ALS-U: Ideas for a Novel 7BA Lattice Using Longitudinal Gradient Bends & Reverse Bends

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Setting the Scene: ALS-U Goals

- ALS-U is a MBA-based upgrade of the 25 year old ALS
- ALS until most recently the world’s brightest SXR source at 2 keV
- ALS-U is a diffraction-limited SXR source delivering ultra-bright, coherent, and round photon beams within the existing ALS hall
Setting the Scene: ALS-U Goals (cont.)

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Over x100 in brightness and coherent flux @ 1 keV
Setting the Scene: Baseline Lattice v20r

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IPAC'17, WEPAB104, p.2824
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IPAC’13, MOPEA008, p.79
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But this kind of ultra-high brightness approach comes at a price:

- **Strained linear optics** → large peak $\beta/\eta$ functions → drives up natural chromaticity and aperture requirements → increases magnet gaps → weakens focusing → breaks MBA feedback cycle

![Graph showing $\beta_x$, $\beta_y$, and $\eta_x$ with annotations for large $\beta_y$ and $\eta_x$ limits.]
Setting the Scene: Baseline Lattice v20r (cont.)

The Multibend Achromat Cycle
(courtesy A. Streun, PSI)

Many Short Cells
for a given circumference

Short Magnets

Strong Gradients

Small Magnet Gaps

Limited Aperture Required
for decent MA and Touschek lifetime

Small Bend Angle

Low Dispersion

Low Power/Cost

Low Emittance

Many Short Cells

Strong Gradients

Small Magnet Gaps

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~1 mm DA required for injected beam with $\varepsilon \approx 2$ nm rad, $\beta \approx 20$ m
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- **Limited MA**: major problem in low-E rings where (despite potentially large RF acceptance) Touschek scattering severely limits lifetime (top off isn’t silver bullet: 1 mA deadband & $\geq 30$ s injection interval → $>4$ hrs lifetime required)

\[
\tau_{ts} \sim \gamma^3
\]
\[
\delta_{rf} \sim \sqrt{\frac{V_{rf}}{\gamma}}
\]
assuming $V_{rf} \gg U_{loss}$

- High-E rings get decent Touschek despite low LMA (RF acc limited so large LMA serves no purpose)

- Low-E rings need large MA to get decent Touschek (LMA needs to exceed naturally larger RF acc)
• But this kind of ultra-high brightness approach comes at a price:

- **Strained linear** chromaticity and aperture requirements → weakens focusing
- **Small DA**: belief can be tolerated by virtue of on-axis injection from low-emittance accumulator ring (swap-out)
- **Limited MA**: major problem in low-emittance rings (despite potentially large RF acceptance)
  
  Large RF acceptance (top off isn’t silver bullet)

### Figure

- **Touschek Lifetime** vs. **RF Voltage**
  
  - **Only 1.2 hours** despite full coupling & assuming factor 4 bunch lengthening from HHCs
  
  Gradient errors included, but no misalignments

#### Graph Details:

- **RF Voltage (kV)**: 200 to 900
- **Touschek Lifetime (hour)**: 0 to 1.4

#### Source:

- **Courtesy: C. Sun**

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**Simon C. Leemann • Alternate 7BA Lattice for ALS-U • CLS Acc Meeting • February 6, 2019**
So what can we do about this?
Outline for an Alternate Design

• Main problem of ALS-U baseline lattice is poor off-momentum performance resulting from excessive chromatic beating (even in perfect HMBA phase advance between sextupoles required for -l transformation breaks down off energy)

• MAX IV-style MBA
  – leverages distributed chromatic correction to ensure large MA
  – employs octupoles to limit tune footprint and hence maximize DA

• However, MAX IV lattice is too relaxed to meet ALS-U target emittance (scaled to energy & circumference: 2850 pm rad) → push to its limits by
  – adding longitudinal gradients to the dipoles
  – leveraging reverse bending to minimize emittance (within limits set by momentum compaction deemed acceptable)
  – tuning linear optics of the unit cell so that overall MBA sector becomes higher-order achromat (geom. aberrations / RDTs minimized within)

PRST-AB 12, 120701 (2009)  PRST-AB 14, 030701 (2011)
Unit Cell Design – Baseline vs. New

- ALS-U Baseline 9BA: 2× dispersion bumps + 7× TME-like bend cells
Unit Cell Design – Baseline vs. New (cont.)

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9 bends
Unit Cell Design – Baseline vs. New (cont.)

• **ALS-U Baseline 9BA:** 2× dispersion bumps + 7× TME-like bend cells

• **New MBA based on:** 2× matching cells (MC) + 2× dispersion suppressors (DS) + \( n \)× unit cells (UC)
Unit Cell Design – Baseline vs. New (cont.)

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- However, new UC must also provide space for SF/SD → \( n < 7 \)
Unit Cell Design – Baseline vs. New (cont.)

• What is maximum $n$ we can fit? And with fewer bends, can we still achieve sufficiently low emittance?

$$\varepsilon_0 \propto \frac{\gamma^2}{N_B^3}$$
Unit Cell Design – Baseline vs. New (cont.)

• What is maximum $n$ we can fit? And with fewer bends, can we still achieve sufficiently low emittance?

• 196 m circumference & $12 \times 5.3$ m SS $\rightarrow \approx 11$ m per achromat

\[ \varepsilon_0 \propto \frac{\gamma^2}{N_B^3} \]

- Insertion Device

\[ \text{\underline{\text{---}} = 11 \text{ m} \quad \text{---} = 5.3 \text{ m} \quad \text{---} = 11 \text{ m} \text{\underline{---}}} \]
What is maximum $n$ we can fit? And with fewer bends, can we still achieve sufficiently low emittance?

• 196 m circumference & $12 \times 5.3$ m SS $\rightarrow \approx 11$ m per achromat

• Assuming roughly 0.5 m bend, 0.3 m quadrupole, $2 \times 0.2$ m for SF/SD $\rightarrow$ basic cell length $\approx 1.3$ m

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• Assuming roughly 0.5 m bend, 0.3 m quadrupole, $2 \times 0.2$ m for SF/SD $\Rightarrow$ basic cell length $\approx 1.3$ m

• Assuming $2 \times 1.6$ m reserved for MCs $\Rightarrow$ leaves $6 \times 1.3$ m which can be implemented as $5 \times$ UCs + $2 \times$ DSs (since DS $\approx \frac{1}{2}$ UC) $\Rightarrow$ new lattice is a 7BA

\[
\varepsilon_0 \propto \frac{\gamma^2}{N_B^3}
\]
Unit Cell Design – Baseline vs. New (cont.)

- For this UC length & bend angle, a first study using the simplest UC structure...
- ... allows parametric studies for achievable $\varepsilon$ vs. UC gradients

![Diagram of unit cell design with Twiss parameters](image)

Twiss parameters for cCell

**Courtesy:** M. Venturini
Unit Cell Design – Baseline vs. New (cont.)

- For this UC length & bend angle, a first study using the simplest UC structure...
- ... allows parametric studies for achievable $\epsilon$ vs. UC gradients → stable solutions exist

![Graph showing twiss parameters for cCell with various curves and data points](image)

**Region of linear stability**

![Diagram illustrating linear stability region with bend $K_1$ and quad $K_1$ axes](image)

*Courtesy: M. Venturini*
Unit Cell Design – Baseline vs. New (cont.)

• For this UC length & bend angle, a first study using the simplest UC structure...

• ... allows parametric studies for achievable $\epsilon$ vs. UC gradients $\rightarrow$ stable solutions exist, but render at best $\epsilon \approx 200$ pm (for $k_{QF} \approx 12$)

Twiss parameters for cCell

$\epsilon_x, \epsilon_y, \beta_x, \beta_y, \eta_x, \eta_y$

$c$-bend $|K_1| \ (m^{-2}) = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$

QF $K_1 \ (m^{-2})$

$\theta_B = 5^\circ; |\theta_Q| = 0$

Courtesy: M. Venturini
• However, **reverse bend (RB)** can substantially suppress emittance

• Assume QF implemented as offset quadrupole → generates both horizontal focusing & reverse bending (need to compensate for in B)
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• Stability diagram indicates there are solutions $\varepsilon < 110$ pm for $k_{QF} \geq 11.8$ and $k_{B} \geq 5$ (assuming RB with 15% of dipole bend angle)

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NIM-A 737, 148-154 (2014)
• However, **reverse bend (RB)** can substantially suppress emittance

• Assume QF implemented as offset

• Stability diagram indicates there are solutions $\varepsilon < 110$ pm for $k_{QF} \geq 11.8$ and $k_B \geq 5$ (assuming RB with 15% of dipole bend angle)

• Solutions allow for suitable phase advances: within each UC want tunes $2\pi \times (\frac{3}{7}, \frac{1}{7}) \rightarrow$ entire 7BA becomes higher-order achromat (canceling geometrical aberrations from sextupoles → cancels RDTs within achromat)

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**NIM-A 737, 148-154 (2014)**

**NIM-A 645, 168-174 (2011)**

**PRST-AB 15, 054002 (2012)**
A More Realistic Unit Cell

• Improve the toy model UC...
A More Realistic Unit Cell (cont.)

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  - Want SF at max $\beta_x \rightarrow$ split QF (RB) & insert SF at center
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"Missing bend scheme": DS dipole has half bend angle of UC dipole.
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- Use approximately same QF gradient as in UC, but adjust QF–B separation to ensure dispersion fully suppressed at dipole end (UC by itself does not close dispersion)
Optics Matching to IDs: Matching Cell

- 4 quadrupoles allows adjusting $\beta_{x,y}$ in IDs & setting working point
Optics Matching to IDs: Matching Cell (cont.)

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- Fewer quadrupoles can be used but usually results in larger peak $\beta_{x,y}$
Optics Matching to IDs: Matching Cell (cont.)

• 4 quadrupoles allows adjusting $\beta_{x,y}$ in IDs & setting working point

- Fewer quadrupoles can be used but usually results in larger peak $\beta_{x,y}$
- Ensure $\beta_{x,y}$ limited in order to minimize natural $\xi_{x,y}$ (MCs increase overall $\xi_{x,y}$ by +40%)

$$\xi_{x/y} = \pm \frac{1}{4\pi} \sum_{i=1}^{N} \beta_{x/y,i} \left( (b_2 L)_i - 2(b_3 L)_i \eta_{x,i} \right)$$
The Resulting 7BA

• Exploit last free knob → set RB angle to minimize emittance

\[ \epsilon_0 \text{ in } \text{UC} \]

\[ 93 \text{ pm rad @ 0.92°} \]
The Resulting 7BA (cont.)

- Exploit last free knob \(\rightarrow\) set RB angle to minimize emittance
- Assemble these UCs together with DSs & MCs, tune \(\beta^*\) \(\rightarrow\) new 7BA

\[
\varepsilon_0 \text{ for entire 7BA}
\]

92 pm rad @ 0.82°

\[
\begin{align*}
\beta_x & \quad \beta_y & \quad \eta_x \\
\hline
\text{Beta Functions [m]} & \text{Dispersion [m]} & \text{s [m]}
\end{align*}
\]
The Resulting 7BA (cont.)

• Exploit last free knob → set RB angle to minimize emittance
• Assemble these UCs together with DSs & MCs, tune $\beta^*$ → new 7BA
• Very attractive parameters for 196.4 m ring:
  – $\varepsilon_0 = 92$ pm, $\beta^* = 2.5$ m @ ID
  – $\varepsilon_{x,y} = 59$ pm rad (fully coupled)
  – $U_0 = 360.6$ keV, $J_x = 1.790$
  – $\nu_x = 39.84$, $\nu_y = 14.41$
  – $\xi_x = -103.6$, $\xi_y = -36.28$
  – peak $\beta_{x,y}$ & $\eta$ very low
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  - peak $\beta_{x,y}$ & $\eta$ very low
... but quasi-isochronous: $\alpha_c = 2.8 \times 10^{-5}$
→ will we be able to stably store 500 mA?
The Dispersion Conundrum

- Low emittance requires low dispersion

\[ \varepsilon_0 \propto \gamma \frac{I_5}{I_2 - I_4} \propto \frac{I_5}{J_x U_0} \]

\[ I_5 = \oint \frac{\mathcal{H}}{\rho^3} \, ds, \quad \mathcal{H} = \gamma \eta^2 + 2\alpha \eta \eta' + \beta \eta'^2 \]

\[ I_2 = \oint \frac{ds}{\rho^2}, \quad I_4 = \oint \frac{\eta}{\rho} \left( \frac{1}{\rho^2} + 2b_2 \right) \, ds \]
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• But low dispersion is what minimizes momentum compaction

\[ \alpha_c = \frac{1}{C} \int \frac{\eta}{\rho} ds \]

... so it would appear ultralow emittance has to result in isochronous lattices
The Dispersion Conundrum (cont.)

• Low emittance requires low dispersion
  \[ \varepsilon_0 \propto \gamma \frac{I_5}{I_2 - I_4} \propto \frac{I_5}{J_x U_0} \]

\[ I_5 = \int \frac{H}{|\rho^3|} ds, \quad H = \gamma \eta^2 + 2\alpha \eta \eta' + \beta \eta'^2 \]

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  ... so it would appear ultralow emittance has to result in isochronous lattices
  \[ ^{\text{almost}} \]

• However, these two conditions do not have to be satisfied equally in all parts of the cell!
Longitudinal Gradient Bends

- The trick we can therefore play is to
  - increase dispersion in QF/RB to increase momentum compaction (where contribution to emittance is small)
  - decrease dispersion in bend to suppress emittance (which also helps shift momentum compaction)
Longitudinal Gradient Bends (cont.)

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  - decrease dispersion in bend to suppress emittance (which also helps shift momentum compaction)

- The silver bullet that enables this is the **longitudinal gradient bend**

\[
\alpha_c = \frac{1}{C} \left( \int_{LGB} \frac{\eta_x}{\rho} ds + \int_{RB} \frac{\eta_x}{\rho} ds \right) < 0
\]

Yes we can!
Longitudinal Gradient Bends (cont.)

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\alpha_c = \frac{1}{C} \left( \int_{LGB} \frac{\eta_x}{\rho} \, ds + \int_{RB} \frac{\eta_x}{\rho} \, ds \right) < 0
\]

- Microwave instability triggered by low \textbf{absolute} \( \alpha_c \)
- Head-tail stability does \textbf{not} require positive \( \alpha_c \)
- If \( \alpha_c \) negative, correct to negative \( \xi_{x,y} \rightarrow \) lower sextupole gradients

Two stages:
- Exploit RB to fully suppress \( \eta_x \) in bend & then leverage LGB to suppress emittance
- Detune from minimum \( \epsilon \) in order to ensure larger negative \( \alpha_c \)

Yes we can!

---

**Beta Functions [m]**

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<th>( \beta_y )</th>
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**Dispersion [m]**

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**s [m]**

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LGB Cell for Lowest Emittance

• Instead of RB angle for minimum $\varepsilon_0$ in UC → minimize $\eta^*$ in bend

$$\varepsilon_0 \propto \gamma \frac{I_5}{I_2 - I_4} \propto \frac{I_5}{J_x U_0}$$

$$I_5 = \int \frac{\mathcal{H}}{|\rho|^3} ds, \quad \mathcal{H} = \gamma \eta^2 + 2\alpha \eta' + \beta \eta'^2$$

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93 pm rad @ 0.92°
• Instead of RB angle for minimum $\varepsilon_0$ in UC → minimize $\eta^*$ in bend
• Calculate LGB profile to optimally suppresses $\varepsilon_0$ at this RB angle → in other words, for given bend angle, $B^*$ (assume 2 T possible), $\beta_x^*$, and $\eta^* \approx 0$ → what is ideal longitudinal profile $B(s)$?
LGB Cell for Lowest Emittance (cont.)

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- Finally, add vertical focusing to weaker outer sections of LGB and adjust (together with RB gradient) for $2\pi \times (3/7, 1/7)$ cell tune
LGB Cell for Lowest Emittance (cont.)

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- Calculate LGB profile to optimally suppresses $\varepsilon_0$ at this RB angle $\rightarrow$ in other words, for given bend angle, $B^*$ (assume 2 T possible), $\beta_x^*$, and $\eta^* \approx 0$ $\rightarrow$ what is ideal longitudinal profile $B(s)$?
- Finally, add *vertical focusing* to weaker outer sections of LGB and adjust (together with RB gradient) for $2\pi \times \left( \frac{3}{7}, \frac{1}{7} \right)$ cell tune
- Then re-tune RB angle for min. $\varepsilon_0$ in UC & final cell tune adjust

![Graph showing 30% $\varepsilon_0$ reduction and 64 pm rad @ 0.95°]
LGB Cell for Lowest Emittance (cont.)

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- Finally, add vertical focusing to weaker outer sections of LGB and adjust (together with RB gradient) for $2\pi \times (\frac{3}{7}, \frac{1}{7})$ cell tune
- Then re-tune RB angle for min. $\varepsilon_0$ in UC & final cell tune adjust

$\rightarrow$ as expected, emittance can be much lower, but still, lattice eventually becomes isochronous
Detuned LGB Cell for Increased Mom. Compaction

• Adjust RB angle to provide sufficient momentum compaction
• Re-adjust LGB and RB gradients for $2\pi \times (\frac{3}{7}, \frac{1}{7})$ cell tune

\[
\alpha_c \leq -2 \times 10^{-4} \approx 1.3°
\]
Linear Optics Summary

- Use this detuned UC for new near-min-ε 7BA
- Add appropriately tuned DS and MC (MC quads tuned to desired WP and for $\beta^* \approx 2.2$ m)
- In DS use regular TGB instead of LGB $\rightarrow$ no HXR shining into SS
Linear Optics Summary (cont.)

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Linear Optics Summary (cont.)

- Use this detuned UC for new near-min-\(\epsilon\) 7BA
- Add appropriately tuned DS and MC (MC quads tuned to desired WP and for \(\beta^* \approx 2.2\) m)
- In DS use regular TGB instead of LGB \(\rightarrow\) no HXR shining into SS
- \(\epsilon_0 = 78\) pm, \(\alpha_c = -1\times10^{-4}\)
- \(J_x = 1.72, U_0 = 442.6\) keV
- \(\epsilon_{x,y} = 49\) pm rad (fully coupled)
- \(\sigma_{x,y} \approx 10\) \(\mu\)m @ ID (\(\beta_{x,y} \approx 2.2\) m)
- \(\nu_x = 40.38, \nu_y = 14.36\)
  (chosen with consideration to NL dynamics)
- \(\xi_x = -106.4, \xi_y = -40.1\)
- Peak \(\beta \approx 10\) m, \(\eta < 27\) mm
• Magnet requirements:
  – Bends 6.2°, RBs 1.2°
  – RB: ≈0.56 T (0.12 m) & max k ≈ 108 T/m → 5.2 mm offset
  – k @ LGB ends: ≈ –57 T/m
  – MC quads max k: ≈ 102 T/m
  – min. separation between magnets: 48 mm
    (>2.5× min. magnet bore)
    (NB: usual spacing between magnets > 100 mm)
Nonlinear Optics

- HMBAs have large dispersion bumps which relaxes (few) sextupoles
- But our 7BA offers large number of sextupoles at various phase advances → cancel RDTs entirely within achromat

PRST-AB 12, 120701 (2009)
PRST-AB 14, 030701 (2011)
Nonlinear Optics (cont.)

- HMBAs have large dispersion bumps which relaxes (few) sextupoles
- But our 7BA offers large number of sextupoles at various phase advances \(\rightarrow\) cancel RDTs entirely **within** achromat
- Introduce 7 **chromatic sextupole families**: 3 SF & 4 SD
  - SD families in UC come in pairs flanking main bends
Nonlinear Optics (cont.)

- HMBAs have large dispersion bumps which relaxes (few) sextupoles
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Nonlinear Optics (cont.)

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• Introduce 7 chromatic sextupole families: 3 SF & 4 SD
  – SD families in UC come in pairs flanking main bends
• Add 3 harmonic sextupole families to MC (completing higher-order achromat)
• Investigated achromatic octupoles in MC → no substantial benefit considering space requirements (NB: do not expect amplitudes >1 mm @ octupoles)
Nonlinear Optics (cont.)

• In total 10 nonlinear knobs
• 7 chromatic sextupole knobs, 5 can be chosen freely
• Tune sextupoles for:
  – linear chromatic correction: \(-106/-40 \rightarrow -1/-1\)
  – 1st/2nd-order RDTs (weighted SVD to cancel)
  – 2nd/3rd-order chromaticities (weighted SVD to achieve specific target values)
  – 1st-order ADTS terms (weighted SVD to achieve specific target values)
Nonlinear Optics (cont.)

• Because of higher-order achromat tuning we suppress RDTs
  – Note, this is just an approximation:
    • finite sextupole lengths
    • $MC+DS \neq UC$ in terms of phase advance
    • detuning of achromat to achieve desired overall WP
    • degeneracy of RDTs
Nonlinear Optics (cont.)

- Because of higher-order achromat tuning we suppress RDTs
  - Note, this is just an approximation:
    - finite sextupole lengths
    - MC+DS ≠ UC in terms of phase advance
    - detuning of achromat to achieve desired overall WP
    - degeneracy of RDTs
- Only linear ADTS can be set, but higher orders present & strong
  - cancelation of linear ADTS is therefore insufficient
  - instead, adjust linear terms to compensate for higher-order contributions over relevant amplitudes (acceptance)
Nonlinear Optics (cont.)

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  - degeneracy of RDTs

Only linear ADTS can be set, but higher orders present & strong

- cancelation of linear ADTS is therefore insufficient
- instead, adjust linear terms to compensate for higher-order contributions over relevant amplitudes (acceptance)

Process requires many iterations with 6D tracking to determine and confirm (errors) optimum tuning
Nonlinear Optics (cont.)

- **Sextupole requirements:**
  - $b_3 \leq 1667 \, 1/m^3$ (assume 18 mm magnet bore, limit PTF to <0.9 T)
  - 18 mm bore $\rightarrow$ uniform 15 mm arc chamber $\rightarrow$ exceeds $\pm 4.5$ mm acceptance (in both planes) across entire ID straight
  - strongest family SF1: $b_3 = 1645 \, 1/m^3$
  - SH and SD families (all but one) substantially weaker
Expected Performance: Tune Shifts

• Resulting tune shifts small across relevant range \( \text{(acceptance)} \) → small tune footprint, clear of harmful resonances \( \text{(proximity to coupling res. for round beam)} \)
Expected Performance: Tune Shifts (cont.)

• Resulting tune shifts small across relevant range (acceptance) → small tune footprint, clear of harmful resonances (proximity to coupling res. for round beam)
Expected Performance: Tune Shifts (cont.)

- Resulting tune shifts small across relevant range (acceptance) → small tune footprint, clear of harmful resonances (proximity to coupling res. for round beam)
Expected Performance: FMA

- Compact tune footprint results in homogeneous low diffusion rates
Expected Performance: DA

- FMA is 4D → verify in 6D tracking that DA large on & off momentum
Expected Performance: DA with Errors

- Verify DA preserved in real machine, i.e. when incl. imperfections

Dipoles & BPMs:
- misaligned & rolled
- Gaussian, $\pm 2\sigma$ cut
- 20 random seeds

Quadrupoles & Sextupoles:
- misaligned & rolled
- Orbit corrected
- No skew correction
- Errors scaled until $\approx 3 \mu m$ rms
- CODs and $\approx 2\%$ beta beat
Expected Performance: DA with Errors (cont.)

- Sufficient off-mom. DA (incl. errors) required to ensure large LMA

![Graph 1: Bare lattice vs Lattice with errors](image1)

**x [mm]**

<table>
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<tr>
<th>δ [%]</th>
<th>Bare lattice</th>
<th>Lattice with errors</th>
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</table>

![Graph 2: Bare lattice vs Lattice with errors](image2)

**y [mm]**

<table>
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<tr>
<th>δ [%]</th>
<th>Bare lattice</th>
<th>Lattice with errors</th>
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<td>4</td>
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</table>
Expected Performance: LMA & Touschek

- LMA from 6D tracking with errors \(\rightarrow\) large overall MA possible by virtue of LMA matching/exceeding RF acceptance (bucket height)
  - LMA somewhat asymmetric due to better DA for \(\delta > 0\)
  - Overall MA calculated assuming 0.715 MV \(\rightarrow\) \(\delta_{rf} = 4\%\)
- 6D Touschek tracking
  \(\rightarrow\) 7.1 hrs incl. HHCs
  \((\approx 7.9\text{ hrs if IBS } @\ 500\text{ mA included})\)
Expected Performance: LMA & Touschek (cont.)

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- 6D Touschek tracking
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- Using 20 error seeds
  → 4.5 ± 0.8 hrs incl. HHCs
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  ($\approx 7.9$ hrs if IBS $\oplus$ 500 mA included)

– Using 20 error seeds
  $\rightarrow$ **4.5 ± 0.8 hrs incl. HHCs**

– Overall MA determined to large extent by assumed RF acceptance $\rightarrow$ exploit $\tau_{ts} \propto \delta_{\text{acc}}^3$
Expected Performance after MOGA Optimization

- MOGA optimization using 10 sextupole families (8 DOF) carried out in collaboration with Masamitsu Aiba (SLS)
  - Sextupole gradients reduced while \( DA \) becomes larger and more uniform both on & off energy \( \rightarrow \pm 2.5 \text{ mm} \) (with errors)
  - **Touschek lifetime** around 6 h (with errors) @ 500 mA, incl. HHCs

---

**Diffusion Map (on momentum)**

**Diffusion Map (off momentum)**

**Momentum Aperture (500 mA, full coupling, \( \delta_{rf} = 4\% \), incl. HHCs)**

- **Bare lattice, no errors, 7 hrs**
- **20 error seeds: 5.8 \pm 0.9 hrs**

---

Simon C. Leemann • Alternate 7BA Lattice for ALS-U • CLS Acc Meeting • February 6, 2019
Summary: A 7BA with LGBs & RBs for ALS-U

- LGBs & RBs allow suppressing emittance → reduce $N_b$ to provide space for distributed chromatic correction → superior DA & LMA
- $\varepsilon_{x,y} = 49 \text{ pm rad}$ (fully coupled)
- $\approx 3 \times 10^{21} \text{ ph/s/m}^2/\text{mrad}^2/0.1\%\text{BW}$ (@ 1 keV from 4-m 28-mm Delta)
- $\varepsilon_0 = 78 \text{ pm, } \alpha_c = -1 \times 10^{-4}$
- $J_x = 1.72, U_0 = 442.6 \text{ keV}$
- @ IDs: $\sigma_{x,y} \approx 10 \text{ m} \mu \text{m (} \beta_{x,y} \approx 2.2 \text{ m)}$
- $\nu_x = 40.38, \nu_y = 14.36$
- $\xi_x = -106.4, \xi_y = -40.1$
- DA approx. ±2.5 mm (incl. errors)
- 6 ± 1 hrs Touschek lifetime
  @ 500 mA (incl. errors and HHCs)
Thank You

Acknowledgments

A. Streun, M. Aiba (PSI)
J. Bengtsson (Diamond)
M. Johansson (SLAC)
H. Tarawneh (MAX IV)
L. Dallin (CLS)
Backup Slides
A few Comments on Negative $\alpha_c$ & $\alpha_2$

- Microwave instability triggered by low absolute $\alpha_c$
- Head-tail stability does not require positive $\alpha_c$
- If $\alpha_c$ negative, correct to negative $\xi_{x,y}$ → reduces sextupole gradients
- Negative but sizable $\alpha_c$ is advantageous compared to almost isochronous ring
- Experience with negative $\alpha_c$ @ other machines:
  - SuperACO, BESSY, ANKA, MLS, DIAMOND
  - SLS-2 designed to operate @ 400 mA with negative $\alpha_c$
- Potential well distortion @ negative $\alpha_c$
  - bunch shortens with rising $Q_b$ at first (slightly lower threshold for turbulent bunch lengthening)
  - even w/o HHCs SLS-2 anticipates $I_b = 2$ mA due to $\alpha_c = -1.3 \times 10^{-4}$
A few Comments on Negative $\alpha_c$ & $\alpha_2$ (cont.)

- Bucket distortion from large $\alpha_2 \rightarrow$ problematic alpha bucket
  - RF acceptance $\delta_{rf} \sim (V_{rf}/\alpha_c)^{1/2} \rightarrow |\alpha_c/\alpha_2|$
  - phase acceptance $\Delta\phi \sim |\alpha_c/\alpha_2| (V_{rf}/\alpha_c)^{-1/2}$

- So why not modify $\alpha_2$ with sextupoles?
  - Would require chromatic sextupoles with $\eta \gg \beta_{x,y}$
  - Instead increase $|\alpha_c|$ to required level determined by “stiff” $\alpha_2$
  - SOLEIL ran experiments with $\alpha_c/\alpha_2 = 10\% \rightarrow$ three simultaneously stored beams
  - SLS-2 designed to operate at $\alpha_c/\alpha_2 \approx 9\%$

- Use tracking (ideally self-consistent including HHC, impedance $\rightarrow$ PWD, etc.) to verify stable longitudinal behavior in presence of negative $\alpha_c$, small $\alpha_c/\alpha_2$, gaps in fill pattern, transients, etc. $\rightarrow$ works for this lattice by virtue of $\alpha_3$ compensation

PRL 84, 5516-5519 (2000)

PRST-AB 16, 054001 (2013)

SLS-2 CDR, Dec 2017
Considerations for the LGB

• How important is the LGB? Could it be replaced with a regular TGB?
  – Used same version of previous lattice for comparison study
  – Instead of LGB use TGB (6.7° → 1.56 T, –33.5 T/m)
  – Tuned to exact same $\alpha_c = -1.7 \times 10^{-4}$ → requires more RB
    • Increases radiated power, $\sigma_\delta$, and $J_x$ (slightly)
    • Results in 116 → 189 pm (+63%)
Considerations for the LGB (cont.)

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    • Increases radiated power, $\sigma_\delta$, and $J_x$ (slightly)
    • Results in 116 → 189 pm (+63%)
• Does the LGB really have to be so aggressive, i.e. are 2 T necessary?
  – Significant emittance penalty from relaxing LGB peak field
  – Without sacrificing $\alpha_c$
    expect >10 pm rad
Considerations for the LGB (cont.)

- How shall the LGB be implemented?
- Possible collaboration with SLS-2 which will require such a magnet?

**Magnets 1 - compound LGB**

- **RC**
  - Resistive coil version

- **PM**
  - Permanent magnet version

*work in progress*

Alternatives:
- Discrete quadrupoles?
- Distributed gradient?
- Incorporation of sextupole component too?
- Tunability?

SLS-2 CDR, Dec 2017

---

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SLS-2 CDR, Dec 2017
Considerations for the LGB (cont.)

- How shall the LGB be implemented?
- Possible collaboration with SLS-2 which will require such a magnet? Or with CLIC?

**TME Cell optimisation**

- Based on the trapezium profile, the designed dipole has a total length of 56 cm and bends the beam by 4 degrees.
- A maximum field of 2.3 T is reached. The $\lambda$ and $\rho$ values achieved are 0.04 and 0.29 respectively, corresponding to a $F_{TME} = 7$.

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<tr>
<th>Parameters</th>
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<th>Lowest field section</th>
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M. Dominguez, F. Toral

Considerations for the LGB (cont.)

• How shall the LGB be implemented?
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TME Cell optimisation

[Graph showing magnetic field profile]

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M. Dominguez, F. Toral
Considerations for the LGB (cont.)

• How shall the LGB be implemented?
• Possible collaboration with SLS-2 which will require such a magnet? Or with CLIC?

• Could LGB be replaced with more relaxed TGB-SB-TGB sandwich?
• Will likely want permanent magnets for LGB (and possibly also RB)
  – only limited tuning capability required
  – do not want to reserve space for coils
    • hard focusing of longitudinally dense UC required for ultra-low emittance
    • in case of TGB-SB-TGB sandwich, dip in field has to be avoided at all cost
  – reduction of power consumption and dissipated heat
Other Technical Considerations

• Magnet strengths are tough → small magnets are strong magnets → ultimately, impedance/resistive wall budget should determine the minimum acceptable magnet bore

• Vacuum design still has to ensure UHV conditions (→ NEG) but also remove entire synchrotron radiation heat load & get light out to users → feeds back to magnet design
Other Technical Considerations (cont.)

- Magnet strengths are tough → small magnets are strong magnets → ultimately, impedance/resistive wall budget should determine the minimum acceptable magnet bore.
- Vacuum design still has to ensure UHV conditions (➔ NEG), but also remove synchrotron radiation heat load & get light out to users, so...

  • Synchrotron radiation heat load: $P \sim I \gamma^4/\rho$
  • More interesting: $P/L \sim I \gamma^4/\rho^2$
    - MAX IV 3 GeV storage ring (500 mA): $\approx 1.5 \text{ W/mm}$
    - ALS-U v20 @ 500 mA $\rightarrow \approx 2.2 \text{ W/mm}$ (1.5× higher than MAX IV)
  • But also need to take into account beam height on chamber
    - $h = 2l/\gamma$, with distance from source $l = (2r_c\rho)^{0.5}$, chamber radius $r_c$
  • Therefore, better measure is power per area: $P/(Lh) \sim I\gamma^5/(r_c^{0.5}\rho^{2.5})$
    - MAX IV 3 GeV storage ring (500 mA): $\approx 6.9 \text{ W/mm}^2$
    - ALS-U v20 with 13/20 mm chamber $\rightarrow \approx 12.2 \text{ W/mm}^2$ (1.8× higher than MAX IV)

* Increased RB of 7BA & its smaller chamber will further increase power density
* However, APS-U also faces a heat load 2–3× higher than MAX IV
Other Technical Considerations (cont.)

• Magnet strengths are tough → small magnets are strong magnets → ultimately, impedance/resistive wall budget should determine the minimum acceptable magnet bore

• Vacuum design still has to ensure UHV conditions (→ NEG) but also remove entire synchrotron radiation heat load & get light out to users → feeds back to magnet design

• A successful design will require several iterations between magnet, vacuum, and lattice design

• This was successfully done at MAX IV → resulted in a design where push was made on all fronts resulting in a balanced and robust design (for its time)

→ now is the time to define the new “state-of-the-art” ring design