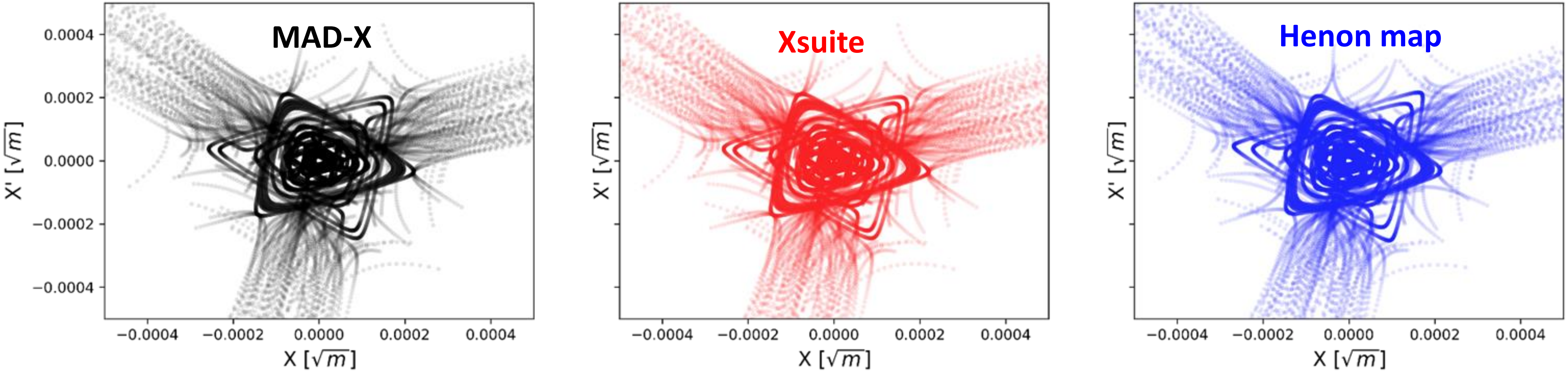
M. Wolf et al.: Expansion of the µTCA based direct sampling LLRF at MedAustron for hadron synchrotron applications

Comparable numbers of posters at previous IPACs

IFAST-REX Working Group 3 (Simulation & Experiment): Introduction to Xsuite

Topic: Development at CERN with general purpose applications

Example of bench marking: Slow extraction phase space portraits are similar for different methods



Status: Most tracking now performed by Xsuite

Courtesy: **P. Arrutia**, T. Bass, M. Fraser, F. Velotti

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

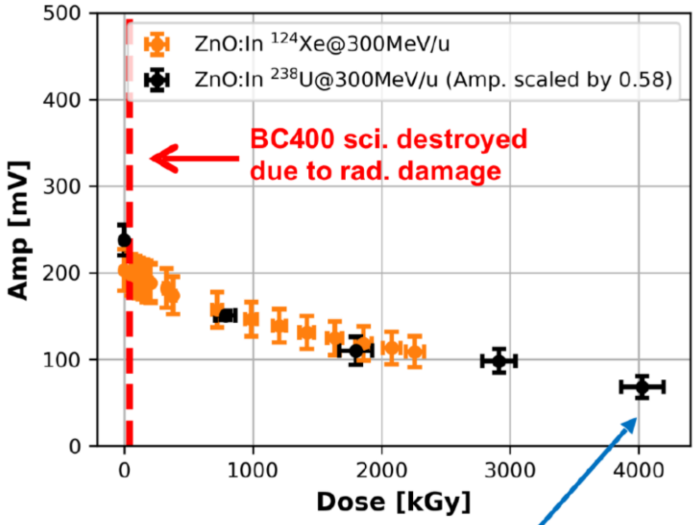
Performed by GSI (P. Boutachkov et al.)

Topic: Alternative to plastic scintillator

→ 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



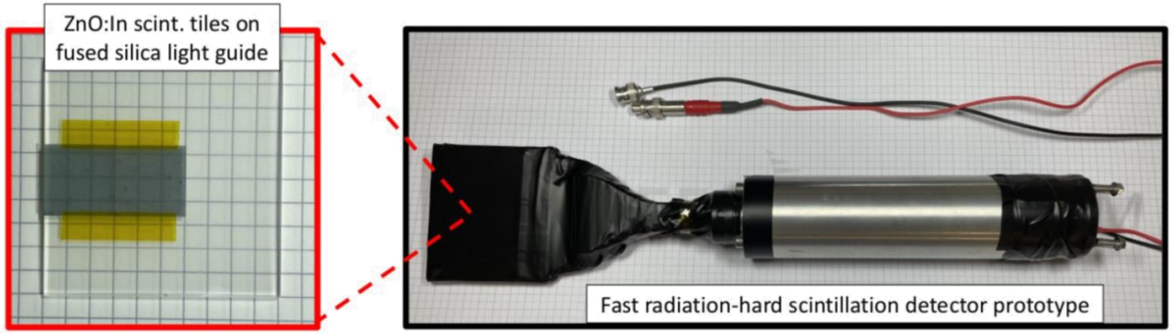
1E+12 ^{238}U/cm^2, or 3E+12 ^{124}Xe/cm^2

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-REX Working Group 4 (Detectors and DAQ): Fast readout by TDC

Performed by GSI and discussed within consortium

Single-particle arrival time read by TDC

DAQ now full functional (at GSI)

- **Characterization of coasting and bunched beams**
- **Experimental results confirmed by MAD-X simulations**

Radiation hard scintillator:

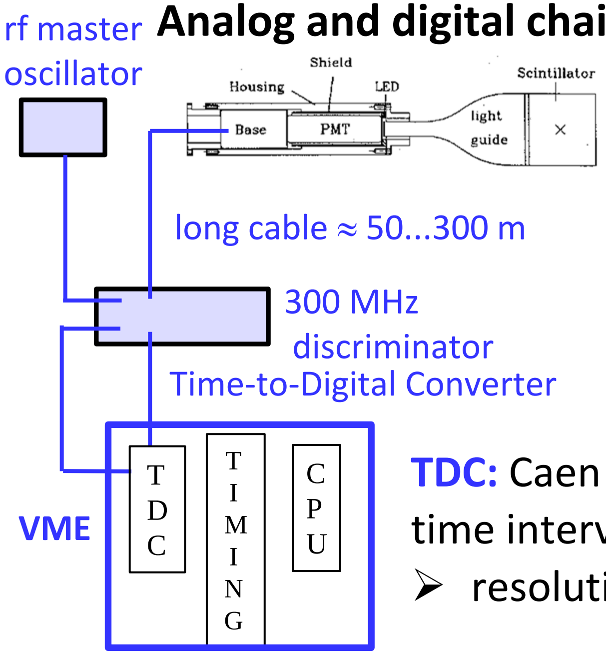
Fast counting (≈ 5 ns) by ZnO:In

Size 45x45 mm^2 made of 3x3 tiles

Radiation hardness ≈ 100 times of plastic scintillator

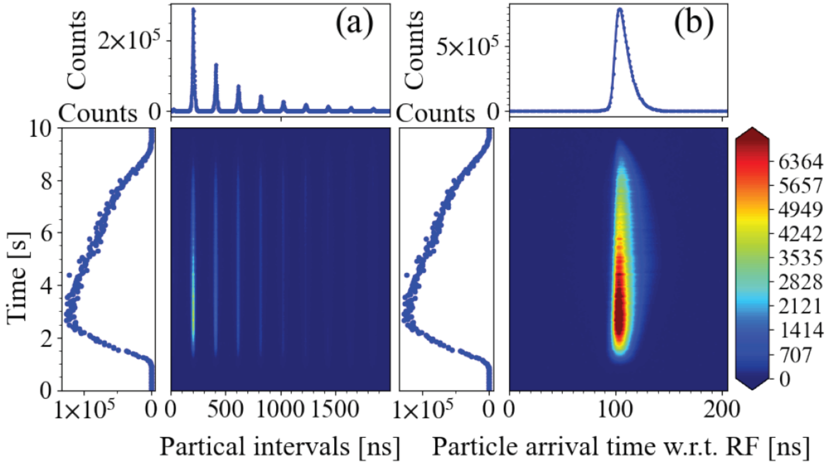
Status: Proof-of-principle done

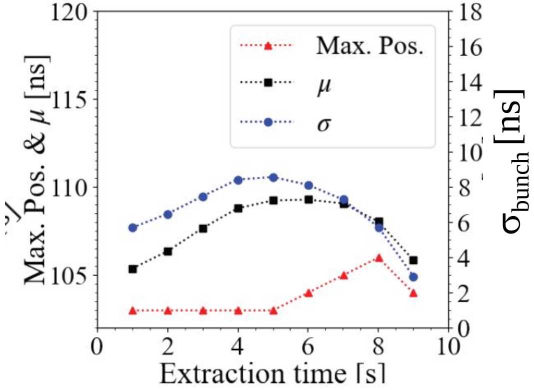
Analog and digital chain:



TDC: Caen V1290N time interval counter

- resolution σ_{rms}= 50 ps





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