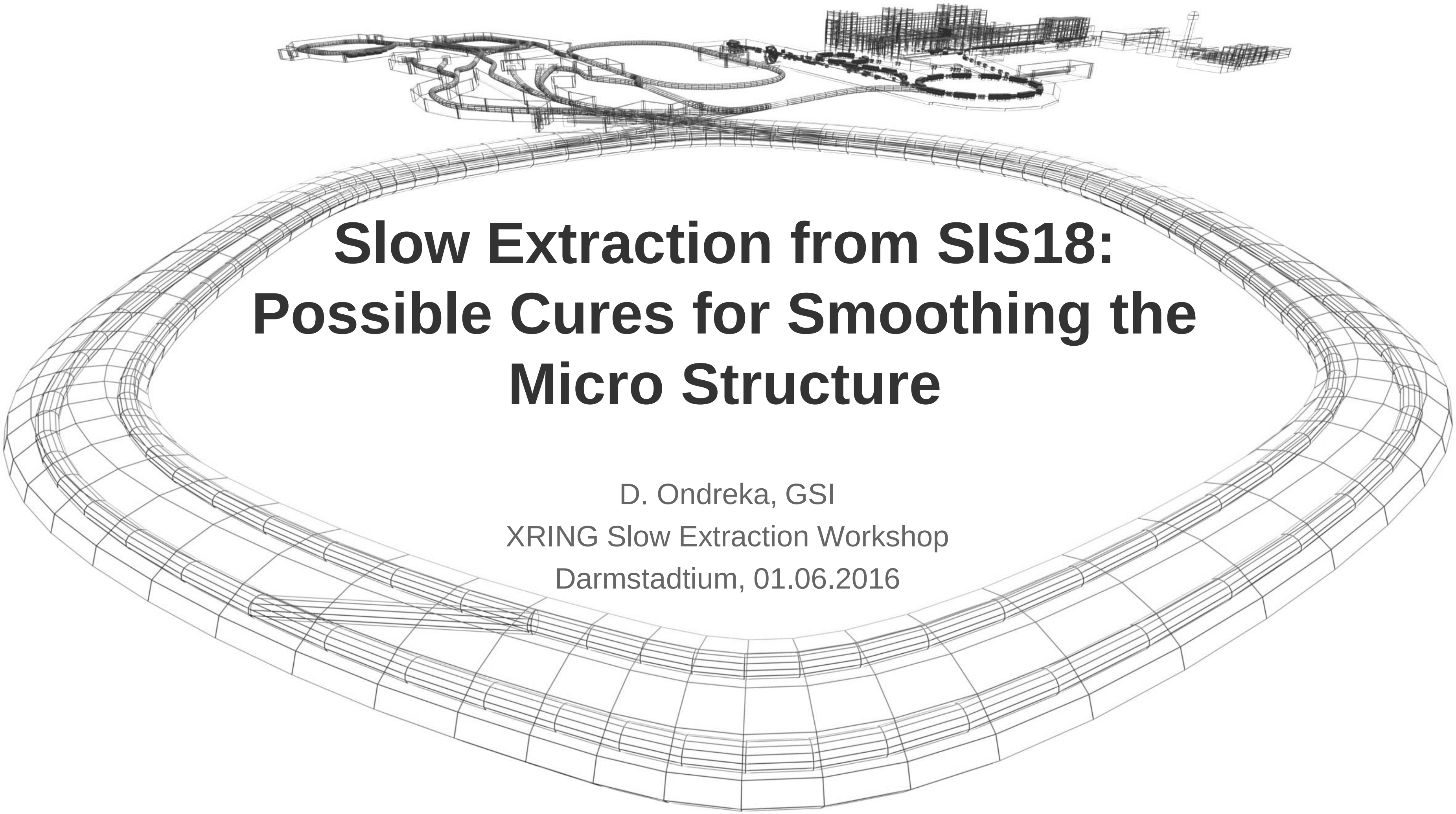


# Slow Extraction from SIS18: Possible Cures for Smoothing the Micro Structure

D. Ondreka, GSI

XRING Slow Extraction Workshop

Darmstadtium, 01.06.2016

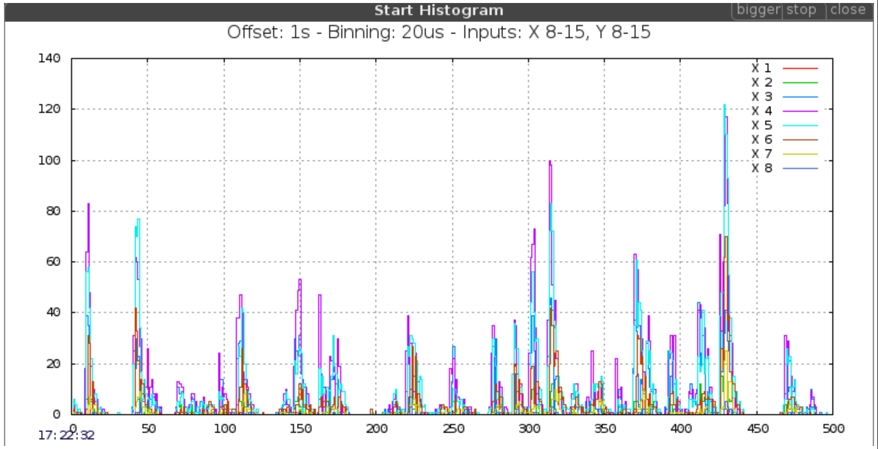
# Outline

- Introduction
- SIS18 layout and slow extraction
- Tune ripple and ripple sensitivity
- Ripple measurements at SIS18
- Ripple mitigation at SIS18
  - Spill feedback
  - Stochastic extraction
  - Bunched beam
- Ripple mitigation options for the future
  - High frequency cavity
- Roadmap
- Summary

# Introduction

- Experimentalists' requirements
  - Detectors with high time resolution suffer from pile-up due to spill structure at the kHz scale
  - Detector duty cycle reduced by factor three or more compared to optimum
  - There's a lot to be gained from improving the micro structure!
- Accelerator physicists' response
  - Workshop organized following MAC recommendation
  - Project for improving spill structure being established at GSI
  - Collection of available data
  - Machine experiments scheduled
  - Long-term strategy being developed

**SIS18 spill observed by HADES detector**



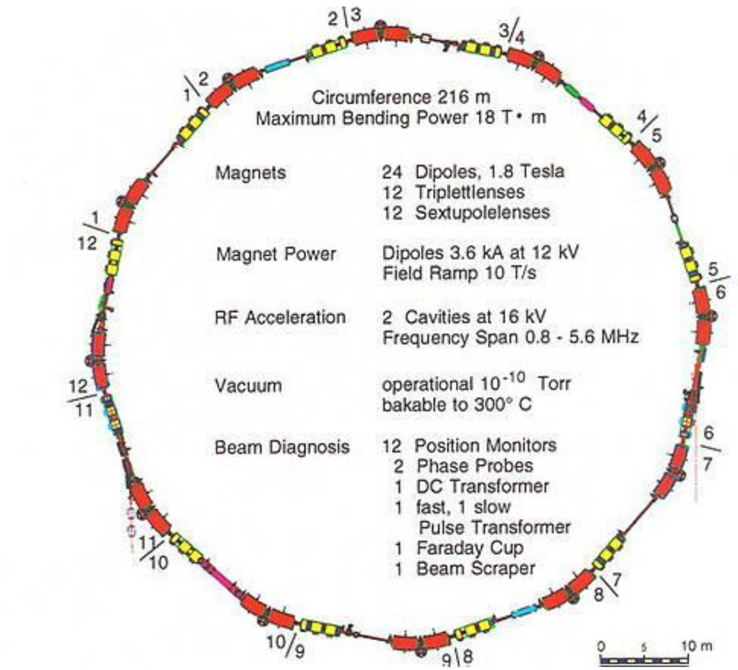

*J. Pietraszko, HIC4FAIR WS, 2016*

"The Committee encourages the project **to actively pursue efforts to improve the spill** and proposes to contact colleagues from other labs to discuss possible solutions and possibly **organise small workshops** on the topic. [...] There are a limited number of accelerators [...] using slow beam extraction and we risk losing expertise. Therefore proceedings from such a meeting would be useful not only for GSI, but for the community in general."

*FAIR MAC 15 Report, 2015*

# SIS18: Overview

- Basic parameters
  - Circumference 216m
  - Max. magn. rigidity 18Tm
  - Max. ramp rate 4T/s (10T/s)
- Ion optical layout
  - Super-periodicity 12 (6)
  - Triplet focusing at injection
  - Doublet focusing at extraction
  - Transition during ramp
- Working modes
  - Multi-turn injection (painting)
  - Slow extraction to fixed targets
  - Fast extraction to fixed targets or storage ring ESR
  - Optional electron cooling at inj.

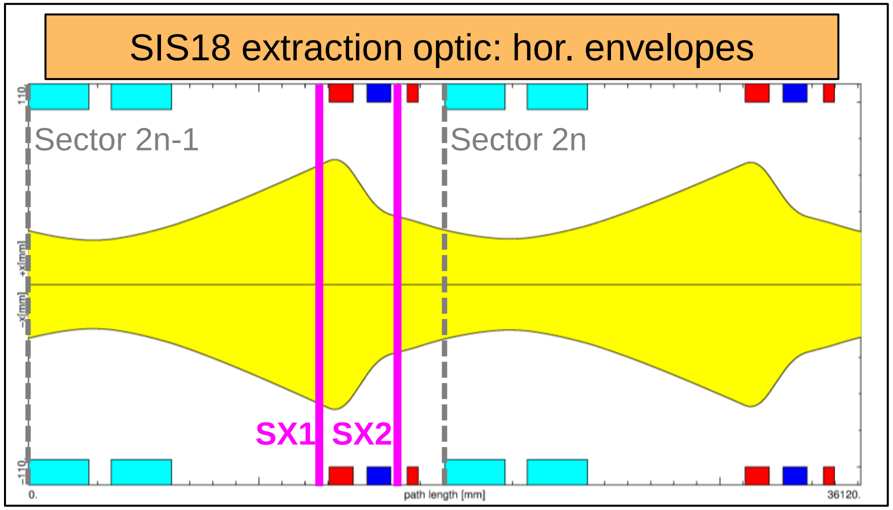


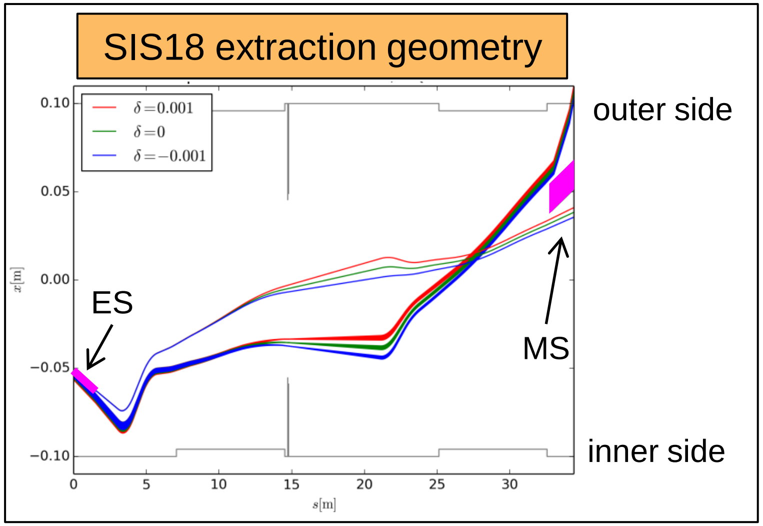

| SIS18 optical parameters | |
|---|---|
| $Q_h$ / $Q_v$ | 4.29 / 3.28 |
| $Q'_h$ / $Q'_v$ | -6.4 / -4.1 |
| $\alpha_p$ (inj. / ext.) | 0.042 / 0.032 |
| $\gamma_t$ (inj. / ext.) | 4.9 / 5.6 |

# SIS18: Slow Extraction Layout

- Devices for slow extraction
  - Twelve sextupoles for resonance excitation and chroma correction
  - Electrostatic wire septum (ES)
    - 1.5m long, 100µm W/Rh wires
    - max. 160kV @ 18mm gap
  - Magnetic septum (MS)
  - 2 fast quads for quad driven extr.
  - Hor. exciter for RF KO extr.

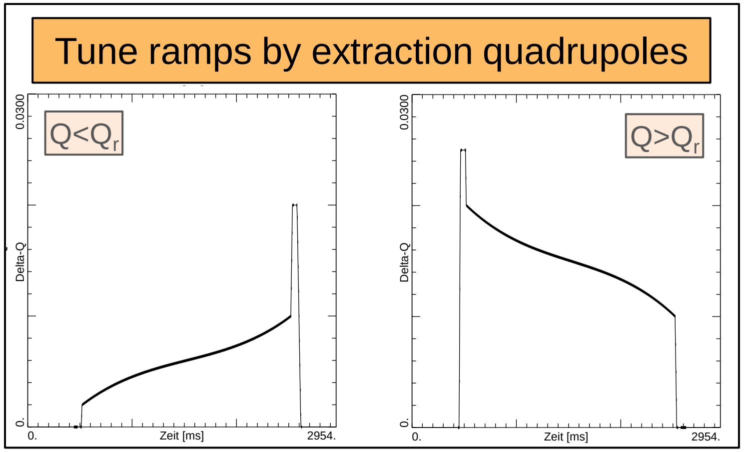
- Possible slow extraction modes
  - Quadrupole driven extraction
  - Transverse RF KO extraction
  - Both DC and bunched beams

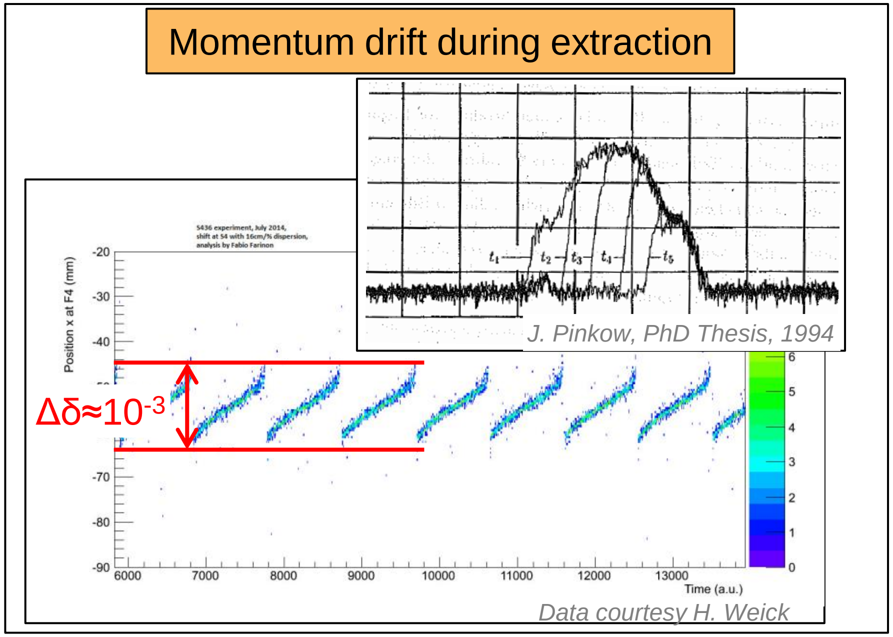


# SIS18: Standard Slow Extraction Scheme

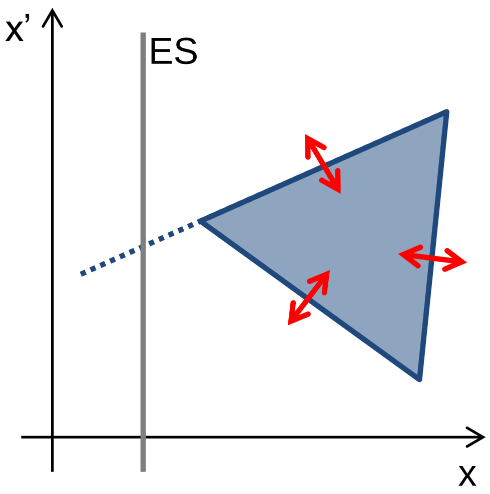
- Resonance conditions
  - Resonance tune $Q_r = 13/3$
  - Excitation by six sextupoles with harmonic distribution (ΔQ'=0)
  - Chromaticity uncorrected (Q'≈-6)
  - Two orbit bumps at ES and MS
- Quadrupole driven extraction
  - Below or above resonance by choice of extraction quad ramp
  - Momentum drift during extraction due to δ dependent separatrix size
  - Small instantaneous width of δ
  - Feature for some experiments
  - Trade-off with extraction efficiency



# Tune Ripple: Separatrix Fluctuations

- Avg. extraction rate characterized by effective tune change Q(t)
  - Real tune change for quadrupole driven extraction
  - Related to excitation strength for KO or stochastic extraction




- Tune ripple R(t)
  - Fluctuations of the separatrix' size
  - Extraction rate momentaneously reduced to zero if dQ/dt + dR/dt = 0
  - For harmonic ripple $R(t) = R_0\sin(\omega t)$ higher frequencies are more dangerous since dR/dt ~ ω

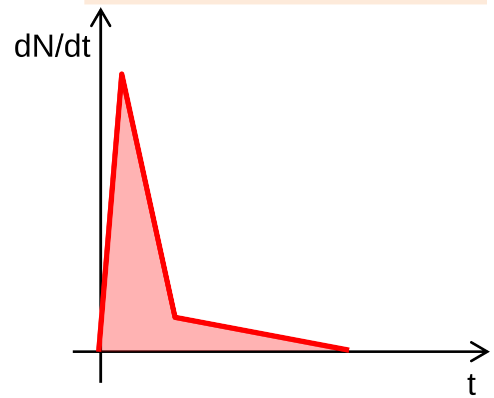
$$A(t) = 48\sqrt{3}\pi \frac{(Q(t) + R(t) - Q_r)^{2}}{S^2}$$

$$\frac{\dot{A}}{A} \approx 2\frac{\dot{Q} + \dot{R}}{Q - Q_r}$$

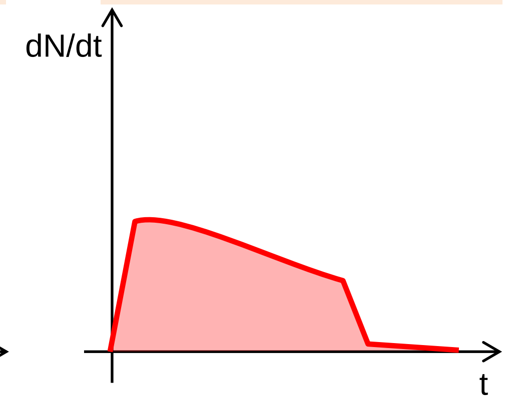
# Ripple Sensitivity: Chromaticity

- Zero chromaticity
  - Effect of ripple independent of δ
  - Extreme ripple sensitivity
- Non-zero chromaticity
  - Spikes smeared out due to different transit times to ES
  - Lower ripple sensitivity
  - Separatrix size depends on Q’
  - Increased losses at ES due to larger angular spread
- Hardt condition
  - Minimal losses due to δ independent angle of separatrix at ES
  - Typically implies low |Q’|, hence high sensitivity to ripples
- Trade-off between extraction efficiency and ripple insensitivity

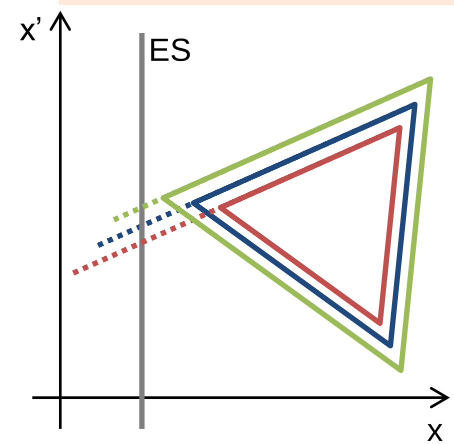
Ripple response (Q’=0)



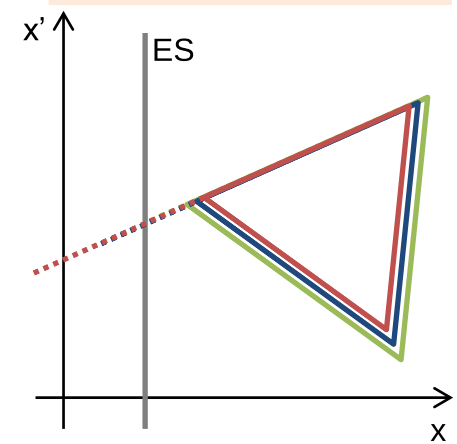

Ripple response (Q’≠0)




No Hardt condition




Hardt condition

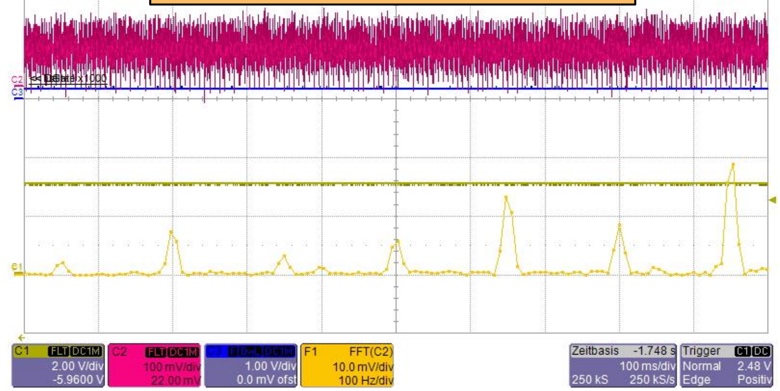



$$D\cos(\mu_0-\Delta\mu)+D'\sin(\mu_0-\Delta\mu)=-4\pi\frac{Q'}{S}$$

# Ripple Measurements: Power Converters

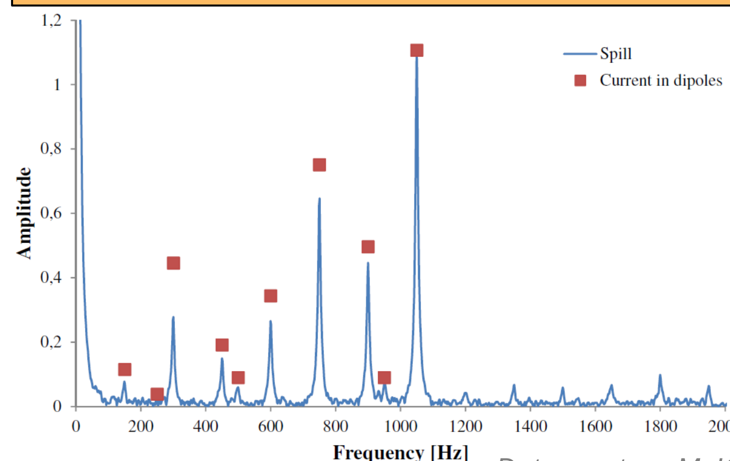
- Measurements on dipole and quadrupole power converters
  - Ripple on flattop
  - Amplitude quite small:
    $\Delta I/I < 10^{-5}$ for dipole, $< 10^{-6}$ for quads
  - No simultaneous measurement of spill
- Frequency spectrum shows peaks at multiples of 150Hz
- Simulations of spill ripple
  - Good correspondence of spill spectrum with PC spectrum when setting Hardt condition, BUT:
  - PC ripple seems too small to explain observed spill ripple
  - Without Hardt condition (standard) even smaller spill ripple

**Dipole PC ripple @Flattop**




*Data courtesy H. Welker/M. Kirk*

**Simulated spill ripple with Hardt condition**

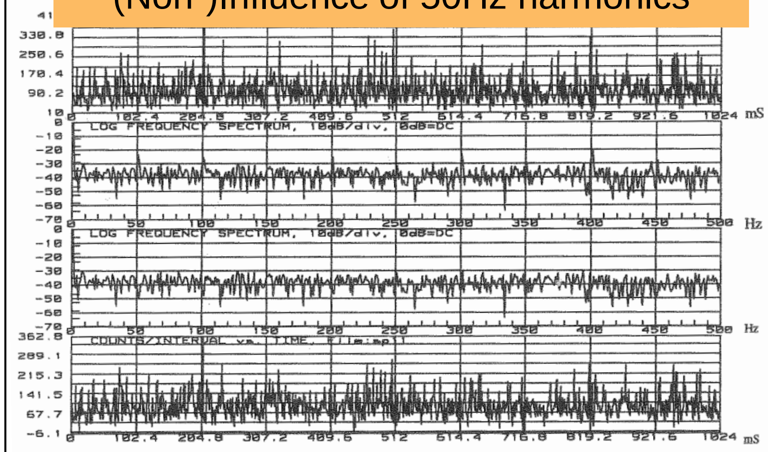



*Data courtesy M. Kirk*

# Ripple Measurements: Spill

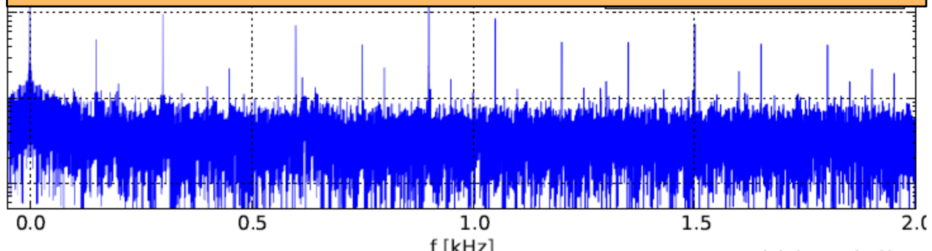
- Data on spill ripple measurements
  - From early 1990's only few reports
  - From more recent times (>year 2000) raw data in addition to reports available
  - No simultaneous measurements of PC ripple and spill ripple
- Results obtained so far
  - Harmonics of 50Hz grid frequency clearly visible in the spill spectrum
  - Spill ripple not dominated by the lines
- Conclusions
  - Observed spill ripple not explained by coherent PC ripple at 50Hz harmonics
  - Campaign initiated for simultaneous measurement of single PC and spill with artificial ripple

(Non-)Influence of 50Hz harmonics



*P. Moritz, 1994*

KO@HADES: Lines at harmonics of 150Hz

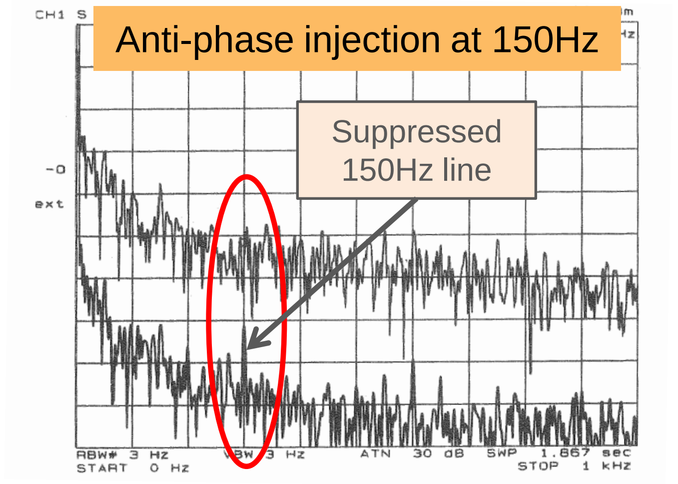



*Data courtesy M. Kirk/C. Kleffner*

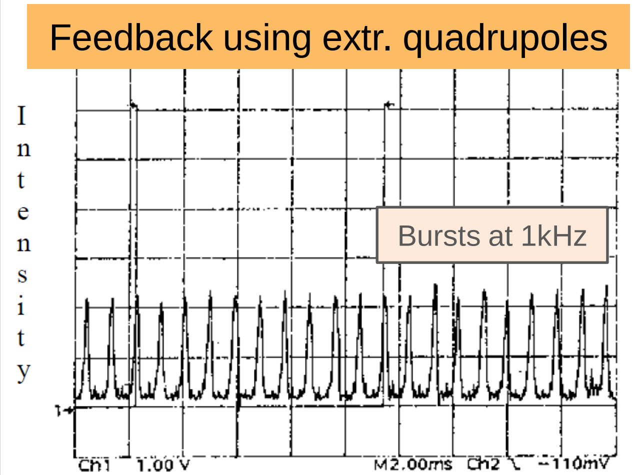
# Ripple Mitigation: Spill Feedback

- Studies in the 1990's
  - Line suppression by anti-phase injection at single frequency
  - Feedback on extr. quads leading to smooth spill below 1kHz
  - Bandwidth limited by transit time on the order of 100µs
  - Never used in routine operation

- Realization with KO extraction relatively simple
  - Well established at medical facilities (e.g. HIMAC or HIT)
  - For FAIR a standard for a real-time digital intensity signal provided by the experiments will be established
  - Bandwidth limitation by transit time limits the reduction of event pile-up



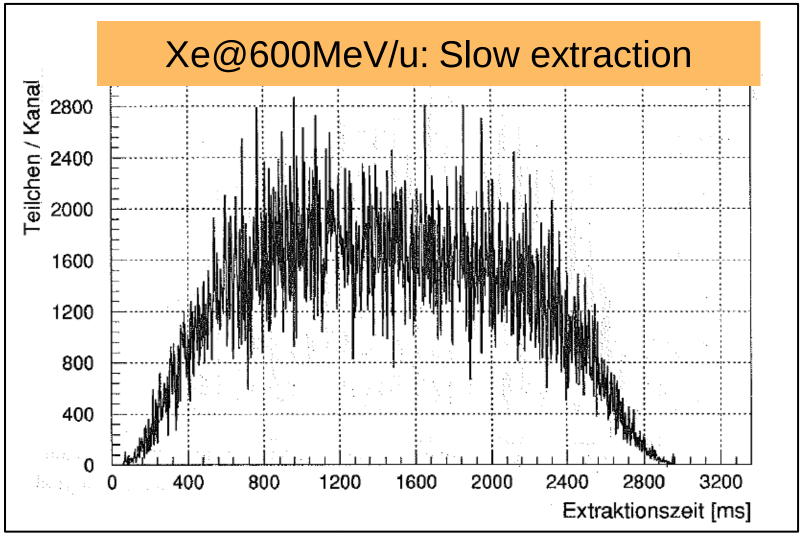
*P. Moritz, 1994*

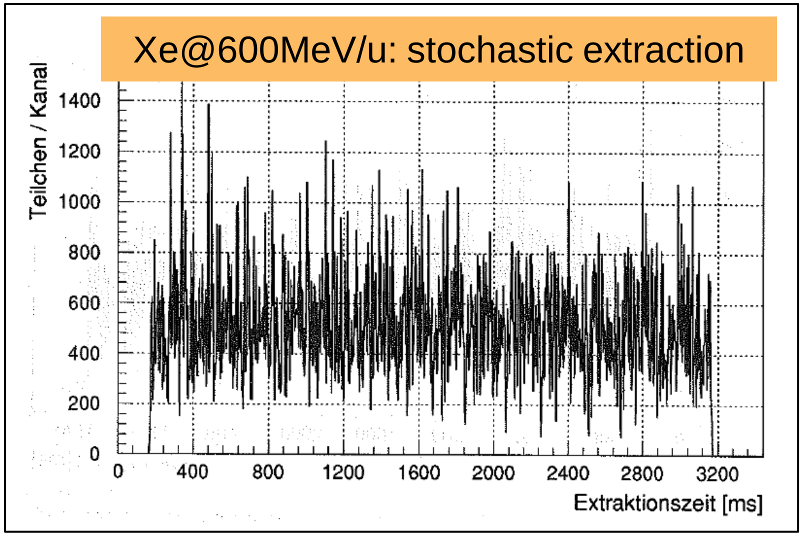


*U. Blell, 1996*

# Ripple Mitigation: Stochastic Extraction

- Beam driven into resonance by longitudinal excitation
  - Idea: higher dQ/dt for particles at stability limit
  - Supposed to be less sensitive to PC ripples by design
  - Small δ width of extracted beam
- Experimentally tested at SIS18 in the early 1990’s
  - No improvement of micro structure over slow extraction
  - Long shaping time
  - Never made operational at SIS18
  - Maybe room for improvements
  - High Q’ possible without affecting performance (unlike transverse RF KO)



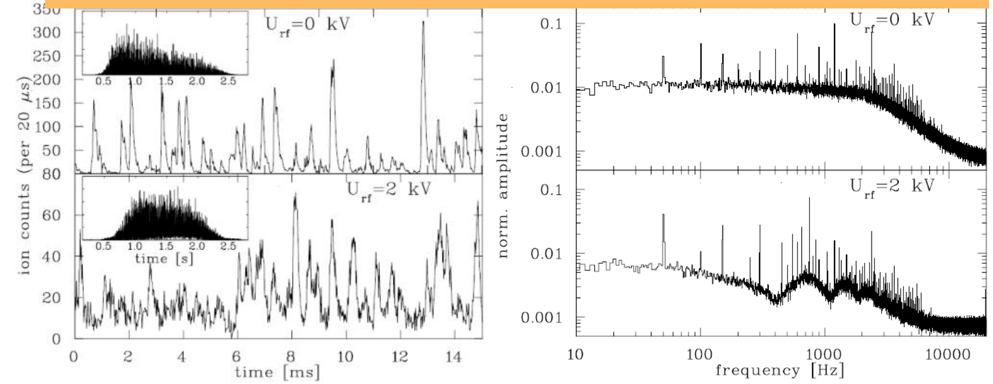




*J. Pinkow, PhD Thesis, 1994*

# Ripple Mitigation: Bunched Extraction

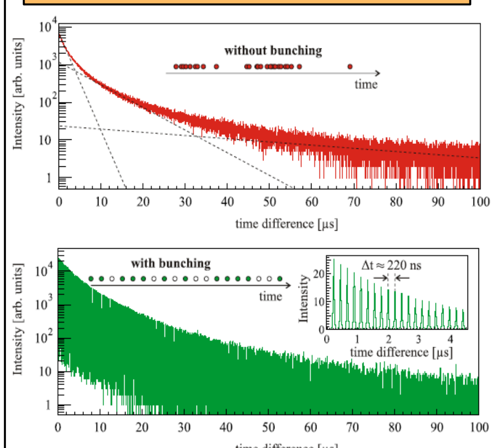
- Bunching at accel. harmonic (5MHz)
  - Smoothing effect due to synchrotron oscillation for large enough Q’
  - Broadening of sharp peaks in spill created by tune ripple
  - Extraction rate never reaches zero
- Experimentally verified at SIS18
  - Used extensively for therapy at GSI (also standard at HIT)
  - Works well for experiments with sufficiently long integration times
- Limited use for experiments with pile-up limited detectors
  - Still significant spill noise in kHz region
  - Particle clustering in very small time slices (10ns at 200ns repetition)
  - Would need bunching at >50MHz

**Spill structure of coasting and bunched beam in SIS18**



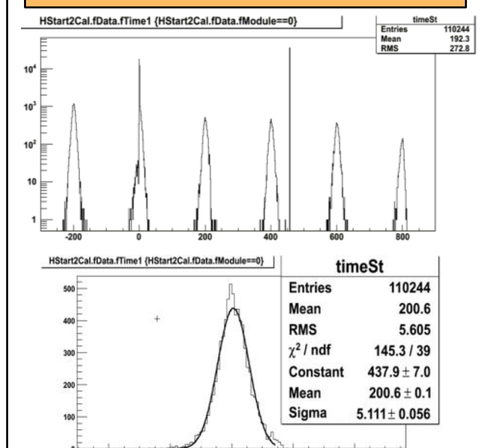

*P. Forck, 2000*

**Bunched extr. at FRS**




*C. Stahl, PhD Thesis, 2015*

**Bunched extr. at HADES**

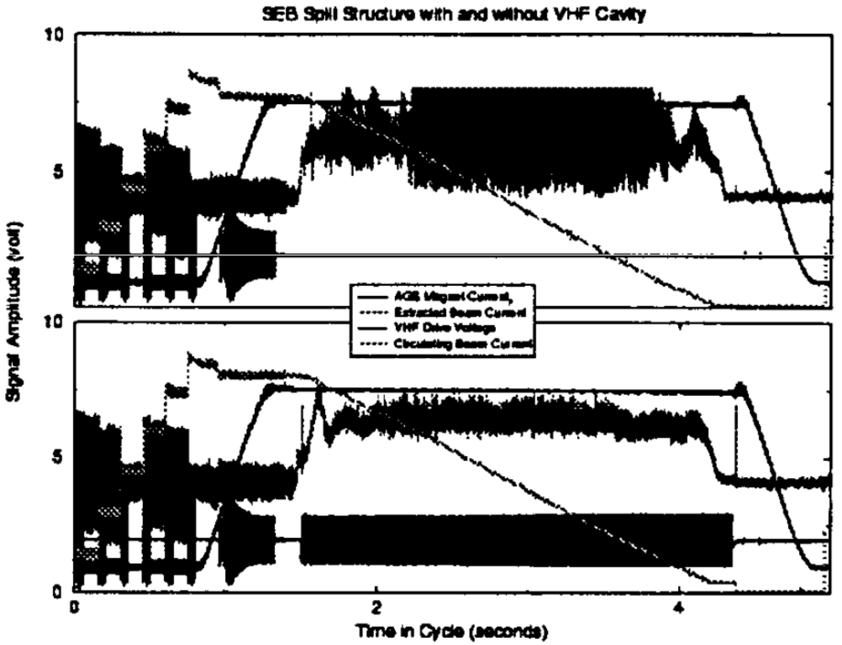



*Data courtesy W. König*

# Future Options: High Frequency Cavity

- Spill smoothing by extracting controlled bursts at high frequency
  - Empty bucket channeling
  - Creation of mini-bunches
- Bunched extraction at SIS18
  - Presently limited to 5 MHz
  - Insufficient for HADES and FRS
- Higher frequencies require new RF cavity (≥50MHz)
  - Theoretical studies for SIS18 necessary
  - Substantial R&D for HW required
  - Ring RF group is looking for a solution which might be available after 2018

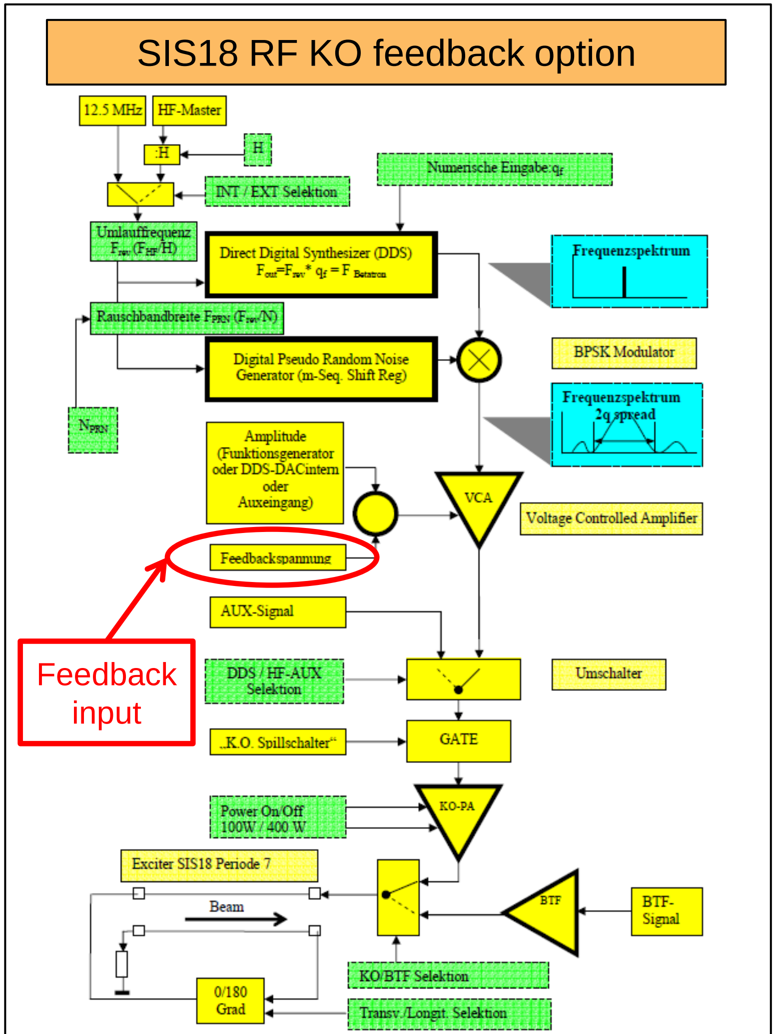
Improved spill at AGS with channeling




*K. Brown, BNL, 1999*

# Roadmap: Next Steps

- Machine experiments to find origin of spill ripples and possible mitigations
  - Simultaneous measurement of power converter and spill ripple
  - Comparison of quad driven and transverse RF KO extraction
  - Influence of chromaticity and resonance strength on ripple sensitivity
  - Inclusion of experimental detectors for spill analysis
- Development of an improved theoretical model
- Development of a prototype spill feedback using KO extraction

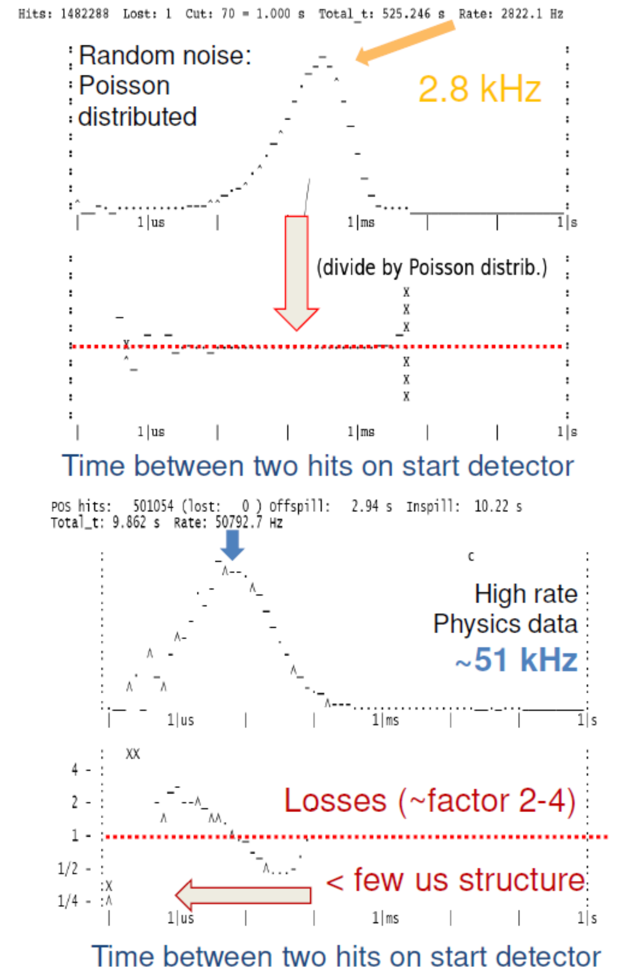


P. Moritz, 2005

# Road Map: Long Term Strategy

- Major problem pile-up
  - Spill ripple at frequencies below 3kHz reduces detector duty cycle
  - Deviations from expected Poisson distribution in time not understood
- Studies on origin of particle clustering
  - Very difficult to observe in the ring
  - Theoretical models required
    - Identification of possible mechanisms
    - Predictions for observables
  - Experiments to verify or refute certain mechanisms
- R&D for technical measures
  - Study of potential of a high frequency RF cavity for smoothing spill structure
  - Development of a prototype high frequency RF cavity

**Why do particles seem to cluster?**




*H. Simon, HIC4FAIR WS 2015*

# Summary

- SIS18 layout and standard slow extraction scheme presented
- Review of past results on spill structure and attempts at smoothing
  - No significant contribution of coherent power grid frequencies
  - Stochastic extraction does not improve the spill ripple
  - Bunched extraction (f<5MHz) does not solve the pile-up problem
  - Spill feedback up to kHz possible but limited by transit time
- Future options for ripple mitigation
  - Machine experiments to determine influence of power converters
  - Investigation of a high frequency cavity (f>50MHz) for spill smoothing
- Theoretical understanding has to be improved

# Thanks for your attention!

*I'd like to thank all colleagues who contributed material for this talk, consciously or unconsciously.*
*There are certainly many more than I mentioned, and I'd like to acknowledge their work.*