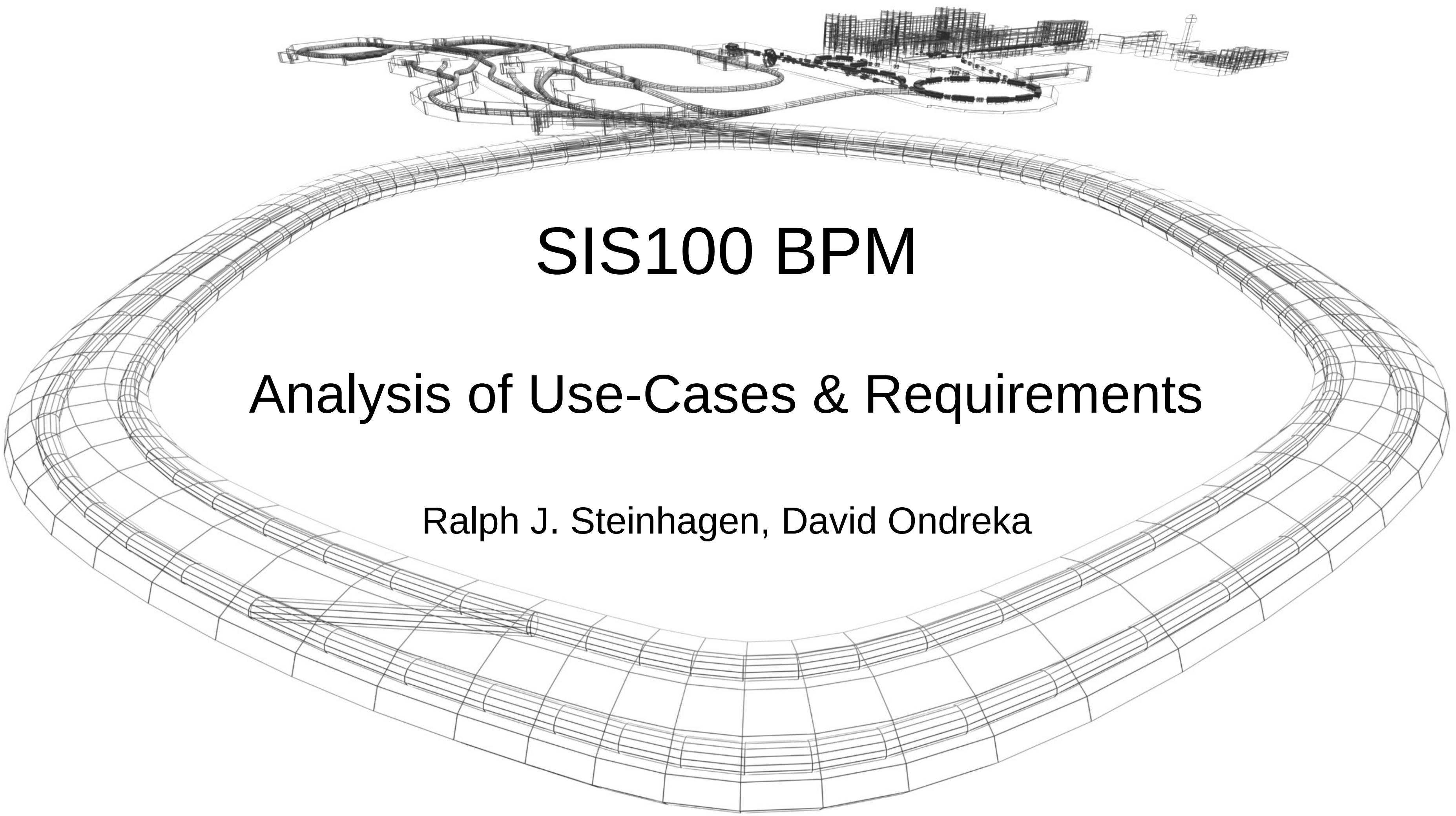
2015-04-13 – V1
2015-11-13 – V2

GSI Helmholtzzentrum für Schwerionenforschung GmbH



SIS100 BPM

Analysis of Use-Cases & Requirements

Ralph J. Steinhagen, David Ondreka

SIS100/18 BPM Topics to be discussed
P. Kowina, D. Ondreka, R. Steinhagen

- Pick-ups: TFS & Head-Tail BPM + warm quadrupoles
- AFE improvement ↔ SIS100 nom. beam operation/parameter
  - A) RF Hybrid → robust electrical BPM centre (common mode rejection > 40 dB) & higher sensitivity (>10)
    - digitize 'amplified Δ' vs. 'A ~ Σ (v. large) ± Δ (~1% w.r.t Σ)'
  - B) RF Low-Pass → reduce req. dynamic range
    - compatibility with nominal bunch-length variations
  - Rationale: operationally robust orbit steering, inj./extr. steering, optics-via-Δμ-advance + intensity variation margin
- DAQ – LOBI & SP/OP use-case analysis
  - need to measure/control beam during whole cycle (injection → extraction)
  - f_{rev} turn trigger/tagging, inj./extr. synchronisation
  - FESA interface for: orbit, injection/extraction steering, 10k-turn analysis, MDs
    - similar to FCTs & BPM → could become prototype for other ring BI
    - 1 kHz closed orbit (per-cycle, @10/25 Hz), first 1k (10k?) turns, last 100 turns, 10k study buffer (arbitrary timing event during cycle)
  - compatibility of orbit & trajectory with Q/Q' acquisition
- CO Controls Integration
  - data concentration, buffers, HW/SW interlocks
  - Archiving & PM (which data? Turn-by-Turn data?)
  - Machine Protection information gathered by BPM system: threshold criteria? time for reaction to FBAS? HW/SW Interface?
  - FESA acquisition paradigm (change from 'virtual accelerator' → 'beam production chains')
  -
- Automated Steering
  - Slow cycle-to-cycle orbit & trajectory control (base-line: work ongoing)
  - Fast in-cycle real-time orbit feedback (is it needed?)

Observables: Orbit (avg. Trajectory)

- Global orbit – minimise the aperture requirements; monitor/log closed orbit
- Local orbit at critical points – fine control of aperture limits (collimators, septa, etc.)
- Machine Alignment – beam-based alignment of quadrupoles, BPMs etc.
- Linear optics model ↔ LOCO (N.B. rel. slow method)
  - Integer tunes – Fourier analyse of closed orbit
  - Dispersion D(s) – closed orbit versus momentum deviation
  - measure β(s) and μ(s), BPM & orbit corrector calibration, polarity checks
  - search for optics imperfections
- Non-linear optics model: b2/a2 to b5, b3/a3 etc.
  - polarity checks of higher-order multipoles
  - optics linearisation

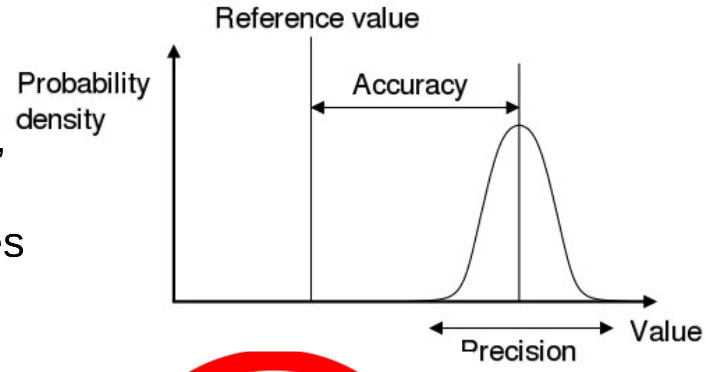
Observables: Trajectory and Oscillations

- Trajectory – beam threading, close trajectory on itself, visual inspection
- Position and momentum error at injection
  - Subtract orbit from first-turn trajectory and compute x,px,y,py at injection (injection matching)
    - N.B. this includes also HEBT BPMs
  - Deduce momentum from trajectory averaged over the azimuth → controls the SIS18/SIS100 energy matching
- Linear optics model ↔ beta-beating via. phase-advance measurement (N.B. rel. fast method)
  - measure β(s) and μ(s) at injection, ramp, extraction, optics changes due to γ_t shift
  - search for optics imperfections
- Phase space measurement
  - separatrix of slow-extraction → sextupole adjustment: amplitude & phase
  - dynamic aperture, driving terms
- Local chromaticity
  - Dependence of β(s) and μ(s) on momentum for the measurement of b3 versus azimuth
- Local impedance – dependence of μ(s) on beam intensity
- Local coupling – Identify the local 4D transport matrices
- Optional/complementary (ie. covered by dedicated Q/Q' diagnostics):
  - Transverse spectrum
    - Check on the presence and amplitude of harmonics of the betatron oscillation
  - Fast Tune → measurement of the tunes with all the BPM's
  - Frequency maps → Variation of (fast) tunes with initial conditions for visual inspection of the non-linearity

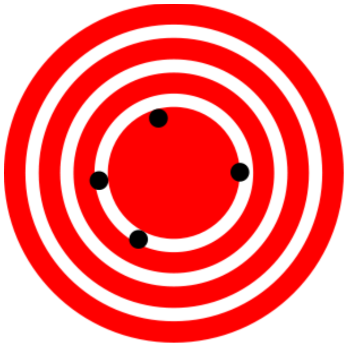
Terminology: Accuracy & Precision
(also ISO 5725)

Good summary: http://en.wikipedia.org/wiki/Accuracy_and_precision

- **Accuracy:** "[..] closeness of measurements [..] to its actual (true) value"
- **Precision** (also: reproducibility or repeatability):
"[..] degree to which repeated measurements
under unchanged conditions show the same results."



- Example: "Target analogy" and the two extreme cases



High **accuracy**, but low **precision**

obtained through beam-based alignment

High **precision**, but low **accuracy**

we need this from the BPMs

- **Resolution**: smallest change that produces a response in the measurement

Operational Robustness I/II

accelerator operation's point-of-view

- Robust (ie. fault tolerant) measurement of orbit & trajectories
  ↔ measurement insensitive to:
  - Bunch-by-bunch intensities, bunch filling patterns ("all bunches are created equal, but ...")
  - Beam intensity losses
    - Intensity ramp-up concept (systematics between pilot and high-intensity beam is paramount)
    - may loose part or full beam during injection, … aim at ~ 90% margin
  - Bunch length or shape changes
    - adiabatic damping, hollow-bunches, …
  - one-gain stage per cycle (if possible), or transparent (automated) gain changes
  - Stability of 'gain calibration' (may recalibrate BPMs 1..2 x day, 1 x per shift but not more for nom. operation)
  - Environmental effects: temperature (amplifier, limiter, cables, …)
  - To a lesser extend: actual orbit in machine (mostly centred)

Operational Robustness II/II

- Assumptions that may simplify BPM acquisition design:

  1 Orbit is most critical for high-intensity operation → high peak-voltages/short bunches

  2 Orbit is mostly (by design) in the centre of the beam pipe, e.g. < ± 5 mm

  - Should distinguish three ranges: nominal machine operation (±5 mm), studies/commissioning (±30 mm), ultimate range
  - larger offsets may occur during commissioning but rarely required to control orbit precisely above ±15 mm

  3 Only orbit & trajectory measurements needed

  - Required bandwidth ~ 1 kHz & ~ 1 MHz (not 50 MHz) → N.B. $(\text{ENOB*Bandwidth})^b$ = *const*
  - bunch-by-bunch or intra-bunch diagnostics is nice to have but not a must (e.g. optics, orbit, … are not b-b-b sensitive) and could be handled by single dedicated device (notable exception, distinction of 1st, 2nd, 3rd injection)

  4 Accuracy, Precision & Resolution:

  - accuracy is important for orbit control but precision is often sufficient
    - need reproducibility, beam-based alignment is key to achieve absolute accuracy
    - centre orbit (↔ el. BPM centre) needs to be rock-solid (i.e. < 0.1 mm)
  - resolution important for relative measurements (e.g. optics, injection/extraction steering, ...)

BPM Precision vs. Machine Reproducibility

Question at the core:

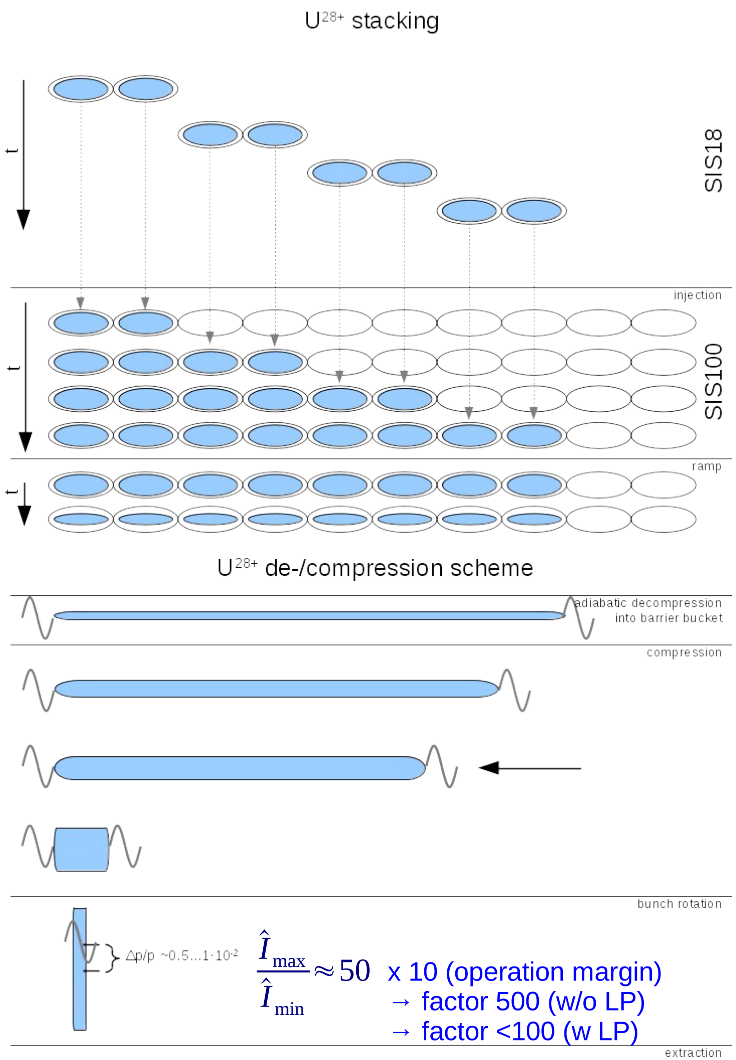
A) If (BPM Precision < Machine reproducibility) → use feedbacks
   - N.B. the only scenario where a real-time (within-cycle) FB makes sense

B) If (BPM precision = Machine reproducibility) → average over cycles →cycle-to-cycle feedbacks

C) If (BPM precision > Machine reproducibility) → forget about FB & switch them 'off'

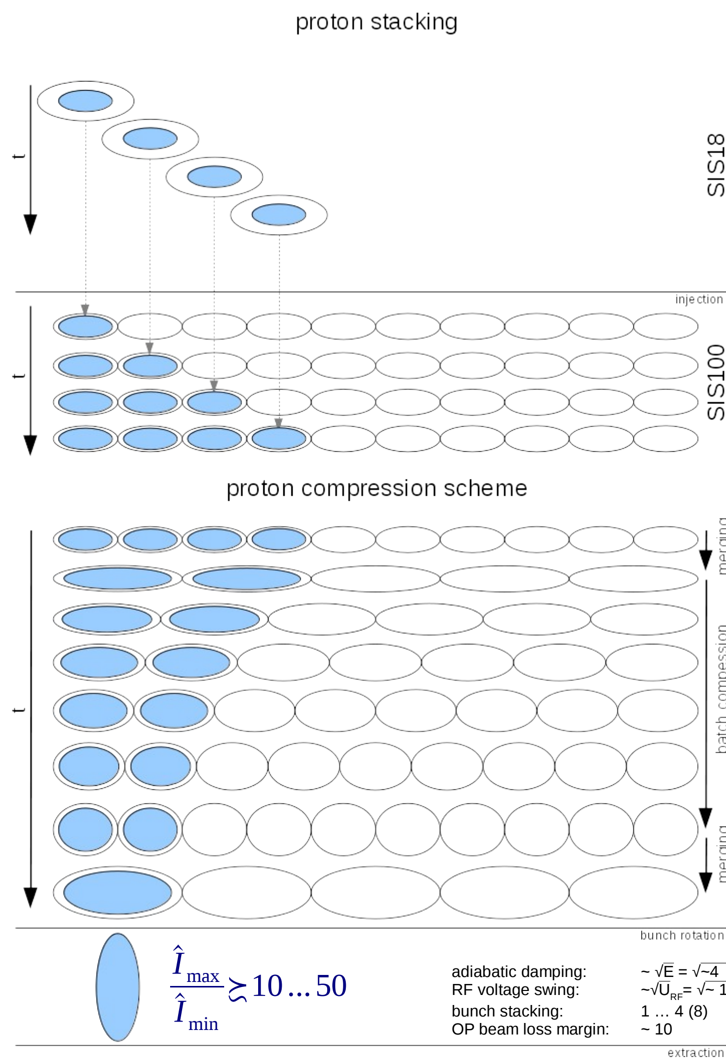
- Experience with slow extraction in SIS18 seem to indicate a fair machine/orbit reproducibility (on the sub-mm level) for regular cycling
  - quantitative estimates would be beneficial

U^{28+} & Proton – BCMS Bunch Compression & Merging Scheme



$$\frac{\hat{I}_{max}}{\hat{I}_{min}} \approx 50$$

x 10 (operation margin)
→ factor 500 (w/o LP)
→ factor <100 (w LP)



$$\frac{\hat{I}_{max}}{\hat{I}_{min}} \gtrsim 10 \ldots 50$$

adiabatic damping:	$\sim \sqrt{E} = \sqrt{\sim 4 \rightarrow 29\ \mathrm{GeV/c}}$	≈ 2.5
RF voltage swing:	$\sim \sqrt{U_{RF}} = \sqrt{\sim 10 \rightarrow 200\ \mathrm{kV}}$	≈ 4
bunch stacking:	1 … 4 (8)	
OP beam loss margin:	~ 10	

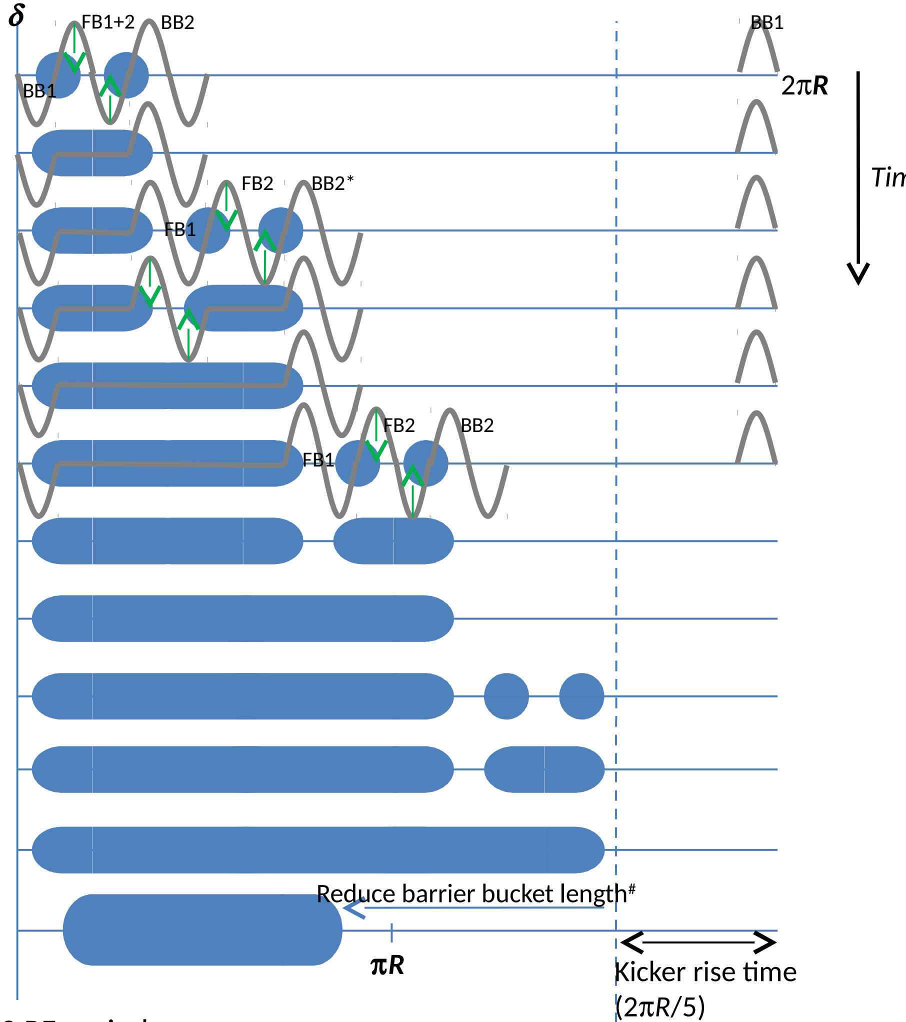
Alternate SIS100 Injection Scheme
M. Kirk et al. (tentative)

Inject from SIS-18 into 2 mono-h buckets:

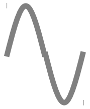
FB1 and FB2 suddenly reappear 1 and 2 RFPs to the right, respectively:

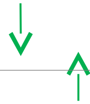
FB1 and FB2 each suddenly reappear 2 RFPs to the right:

***Option**: after this point, gradually form 8 bunches with the h=10 CW cavities.*



Barrier Bucket cavities:
BB1 (15 kV)
BB2 (15 kV)
Longitudinal Feed-Back cavities:
FB1 (15 kV)
FB2 (15 kV) N.b. TDR 10 kV each.


RF waveform over a single RF Period (RFP)


Direction of change in RF during merging

* BB2: fast change in phase by 2 RF periods.

Alternative for preparation of beam into a h=2 bucket for bunch rotation.

Operational Robustness

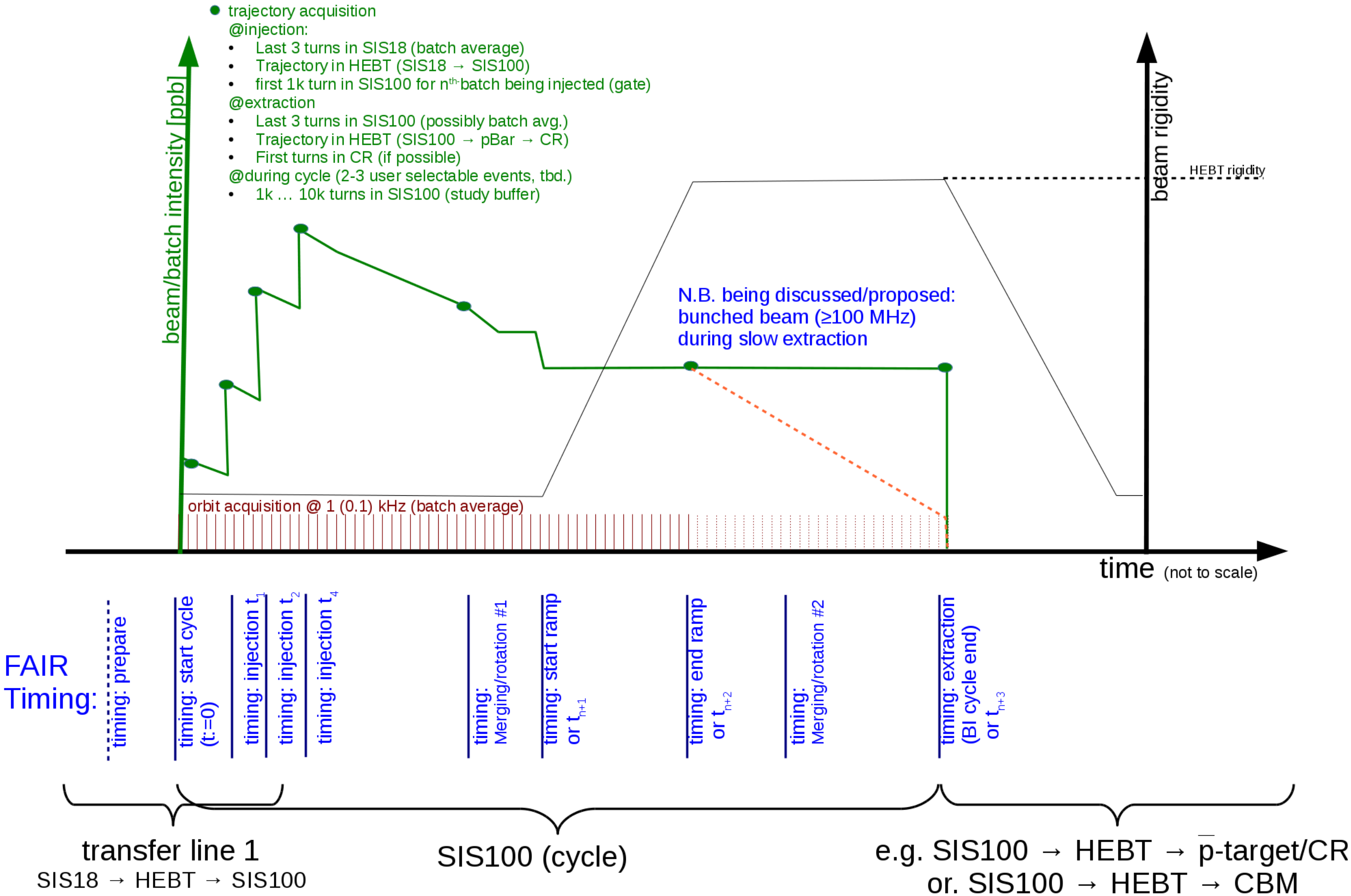
- FAIR beam parameters vary widely for different species but also within a given cycle setup (e.g. p-bar chain in SIS100):
- BPMs need to be able to cope with:
  - > 10 x bunch length variations
    - adiabatic damping: $\sim\sqrt{E} = \sqrt{\sim 4 \rightarrow 29\ \text{GeV/c}} \approx 2.5$
    - RF voltage swing: $\sim\sqrt{U_{RF}} = \sqrt{\sim 10 \rightarrow 200\ \text{kV}} \approx 4$
    - transition crossing
  - ~ 4 peak signal change (bunch merging/compression scheme)
  - > 90% beam intensity loss during any given cycle
    - dynamic vacuum, UNILAC variations, …
    - also bunch-by-bunch
  - Insensitive to bunch-by-bunch/filling pattern
    - Having a high lower-cut-off frequency is good in this respect
    - Also simplifies base-line restitution
  - typical BPM spec: 30-40 dB instantaneous dynamic range (cable reflections are the limit)

SIS18/SIS100 Closed Orbit & Trajectory Control Tolerances – DRAFT

			precision		
			$\lvert\Delta x\rvert_{max}$ [$\sigma_{r.m.s.}$]	$\lvert\Delta x\rvert_{max}$ [mm]	Ref
CO1	Aperture constraints	mechanical aperture vs. ± n·'beam size'	< 0.5	4	tbc.
CO2	Local orbit at critical points	Collimators hierarchy: local vs. global aperture	1...1/3?		tbc.
CO3		Septa (slow-extraction)	1/3...1/10	??	tbc.
CO3		other aperture constraints		??	tbc.
CO4	Feed-down minimisation	• 'ΔQ < 0.001' (slow-extraction) • dynamic aperture		1??	tbc.
CO5	Active Systems	• centring orbit in RF cavities: minimising field transients & synchro-betatron resonances • TFS/Schottky: improves gain/bandwidth • Interlock BPMs: improves reliability/safety	min.	0.2	tbc.
TR1	Emittance preservation	Injection/extraction mismatch target: • 'Δε/ε < 10%' trans. emittance blow-up • 'Δp/p < 10-3' long. emittance blow-up	1/5	1 … 0.2	X
TR2	Optics Measurement	Beta-beat via phase-advance measurement (relative measurement ↔ resolution)		<0.1 … 0.2 & σ(φ) < 0.3°	X
TR3	extr. channel acceptance	aperture constraints		4	
TR4		collimators		??	
TR5		fixed target (e.g. $\bar{p}$-Target)/machine interfaces		0.25	X

N.B.SIS100-protons inj: $\sigma_{x,y} \approx 7.7, 3.6$ mm extr: $\sigma_{x,y} \approx 3.1, 1.8$ mm (@ β = 18 m)

Trajectory/Orbit Acquisitions I/II
SIS100 Cycle Example



Trajectory/Orbit Acquisitions II/II
Expected FESA Data Streams (Concentrator)

Following modes of acquisition would be expected to be served simultaneously (though some of them could be implemented as down-sampled copies of the higher bandwidth acquisition):

A. Slow-acquisition (FESA property: e.g. 'Orbit'):
   1) Cycle-based acquisition: SIS100 typ. 100 Hz for Archiving System (1k Hz for OP/MDs) → complete trace as a function of time at the end of the cycle
   2) Continuous real-time data publication during the cycle: typ. update rates are around 10-25 Hz for user-level applications or software-based real-time feedbacks
   3) Individual samples at specified times in the cycle: → software interlock on orbit deviations

B. Fast turn-by-turn acquisition (FESA property: e.g. 'Trajectory'):
   1) average batch trajectories in HEBT/HEST (possibly different device)
   2) First 1000 turns for 1st, 2nd, … nth injection
      - Default & 1st injection: average batch position
      - ≥ 2nd inj.: gated turn signal on newly injected batch
   3) Last 3 turns → injection/extraction steering
   4) 1..3 study buffers with 10... 100 k turns (to be discussed)
      - data should be retained for one sequence and can be overwritten in subsequent sequences
      - event time window may overlap with above reduced acquisition (e.g. BCMS & last turn).

C. Post-Mortem (FESA property 'PostMortem'): not finalized yet but provisionally, it can be foreseen that:
   1) first circular buffer storing the orbit @ 1 kHz for the last second of beam or full cycle
   2) second circular buffer storing the last 1k (10k?) turns.

BPM SW Requirements I/II

- All BPM data available from one single source/concentrator
- Expect two separate FESA properties: Orbit & Trajectory
  - N.B. 'Orbit' and 'Trajectory' assumed to be based on turn averages (ie. no bunch-by-bunch → other property for optics control & MD purposes)
- Expected 'Orbit' & 'Trajectory' information (e.g. 2D arrays: BPM index, time):

A) Average position: $\overline{x}(t_i)=[x_0(t_i), x_1(t_i), \ldots, x_i(t_i)]^T$

- Orbit: fixed 1 kHz rate or user-defined time stamps (adaptive rate)
- Trajectory: always first turn (injection), last turn (extraction), + user defined timing events

B) Measurement noise/error: $\overline{\sigma}(t_i)=[\sigma_0(t_i), \sigma_1(t_i), \ldots, \sigma_i(t_i)]^T$

- Error propagation of actual averaging variance and known HW noise (e.g. ADC, amplifier)

C) Relative (qualitative) sum signal $\Sigma = [-1, +1]$ w.r.t. ADC range

- allows: cross-checks of ADC range w.r.t. amplifier gain & relative loss localisation

D) BPM statuses (32/64 bit mask)

- de-selection masks (BI expert, OP), ADC status, timing errors, bunch detection errors, temperature control, range checks, transient errors, etc.

BPM SW Requirements II/II

- SIS18/100 - one-to-one mapping: Quads ↔ CODs ↔ BPMs
  - no singularities by design – good
  - But no redundancy: any missing BPM/COD may cause bump in that region
  - for details see later SVD analysis
- BPM targeted data transfer performance
  - Latency: a priori less of an issue for cycle-to-cycle feedbacks
    - Assumption: data can be read out within ~ 1 s → to be verified
    - Orbit sampling (SIS100) at e.g.:
      - t_s= 10 ms (100 Hz) → 100 orbits/cycle (1s) → < 2.7 kByte/s – non issue
      - t_s= 5 ms (200 Hz) → 200 orbits/cycle (1s) → < 0.5 MByte/s – OK
      - t_s= 1 ms (1 kHz) → 1000 orbits/cycle (1s) → ~ 2.6 Mbyte/s – bit more challenging but possible
    - Need to see whether we need constant sampling or whether we can increase/decrease sampling in relation to e.g. the ramp rate, optics changes, slow-extraxtion start etc.
- N.B. need to check whether 'LSA trim' supports these speed and latencies

SIS100 BPMs: Input to Archiving

FAIR Archiving Variable Definition & Estimates

…, only known most volume intensive sources)

…f n-dim array…

#Devices	Property/ Group	Variable Name (time-stamp included per Property/group)	Brief Description	Variable Type	SI unit	#entries dim-1	#entries dim-2	Post-Mortem?	Archiving==PM Data Structure?	Is FESA Device?	Expected Data Rate	Long-term Storage Needed?	Data Reduction Possible?	Comments	internal: data rate	internal: [bytes]	int: bandwidth [bytes/s]	int: bandwidth [Mbytes/s]		
36	Measurement	Current	meas. current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO	(12 quadrupole correctors, 12 sextupole correctors, 12 octupoles correctors)	100	4	14400	0		
36	Measurement	RefCurrent	reference current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO		100	4	14400	0		
36	Measurement	Voltage	meas. Voltage	Float (32 bits)	[V]			YES	YES	YES	100 Hz	YES	NO		100	4	14400	0		
36	Measurement	RefVoltage	reference voltage	Float (32 bits)	[V]			YES	YES	YES	100 Hz	YES	NO		100	4	14400	0		
36	Measurement	Status	power converter status bit-mask	Integer (32 bits)	[]			YES	YES	YES	100 Hz	YES	NO		100	4	14400	0		
36	Measurement	PCTemperature	power converter temperature	Float (32 bits)	[°C]			NO		YES	0.1 Hz	NO			0.1	4	14.4	0		
36	Measurement	CableTemperature	cable temperature	Float (32 bits)	[°C]			NO		YES	0.1 Hz	NO			0.1	4	14.4	0	Sum:	
36	Measurement	EarthFault	earth fault current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO		100	4	14400	0	0.08	[MB/s]
															0	0	0	0		
166	Measurement	Current	meas. current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO	(164+2 slow orbit correctors)	100	4	66400	0		
166	Measurement	RefCurrent	reference current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO		100	4	66400	0		
166	Measurement	Voltage	meas. Voltage	Float (32 bits)	[V]			YES	YES	YES	100 Hz	YES	NO		100	4	66400	0		
166	Measurement	RefVoltage	reference voltage	Float (32 bits)	[V]			YES	YES	YES	100 Hz	YES	NO		100	4	66400	0		
166	Measurement	Status	power converter status bit-mask	Integer (32 bits)	[]			YES	YES	YES	100 Hz	YES	NO		100	4	66400	0		
166	Measurement	PCTemperature	power converter temperature	Float (32 bits)	[°C]			NO		YES	0.1 Hz	NO			0.1	4	66.4	0		
166	Measurement	CableTemperature	cable temperature	Float (32 bits)	[°C]			NO		YES	0.1 Hz	NO			0.1	4	66.4	0	Sum:	
166	Measurement	EarthFault	earth fault current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO		100	4	66400	0	0.38	[MB/s]
															0	0	0	0		
11	Measurement	Current	meas. current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO	(1 fast quadrupole, 2 magnetic injection septum, 1 Lambertson septum, 3 magnetic extractio…	100	4	4400	0		
11	Measurement	RefCurrent	reference current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO	comment rstein: variable lists probably too coarse needs to be detailed by system expert	100	4	4400	0		
11	Measurement	Voltage	meas. Voltage	Float (32 bits)	[V]			YES	YES	YES	100 Hz	YES	NO		100	4	4400	0		
11	Measurement	RefVoltage	reference voltage	Float (32 bits)	[V]			YES	YES	YES	100 Hz	YES	NO		100	4	4400	0		
11	Measurement	Status	power converter status bit-mask	Integer (32 bits)	[]			YES	YES	YES	100 Hz	YES	NO		100	4	4400	0		
11	Measurement	PCTemperature	power converter temperature	Float (32 bits)	[°C]			NO		YES	0.1 Hz	NO			0.1	4	4.4	0		
11	Measurement	CableTemperature	cable temperature	Float (32 bits)	[°C]			NO		YES	0.1 Hz	NO			0.1	4	4.4	0	Sum:	
11	Measurement	EarthFault	earth fault current	Float (32 bits)	[A]			YES	YES	YES	100 Hz	YES	NO		100	4	4400	0	0.03	[MB/s]
															0	0	0	0		
															0	0	0	0		
1	Orbit	Position_H	average beam position H	1D-array of integers (32 bits)	[m]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	336	33600	0		
1	Orbit	Position_V	average beam position V	1D-array of integers (32 bits)	[m]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	336	33600	0		
1	Orbit	Ref_Position_H	reference beam position H	1D-array of integers (32 bits)	[m]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF…	N.B. reference does compress significantly since it is nearly constant function from one cy…	100	336	33600	0		
1	Orbit	Ref_Position_V	reference beam position H	1D-array of integers (32 bits)	[m]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	336	33600	0		
1	Orbit	StDev_H	stdev of orbit H	1D-array of floats (32 bits)	[m-rms]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	336	33600	0		
1	Orbit	StDev_V	stdev of orbit V	1D-array of floats (32 bits)	[m-rms]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	336	33600	0		
1	Orbit	Sum_H	rel. pick-up sum signal H	1D-array of floats (32 bits)	[a.u.]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	336	33600	0		
1	Orbit	Sum_V	rel. pick-up sum signal V	1D-array of floats (32 bits)	[a.u.]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	336	33600	0		
1	Orbit	Status_H	status bit-mask H	1D-array of integers (64 bits)	[]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	672	67200	0		
1	Orbit	Status_V	status bit-mask V	1D-array of integers (64 bits)	[]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	672	67200	0		
1	Orbit	Mask_H	used/selected for steering/measurement…	1D-array of booleans	[]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	84	8400	0		
1	Orbit	Mask_V	used/selected for steering/measurement…	1D-array of booleans	[]	84	2	YES	YES	YES	100 Hz	YES	YES, if (!BPF)		100	84	8400	0		
1	Trajectory	Position_H	Single-pass trajectory H	2D-array of floats (32 bits)	[m]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF…	e.g. First 1000 turns at injection, last 10 turns at extraction + user selected timing (variable)	1	504000	504000	0		
1	Trajectory	Position_V	Single-pass trajectory V	2D-array of floats (32 bits)	[m]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	504000	504000	0		
1	Trajectory	StDev_H	Noise-estimate H	2D-array of floats (32 bits)	[m-rms]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	504000	504000	0		
1	Trajectory	StDev_V	Noise-estimate V	2D-array of floats (32 bits)	[m-rms]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	504000	504000	0		
1	Trajectory	Sum_H	rel. pick-up sum signal H	2D-array of floats (32 bits)	[a.u.]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	504000	504000	0		
1	Trajectory	Sum_V	rel. pick-up sum signal V	2D-array of floats (32 bits)	[a.u.]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	504000	504000	0		
1	Trajectory	Status_H	status bit-mask H	1D-array of integers (64 bits)	[]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	672	672	0		
1	Trajectory	Status_V	status bit-mask V	1D-array of integers (64 bits)	[]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	672	672	0		
1	Trajectory	Mask_H	used/selected for steering/measurement…	1D-array of booleans	[]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	84	84	0		
1	Trajectory	Mask_V	used/selected for steering/measurement…	1D-array of booleans	[]	84	1500	YES	YES	YES	1 Hz	YES	YES, if (!BPF)		1	84	84	0	Sum BPMs:	
1	Status	Temperature	temperature of AFE, etc.	1D-array of floats (32 bits)	[°C]	84	10	YES	YES	YES	1 Hz	YES	YES, if (!BPF…	note: 1st-dim used to account for temperature of sub-components	1	336	336	0	3.29	[MB/s]

Summary | SIS100

Assumption:

- Single Concentrator handling (/republishing) 84 BPMs @ 100 Hz → 3.3 MB/s
  - N.B. Raw BPM Concentrator Data Rate ~ 32 MB/s (Orbit @ 1 kHz, 10 x 1.5k turn Acq/s)

Tentative List of Known Users/Use-Cases

A. Cycle-to-Cycle Feedbacks:
   1. Injection Steering *<orbit & trajectory>*
   2. Extraction Steering *<orbit & trajectory>*
   3. SW Orbit-FB during ramp (& Radial-Loop) *<orbit only>*

B. Archiving System
   1. Regular/OP Archiving *<orbit & trajectory>*
   2. Post-Mortem System *<primarily trajectory>*

C. Software Interlock System *<orbit & trajectory>*

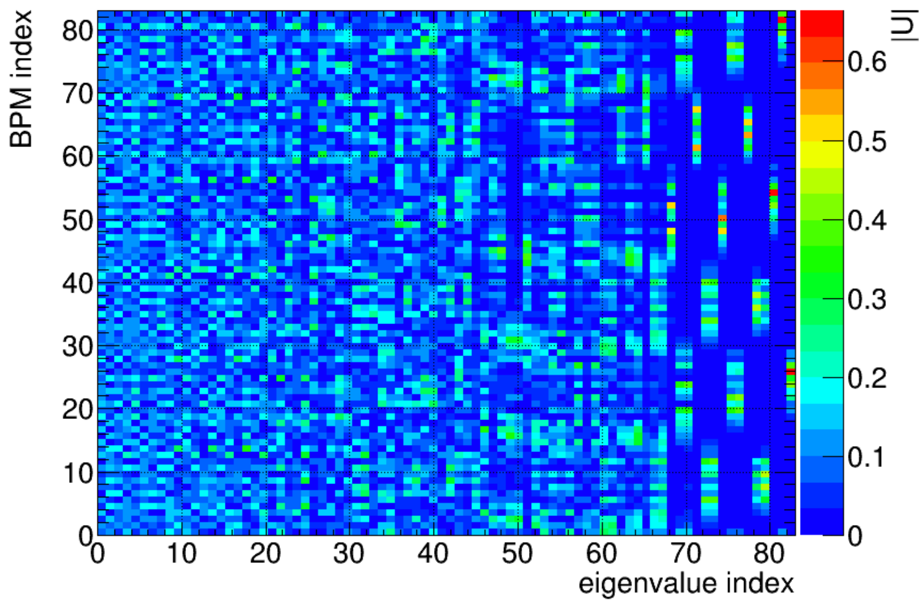
D. Optics Measurement
   1. LOCO-based *<primarily orbit & trajectory>*
   2. Optics via phase-advance *<primarily trajectory>*

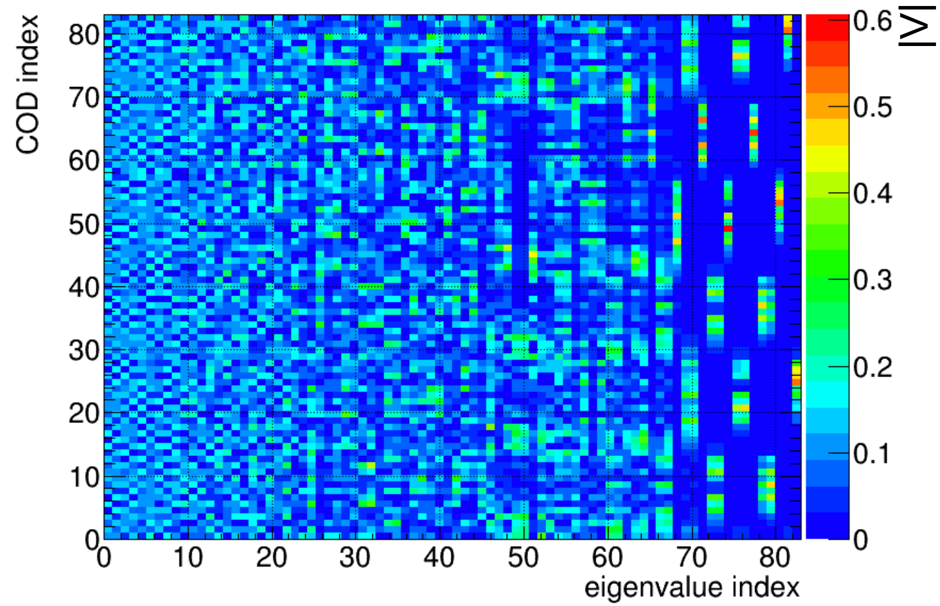
E. Machine Specific Clients
   1. Multi-Turn Injection Optimisation (SIS18) <orbit & trajectory (1-10k)>
   2. Collimator/Cleaning set-up (SIS100) *<orbit>*
   3. *MPS validation (SIS100) <orbit & trajectory>*
   4. *Luminosity Steering (HESR) <orbit & trajectory>*

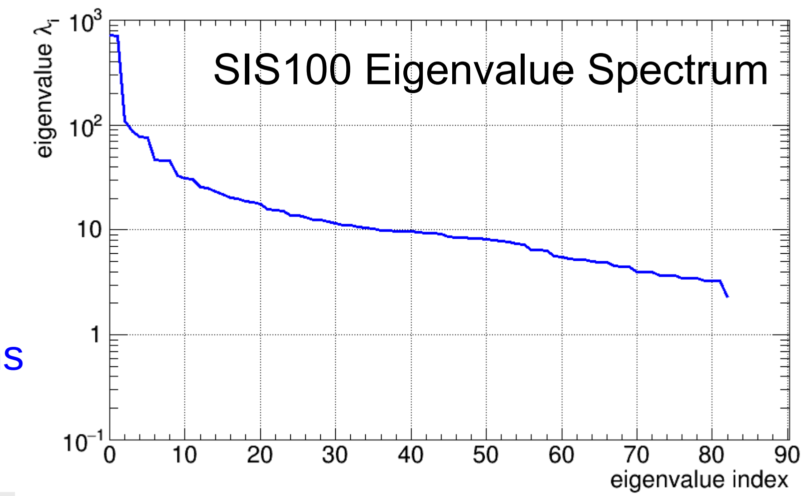
F. Machine-Development – all of the above and beyond *<orbit & trajectory>*

G ...

SIS100 Eigenvector-Matrices

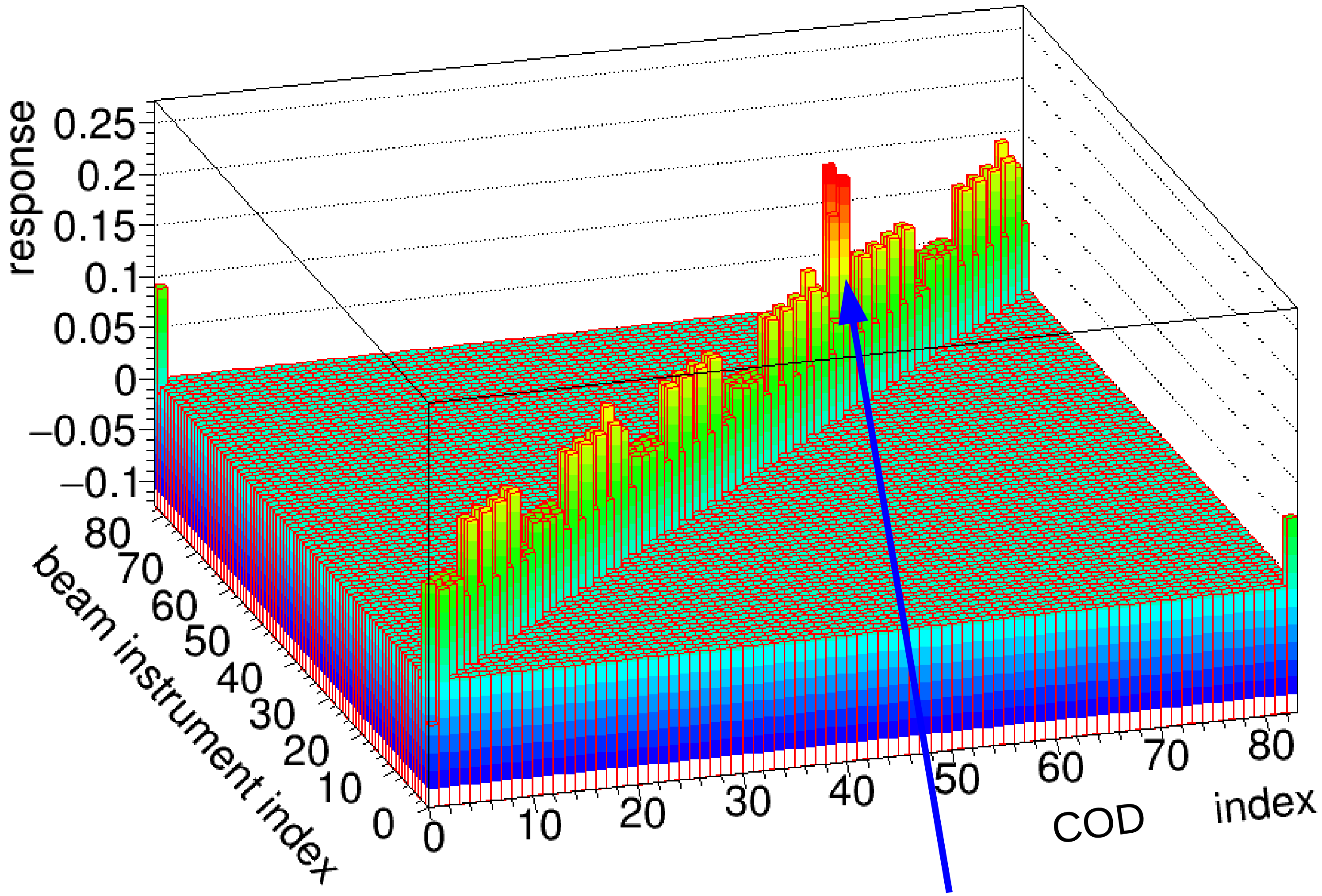






- Eigenvector matrices:
  - U (left) – orthogonal basis for BPMs
  - V (left) – orthogonal basis for CODS
- To note:
  - higher eigenvalues → more local corrections
  - six-fold symmetry visible

Full Inverse COD→BPM Response Matrix



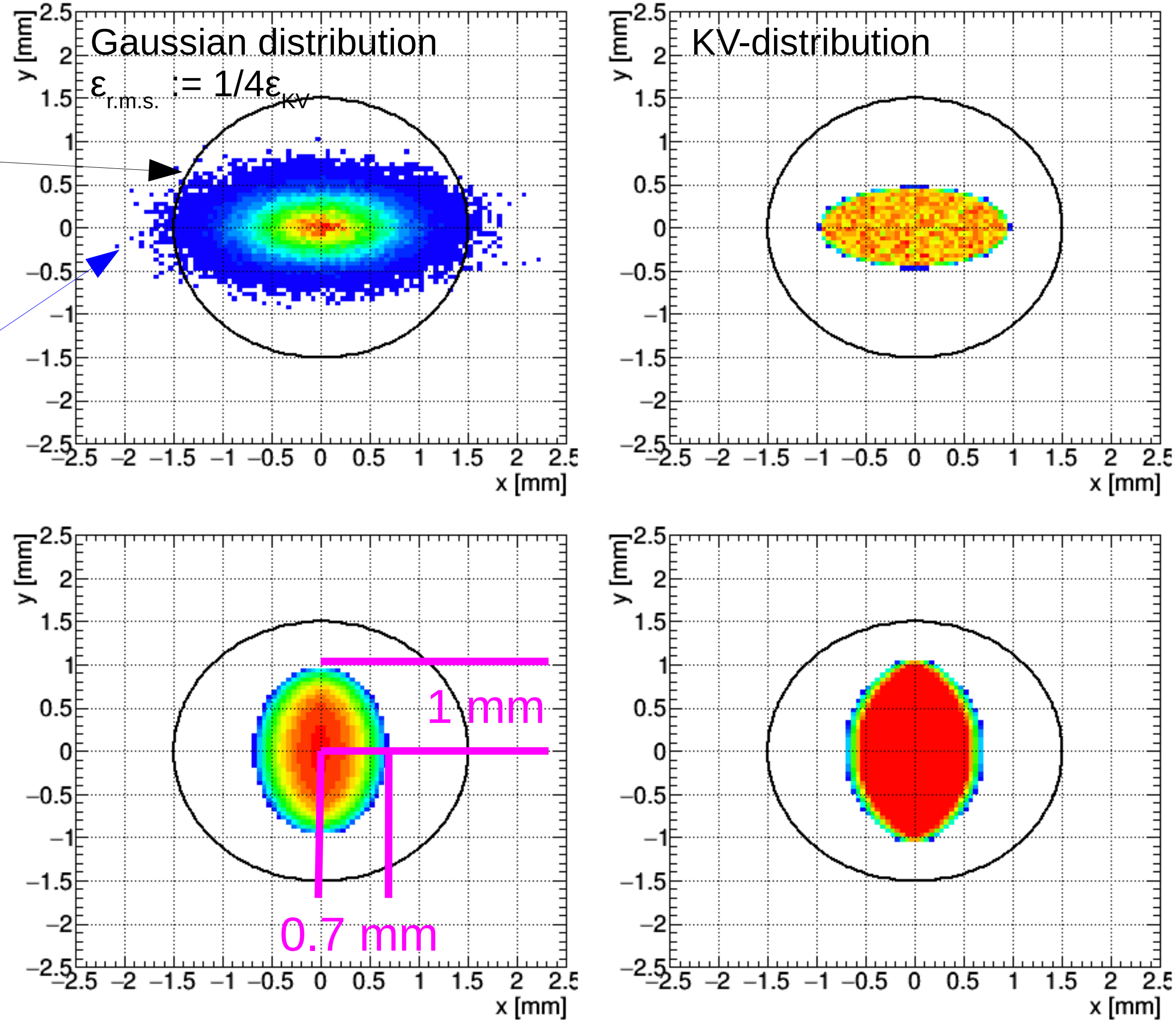
N.B. near singularity around extraction (ie. Correction sensitive to BPM noise)

Required pbar-Target Position Stability
Asymmetric Beams

target

N.B. <0.2% of particles outside

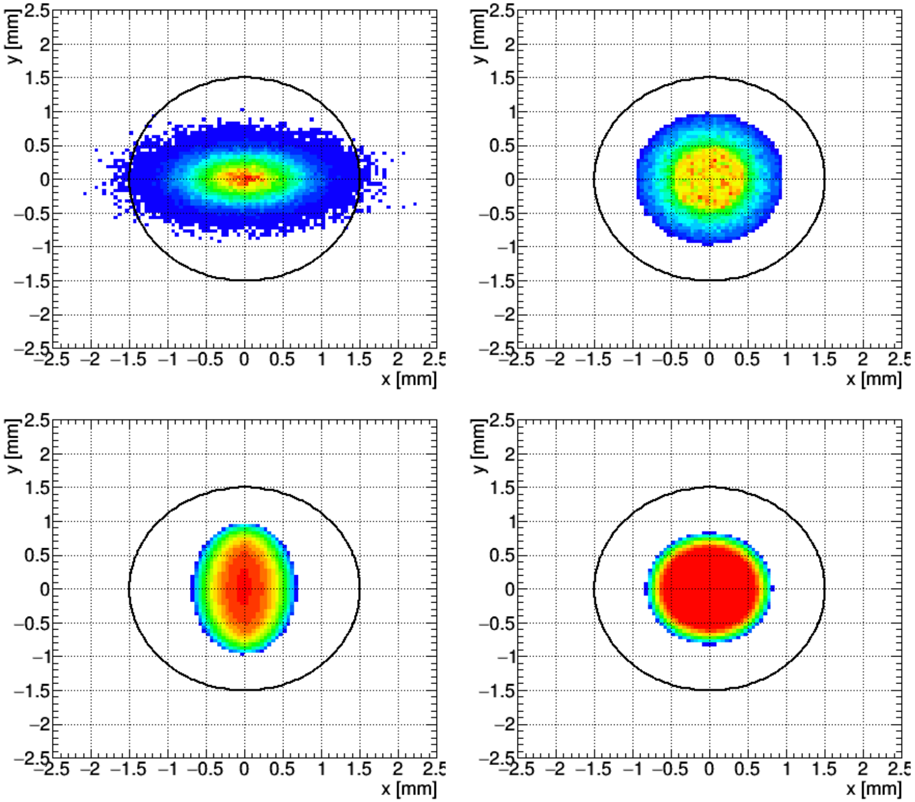
Red = 100% interaction with target
Blue: 95% interaction with target



Convolution:

Beam profile
•
Target

Required pbar-Target Position Stability
Round Beams (e.g. via skew-quads in SIS18)



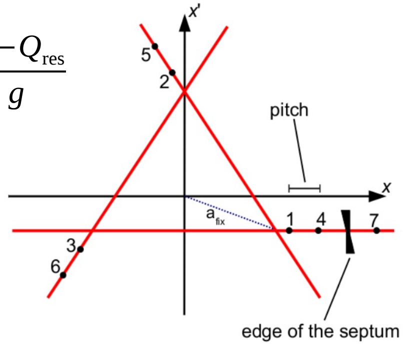
- Gain: ~ 0.1 mm in H for round beams → ± 0.8 mm peak-to-peak variations allowed
- Goal: achieve 95% transmission for 99% of all shots → position control < ~ 250 um
  - Present BPM performance has about 1 mm resolution → needs to be improved (e.g. using hybrids & LP filter)

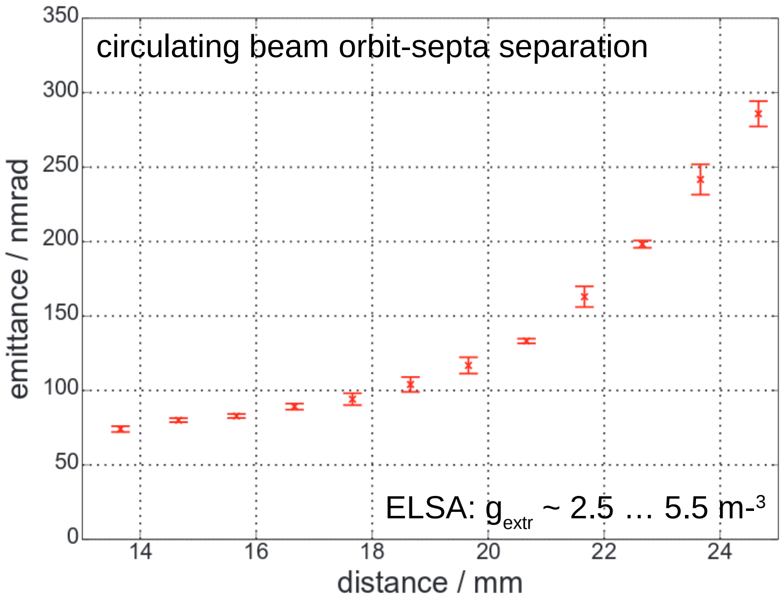
SIS18/SIS100 Slow Extraction I/II

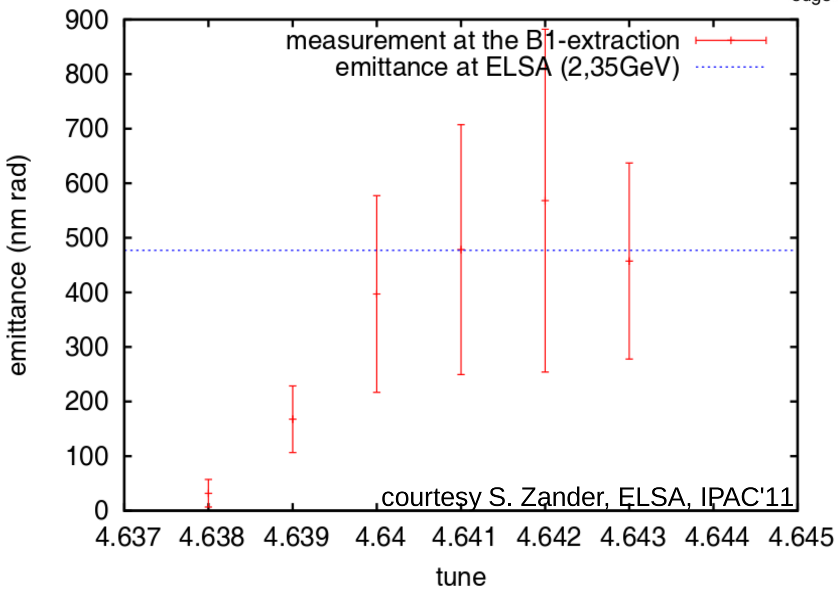
Experiences from ELSA (N.B. e-Machine)

- Slow-Extraction dependence on
  - circulating beam orbit ↔ septa position
  - Feed-down in sextupoles → change of ΔQ & Δβ/β
- Qualitative results from ELSA (hor. emittance ~ step width/efficiency):

$$a_{fix} \propto \frac{Q - Q_{res}}{g}$$



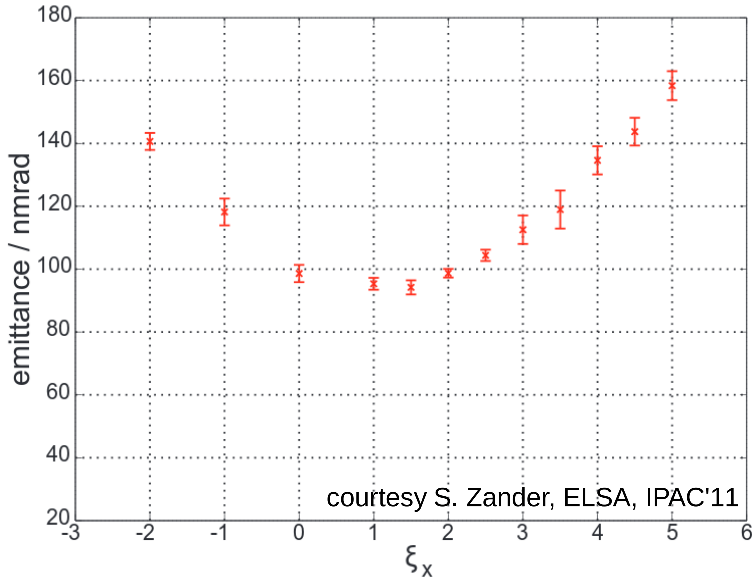


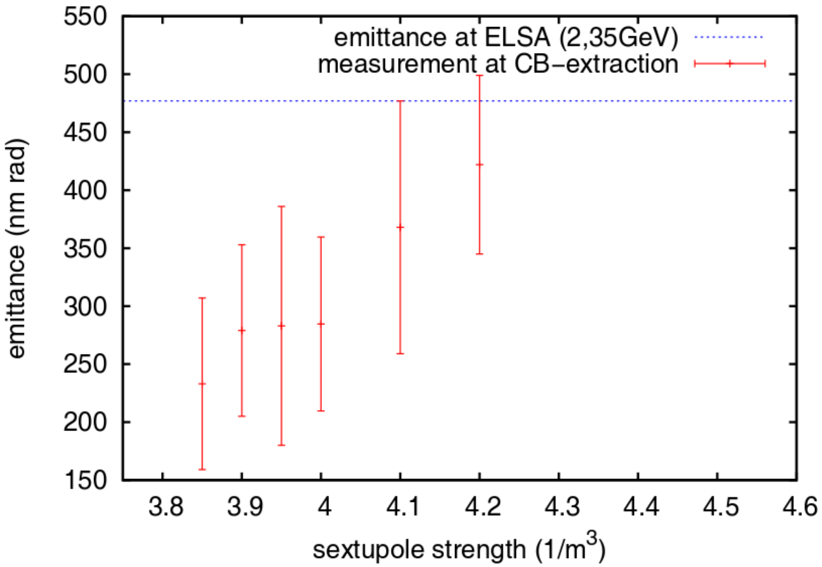


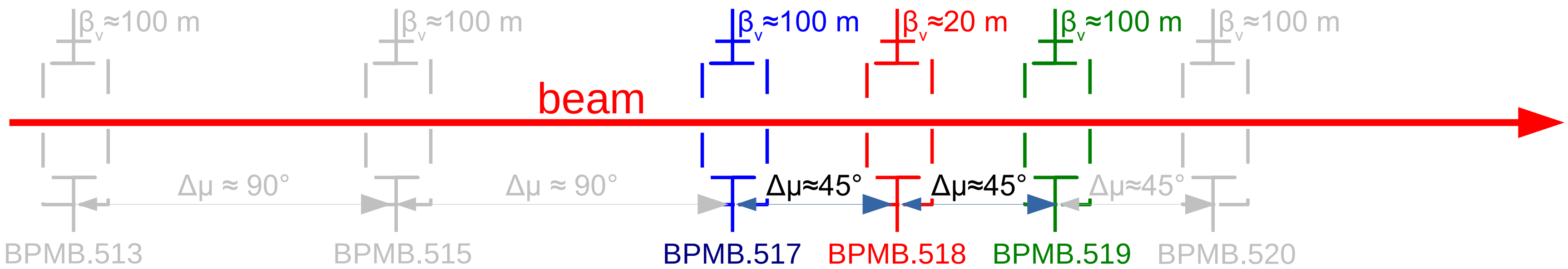
- may consider checking this quantitatively also for SIS18/100 parameters

SIS18/SIS100 Slow Extraction II/II
Experiences from ELSA (N.B. e-Machine)

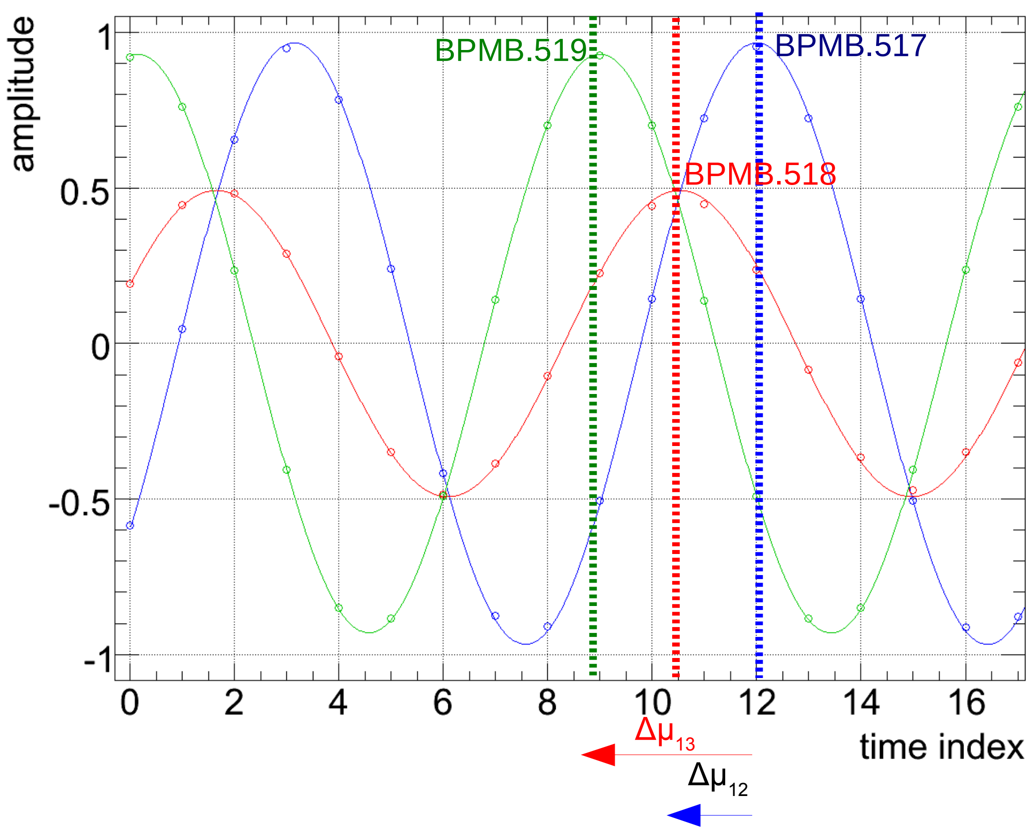
- Dependence on chromaticity & sextupole strength
  - emittance becomes larger near resonance







- Measurement (markers), sinusoidal fit (solid line):



$$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

$$\frac{\Delta\beta_2}{\beta_2} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{23}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{23}^{theo.})}$$

$$\frac{\Delta\beta_3}{\beta_3} = \frac{\cot(\Delta\mu_{23}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{23}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

[1]P.Castro, *Luminosity and Betatron Function Measurement at [..] LEP*, CERN SL/96-70 (BI)

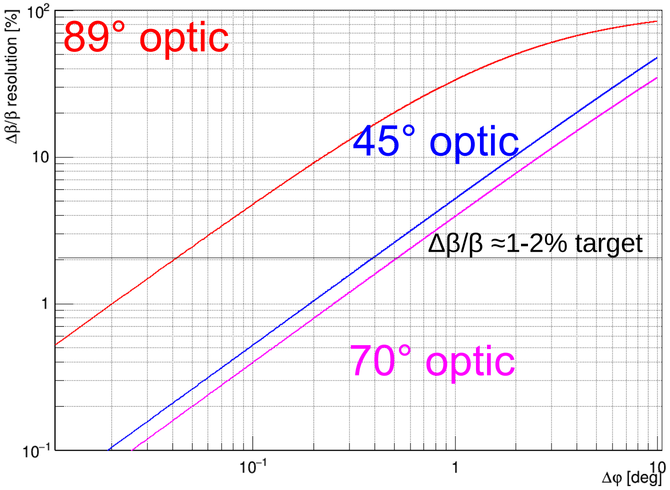
Beta-Beat Measurement Sensitivity

- Residual resolution/systematic error

$$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

$$\Delta\mu_{1i}^{meas.} := \Delta\mu_{1i}^{theo.} + \Delta\varphi_{1i}$$

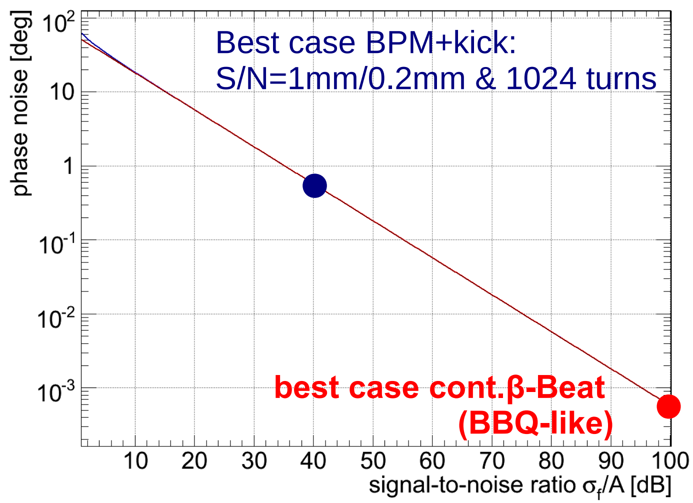
  - 45° optics: requires error below ~1°
  - 89° optics: requires error below ~0.02°



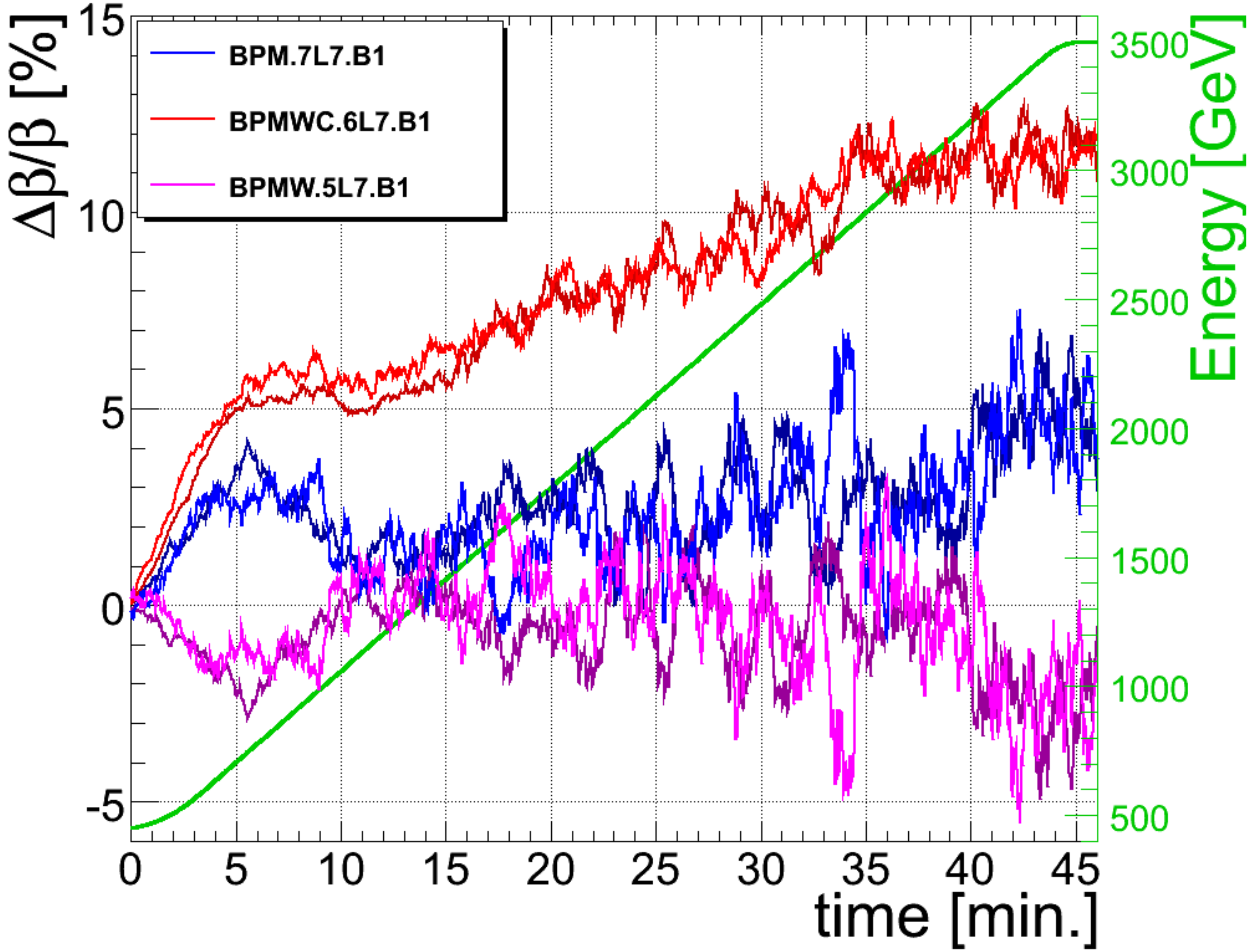
- Statistical noise adds vectorial to the carrier signal:
  - excitation amplitude (carrier signal): A
  - noise in time (frequency) domain: σ_t (σ_f)
  - Equivalent number of turns: N

$$\sigma(\varphi) = \arcsin\left(\frac{\sigma_f}{A}\right) = \arcsin\left(\sqrt{\frac{2}{N}}\frac{\sigma_t}{A}\right)$$

for small noise to signal ratios $\approx \sqrt{\frac{2}{N}}\frac{\sigma_t}{A}$



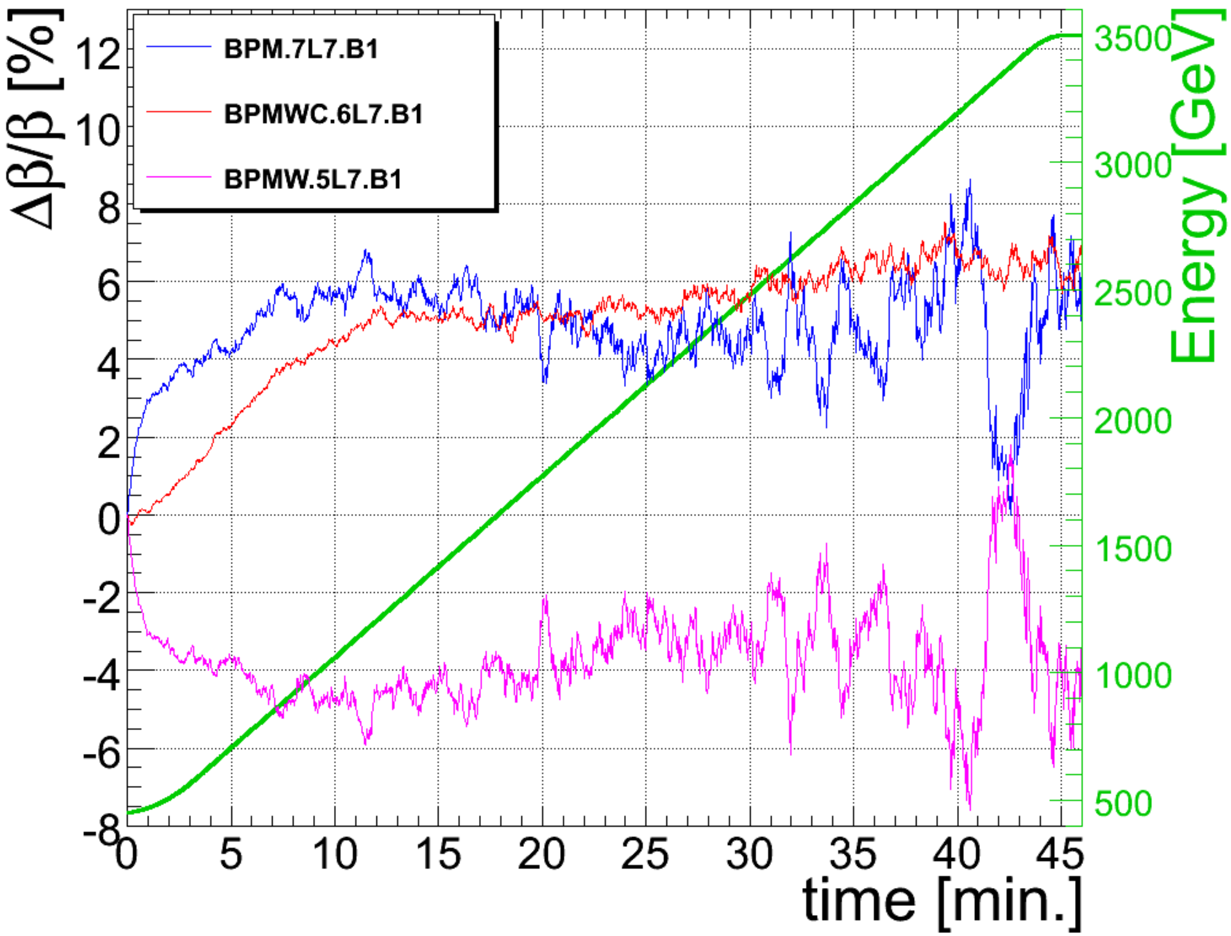
Example: LHC Beta-Beat during the Energy Ramp I/II – Reconstructed Local Beta-Beat



- Excellent fill-to-fill reproducibility of about 1% – provided machine underwent a standard magnetic pre-cycle and no quenches have occurred.
- Complemented also by Rogelio's reproducibility assessment

Example: LHC Beta-Beat during the Energy Ramp II/II – Evolution during a "less-perfect" Ramp

- 3/8 main dipole circuits being pre-cycled to 2 kA instead of the default 6 kA.
- Percent-level correction of the transfer function of one of the warm quadrupole magnet in the vicinity of the test setup



- Still, small compared to required dynamic beta-beat of $\Delta\beta/\beta|_{max} < 20\%$

Appendix

LHC BPM Specification

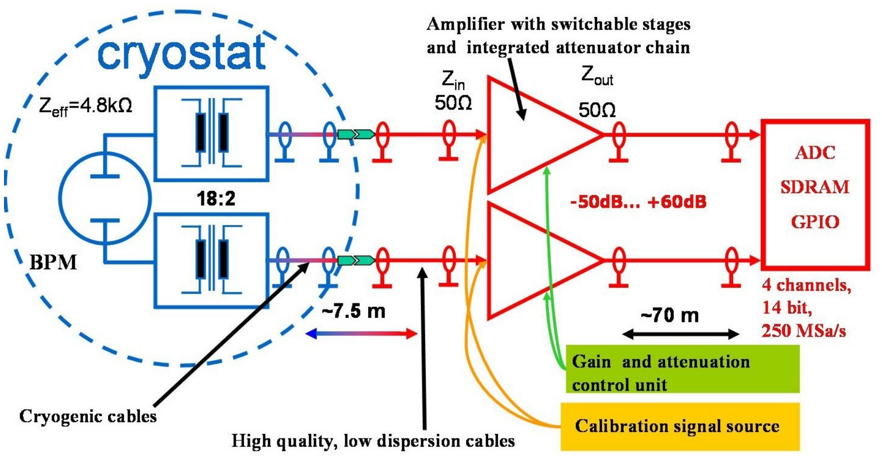
- LHC-BPM-ES-0004 rev. 2.0, EDMS #327557, 2002, p. 25:

	Measurement	P	Range	Accuracy	Scale error	Offset	Non-linearity	Resolution
				peak	peak	peak	peak	rms
Beam threading	TR2	*	R2	±2000µm	+	+	+	+
Close trajectory on itself	TR3	*	R1	±500µm	+	NR	+	+
Position error at injection	TR4	*	R1	±500µm	+	NR	+	+
			R1	±50µm	+	NR	+	+
Momentum mismatch detection at injection	TR5	*	R1	±1500µm	+	NR	+	+
			R1	±250µm	+	NR	+	+
Optics and local Q' checks	TR7/TR8	*	± 1 mm ⊂ R1	±400µm	+	NR	+	+
				±50µm	±4%	NR	+	+
	TR11		R2		NR	NR	±500µm	50µm
Aperture optimisations	CO2	*	R1	±500µm	+	±250µm (±750µm)	+	+
LHC Collimation/Orbit FB	CO3		± 1 mm ⊂ R1	±20µm	NR	NR	NR	+
Orbit at injection elements	CO4		± 1 mm ⊂ R1	±30µm	+	+**	+	+
Position error at injection	CO7		R1			±100µm	±200µm over ±4mm	1000µm
Momentum FB (radial loop)	CO8		R1	±250µm	+	NR	+	+
Dispersion measurements	CO9 IP		± .1 mm ⊂ R1	±15µm	+	NR	+	+
	CO9 other		± 1 mm ⊂ R1	±175µm	+	NR	+	+
b2/a2 to b4/a4 (~TOTEM)	CO14		± .1 mm ⊂ R1	±10µm	+	NR	+	5µm

Are we happy with this type of format? Other constraints? Open...?

BPM System Design & pres. Specifications (f-ds-bd-22e_pos_bpm_1s_v1.0a)

- Accuracy: < 1 mm
  - With k-modulation < 0.2 mm
    - limited to few BPMs at beginning/end of arcs (~12 (24?) out of 84 BPMs)
  - Need other alternatives → RF commutation switches
- Resolution
  - Orbit: ~ 0.1 mm @ 1 kHz
    - OK w.r.t. keeping Δx(s) < 1mm
    - N.B. incompatible with Fast-OFB → possible emittance blow-up
  - Trajectory/turn-by-turn resolution: ~ 1mm
    - Insufficient for target steering & optics measurement → should aim at 0.1 (0.2) mm

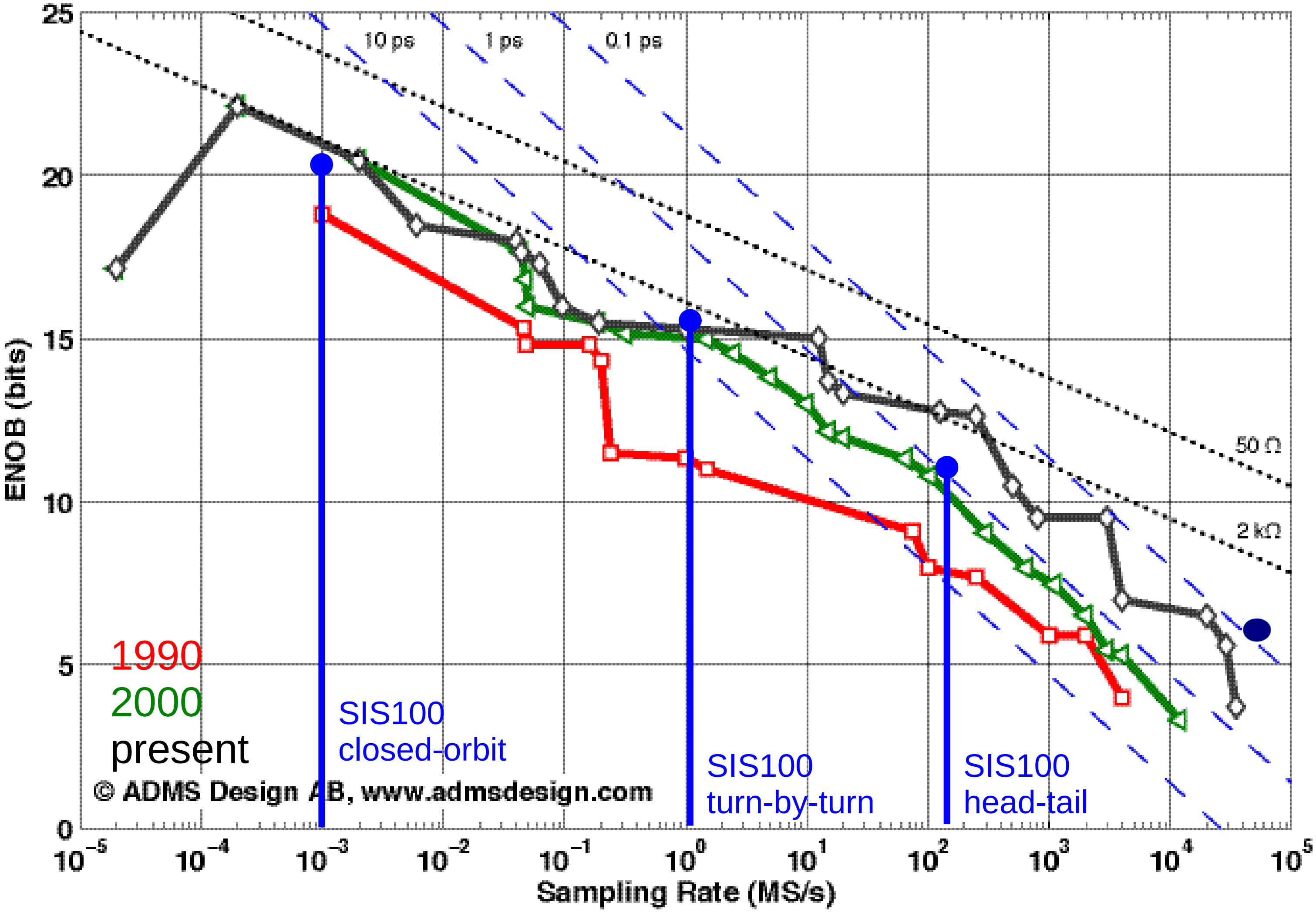


- um-level orbit resolution is not a requirement but a consequence of required turn-by-turn resolution in the order of 100-200 um
  - K.O. exciter as A.C. dipole can produce oscillation amplitudes in the order of 100 um ↔ 500 um → need S/N of ideally > 5/1 → turn-by-turn resolution of ~100 um

$$\sigma_{orbit@1\,kHz} \approx \underbrace{\frac{1}{\sqrt{n_{turns}}}}_{\approx 17} \cdot \sigma_{single-shot@278\,kHz}$$

Robustness? Why are RF hybrids & LPF/BPF omitted for SIS18 & SIS100 BPMs? Review?
↔ N.B. other (very) similar machines at BNL (AGS) & CERN (PS, PSB, SPS) use them for a good reason.

Limits of Direct Time-Domain Digitization



Proposal

- BPM-ECR: deploy RF hybrid, low-pass filter & RF commutation switches
  - Improve what is important: reliability/robustness of orbit & trajectory measurement
    - ie. don't need 83 'Head-Tail Monitors' that can also measure the orbit/trajectory
    - Ensure function under non-ideal conditions, setup, and commissioning (the “bad days”)
  - Modification proposals:
    - RF hybrid: improves resolution but also accuracy for the mostly centred beams
      - robust centre determination (passive device: insensitive to signal level, power, radiation, gains, ...)
      - Implies ECR for decoupling amplifier gains for individual channels
      - Improved turn-by-turn resolution → enables optics measurement & control
      - Minimises the need for higher-amplitude and multiple kick-per-cycle Q-kicker
    - Low-pass filters:
      - minimise the bunch length & shape dependency
      - but also: improves more robust bunch trigger (more samples/bunch)
    - k-modulation not viable for all SIS100 BPMs to establish 1 mm accuracy target
      - RF commutation switches in front of RF-Hybrid would enable alternate solution
- Deploy 2 (+1) BPMs for the TFS System
  - Permit future vector-sum operation & redundancy for optimal optics
  - additional pick-up for Q/Q' & Head-Tail diagnostics
  - is diode-based base-band-tune (BBQ) Q/Q' technique considered base-line for SIS18/SIS100 operation? Integration?