Project HK-12
"Synchrotron Beam Measurement and Control"

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Novel DC Current Transformer for Synchrotrons and Storage Rings

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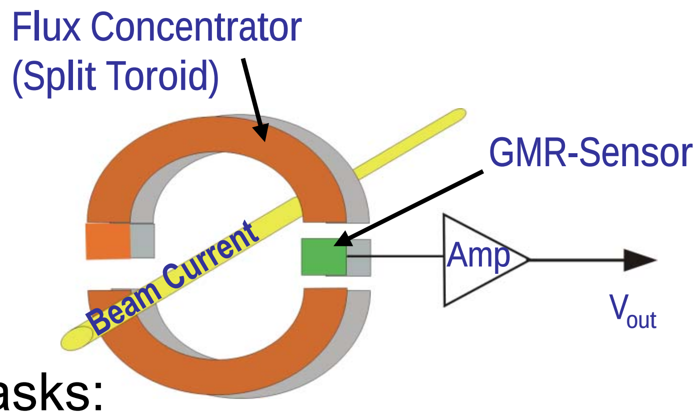
For non-intercepting measurement of beam intensity of the circulating ion beam a novel type of beam current transformer based on the GMR effect is foreseen for FAIR. First prototype studies have shown very promising results.

Measurement Principle



- idea: **clip-on Amperemeter** design
- **split toroid** to allow **dismounting** before bake-out
- soft-magnetic **flux concentrator**
- **gap** with induction of 80 µT @ 1 A beam current
- **sensitive GMR** (Giant Magneto Resistance) magnetic field sensor (resolution: 10^{-9} T/√Hz) → used for harddisks

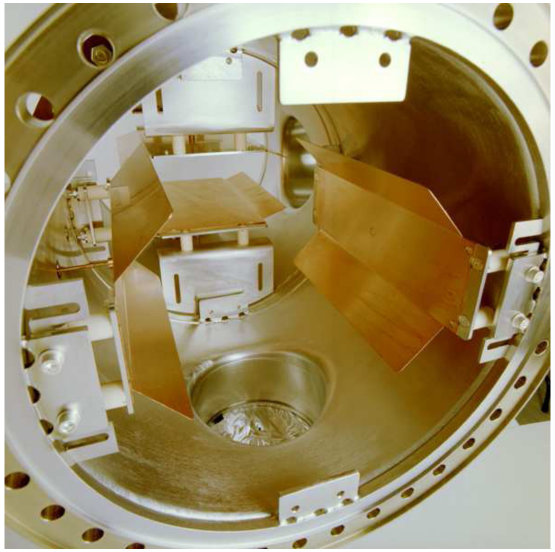
Tasks:

- Layout of enhanced setup: add single ACT-winding to core, add high-pass filtered ACT-branch to electronics (flux feedback loop)
- Development of first pcb prototype including AC- and DC-readout branch
- Optimizations regarding analogue bandwidth, sensitivity, loop cross-over
- Improvements of magnetic field sensor, e.g. use 2 GMR sensors (1 sensor per gap)
- Full system tests: testbench and prototype installation at beam line

High Bandwidth Schottky-Pickups (TUD – GSI)

The hadron synchrotron SIS100 at the FAIR facility requires a novel Schottky Pickup to measure tune and chromaticity at very high harmonics (h=1000) to achieve the needed precision and accuracy, e.g. to detect also space charge effects. Therefore the system has to fulfill the following requirements:

- A high bandwidth in the range of 10 MHz to 1.5 GHz
- The system has to work for low velocity as well as relativistic ions, i.e. different revolution frequencies
- Low noise signal path at room temperature for operational mode with small signal levels
- Second operational mode at high beam intensities near the space charge limit
- High dynamic range of relevant signals due to the different orders of magnitudes between the coherent signal and the Schottky signals



ESR Broadband Schottky Pickups at GSI. Courtesy: GSI

Goal: Development of a broadband, low noise pick-up geometry for tune measurements at frequencies of 10 MHz to 1.5 GHz as required for Schottky measurements at high harmonics (e.g. h=1000) for SIS100.

GSI and TU Darmstadt (TEMF)
Design of a High Bandwidth Schottky-Pickup

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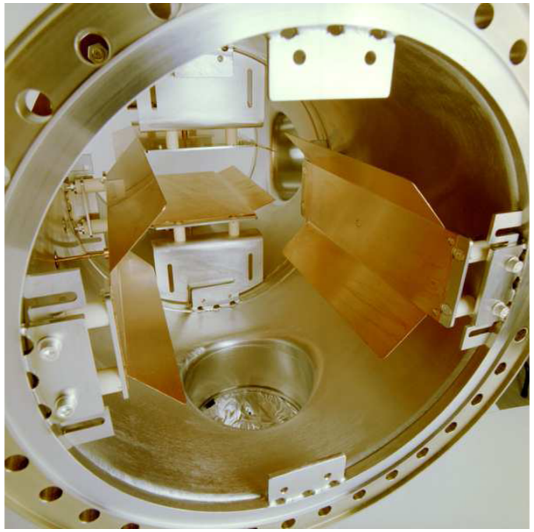
Schottky spectra allow for the extraction of

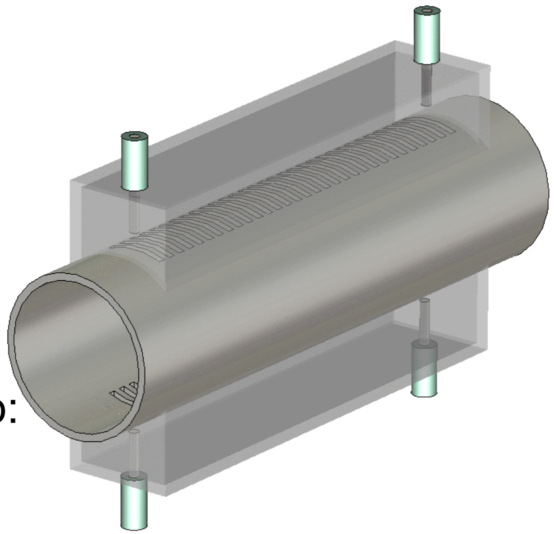
- tune
- chromaticity
- momentum spread

in a single measurement



ESR capacitive Schottky Pickups at GSI.

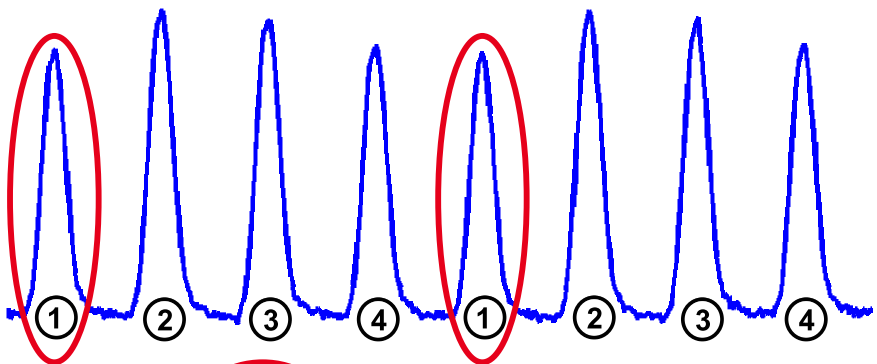
- Measuring high harmonics reduce/eliminate space charge driven signal deformation
- Extraction of bunch-by-bunch information requires high frequency observation
- This requires the design of a new pickup



High Bandwidth Schottky Pickup: e.g. ‘slotted waveguide’

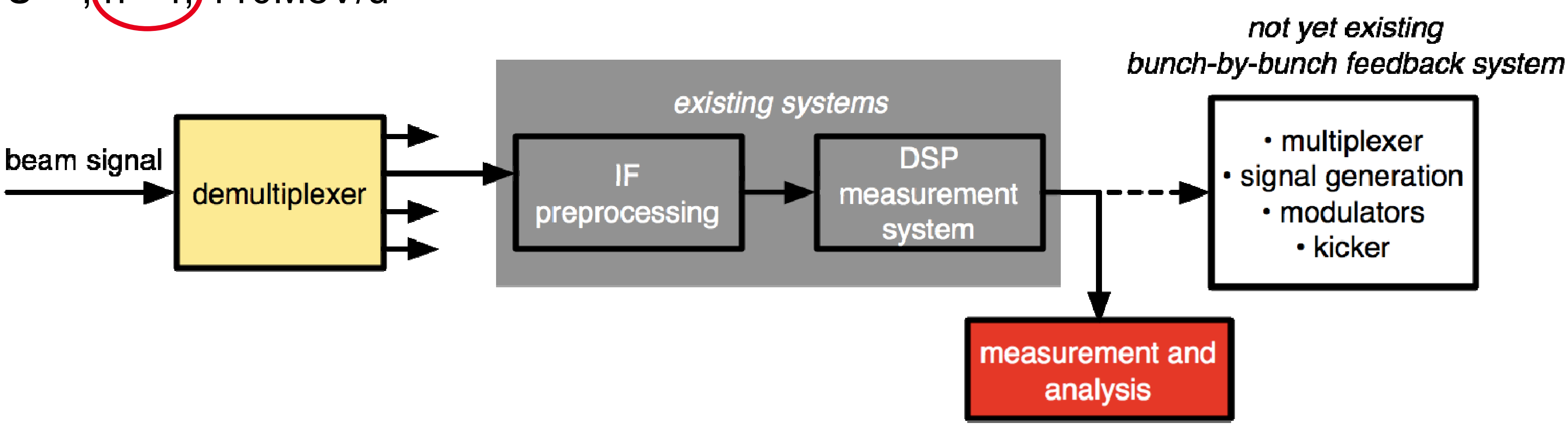
Bunch-by-Bunch Signal Processing

Measurement of Oscillation Modes



$^{238}U^{73+}$; h= 4; 110MeV/u

- Individual bunches show individual behavior
- Single-bunch processing needed
- De-multiplexing Fachgebiet Digital-technik, Uni Kassel
- Overall system design this task



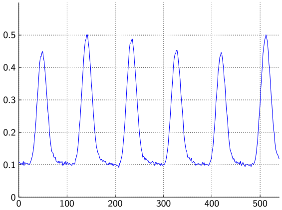
- Comparison lab setup ⇔ theory ⇔ beam experiment
- Bandwidth, dynamic range, detection of oscillation modes

Bunch-by-Bunch Signal Processing

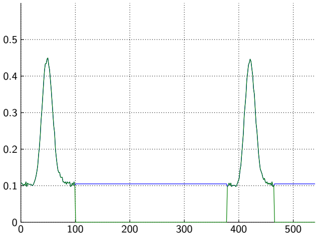
De-Multiplexing and Frequency Transform

- Bunch separation & frequency multiplication are needed for bunch-by-bunch feedback systems to damp longitudinal beam oscillations
- The current separation is done using fast analog switches leading to **unacceptable** DC-offset **errors**
- A frequency multiplication of signals with high frequency dynamic (several octaves) is hard to achieve with analog components
- Our approach: **Using FPGAs** for digital signal processing
- A hardware-optimized architecture for separation & frequency multiplication is still challenging: Our experiences from other projects can be applied to this problem

BPM Output signal:



Splitted BPM Output signal:
(blue with DC correction)



Automatic Scaling of Beam Signals for Feedback Systems

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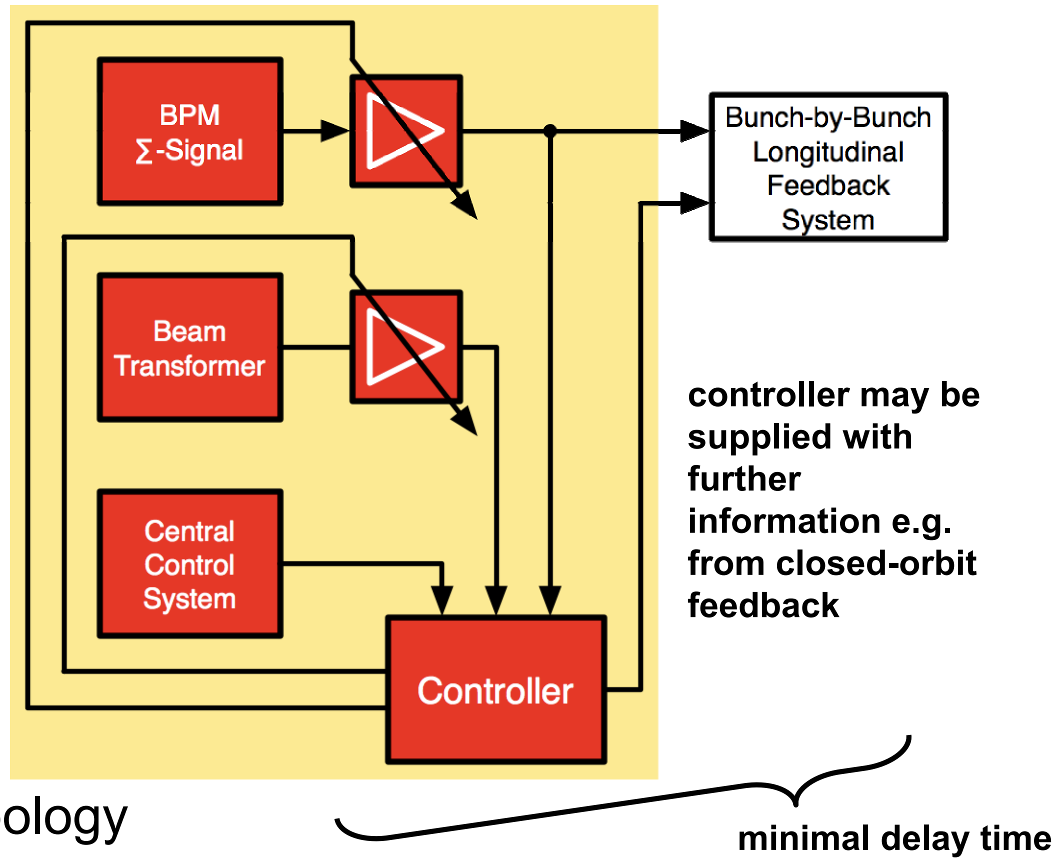
Challenges:

- Switching forbidden during system operation
- Prediction of beam current
- Suitable for all ion species, energies, operation modes
- Intensity fluctuations (e.g. depending on ion source)
- Support of virtual accelerators



Tasks:

- Concept
- Definition of modules, interfaces, topology
- Development of amplifier with digitally-controlled measurement range
- RF triggering for bunch identification
- Prototype Realization
- Test SIS18 (e.g. damping of coherent longitudinal mode n=0, m=2)

Digital Filtering for Feedback Systems

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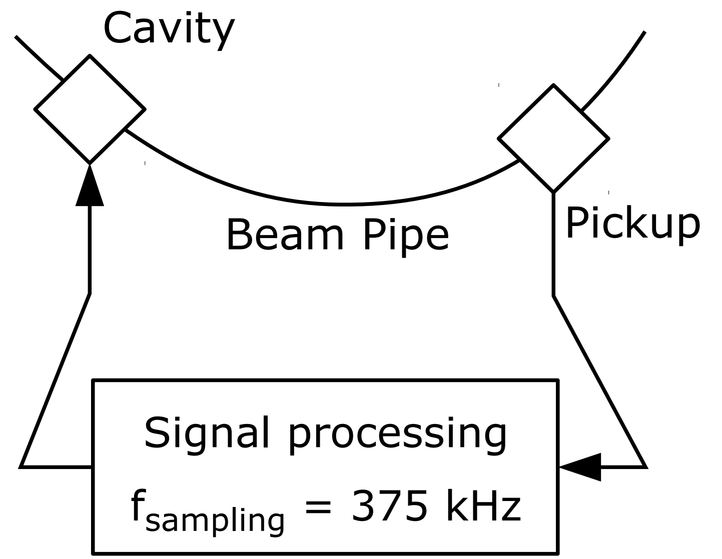
Beam-Phase Control (BPC)

- Usually continuous-time controller design [1], but:
- Interaction of RF control with longitudinal beam dynamics is an inherently discrete process [2]
- Digital filters and signal processing

Synthesis based on discrete-time system theory:

- Modeling of control loop with a discrete state-space approach including delays
- Pole-placement designs for linearized system
- Stability and robustness analysis



[1] D. Boussard: „Design of a ring RF system“, CAS CERN Accelerator School, 1992

[2] K. J. Åström, B. Wittenmark: Computer-Controlled Systems, Prentice Hall, 3rd ed., 1997

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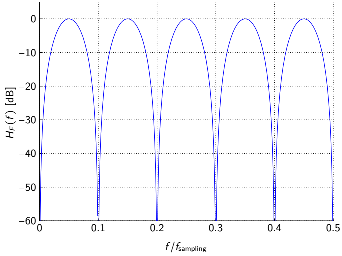
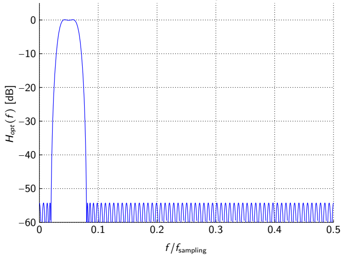
Frequency Variable Design

- One important Component in the digital beam-phase control (BPC) is a digital band-pass filter
- The center frequency must be variable (tracked to synchrotron frequency)
- This is challenging as the filter has to be redesigned online
- **Current** filter is **strongly simplified** to circumvent this problem
- An **improvement** of BPC for better filters is **needed**
- Methods for frequency adaption exist, but: Optimizations for efficient hardware architecture necessary
- Active research topic of digital technology group

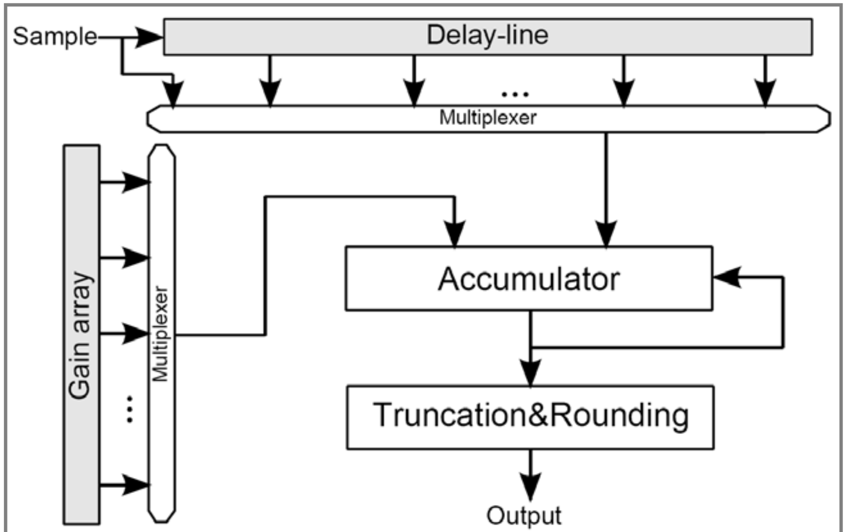
Current Filter Response:



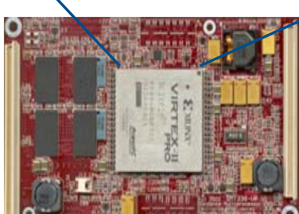
Desired Filter Response:



Digital Filtering for Feedback Systems



Generic filter architecture



Efficient hardware architectures

- Hard real-time constraints and high sampling rates necessitate a hardware implementation.
- Inherent parallel computation yields maximal performance.
- In close cooperation with the other groups involved in this project, **architecture-algorithm codesign** will lead to an optimal implementation
- Resource consumption will be minimized by providing just the right amount of flexibility and accuracy.
- Our research group has many years of experience in designing digital signal processing architectures.

Nonlinear Control Loop Theory for Damping of Sextupole Modes

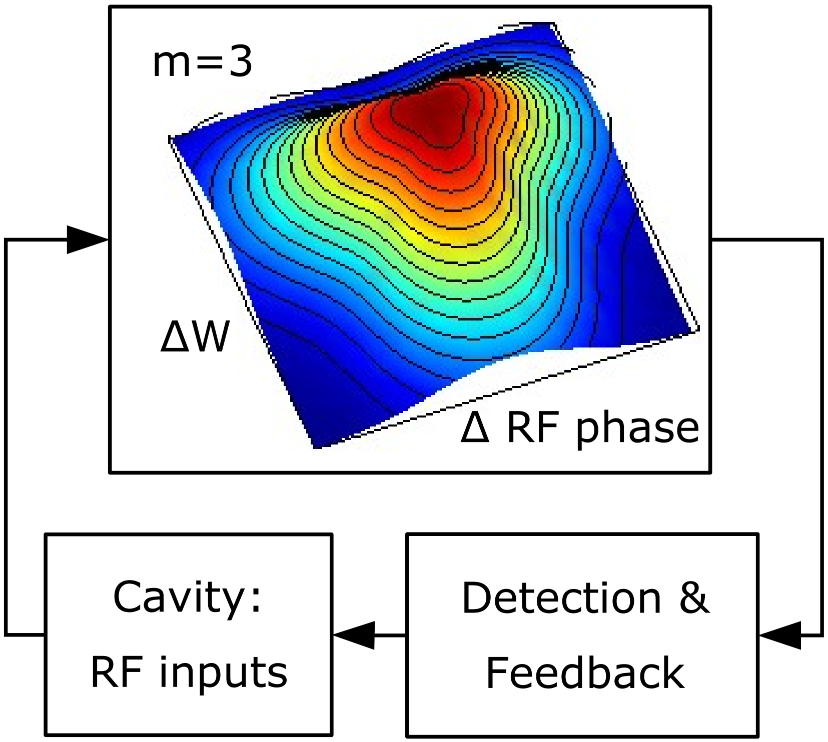
Longitudinal single bunch oscillations:

- Theory and proof of principle for dipole and quadrupole mode [1]
- Results indicate that sextupole mode behaves differently [2]

Goal:

- Modeling, analysis, and controller design with methods from control theory
- Design of feedback algorithms for damping of sextupole modes

Longitudinal phase plane



[1] M. Mehler et al.: Longitudinal Feedback Systems for FAIR, EU FP6 Design Study, Final Report, 2009

[2] H. Klingbeil et al.: „Modeling Longitudinal Oscillations of Bunched Beams in Synchrotrons“, Eprint arXiv:1011.3957

Influence of Empty Buckets on Control Loops

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SIS100: Effects of empty buckets

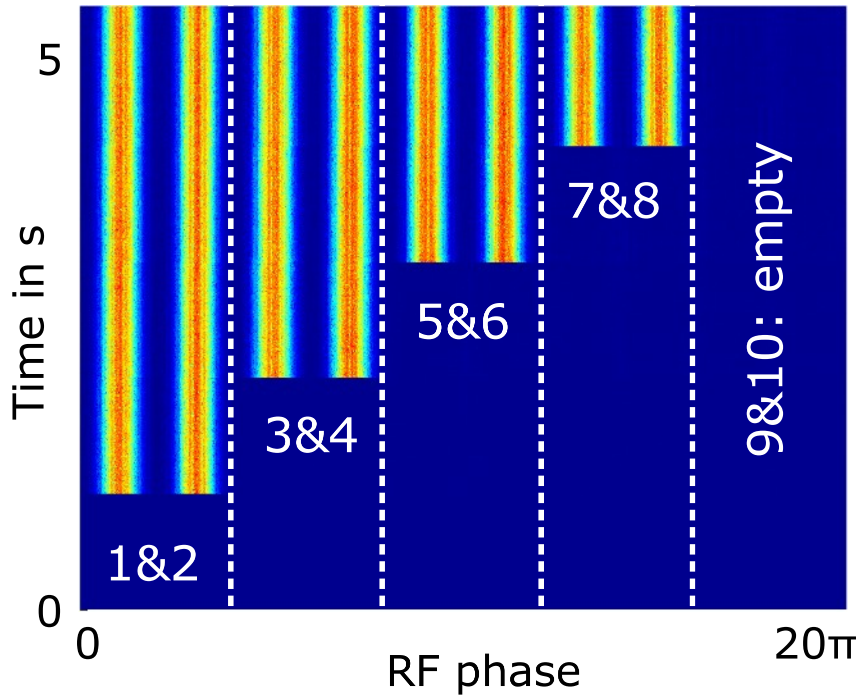
- Q of cavities too low to neglect higher harmonics (Robinson)
- Q too high to assume that induced voltages decay until next bunch arrives

Goal:

- Modeling of nested control loops, consider coupled-bunch oscillations
- Analyse effects of empty buckets on RF control loops including beam-loading
- Evaluate possible injection & ejection schemes for bucket filling

SIS100 simulation

RF feedback switched off

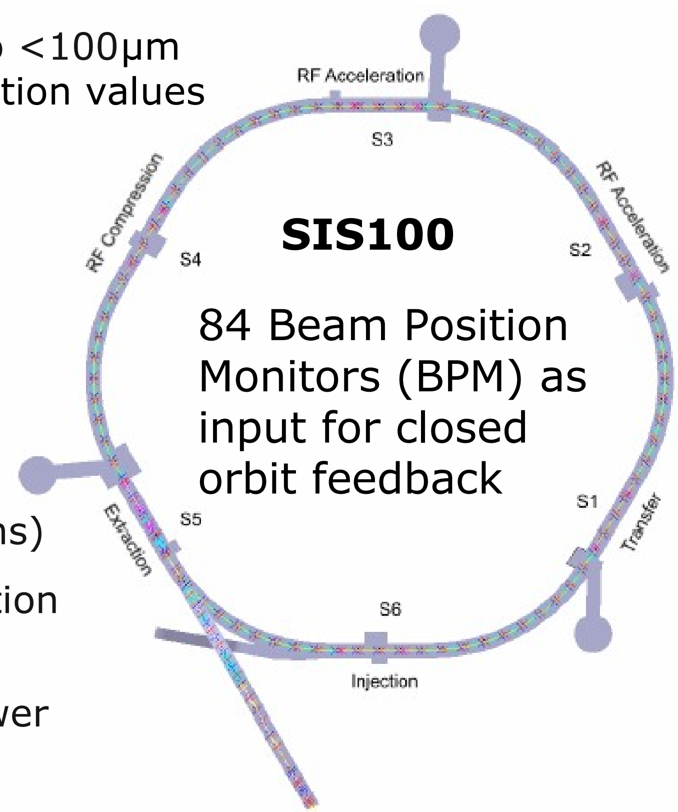


Closed Orbit Feedback for SIS100

Goal and requirements for FAIR synchrotron:

Fast (ms) closed orbit feedback system to stabilize beam to <100μm
Fully digital signal treatment for online calculation of correction values

- 84 BPMs along SIS100 for online position evaluation
- Reaction time of 10 ms for orbit feedback along 100 ms acceleration ramp
- Hardware concept foresees pure digital signal transport and FPGA-based calculation of corrector settings



Tasks:

- Modeling of control loop with quick response time (<10 ms)
- Implementation of optimized digital algorithm for calculation of corrector settings for SIS100
- Optimization of communication interfaces (controller, power supplies etc.) for low response time
- Installation, commisioning and beam tests of prototype setup at existing SIS18

GSI and TU Darmstadt (SPG)
Measurement of Oscillation Modes

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Subject

- Estimation of schottky spectra in real time with high resolution and extraction of tune, chromaticity and momentum spread

Challenges

- Consideration of device noise
- Consideration of signal deformation by space charge effects

Research

- Develop advanced signal procesing tools for high speed, large dynamic range of parameters and robustness

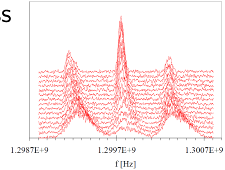

Figure: Recorded Schottky spectra at the GSI storage ring