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SPEAR 3: Orbit Stability and Corrector Noise Specs

1. Orbit stability specs:

$\Delta y < 0.1\,\sigma_y$ (= **3 μm rms** at IDs)

$\Delta y' < 0.1\,\sigma_{y'}$ (= **1.5 μrad rms** for 100-per undulator) [1]

- **< 5%** (or less) preferable (= 1.5 μm rms at IDs)
- over period T:

data integration time (μsecs) < T < hours (~24 h) [2]

2. Orbit noise power spectral density:

$$\langle \Delta y^2 \rangle = \int \mathrm{PSD}\, df$$

$$\Delta y\ (\text{peak}) = 3\text{-}5 \times \Delta y_{rms}$$ [3]

3. Sources of orbit instability:

- thermally induced mechanical motion (dominant)

    few μm vert. for 1°C girder temp change (⇒ ~30 μm orbit)

    beam-related chamber motion (small)

- mechanical vibration (sub-micron)

- stray fields

- power supplies

    drift (gain + offset) (± ~3°C diurnal ambient temp)

    noise spectrum:

        regulation level and bandwidth
        ripple
        DAC quantization noise

Want contribution from each of these sources to be << than total noise budget, if possible.

4. Orbit stabilization:

- Minimize sources of instability:

  tunnel temp stability ($\sim 1^{o}C$)

  water-cooled chamber

  decouple/damp vibration sources

  shield stray fields

  use low-noise, low drift power supplies

    limit contribution to ~10% of noise budget
    (<1% beam dimensions)

estimate ~10 - 50 μm vertical orbit stability without feedback (dominated by diurnal temp)

- Orbit Feedback:

  use 54 correctors per plane to stabilize beam at 90+ BPMs

  BPMs stable to ~3 μm vertically over 24 h

  100 Hz BW (3 dB); 2-4 kHz cycle freq

  Orbit resolution (averaged over fdbk cycle) ~1 μm

goal: stabilize beam at BPMs to ~ 3 μm vert. over 24 h, dominated by BPM motion

NOTE: Feedback adds noise in bandwidth ≥ cycle freq

5. Corrector-orbit response:

Orbit disturbance caused by DC kick θ_i from corrector i:

$$\Delta y(s) = \theta_i \frac{\sqrt{\beta_i \beta_s}}{2 \sin \pi \upsilon} \cos(|\varphi_i - \varphi_s| - \pi \upsilon) \qquad [4]$$

Assume $\beta_i = 8$ m, $\beta_s = 5$ m, $\upsilon = 5.23$:

$\Delta y_i(s, max) = 4.8\ \theta_i$ (peak around ring)

$\Delta y_i(s, rms) = 3.4\ \theta_i$ (rms around ring) [5]

6. Noise from many correctors:

For **uncorrelated** ensemble of N correctors (N = 54):

$$\Delta y_{tot}(s, rms) = 3.4\sqrt{N}\ \theta_i\ (rms) = 25\ \theta_i\ (rms) \qquad [6]$$

Limit noise contribution from correctors to **~10%** of total noise budget ---->limit $\Delta y_{tot}(s, rms)$ from correctors to **<1%** of vert beam size (0.3 μm rms) with **feedback on**:

$$\Rightarrow \quad \theta_i\ (\text{rms noise}) < 0.3\ \mu m / 25 = 0.012\ \mu rad\ rms \qquad [7]$$

$$\theta_i\ (\text{noise}) / \theta_{Vcorr}\ (FS) = .012/1500 = 8 \times 10^{-6} = 2^{-16.9} \qquad [8]$$

⇒ want **17 bit** rms beam noise from corrector kick **with feedback on**
Includes: - high freq filtering from vac chamber + magnets
- low freq noise attenuation by feedback

Feedback off: low-freq noise from 54 correctors ~10%-50% of vertical beam size ⇒ **14-11 bit** low freq stability

7. Orbit measurement resolution:

IF ADC ENOB:	12.2 bits
IF samples/turn:	50 ($\sqrt{50} = 2.8$ bits)
IF ADC ENOB/turn	15 bits/turn
ADC FS:	±14 mm
Digital res/turn:	0.85 µm/turn
RF-IF analog res/turn:	~1 µm/turn @ 500 mA
Total res/turn:	1.3 µm/turn @ 500 mA

Averages/feedback cycle: 160 @ 2 kHz cycle
80 @ 4 kHz cycle

⇒ orbit resolution = 1.3 µm /$\sqrt{\text{avgs}}$

= **0.1 µm/cycle** @ 2 kHz [9]
0.15 µm/cycle @ 4 kHz

(realistic - 0.5-1 µm/cycle?)

NOTE: can get higher resolution orbit with more averages

Would like to **match corrector kick resolution to orbit measurement resolution**. From Eq 5, single corrector kick to produce 0.1 µm:

θ_{min} = 0.1 µm /4.8 m = 0.021 µrad

= 1500 µrad / $2^{16.1}$ ⇒ **16 bit** or better kick resolution [10]

8. Corrector digital quantization error:

$$\theta_{quant}\,(\text{rms}) = \theta_{min}\ /\sqrt{12} \qquad [11]$$

Effect on orbit from 1 corrector (Eq. 5):

$$\Delta y(s, \text{rms}) = 3.4\ \theta_{quant}\,(\text{rms}) = 1.0\ \theta_{min} \qquad [13]$$

Effect on orbit from N = 54 correctors:

$$\Delta y(s)\ \text{rms} = \sqrt{54}\ \theta_{min} = 7.3\ \theta_{min} \qquad [14]$$

Limit $\Delta y(s)$ rms < 0.3 μm rms from quantization noise:

$$\theta_{min} < 0.04\ \mu\text{rad rms} \Rightarrow \textbf{15.2 bit} \qquad [15]$$

If want to limit peak disturbance to < 0.3 μm, or if want quantization noise to be fraction of total noise: **17-18 bit**

NOTE: Quantization noise spread over bandwidth given by DAC update rate

⇒ higher DAC rate = lower PSD

⇒ high freq quantization noise filtered by corr + vac chamber

⇒ may want fast DAC update + dither, even when no feedback
---this may give higher effective DAC res as well

9. Integrated noise from DAC + power supply (DRAFT!):

$$0.012\,\mu m = \left(\int PSD\,df\right)^{1/2} = \left(\int_0^{0.1} PSDdf + \int_{0.1}^{1} PSDdf + \int_{1}^{10} PSDdf + \int_{10}^{1k} PSDdf + \int_{1k}^{10k} PSDdf\right)^{1/2}$$

Let θ_{noise} = equivalent deflection noise at output of power supply

θ_{beam} = actual noise reaching beam after filtering by magnet + vac chamber and attenuation by feedback

Bandwidth	Attenuation	θ_{noise} (μrad rms)		θ_{beam} (μrad rms)
DC-0.01 Hz	fdbk ~1000	1.5	(10 bit)	0.002
0.01-0.1 Hz	fdbk ~100	0.4	(12 bit)	0.004
0.1-1 Hz	fdbk ~10	0.05	(15 bit)	0.005
1 – 10Hz	fdbk ~ 2	0.01	(17 bit)	0.005
10 – 1 kHz	none	0.005	(18 bit)	0.005
1 kHz -10 kHz	~10	0.03	(15-16 bit)	0.003
10 kHz - >100 kHz	~100	0.4	(12 bit)	0.004
100 kHz - ∞	~1000	1.5	(10 bit)	0.002

Total noise: with fdbk: 0.011 μrad rms
without fdbk: 1.6 μrad rms (130% vert beam size)

NOTE: Integrated noise without feedback can be reduced to 10% of vertical beam size (0.3 μm rms) if low freq performance is improved to ~13 bits, dominated by power supply, not DAC

⇒ 14-bit low freq DAC stability is desirable.

10. DAC considerations:

DAC should provide small fraction of DAC+supply noise budget if possible.

Oversampling low-bit DAC + reconstruction filter (e.g x 8, etc) can reduce quantization noise.

Oversampling + dither can get higher resolution, even for DC setting.

DAC differential non-linearity: < 1 LSB over temp range; monotonicity required for feedback

Absolute accuracy, integral non-linearity, THD not crucial. Stability is more important.

Low-freq DAC drift/offset and INL can be corrected with feedback + good ADC.

DAC convert time/delay/settling: < ~100 μs for 4 kHz feedback.

A "sign magnitude" DAC has better noise properties around 0 than an "offset binary" DAC.

Serial DAC control desirable to minimize interface connections.

11. Conclusions:

- If beam noise from 54 vertical correctors limited to 1% of 30 μm vertical beam size, single corrector noise ~0.012 μrad rms (17 bit; 1500 μrad FS).

  Includes:
  - noise from DAC and power supply
  - filtering from supply, magnet, chamber
  - feedback attenuation of low frequency

- DAC specs **(DRAFT!):**

resolution for orbit change:	16 bit
monotonicity:	16 bit or better (?)
DNL:	<1 bit
INL:	<~0.1%
drift+offset (24 h):	14 bit
total noise:	17 bit or better
speed:	>10 kHz

NOTES: Feedback around DAC with good ADC may permit using DACs with high INL, drift, offset (audio DAC).

High update rate + filtering may give 18-bit quantization noise with 16-bit DAC

High update rate + filter + dither may give 18 bit resolution with 16-bit DAC

- For more accurate DAC specs, need:
  - Corrector power supply + crate performance measurements
  - Feedback model
  - Better understanding of DAC and ADC issues, specs