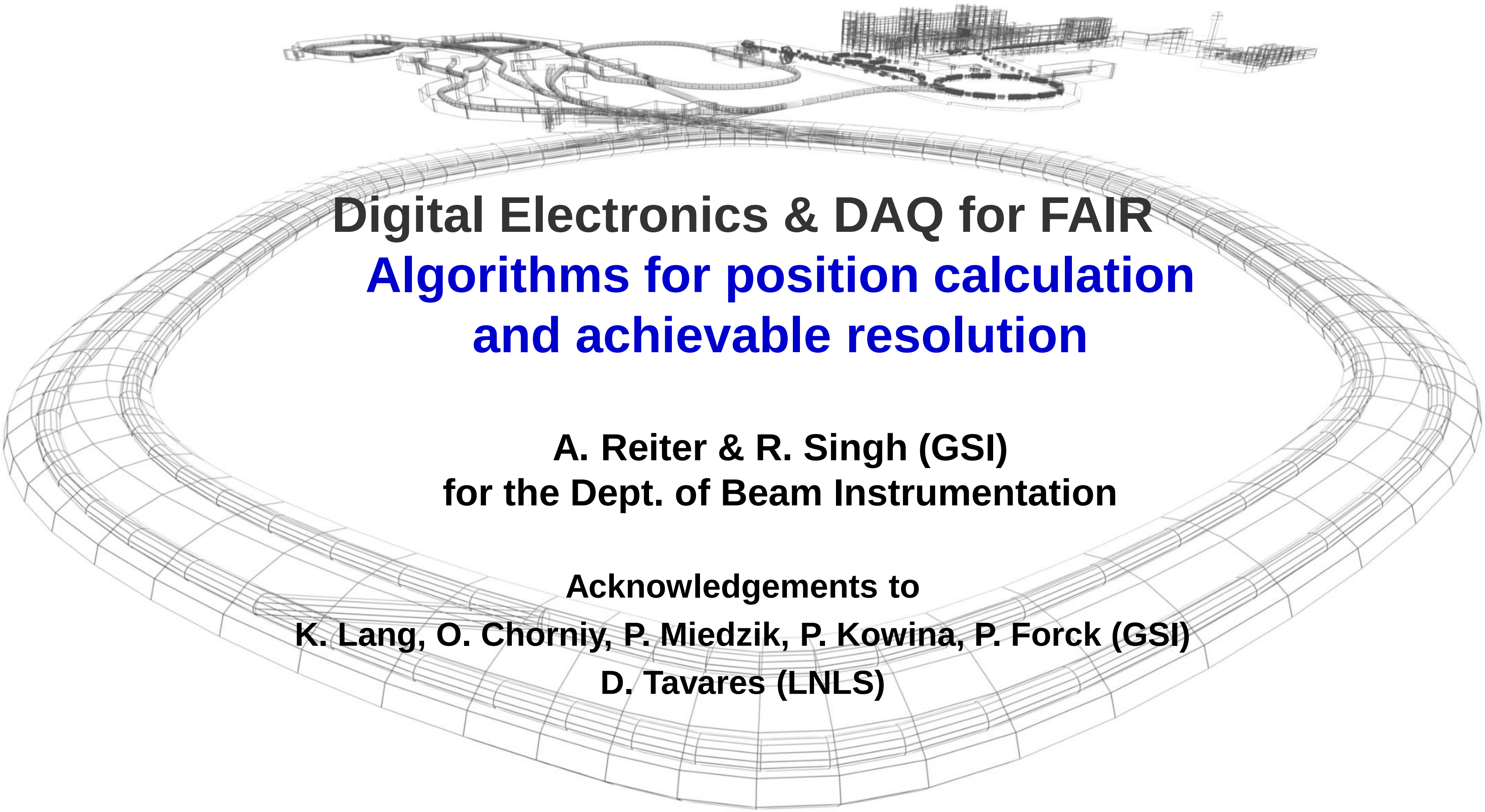
Joint ARIES Workshop on Electron and Hadron Synchrotrons
Barcelona, 12-14th November 2018



Digital Electronics & DAQ for FAIR

Algorithms for position calculation and achievable resolution

A. Reiter & R. Singh (GSI)
for the Dept. of Beam Instrumentation

Acknowledgements to
K. Lang, O. Chorniy, P. Miedzik, P. Kowina, P. Forck (GSI)
D. Tavares (LNLS)

Outline of talk

- Motivation
  - BPM systems at GSI & FAIR

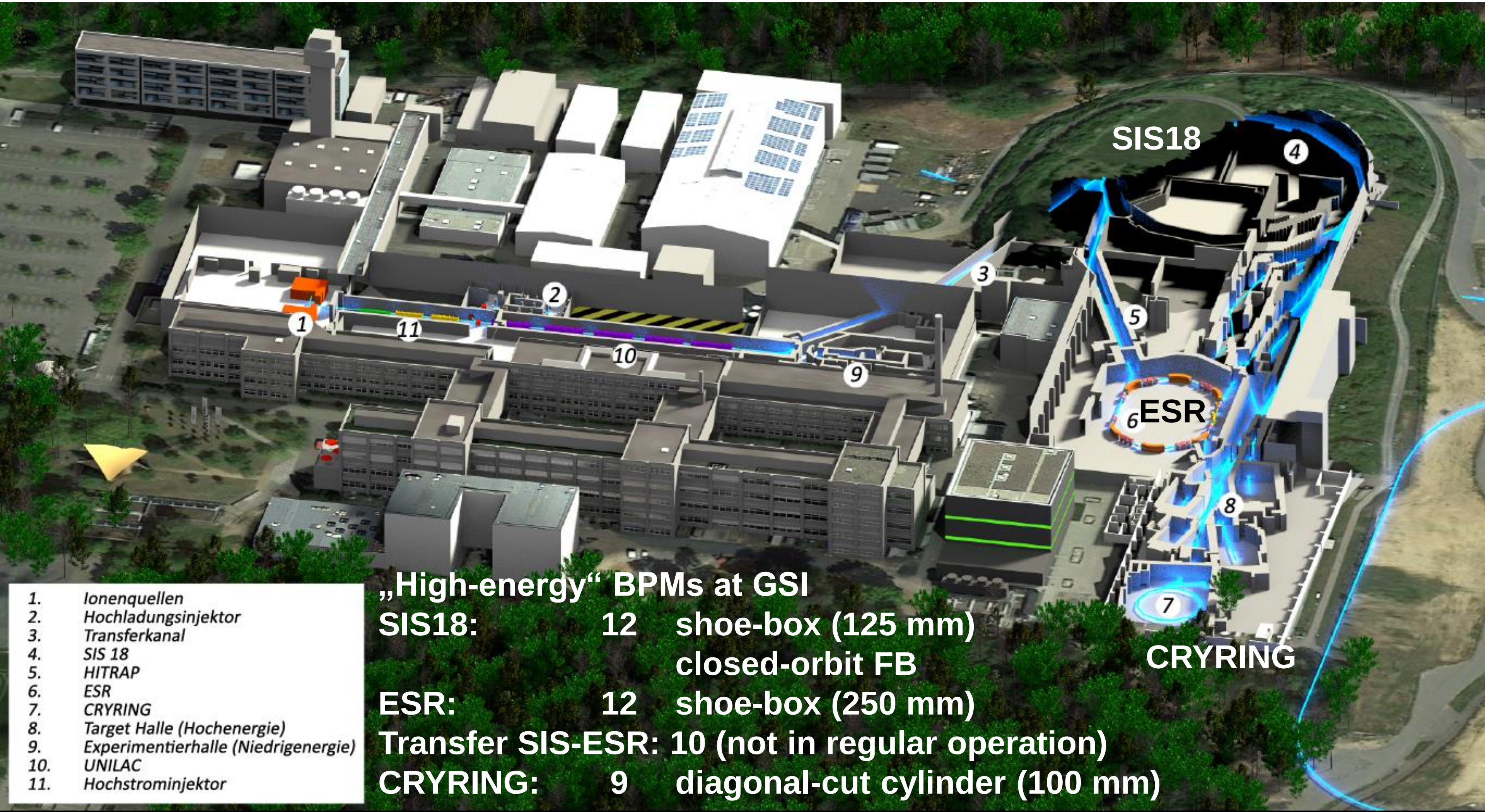
- Beam position in time-domain analysis
  - Asymmetry measurement (Δ/Σ)
  - Comparison of „classical“ estimators and least-squares fit of (Δ/Σ) tuples
  - Model prediction of position uncertainty

- Experimental verification: applications and tests
  - Bunch and orbit position uncertainty
  - Robustness of position and tune spectra
  - Multi-turn injection & coasting beam
  - Detour on electron machines: comparison to IQ demodulation

- Conclusion & Outlook

Motivation

BPM systems at GSI



1. Ionenquellen
2. Hochladungsinjektor
3. Transferkanal
4. SIS 18
5. HITRAP
6. ESR
7. CRYRING
8. Target Halle (Hochenergie)
9. Experimentierhalle (Niedrigenergie)
10. UNILAC
11. Hochstrominjektor

„High-energy“ BPMs at GSI

SIS18: 12 shoe-box (125 mm)
closed-orbit FB

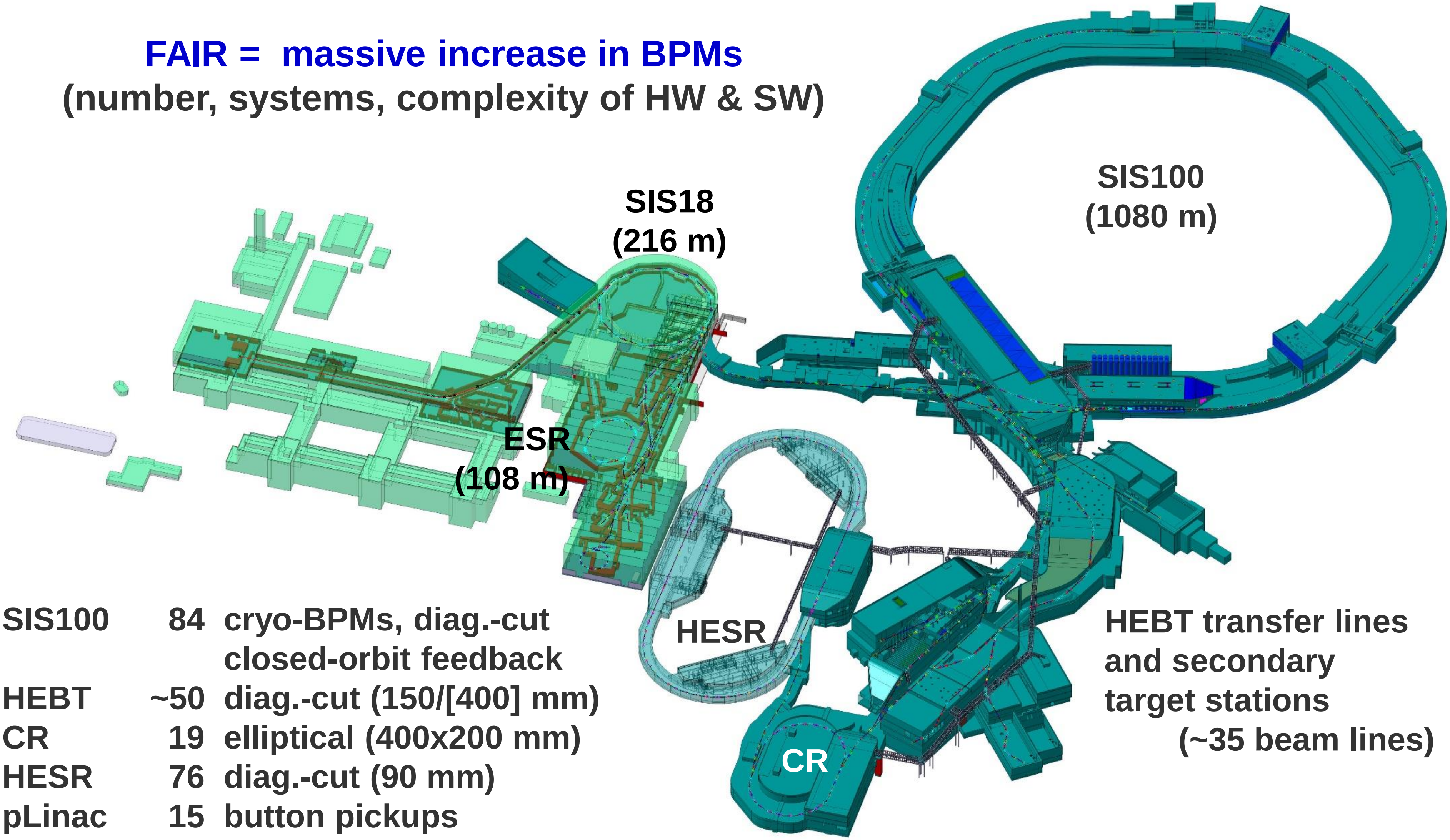
ESR: 12 shoe-box (250 mm)

Transfer SIS-ESR: 10 (not in regular operation)

CRYRING: 9 diagonal-cut cylinder (100 mm)

Motivation
BPM systems at FAIR

FAIR = massive increase in BPMs
(number, systems, complexity of HW & SW)



SIS100	84	cryo-BPMs, diag.-cut closed-orbit feedback
HEBT	~50	diag.-cut (150/[400] mm)
CR	19	elliptical (400x200 mm)
HESR	76	diag.-cut (90 mm)
pLinac	15	button pickups

HEBT transfer lines and secondary target stations (~35 beam lines)

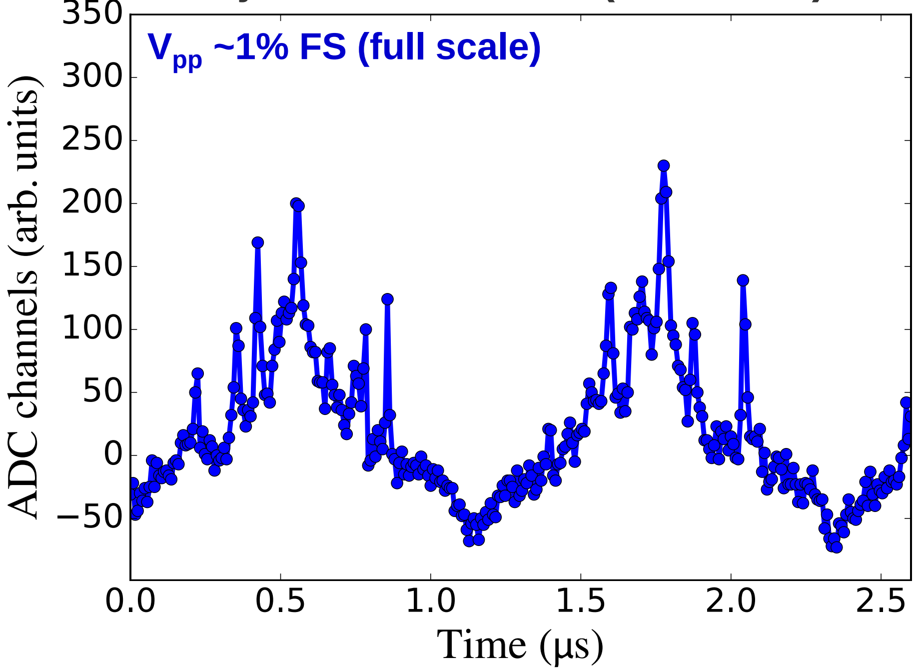
Motivation

Extremes of FAIR machines

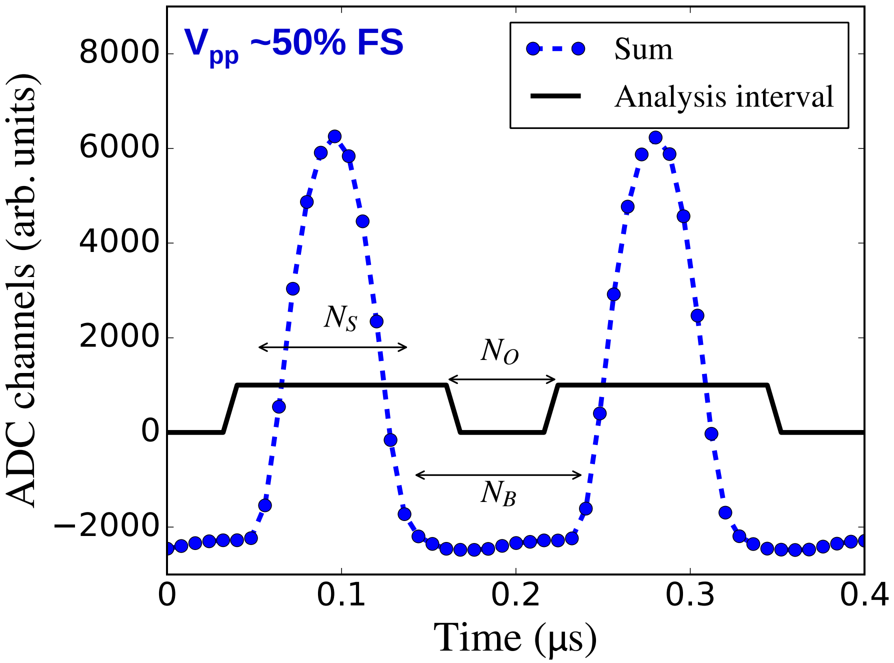
	SIS100 (100 Tm) pBar Production	**CRYRING (1.44 Tm) March 2018 test**
Beam	protons	Magnesium Mg^{1+}
No. of particles	2.5x10^{13}	~1x10$^{[6-8]}$
Energy	30 GeV	32 keV/u (max. energy)
Harmonic number	10 → 1	18
Pulse length	~500 – 50 ns	few µs
Electrode signal	~2000 Volt	µV – tens of mV
Front-end electronics	• 18:2 matching transformer • (-50 – 60) dB amplifier • BW = (0.04 – 7/55) MHz	• High-impedance +40/60 dB amplifier • BW = (0.01 – 4/40) MHz
Data acquisition	250 MSa/s ADC (± 1 Volt, 16 bit, ENOB= 12)	125 MSa/s ADC (± 1 Volt, 16 bit)
RF gymnastics	bunch merging & compression (SIS100), bunch rotation & stochastic cooling (CR), longitudinal slip stacking (HESR)	

Real signals from SIS18

- DAQ hardware : 125 MSa/s, 14 bit ADC, ENOB~10 (Libera Hadron Platform A)
- TOPOS system: integral with baseline restoration and dual-threshold detection



Injection mismatch (8.6 MeV/u)



After acceleration to 300 MeV/u

- Bunch quality differs strongly throughout cycle: Baseline restoration or bunch detection difficult or unreliable. Ideally, new analysis is independent of bunch shape.
- General question: How can we predict the uncertainty of a bunch or orbit position?

Approach of evaluation

BPM: symmetric detector sensing an asymmetry between signals $S_{\{L,R,T,B\}}$

many geometries with „linear“ and non-linear response to beam offsets

variety of algorithms and approaches

difference-over-sum (Δ/Σ)   logarithmic ratio   amplitude to phase conversion   …

most methods can be expressed as functions of (Δ/Σ)

R. Shafer, Beam position monitoring, AIP Conf. Proc. 249 (1992)

focus on asymmetry (Δ/Σ)

$$\mathrm{x} = (1/sX) \bullet \frac{f(S_R) - f(S_L)}{f(S_R) + f(S_L)} \quad \text{with sensitivity } s_X\ (\%/mm)$$

$f(S_R)$, $f(S_L)$ is the scalar result of a function *f( )*

operating on a set of data samples of right/left signal S_R / S_L

Approach of evaluation

Any function $f(c \bullet S) = c \bullet f(S)$ is eligible, even better: $f(c \bullet S + offset) = c \bullet f(S)$

But which candidate is „optimal“, at least for us?

peak value (S_{max}) integral after baseline restoration (INT) ……..

integral of absolute value |S| root-sum-square (RSS) standard deviation (STD)

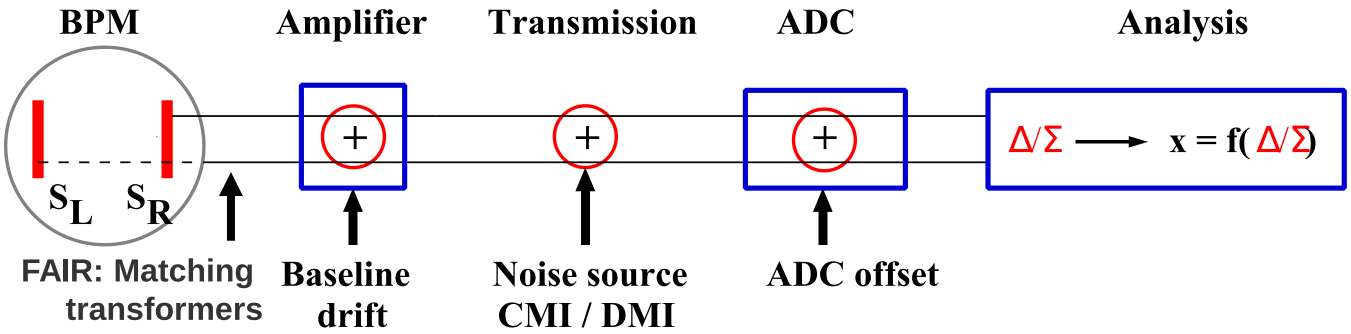
We overlooked STD initially !

define empirical requirements for “optimum” result

judge by robustness (behaviour, characteristics) & uncertainty

evaluate direct digitisation by a linear system in time-domain

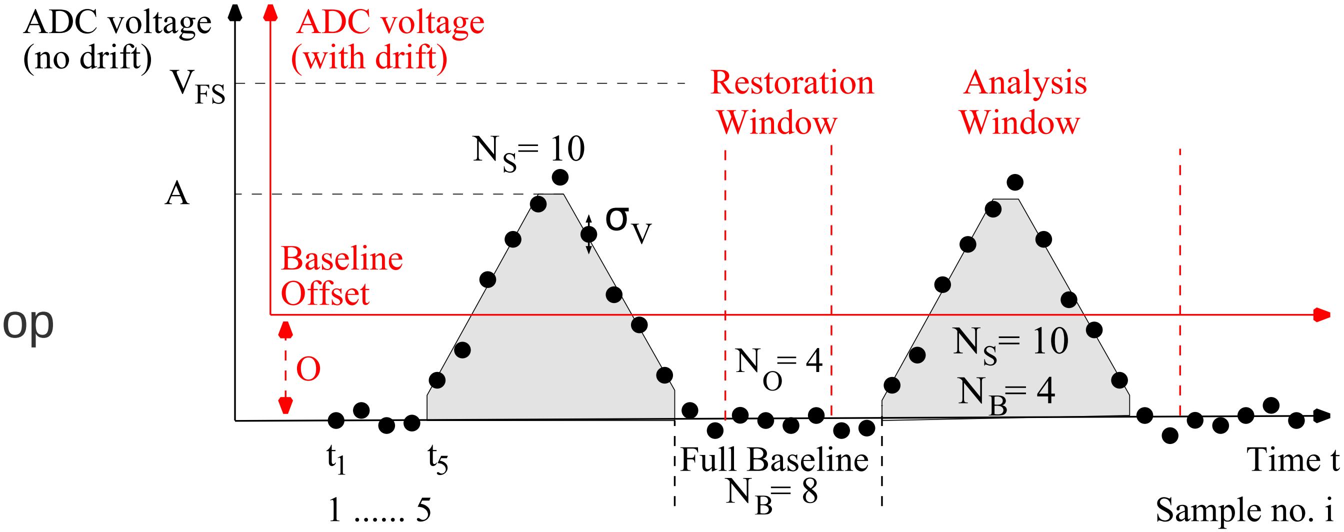
Synchrotron or beam line BPM (or linac button)



Time-domain model
“Classic” (Δ/Σ) approach

Statistical model: triangle (or square) of independent samples with uncertainty σ_V

Analytical calculation
- for arbitrary position
- with & w/o baseline droop
- for INT, RSS, STD



Position uncertainty of centred beam for

- integral with baseline restoration

$$\sigma_{INT} = \frac{1}{s} \frac{\sqrt{N + (N^2/N_O)}\ \sigma_V}{\sqrt{2}\ I} \qquad (N = N_S + N_B)$$

- root-sum-square (RSS=$\sqrt{\sum_i (S_i)^2}$)

$$\sigma_{RSS} = \frac{1}{s} \frac{\sigma_V}{\sqrt{2}\ RSS}$$

Uncertainty depends on offset / baseline droop!

- standard deviation (STD)

$$\sigma_{STD} = \frac{1}{s} \frac{\sigma_V}{\sqrt{2N}\ STD}$$

Time-domain model
Least-squares fit

Analytic evaluation of model signals in least-squares fit of (Δ,Σ) tuples

- position given by slope m, i.e. signal correlation
- uncertainty is a natural „by-product“
- Δ = m • Σ (direct proportion)

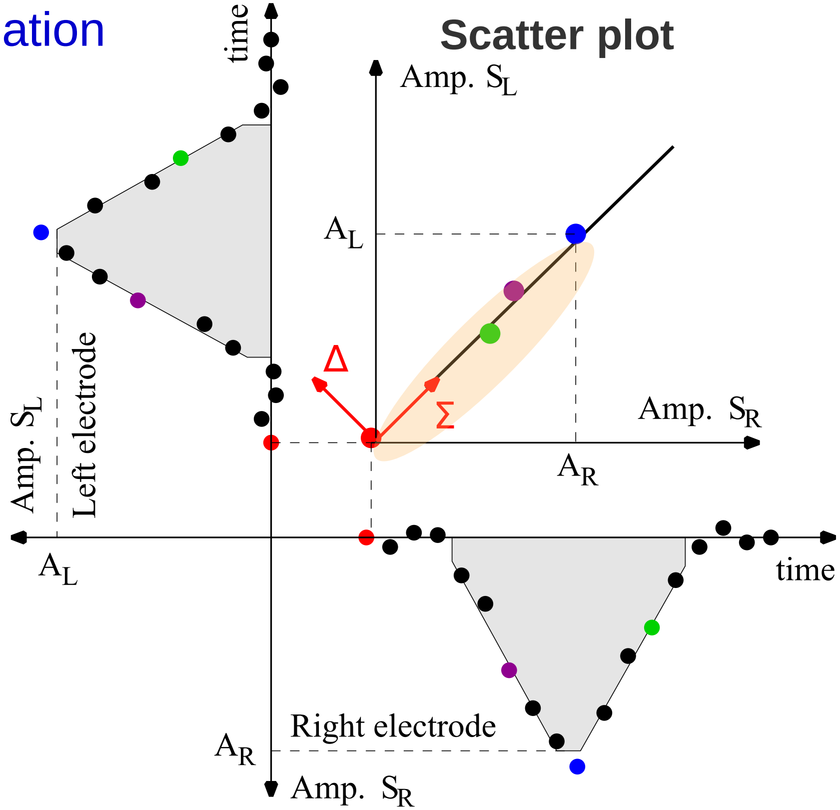
  ! note: $m = (x \bullet s)$!

  $$\langle m \rangle = \frac{\overline{\Delta \bullet \Sigma}}{\overline{\Sigma^2}} \qquad \sigma^2_{\langle m \rangle} = \frac{\sigma^2_{\Delta}}{N\ \overline{\Sigma^2}}$$

- Δ = m • Σ + c (straight-line)

  $$\langle m \rangle = \frac{cov(\Delta, \Sigma)}{\sigma^2_{\Sigma}} \qquad \sigma^2_{\langle m \rangle} = \frac{\sigma^2_{\Delta}}{N\ \sigma^2_{\Sigma}}$$

  $$\langle c \rangle = \bar{\Delta} - \langle m \rangle\, \bar{\Sigma}$$



Result:

- Integral with baseline restoration: $\langle c \rangle = 0 \Rightarrow \langle m \rangle = \bar{\Delta}/\bar{\Sigma}$
- For centred beams, uncertainties are identical to those of classical approach,

e.g. for direct proportion: $\sigma^2_{\langle m \rangle} = \frac{\sigma^2_{\Delta}}{N\ \overline{\Sigma^2}} = \frac{\sigma^2_{\Delta}}{\sum(\Sigma_i)^2} = \frac{2\,\sigma^2_V}{\sum(2\,S_i)^2} = \frac{\sigma^2_V}{2\,RSS^2} = (s \bullet \sigma)^2_{RSS}$

Time-domain model

Analysis properties

Facility for Antiproton
and Ion Research in Europe

Classical approach	Integral	RSS	STD
Least-squares	**constrained fit**	**direct proportion**	**straight line**
Coordinate system	absolute	absolute	**relative / floating**
Position weight	Σ	Σ^2	$(\Sigma - \bar{\Sigma})^2$
Need for			
- baseline restoration	yes	no	no
- ADC zero adjustment	no	yes	no
Tolerance to			
- AC coupling (baseline droop)	no	yes	yes
- random offsets	no	no	yes
- low-frequency distortion (for small amplitudes)	no	no	$v < 10\frac{MHz}{N}$ (rough rule of thumb)

Time-domain model
Achievable resolution

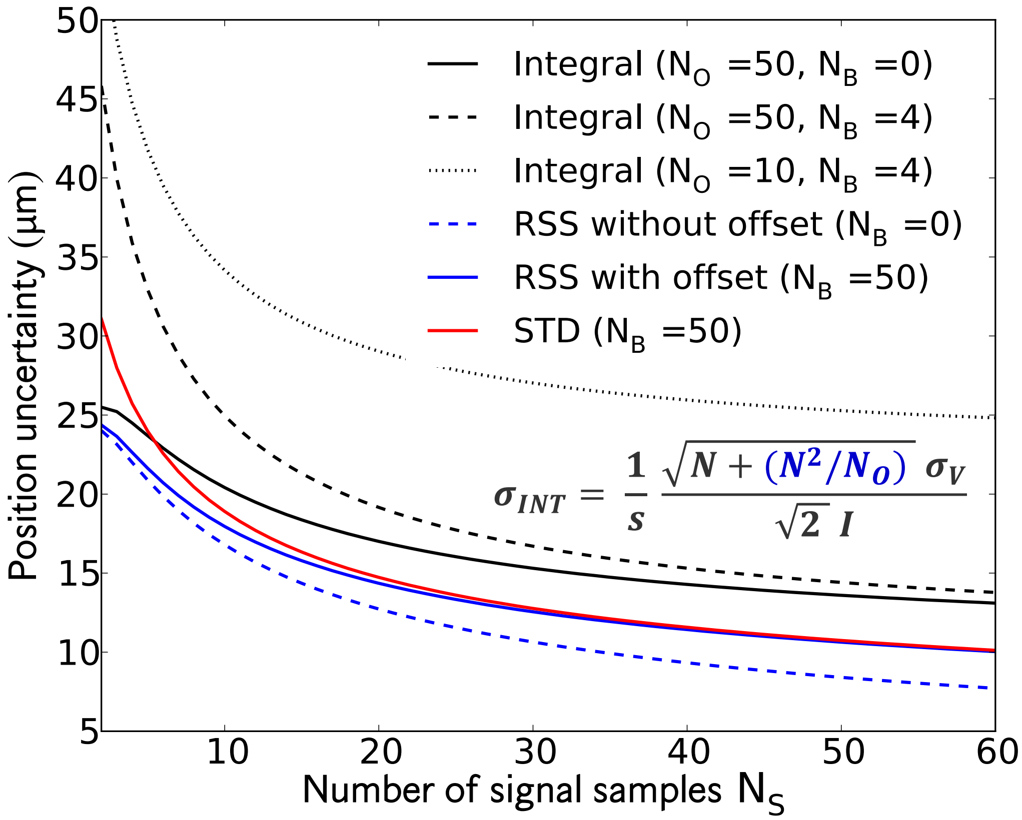
- Uncertainty comparison for centred, triangular pulse
- Example: straight-line fit

$$\sigma_{<m>} = \sqrt{\frac{3}{2}}\left(\frac{\sigma_V}{A\,V_{FS}}\right)\sqrt{\frac{(N_S+N_B)}{(N_S+2)\,(\frac{1}{4}N_S+N_B)}}$$

- Analysis parameters
  - no. of signal samples N_S
  - no. of baseline samples N_B

- SIS18 hardware parameters
  - noise σ_V = 1 mV
  - full scale V_{FS} = 2 Volt
  - signal amplitude A = 0.5 FS
  - sensitivity s_V = 2 (%/mm)

  equiv. to diag.-cut cylinder (s = 1/r) of r = 50 mm radius



FAIR: 250 MSa/s is sufficient for smallest 50 ns pulse length, yielding ~13 samples (requirement $\sigma_{x/y}$< 0.1 mm)

Uncertainty comparison

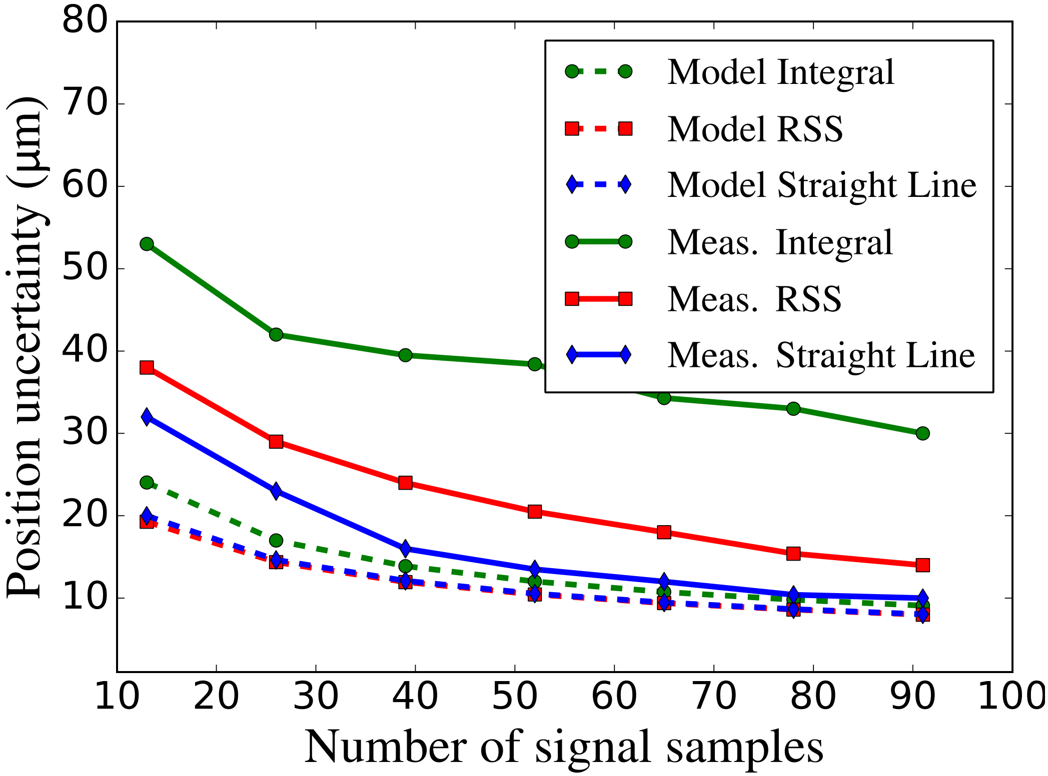
Experiment conditions

- Data taken after acceleration to 300 MeV/u
- Vertical BPM: pulse shape (N_S~13) as in slide 8 (A= 0.5), sensitivity s_V = 2 (%/mm)
- Analysis: Include increasing number of bunches to statistically simulate larger number of signal samples, for a case where expected uncertainties are similar

Result

- Simple model seems to provide reasonable estimates
- Only straight-line fit approaches theoretical limit for N_S >40
- σ_y(short bunch) < 0.05 mm

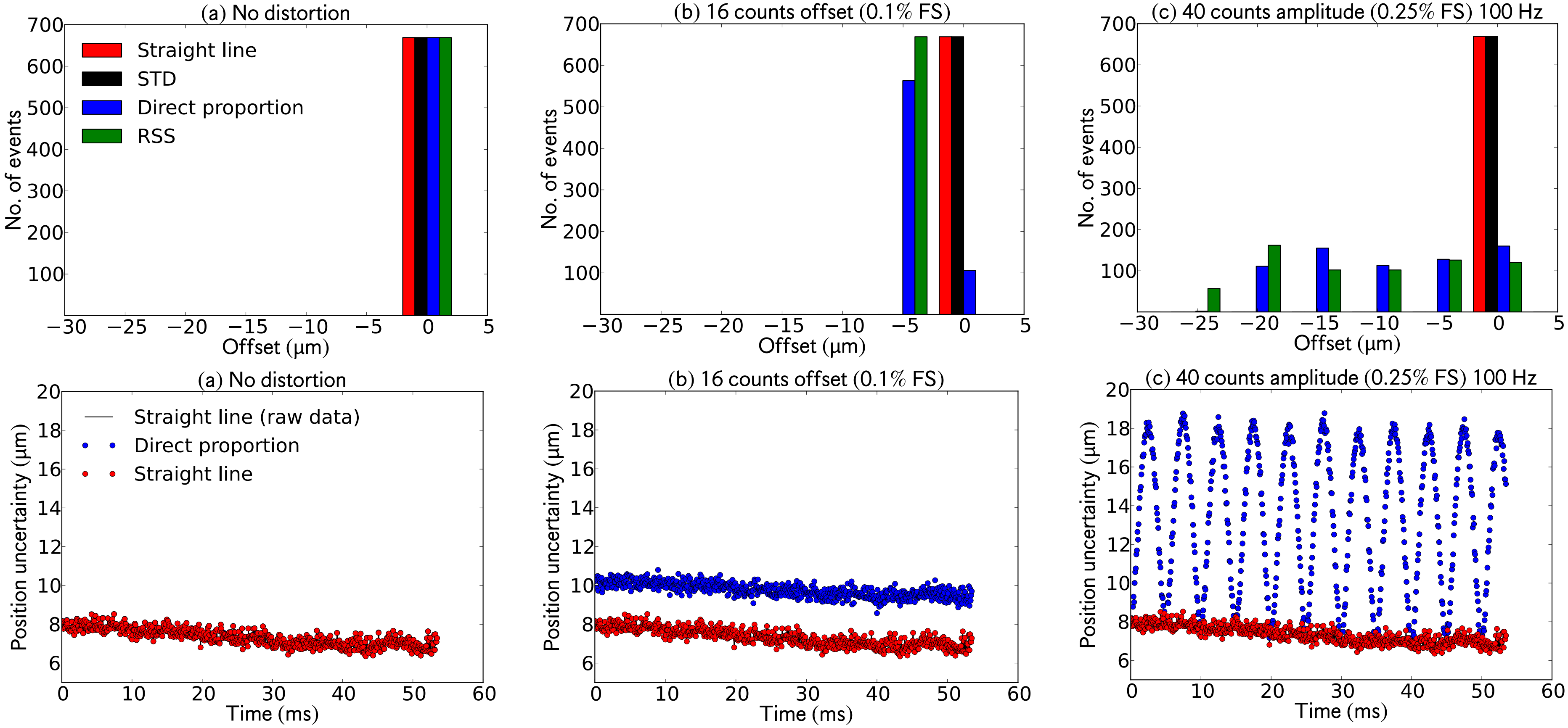
or **$\sigma_m = (\sigma_y \cdot s) < 1\times10^{-3}$**



Experiments (flat top)

Orbit uncertainty & robustness

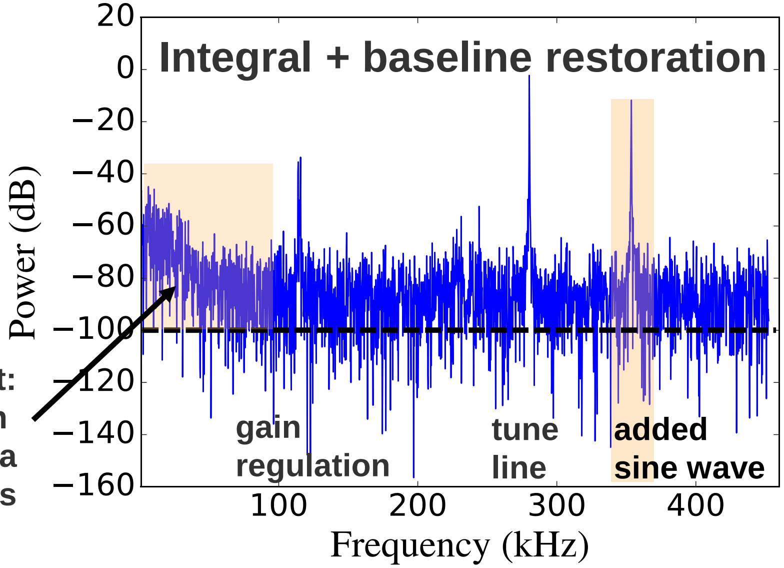
- 300 MeV/u data (hor. BPM, s_H= 0.8%/mm, 10000 samples/fit ~ 75 turns, A= 0.3)
- Add distortion to one electrode signal in analysis and calculate offset to raw data



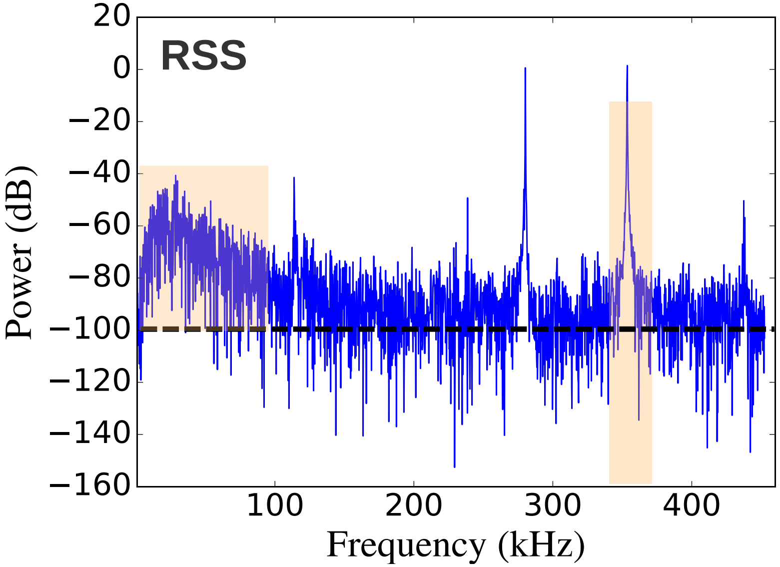
Result: Orbit uncertainty <10 μm; RSS and direct proportion sensitive to distortions

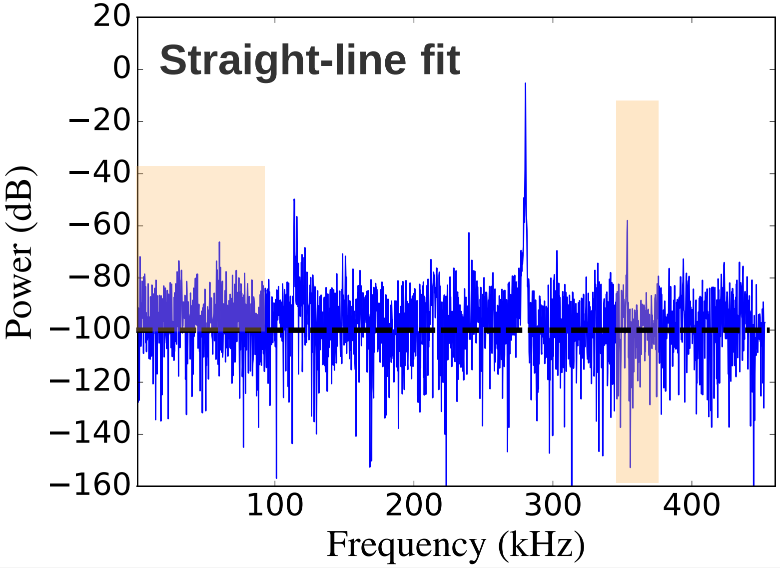
Experiments (flat top)

Horizontal tune & robustness



Amplifier effect: Not present in tune spectra of other BPMs





- Tune measurement: 2000 turns, 20 samples/fit
  v = 280 kHz (v_{ref} = 905 kHz)
- 112, 224 kHz by amplifier gain regulation loop
- Add 353 kHz sine wave of 0.15% FS amplitude wave to one BPM electrode in analysis

Result: Straight-line fit able to suppress added interference and real amplifier noise (< 100 kHz)

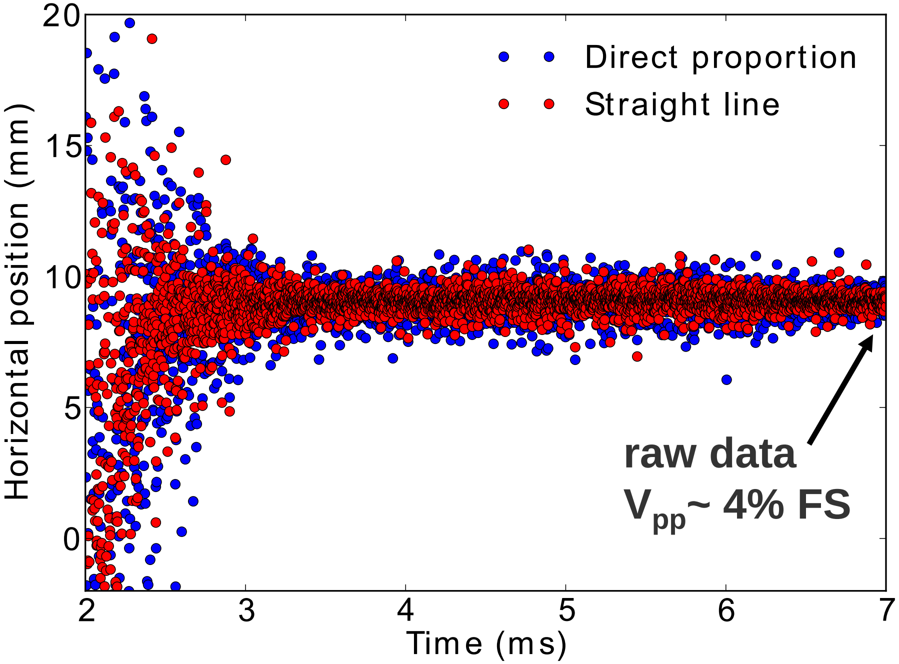
rule of thumb: $v < 10\frac{MHz}{N}$ = 500 kHz

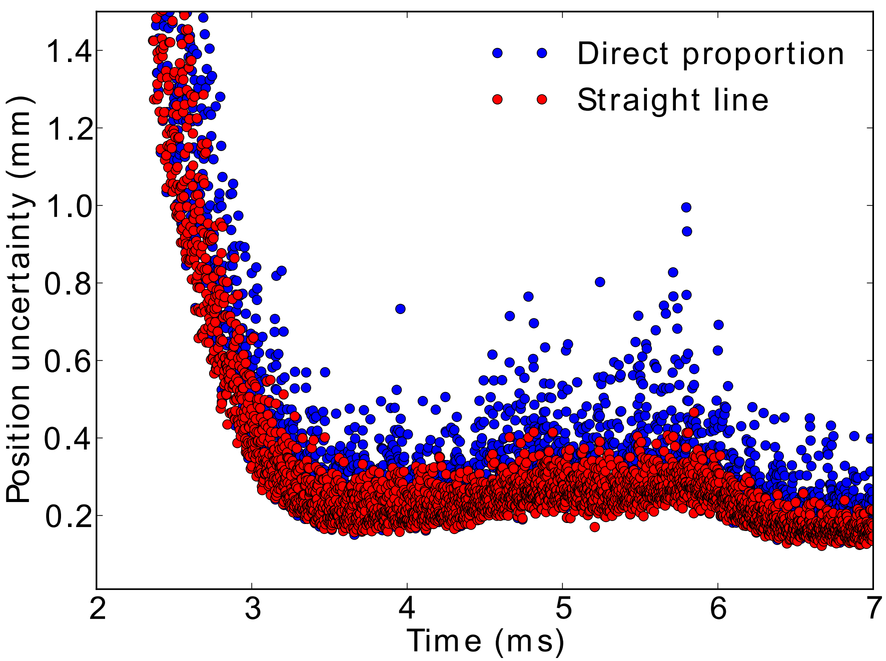
Experiments (start of cycle)

Orbit by asynchronous mode

- Asynchronous mode: Data stream of fit results for fixed number of samples
  200 samples/fit = 625 kHz stream (3125 positions in 5 ms)
  „observer“ mode: no external signals, no bunch detection,…

- Check positions after multi-turn injection in SIS18 for direct prop. and straight-line





Result: RSS yields slightly larger jitter, its uncertainty shows outliers / asymmetric tail

Experiments (start of cycle)

Asynchronous mode vs SIS18 TOPOS

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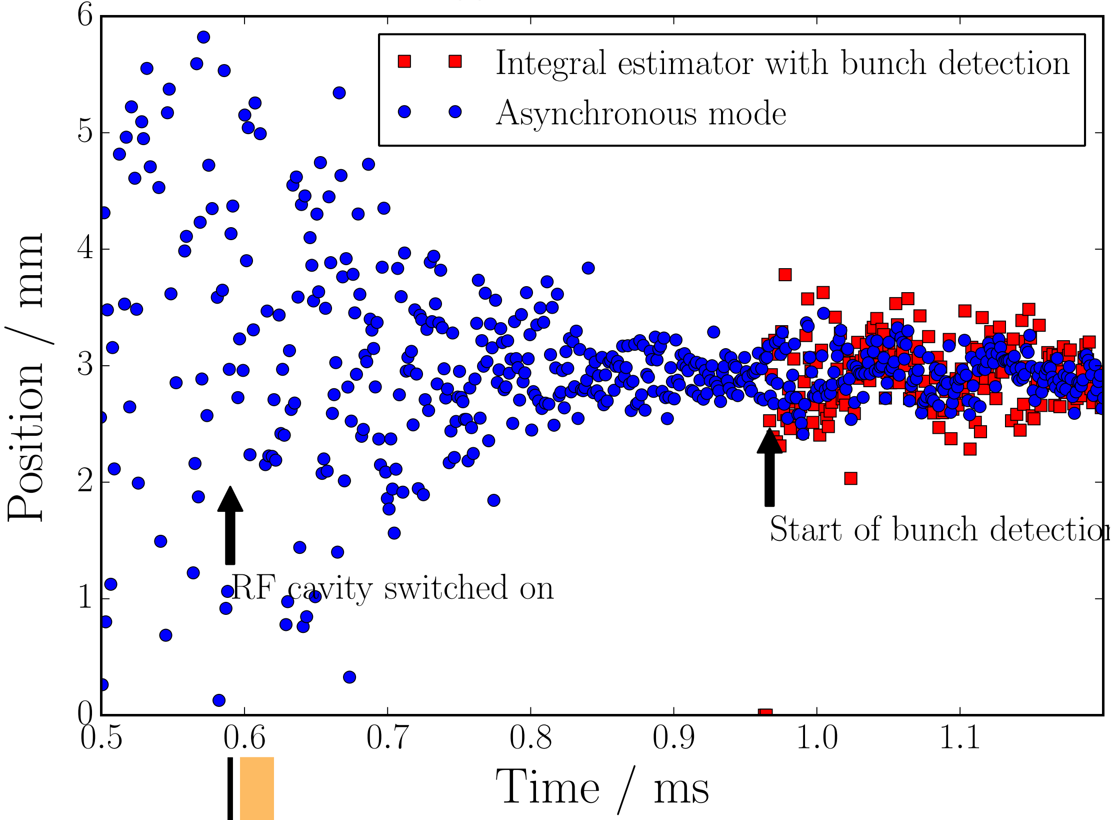
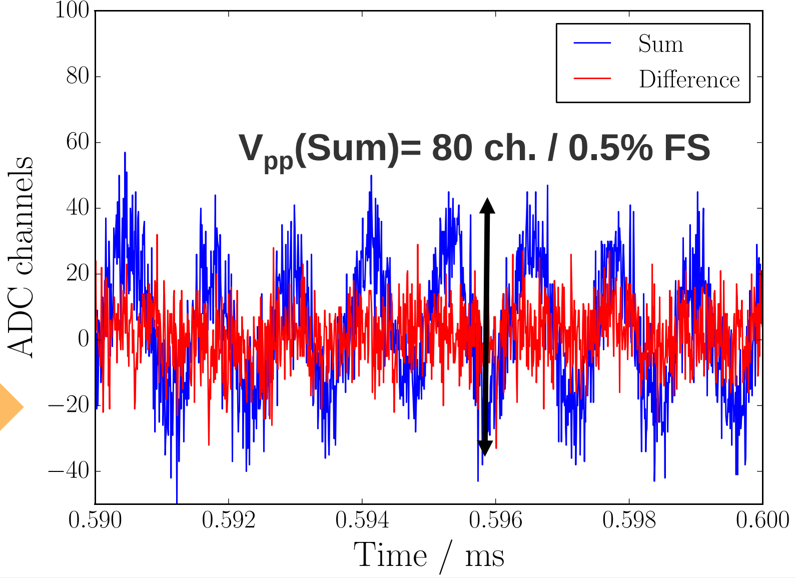
Note: different trigger time compared to previous slide



Result:

- Asynchronous mode „locks“ quickly onto bunch signal and exceeds TOPOS performance
- Dual-threshold detection needs minimum bunch quality to start tracking of positions

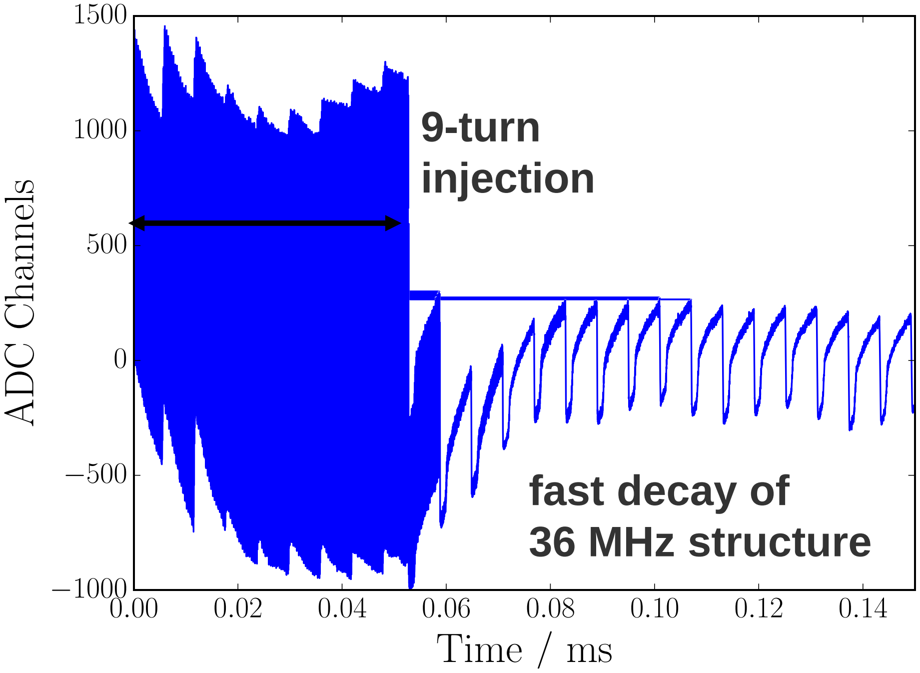
Δ / Σ signals in 10 μs interval



V_{pp}(Sum)= 80 ch. / 0.5% FS

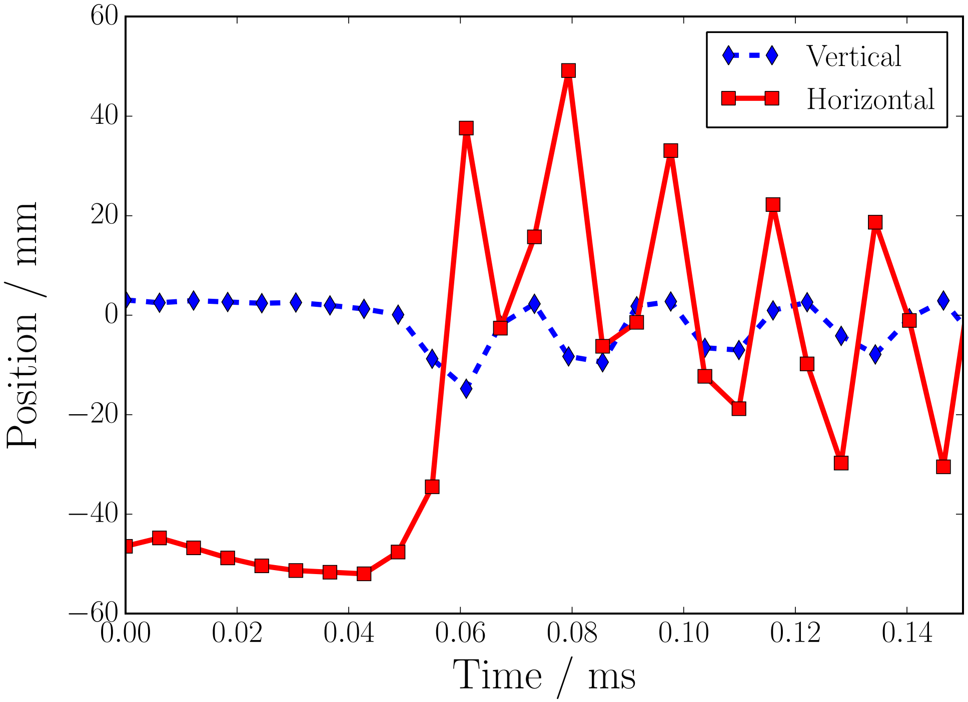
“Exotic“ applications

- Multi-turn injection from UNILAC injector
- Turn-by-turn position evaluation using standard deviation (STD)
- Last injected turn dominates position due to fast decay of structure
- Reproduction of design offset due to injection bumper



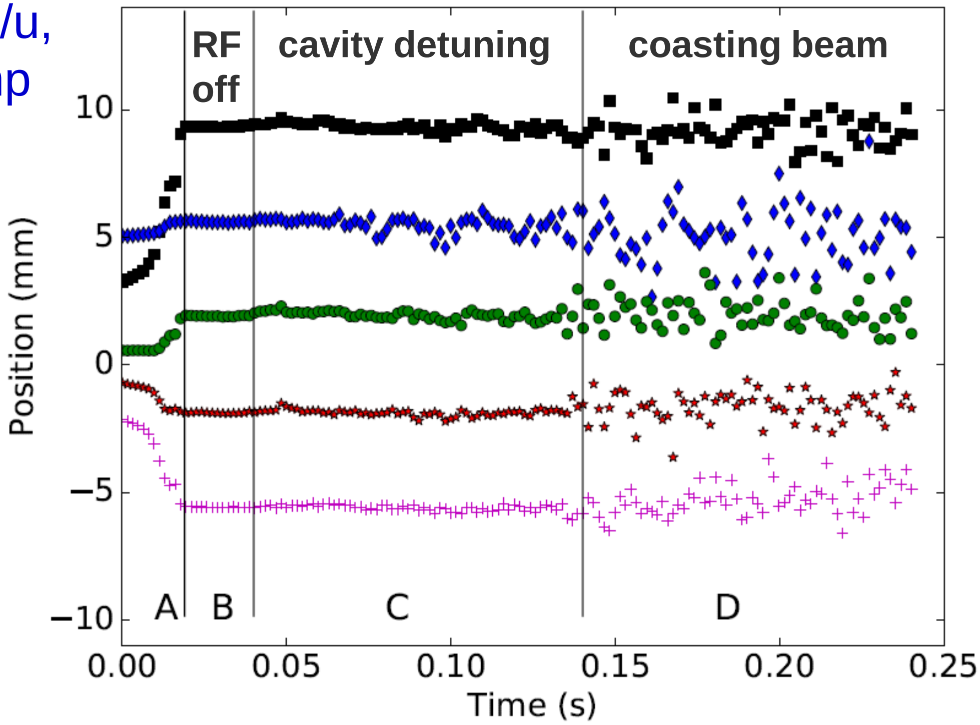
9-turn injection

fast decay of 36 MHz structure

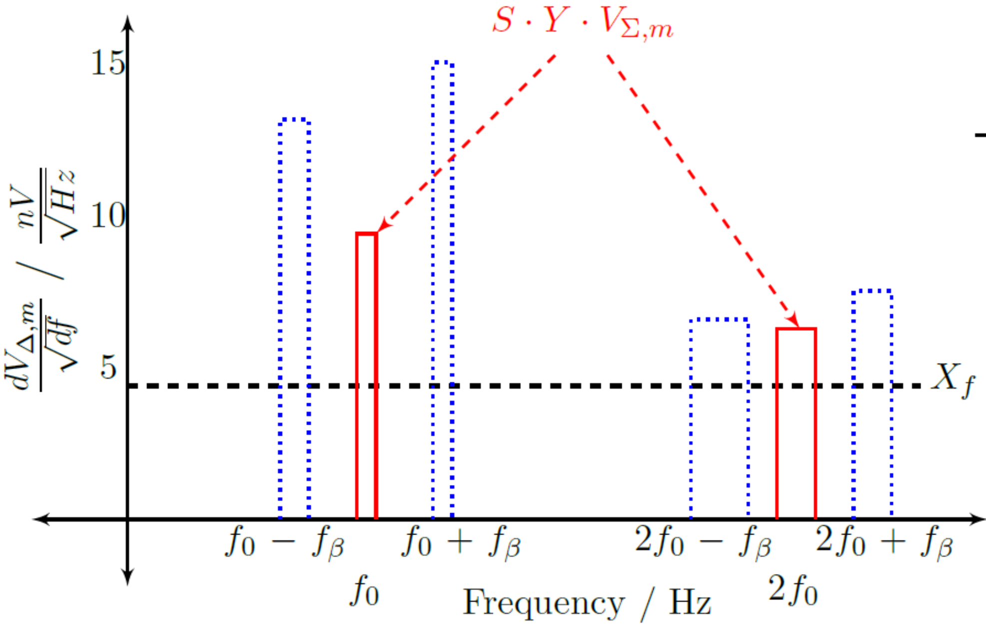


“Exotic“ applications

- Coasting high-intensity beam (400 MeV/u, Xe^{43+}, 11 mA DC current) with orbit bump
- Position calculation by straight-line fit after FFT filter on revolution frequency and higher harmonics (up to 20)
- Confirmation by IPM profile monitor



Region A: Amplifier overload
(⇒ positions not correct)
for all position, but 5 mm data
where we used a smaller gain!

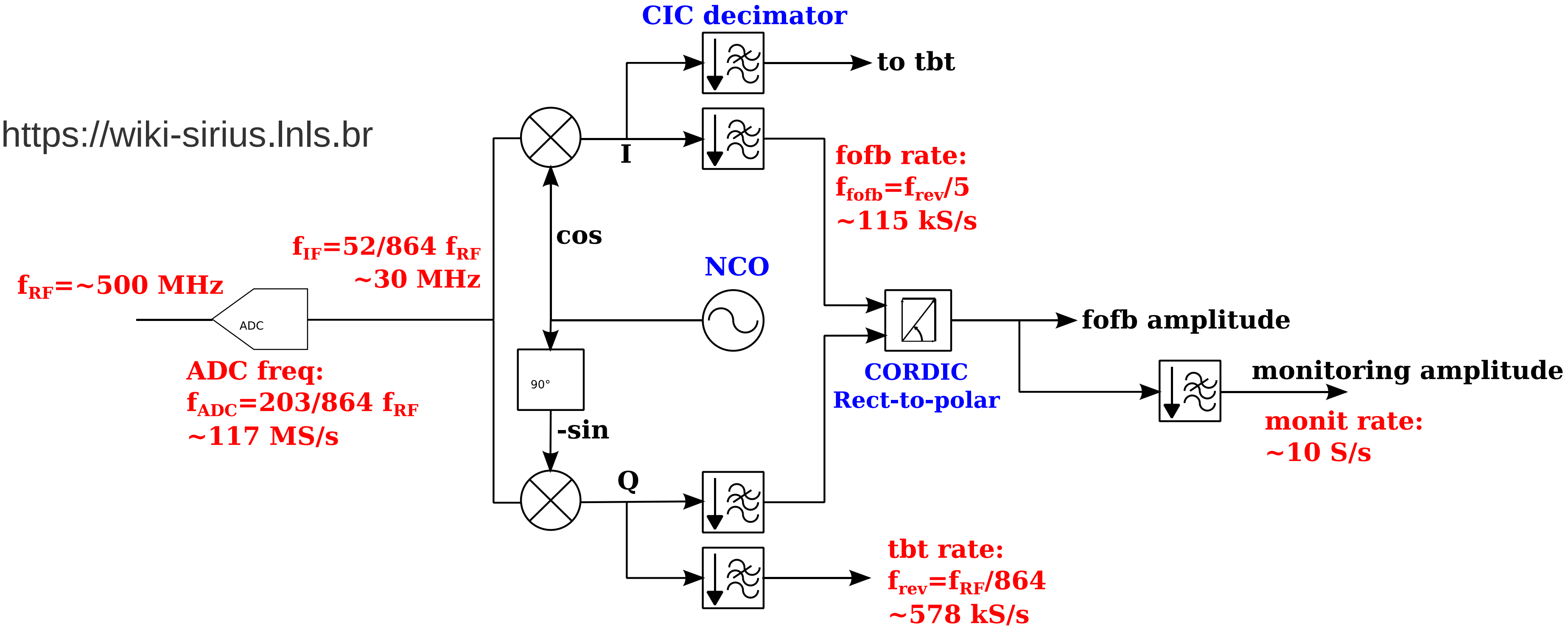


R. Singh et al., accepted for publication in Rev. of Sci. Instr.
https://doi.org/10.1063/1.5063324

Comparison to IQ demodulation

- BPM system for Sirius light source (by courtesy of D. Tavares, LNLS)
- Simulated ADC raw data analysed as
  turn-by-turn blocks using STD
- Results of both approaches in good agreement

https://wiki-sirius.lnls.br



CIC decimator

to tbt

fofb rate:
$f_{fofb}=f_{rev}/5$
~115 kS/s

f_{IF}=52/864 f_{RF}
~30 MHz

f_{RF}=~500 MHz

NCO

fofb amplitude

CORDIC
Rect-to-polar

monitoring amplitude

monit rate:
~10 S/s

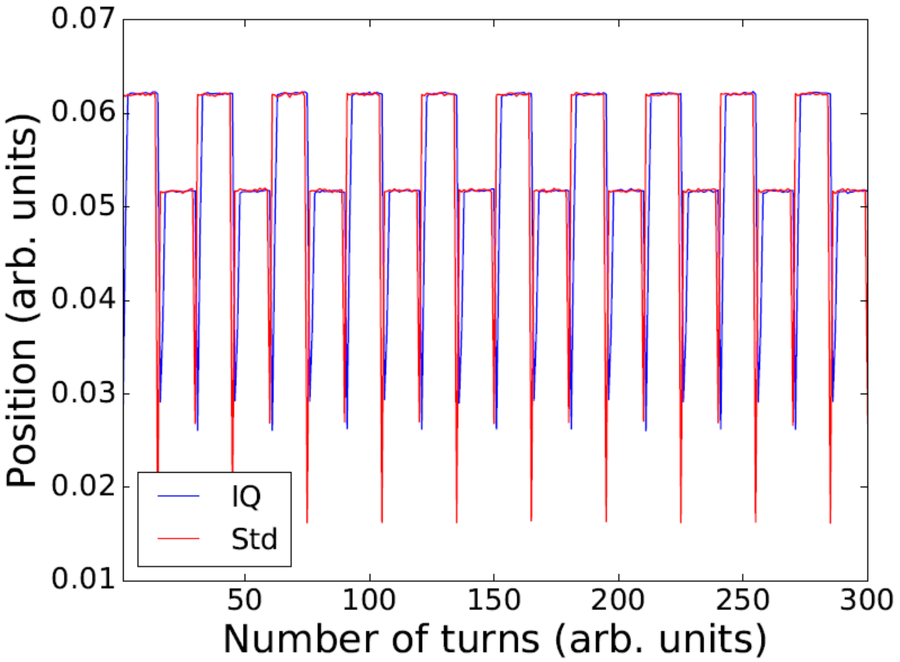
ADC freq:
f_{ADC}=203/864 f_{RF}
~117 MS/s

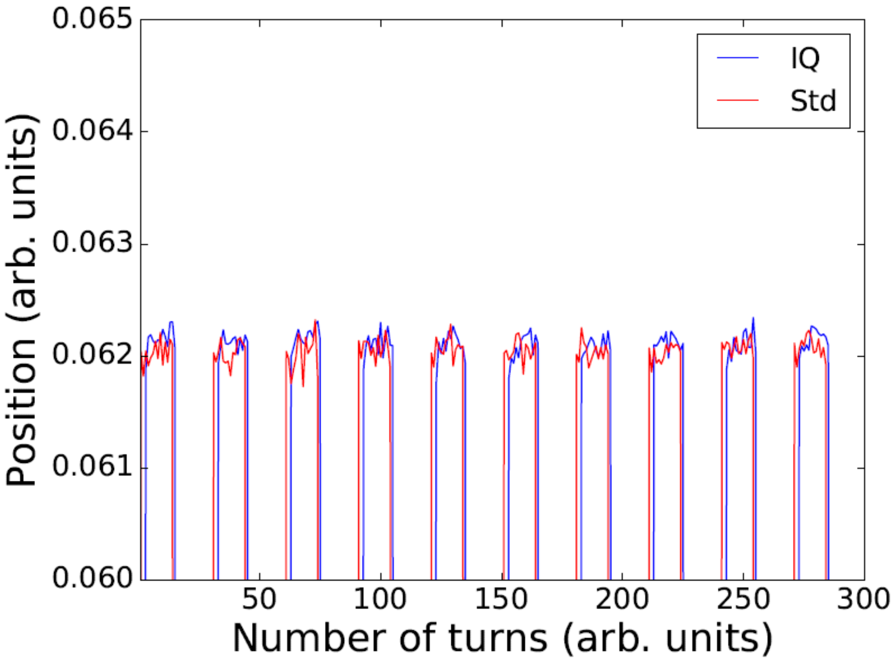
tbt rate:
$f_{rev}=f_{RF}/864$
~578 kS/s

Simulation

Comparison to IQ demodulation

- BPM system for Sirius light source (by courtesy of D. Tavares, LNLS)
- Simulated ADC raw data analysed as
  turn-by-turn blocks using STD
- Results of both approaches in good agreement





Conclusion & Outlook

- Review of position analysis for a linear system in time-domain
  - “Practical” statistical model: position uncertainty & robustness
  - Straight-line fit (or STD) provides good robustness and resolution, matching model prediction (more information: A. Reiter, S. Singh, NIM A 890 (1018) 18-27 and “arXiv 1609.01332”)
- New approach has led to significant improvements (and some new applications)
  - smaller measurement uncertainty
  - orbit position stream via asynchronous mode in extended interval in cycle
  - analysis of tune, multi-turn injection and coasting beam pilot test
  - was compared to simulated data for Sirius BPM system
  - can be applied to linac buttons
- Development status / realisation
  - CRYRING: Straight-line fit (and averaging) stage implemented on FPGA
    bunch-by-bunch position via RF clock signal
  - SIS18: Direct proportion
  - FAIR: Tests at SIS18 (incl. COFB) and ESR, position calculation options:
    bunch detection & integral / narrow-band analysis / user-defined calc.

Finally, …

I show some room for improvement

and thank the organisers for the invitation …

….. and everyone of you for your kind attention !

Spare slides

Rendering of FAIR Research Campus

FAIR BPM system

Data paths

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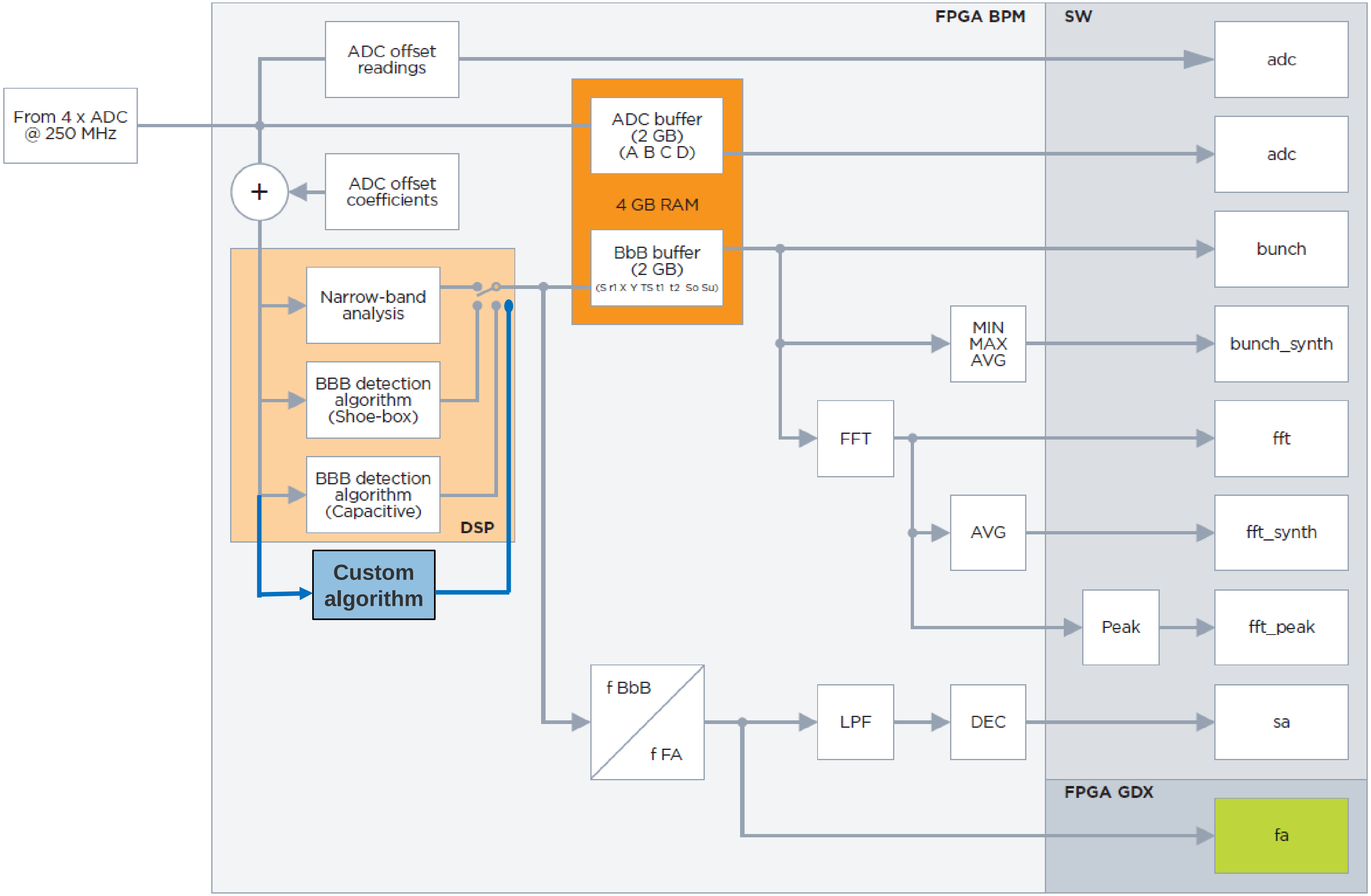
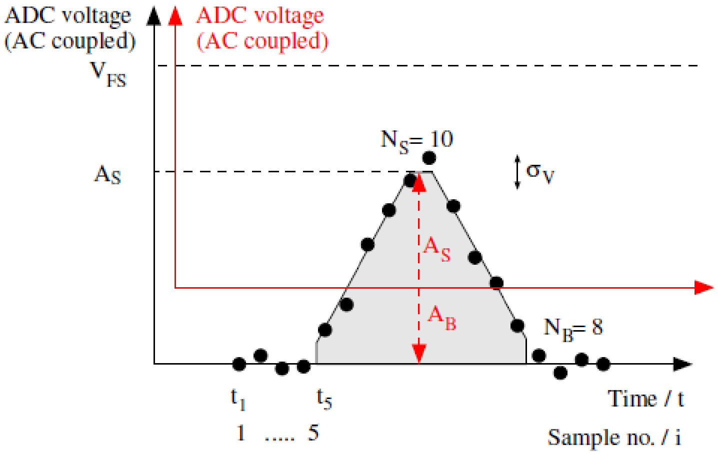


Time-domain model

Analytic formulae

Triangular pulse with baseline offset due to cyclic pulses
Turn-by-turn analysis (h=1):
Analyse all signals in one period N_S and N_B
Amplitudes refer to black coordinate system without offset



Integral:

$$\frac{\sigma_{<x>}}{r} = \frac{4\cdot\sigma_V}{V_{FS}}\,\frac{\sqrt{A_L^2+A_R^2}}{(A_L+A_R)^2}\cdot\frac{1}{N_S}\sqrt{(N_S+N_B)+\frac{(N_S+N_B)^2}{N_O}}$$

RSS: Balanced system - N_B samples between pulses

$$\frac{\sigma_{<x>}}{r} \approx \frac{2\sqrt{3}\cdot\sigma_V}{V_{FS}}\cdot\frac{\sqrt{A_L^2+A_R^2}}{(A_L+A_R)^2} \cdot\sqrt{\frac{N_S(N_S+N_B)}{(N_S+2)(\frac{1}{4}N_S^2+N_SN_B+N_B+\frac{1}{4}N_S)}}$$

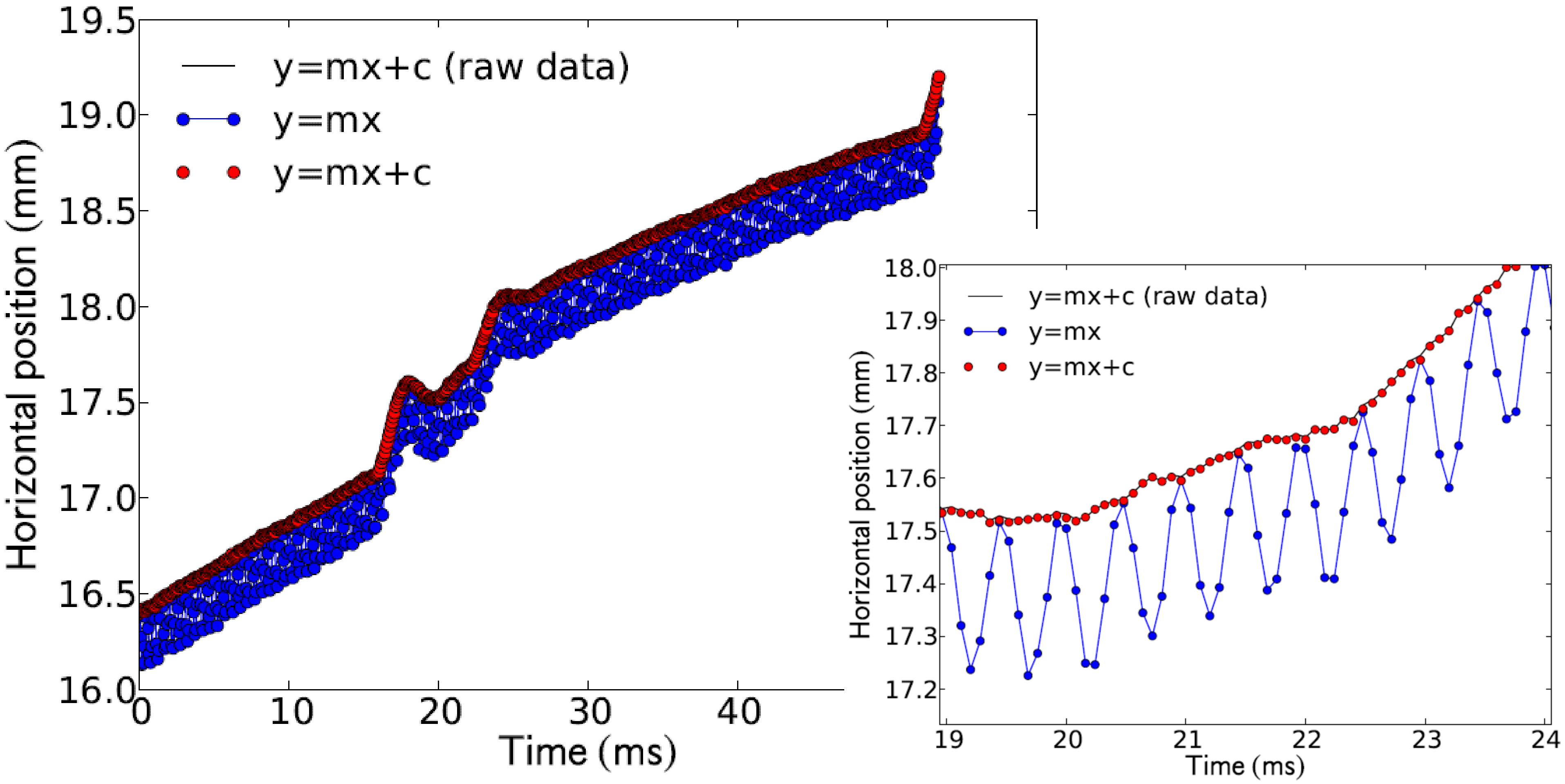
Fit: Identical for RSS for leading terms of N_S and N_B

$$\frac{\sigma_{<x>}}{r} \approx \frac{2\sqrt{3}\cdot\sigma_V}{V_{FS}}\cdot\frac{\sqrt{A_L^2+A_R^2}}{(A_L+A_R)^2}\cdot\sqrt{\frac{N_S(N_S+N_B)}{(N_S+2)(\frac{1}{4}N_S^2+N_SN_B)}}$$

Experiments (flat top)

SIS18 cycle

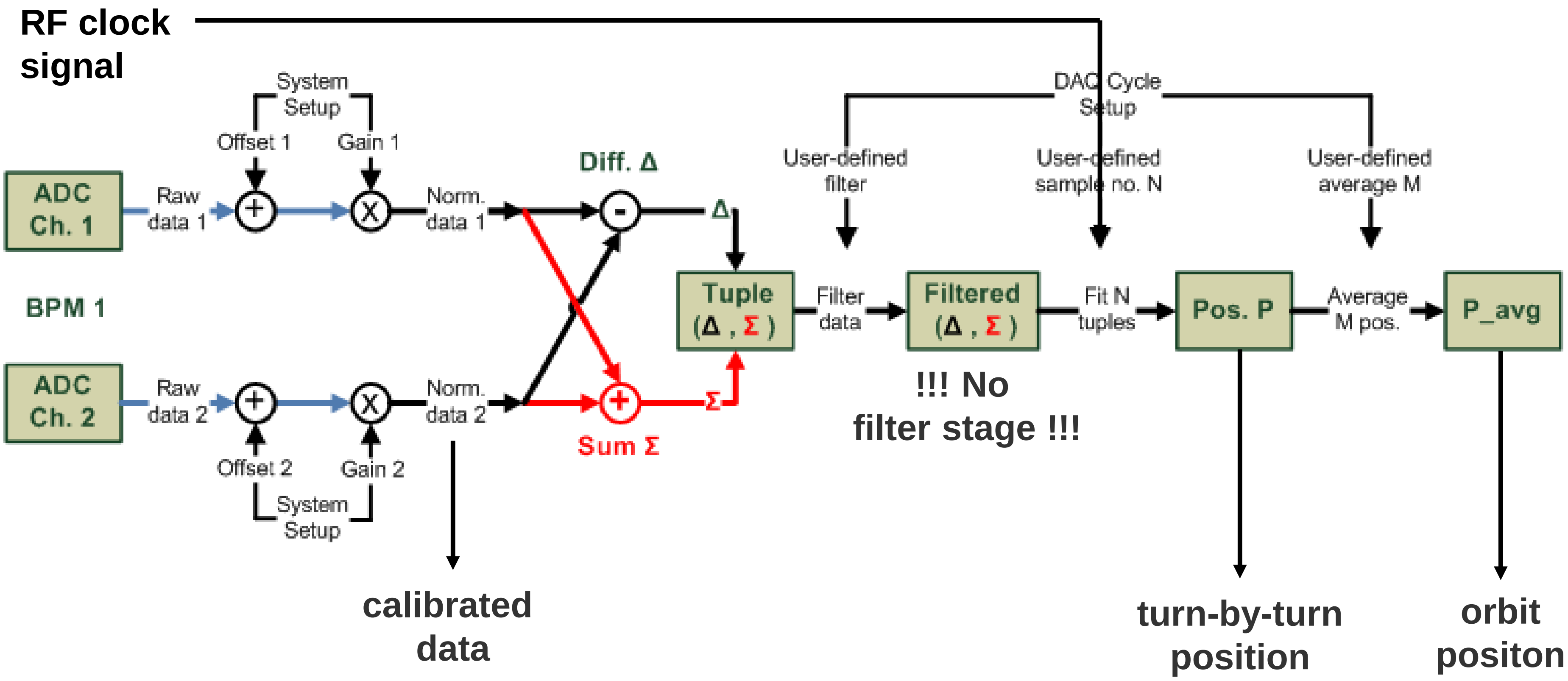
- Signal amplitude 30% FS, 10000 samples / fit (ν_{cut} ~ 1 kHz)
- Added distortion: 1 kHz sine wave of 160 ch. amplitude (1% FS)



CRYRING BPM system

Data path

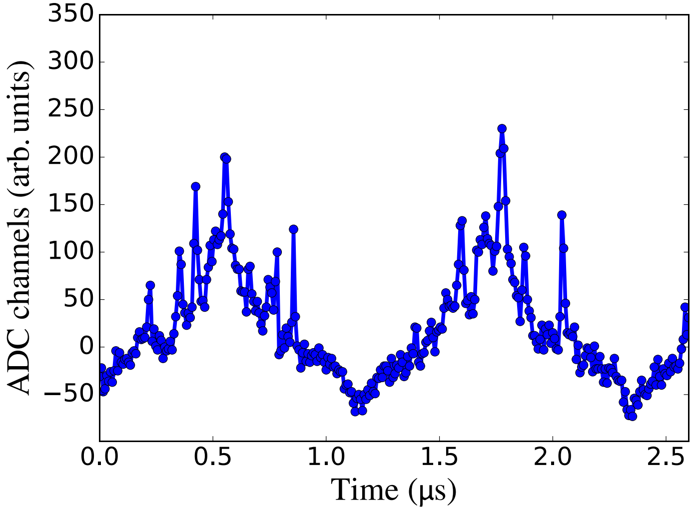
- µTCA open-hardware system with FAIR timing receiver node (FTRN)
- 125 MSa/a, 16 bit, +/- 1 Volt input range
- RF clock input for turn-by-turn fits (or maximum of 1023 samples)



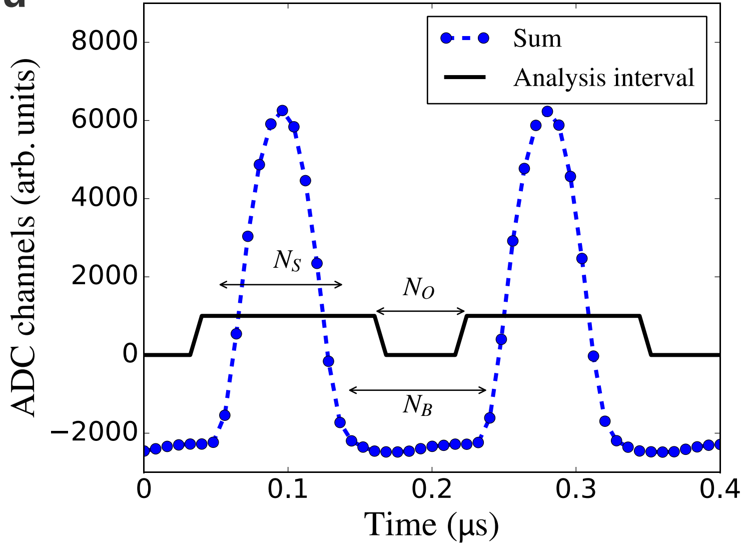
Signal Examples

- SIS18: 125 MSa/s, 14 bit ADC, Platform A

Injection mismatch

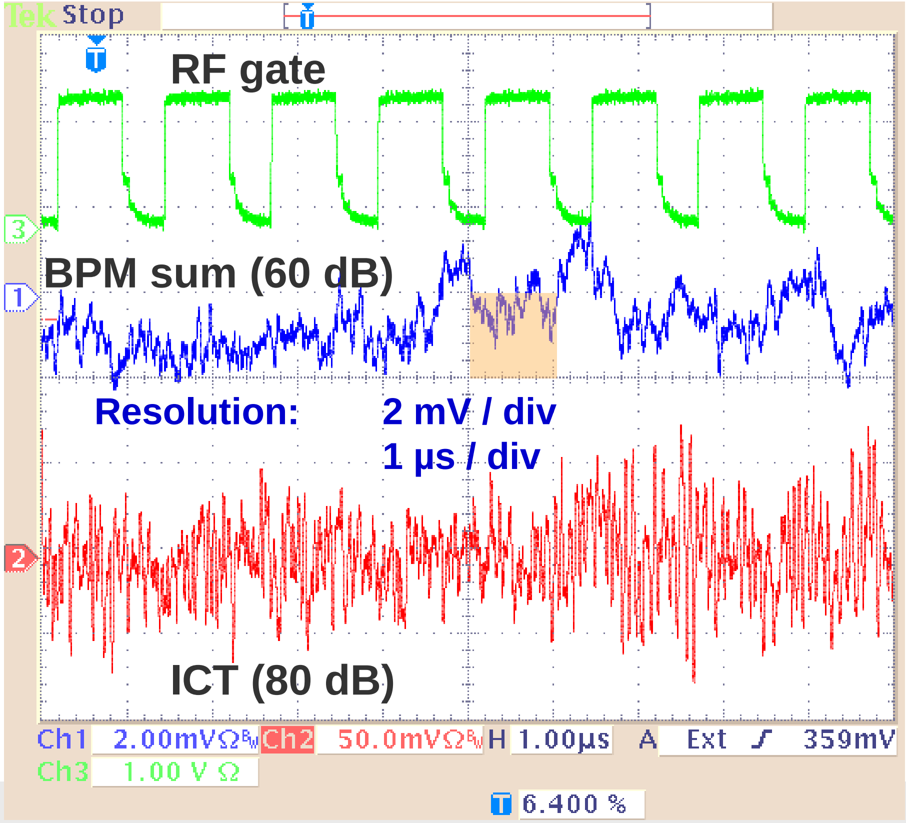


300 MeV/u



CRYRING: 125 MSa/s µTCA DAQ

**Mg+ „bunches“ after acceleration
gain +60 dB, 4 MHz filter**



Resolution: 2 mV / div
1 µs / div

```
Ch1  2.00mVΩ BW  Ch2  50.0mVΩ BW  H 1.00µs  A  Ext  ∫  359mV
Ch3  1.00 V Ω
T 6.400 %
```

MSO-X 2024A, MY58101875: Sat Nov 10 03:45:44 2018

1 10mV/ 2 2mV/ 3 50mV/ 4 2.00V/ 0.0s 2.000µs/ Stop 4 800mV

Acquisition
Averaging: 2048
1.00GSa/s

Channels
DC 1.00:1
DC 1.00:1
DC 1.00:1
DC 1.00:1

Measurements
+Width(1): 370ns
+Duty(4): 29.82%
DC RMS - FS(3): 21.9mV
Freq(4): 138.28kHz

Acq Mode: Averaging
Avgs: 2048

MSO-X 2024A, MY58101875: Sat Nov 10 03:48:21 2018

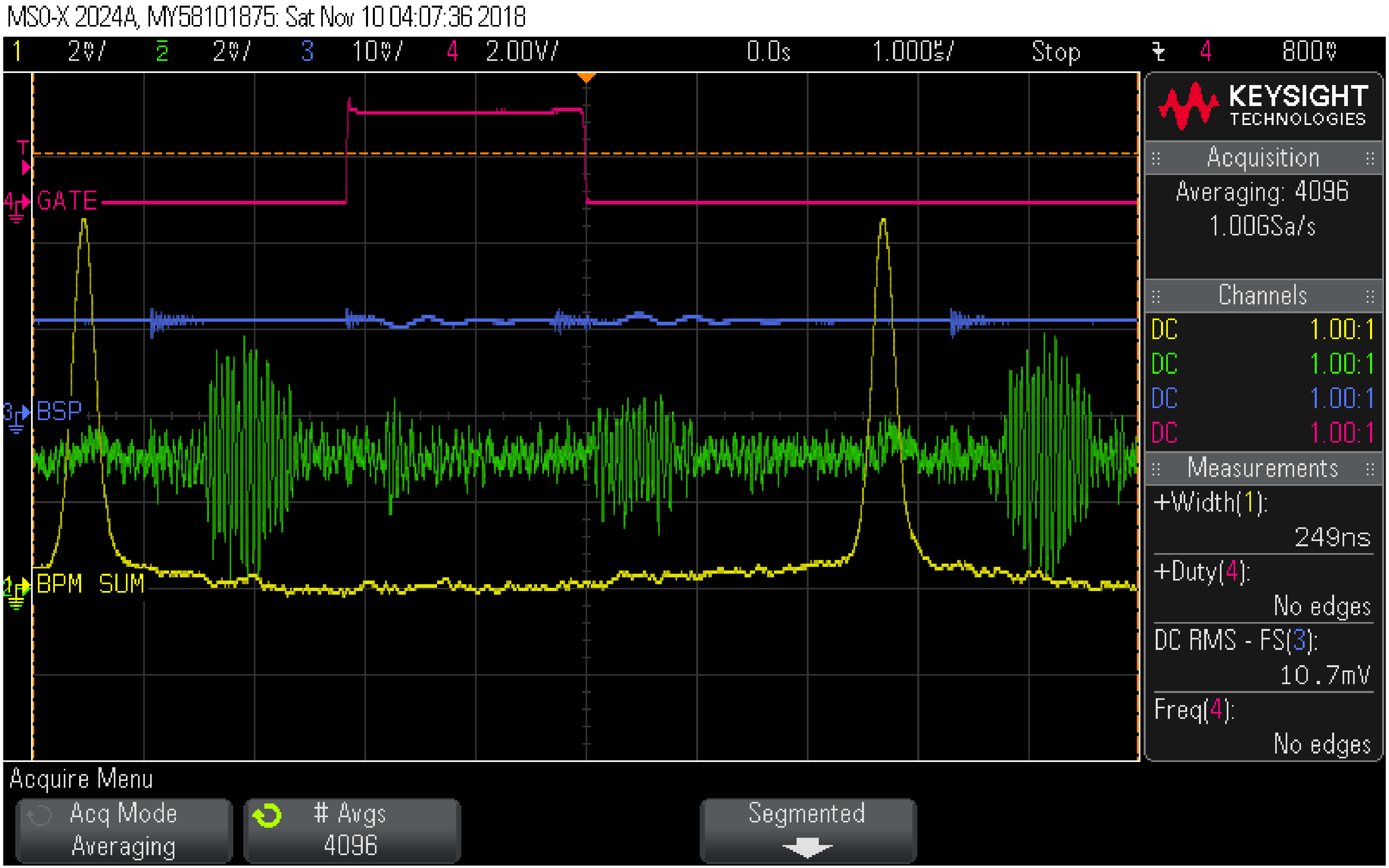
Saving to file "hict_min35.png". Please wait.

Acquisition
Averaging: 2048
1.00GSa/s

Channels
DC 1.00:1
DC 1.00:1
DC 1.00:1
DC 1.00:1

Measurements
+Width(1): 240ns
+Duty(4): 29.78%
DC RMS - FS(3): 9.3mV
Freq(4): 138.28kHz

Acquire Menu
Acq Mode: Averaging
Avgs: 2048



MSO-X 2024A, MY58101875: Sat Nov 10 04:07:36 2018

Acquisition
Averaging: 4096
1.00GSa/s

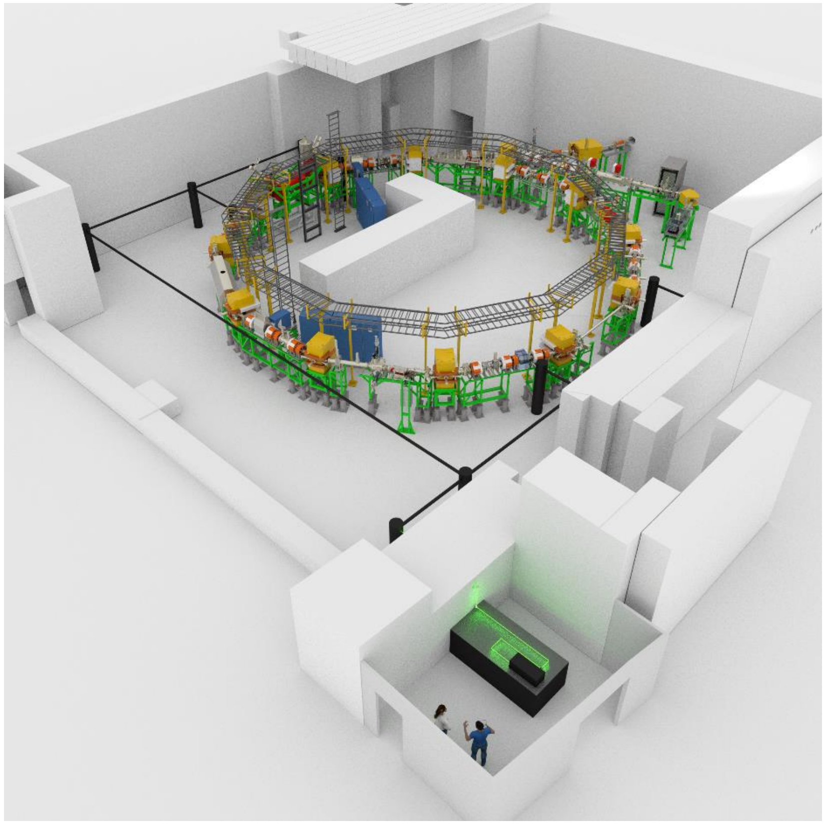
Measurements
+Width(1): 249ns
+Duty(4): No edges
DC RMS - FS(3): 10.7mV
Freq(4): No edges

Acquire Menu
Acq Mode: Averaging
Avgs: 4096

Our latest child
CRYRING – a low energy synchrotron

- 1.44 Tm storage ring
- 54 m circumference
- mainly for atomic physics
- Storage of cooled heavy ions from experimental storage ring ESR
- Electron cooler and laser facility

- Research opportunities to study interaction of heavy ions, electrons and photons

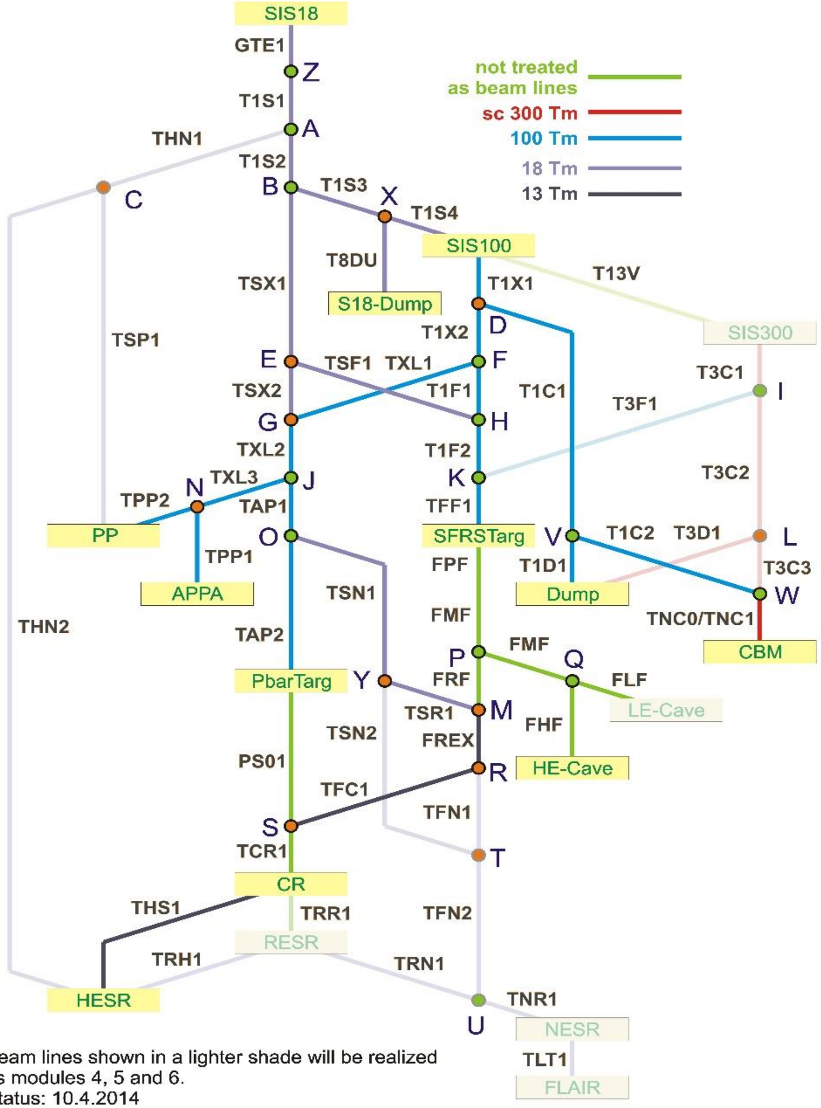


… and other reasearch
Atomic
Nuclear and particle
Material Science
Accelerator Physics
…
…

Parallel Operation
New Beam Line Network

- „Design ions“: proton and U$^{+(28 / 73 / 92)}$
- Other ions: C, N, Ne, Ar, Ni, Kr, Xe, Au, etc.
- SIS18 & SIS100 beams for users
- Slow / fast extraction: 10-30 s / 30-100 ns

- NuSTAR
  - U^{28+}; 1 GeV/u, 3x10^{11} to fixed target
  - U^{28+}; 1 GeV/u, 70 ns, 5x10^{11} to CR
- CBM
  - U^{92+}; 10 GeV/u; 1.5x10$^{10;}$ 10 s spill
- pBar Production
  - p ; 30 GeV; 2.5x10^{13}; 50 ns
- APPA
  - BioMat, SPARC: highly charged ions up to 10 GeV/u; slow extraction
  - Plasma Physics: see NuSTAR; 1 shot every 2 minutes (PHELIX laser)
- FLAIR (ESR/CRYRING/HITRAP)
  - Highly charge ions
  - Deceleration 4 MeV/u – 500 keV/u – 6 keV/u
  - Trapping of ions for experiments

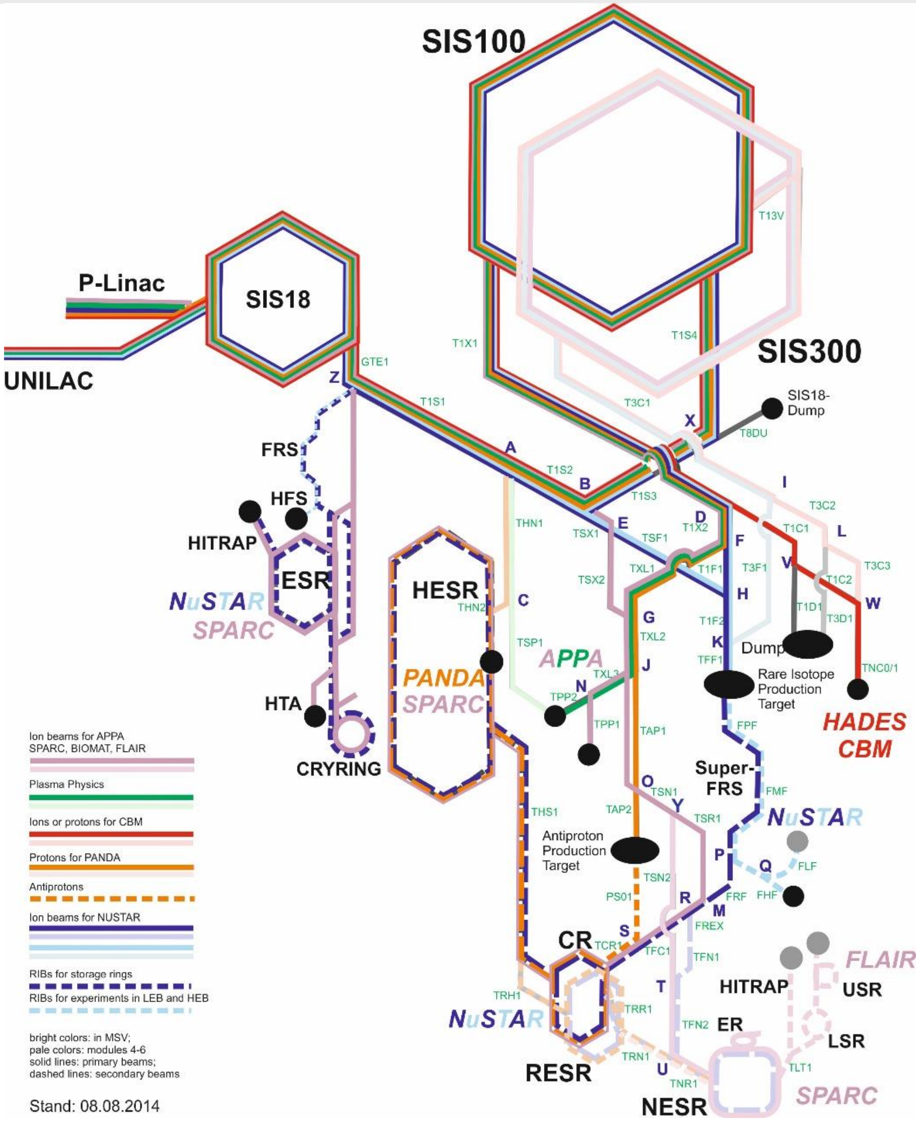


Beam lines shown in a lighter shade will be realized as modules 4, 5 and 6.
Status: 10.4.2014

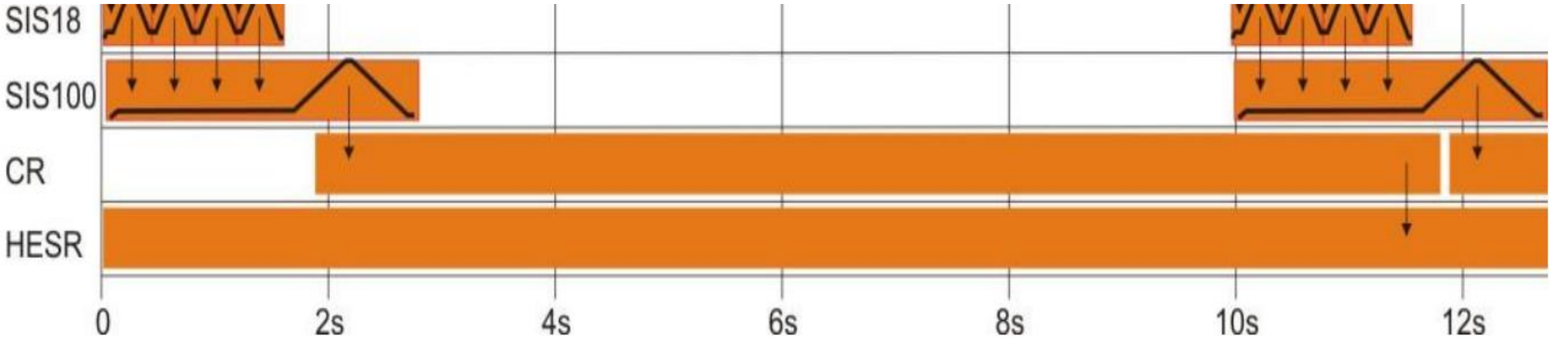
Green spots at junctions indicate that the connection going straight is open when the junction dipole is switched off.

Parallel Operation
The Underground Map

- Parallel operation to supply several users simultaneously
- Complex pattern of beam chains to be implemented
- White Rabbit Timing system (CERN) and BuTiS Bunch Timing system BuTiS (GSI) and an effective beam scheduling logic will be most crucial
- More than 60 timing domains



pBar Beam Production
Beam Pattern



- Design luminosity L = 2x10^{32} cm^{-2} s^{-1} (100 mb total inelastic pBar-p cross section: 2x10^{7} s^{-1} consumption)
- p-Linac produces 4 pulses of 70 MeV proton beam in ~1.2 s (2.5 Hz)
- SIS18 accelerates each pulse to 4 GeV and needs ~1.6 s, including pre- and postprocessing
- SIS100
  - Injection of 4 batches from SIS18 needs ~1.2 s, yields ~2x10^{13} protons
  - Merging into one single bunch, acceleration to 28.8 GeV/u
  - Compression to bunch length of ~30 ns
  - Cycle length ~2.7 s in MSV with reduced no. of RF cavities, 2.55 s in final setup
- Cooling in CR
  - Bunch rotation to reduce momentum spread (Δp/p ±3%)
  - Adiabatic de-bunching
  - Stochastic cooling down to p/p 0.1%, Emittance(h,v) ~5 pi mm mrad
  - Repetition time 10 s
- Accumulation in HESR
  - Accumulation of 1x10^{10} antiprotons in 1000 s
  - Decelerate/accelerate
  - Beam on target for ~1000 s

pBar Beam Production
Example Beam Chain

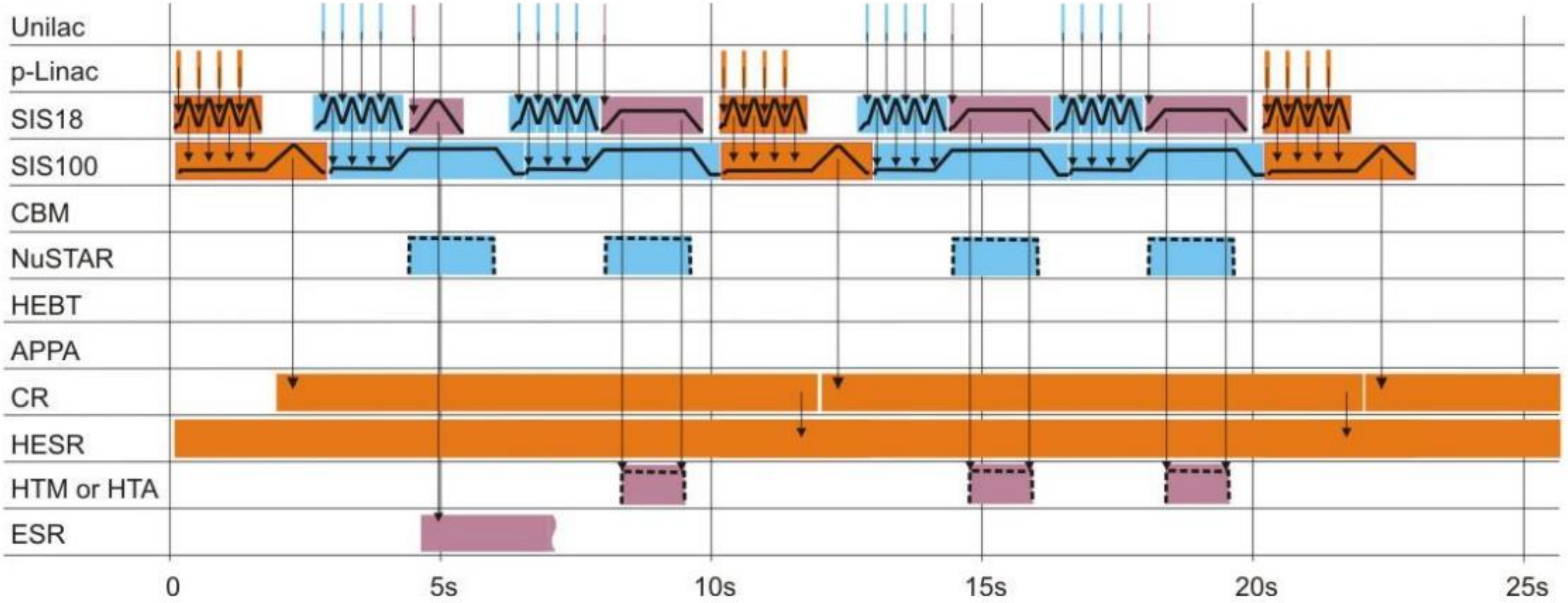


Figure 3-3: Reference Pattern with Antiproton Production as Main Process and NuSTAR as second priority user.