Accelerator Physics Challenges for the SuperKEKB

D. Zhou

With contributions from

KEK: K. Akai, K. Ohmi, Y. Ohnishi, N. Ohuchi, H. Sugimoto, ...

IHEP: Y. Zhang

Theory club, FEL & Beam Physics Department, SLAC
Mar. 13, 2015
Outline

➤ Introduction
➤ Lattice nonlinearity (LN)
➤ Beam-beam (BB) effects
  ● Crab waist (CW)
  ● Interplay of BB and LN
➤ Space charge (SC) effects in LER
  ● Interplay of BB, SC and LN
➤ Impedance issues
➤ Summary and Future plan
Outline

➤ Introduction
   ➤ Lattice nonlinearity (LN)
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➤ Summary and Future plan
1. Introduction

Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)

SuperKEKB

- Nano-Beam scheme extremely small $\beta_y^*$ low emittance
- Beam current double

$L = \frac{\gamma - 1}{2e e_r} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{L_z}{\delta \rho_y} \right) \left( \frac{R_L}{R_y} \right) \left( \frac{\beta_y^*}{\beta_x^*} \right)$

40 times higher luminosity $2.1 \times 10^{34} \rightarrow 8 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$

From K. Akai, KEKB ARC 2015
1. Introduction

From K. Akai, KEKB ARC 2015
1. Introduction: Expected lum. gain

- Increase the luminosity by 40 times based on “Nano-Beam” scheme

\[ L = \frac{\gamma_\pm}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \frac{I_{\pm \xi \pm y} R_L}{\beta_y^* R_y} \right) = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} \]

- Vertical \( \beta \) function at IP: 5.9 \( \rightarrow \) 0.27/0.30 mm \( \times 20 \)
- Beam current: 1.7/1.4 \( \rightarrow \) 3.6/2.6 A \( \times 2 \)
- Vertical beam-beam parameter: 0.09 \( \rightarrow \) 0.09 \( \times 1 \)
- Beam energy: 3.5/8.0 \( \rightarrow \) 4.0/7.0 GeV

LER: Longer Touschek lifetime and mitigation of emittance growth due to the intra-beam scattering
HER: Lower emittance and lower SR power

From N. Ohuchi, IPAC14, WEOCA01
1. Introduction: Machine parameters

<table>
<thead>
<tr>
<th>Date</th>
<th>LER</th>
<th>HER</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E</td>
<td>4.000</td>
<td>7.007</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>3.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2,500</td>
<td></td>
<td></td>
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<tr>
<td>Bunch Current</td>
<td>1.44</td>
<td>1.04</td>
<td>mA</td>
</tr>
<tr>
<td>Circumference</td>
<td>3,016.315</td>
<td></td>
<td>m</td>
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<tr>
<td>$\varepsilon_x/\varepsilon_y$</td>
<td>3.2(1.9)/8.64(2.8)</td>
<td>4.6(4.4)/12.9(1.5)</td>
<td>nm/pm</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.27</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>$\beta_x^<em>/\beta_y^</em>$</td>
<td>32/0.27</td>
<td>25/0.30</td>
<td>mm</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>83</td>
<td></td>
<td>mrad</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>3.18x10^{-4}</td>
<td>4.53x10^{-4}</td>
<td></td>
</tr>
<tr>
<td>$\sigma_6$</td>
<td>8.10(7.73)x10^{-4}</td>
<td>6.37(6.30)x10^{-4}</td>
<td></td>
</tr>
<tr>
<td>$V_c$</td>
<td>9.4</td>
<td>15.0</td>
<td>MV</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>6.0(5.0)</td>
<td>5(4.9)</td>
<td>mm</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-0.0244</td>
<td>-0.0280</td>
<td></td>
</tr>
<tr>
<td>$\nu_x/\nu_y$</td>
<td>44.53/46.57</td>
<td>45.53/43.57</td>
<td></td>
</tr>
<tr>
<td>$U_0$</td>
<td>1.86</td>
<td>2.43</td>
<td>MeV</td>
</tr>
<tr>
<td>$\tau_{x,y}/\tau_s$</td>
<td>43.2/21.6</td>
<td>58.0/29.0</td>
<td>msec</td>
</tr>
<tr>
<td>$\xi_x/\xi_y$</td>
<td>0.0028/0.0881</td>
<td>0.0012/0.0807</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>$8x10^{35}$</td>
<td></td>
<td>cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

- HOM heating
- Impedance-driven instability
- Electron cloud
- Error tolerances
- Intra-beam scattering
- Space charge
- Beam-beam
- Dynamic aperture, Lifetime
- Lattice nonlinearity
- Background
- Beam-beam
- IR optics
- Impedance budget

See http://www-superkekb.kek.jp/index.html for details
Outline

➤ Introduction

➤ **Lattice nonlinearity (LN)**
  ➤ Beam-beam (BB) effects
    • Crab waist (CW)
    • Interplay of BB and LN

➤ **Space charge (SC) effects in LER**
  • Interplay of BB, SC and LN

➤ Impedance issues

➤ Summary and Future plan
2. Lattice nonlinearity

- High-order correctors added to each SC magnet
- Linear optics is OK, but IR is not transparent for off-momentum and large-amplitude particles

From Y. Ohnishi
2. Lattice nonlinearity

- Realistic lattice
- Poincare map in y direction as function of X offset

From Y. Zhang
2. Lattice nonlinearity

➤ Realistic lattice
➤ Strong nonlinear X-Y coupling in LER

From Y. Zhang
2. Lattice nonlinearity: LER

- **Simplified LER lattice** [No solenoid, QC* magnets simplified: no offset, dipole and skew-quad correctors removed]
- **Confirmed:** solenoid and high-order terms in QC* magnets cause nonlinear X-Y coupling

![Diagram of Lattice Nonlinearity: LER](image-url)

From Y. Zhang
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3. Beam-beam effects

➤ Lum. tune scan for LER by BBWS (weak-strong with linear map for arc)

Choice of tune operating point $v_x$ near half integer, keep away from synchrobeta resonance $v_x, v_y = 0.53, 0.57$
3. Beam-beam effects

➤ Lum. tune scan for LER by BBWS: w/o and w/ crab waist

\[ H_I^* = \pm \frac{1}{2\theta_h} x p_y^2 \]

The crab waist is very powerful. Degradation of dynamic aperture is inevitable, because nonlinearity between IP and crab waist sextupole is not transparent.
3. Beam-beam effects: DA and lifetime

➤ DA and lifetime are sensitive to beam-beam interaction

Transverse aperture is reduced significantly.

From Y. Ohnishi
3. Beam-beam effects: DA and lifetime

➤ Tune survey of DA

There is a good region near half integer resonance for the vertical tune.

Chromaticity correction becomes very difficult near half integer.

From Y. Ohnishi
3. Beam-beam effects: DA and lifetime

➤ DA with BB and ideal CW

Stability of an initial amplitude in the horizontal and vertical plane.

Initial momentum deviation is zero.
(synchrotron motion is included.)

Ideal LER lattice

with Beam-Beam

with ideal CW

Injection aperture

Aperture limit

Ideal crab-waist is a map of

\[ f_{BB} \rightarrow f_{CW}(+\lambda) f_{BB} f_{CW}(-\lambda) \]

\[ f_{CW}(\lambda) : p_x \rightarrow p_x + \frac{\lambda}{2} p_y^2, \quad y \rightarrow y - \lambda x p_y \]

From Y. Ohnishi
3. Beam-beam effects: DA and lifetime

➤ CW optics

From Y. Ohnishi
3. Beam-beam effects: DA and lifetime

➤ CW optics

Crab-waist sextupole reduces dynamic aperture under the influence of beam-beam effect.

\[
\frac{\Delta x_0}{\sigma_x} \quad \text{LER with Beam-Beam}
\]

\[
\frac{2J_y}{2J_x} = 0.27 \%
\]

\[
K_2 = 0
\]

\[
K_2/K_2,\text{nominal} = 50 \%
\]

\[
K_2/K_2,\text{nominal} = 75 \%
\]

\[
K_2/K_2,\text{nominal} = 100 \%
\]

From Y. Ohnishi
3. Beam-beam effects: DA and lifetime

➤ CW optics

Crab-waist sextupole reduces dynamic aperture without beam-beam effect significantly.

\[
\frac{\Delta x_0}{\sigma_x} \quad \frac{\Delta \delta_0}{\sigma_\delta}
\]

\[H_{SX} = -9871x^3 + 6xp_y^2\]

The \(x^3\) term does not affect DA.

\[
\frac{2J_y}{2J_x} = 0.27 \%
\]

\[
K_2 = 0
\]

\[
K_2/K_{2,\text{nominal}} = 50\%
\]

From Y. Ohnishi
3. Beam-beam effects: BB+LN

➤ Interplay of BB and LN causes significant lum. loss

➤ LER: Lum. loss is attributed to amplitude-dependent nonlin.
  ● Vertical emittance is very sensitive to beam-beam perturbation
  ● Hard to suppress

➤ HER: Lum. loss is attributed to chromatic nonlin.
  ● Controllable if skew-sextupoles installed

![Graph](sler_1684)

![Graph](sher_5755)
3. Beam-beam effects: BB+LN

- Realistic lattice: lum. drops at low beam currents
- Crab-waist:
  - To cancel beam-beam driven resonances
  - Work well at high currents, but not well at low currents
3. Beam-beam effects: BB+LN: LER

➤ Beam tail distribution for LER

- CW not work well when LN exists
- Beam tail => Collimation => Impedance budget => Instability => commissioning

- $N_e = 6.53 \times 10^{10}$,
3. Beam-beam effects: BB+LN: LER

➤ Simplified lattice
  • No solenoid
  • QC* magnets simplified: no offset, dipole and skew-quad correctors removed

➤ No significant lum. degradation at low current

➤ Solenoid and high-order terms in QC* are the main sources of lattice nonlinearity
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- Summary and Future plan
4. SC effects: LER

» Linear tune shift
  ● Same order for SC and BB
  ● But have opposite signs

<table>
<thead>
<tr>
<th></th>
<th>SuperKEKB(^1))</th>
<th>KEKB(^4))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER(^2))</td>
<td>HER(^3))</td>
</tr>
<tr>
<td>(\varepsilon_x) (nm)</td>
<td>3.2</td>
<td>4.6</td>
</tr>
<tr>
<td>(\varepsilon_y) (pm)</td>
<td>8.64</td>
<td>11.5</td>
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<tr>
<td>(\xi_x)</td>
<td>0.0028</td>
<td>0.0012</td>
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<td>(\xi_y)</td>
<td>0.0881</td>
<td>0.0807</td>
</tr>
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<td>(\Delta\nu_x)</td>
<td>-0.0027</td>
<td>-0.0004</td>
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<tr>
<td>(\Delta\nu_y)</td>
<td>-0.0943</td>
<td>-0.0121</td>
</tr>
</tbody>
</table>

\(^1\)Main parameters from Y. Ohnishi et al., Prog. Theor. Exp. Phys. 2012;
\(^2\)sler_1682;
\(^3\)sher_5753;
\(^4\)Lattice used on Jun.17, 2009.
4. SC effects: LER

➤ FMA shows betatron tunes of particles at the beam core are close to half-integer with only SC considered.

From H. Sugimoto

---

4\textsuperscript{th} order
5\textsuperscript{th} order
6\textsuperscript{th} order
7\textsuperscript{th} order

Detailed Studies are now ongoing.
- Optics matching
- Checking simulation code including SAD code itself.

From H. Sugimoto
4. SC effects: LER

➤ FMA with beam distribution: \(10\sigma_x \times 10\sigma_y\)

**LN + SC**

**LN + SC + BB**
4. SC effects: LER

Luminosity: Tune scan w/ and w/o SC

Hor. tune scan

Vert. tune scan

BBWS

SAD-sler-1682
SAD-sler-1684
SAD-sler-1684(w/ SC)

BBWS

w/ CW sler-1689 SAD
w/ SC sler-1689 SAD

Design

Hor.

Vert.

specific Luminosity [10^35 cm^-2 s^-1]

Fractional $v_x$

Fractional $v_y$
4. SC effects: LER

➤ First try: **optics matching w/o SC**
➤ Compensate linear SC tune shift => Not successful
➤ Next try: **optics matching w/ SC** => Ongoing
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5. Impedance issues: Impedance budget

➢ Impedance budget with $\sigma_z=5/4.9\text{mm}$:

● Loss factors, resistance and inductance are calculated at nominal bunch lengths

● Bellows, flanges and pumping ports contribute more impedance in HER than in LER

Table 1. The PEP-II HER inductive impedance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>L (nH)</th>
<th>$k_t$ (V/pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole screens</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>BPM</td>
<td>11.</td>
<td>0.8</td>
</tr>
<tr>
<td>Arc bellow module</td>
<td>13.5</td>
<td>1.41</td>
</tr>
<tr>
<td>Collimators</td>
<td>18.9</td>
<td>0.24</td>
</tr>
<tr>
<td>Pump slots</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Flange/gap rings</td>
<td>0.47</td>
<td>0.03</td>
</tr>
<tr>
<td>Tapers oct/round</td>
<td>3.6</td>
<td>0.06</td>
</tr>
<tr>
<td>IR chamber</td>
<td>5.0</td>
<td>0.12</td>
</tr>
<tr>
<td>Feedback kickers</td>
<td>29.8</td>
<td>0.66</td>
</tr>
<tr>
<td>Injection port</td>
<td>0.17</td>
<td>0.004</td>
</tr>
<tr>
<td>Abort dump port</td>
<td>0.23</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>83.3</td>
<td>3.4</td>
</tr>
</tbody>
</table>

From slac-pub-6798

| Component    | LER $k_{||}$ | LER $R$ | LER $L$ | HER $k_{||}$ | HER $R$ | HER $L$ |
|--------------|--------------|---------|---------|--------------|---------|---------|
| ARES cavity  | 8.9          | 524     | -       | 3.3          | 190     | -       |
| SC cavity    | -            | -       | -       | 7.8          | 454     | -       |
| Collimator   | 1.1          | 62.4    | 13.0    | 5.3          | 309     | 10.8    |
| Res. wall    | 3.9          | 231     | 5.7     | 5.9          | 340     | 8.2     |
| Bellows      | 2.7          | 159     | 5.1     | 4.6          | 265     | 16.0    |
| Flange       | 0.2          | 13.7    | 4.1     | 0.6          | 34.1    | 19.3    |
| Pump. port   | 0.0          | 0.0     | 0.0     | 0.6          | 34.1    | 6.6     |
| SR mask      | 0.0          | 0.0     | 0.0     | 0.4          | 21.4    | 0.7     |
| IR duct      | 0.0          | 2.2     | 0.5     | 0.0          | 2.2     | 0.5     |
| BPM          | 0.1          | 8.2     | 0.6     | 0.0          | 0.0     | 0.0     |
| FB kicker    | 0.4          | 26.3    | 0.0     | 0.5          | 26.2    | 0.0     |
| FB BPM       | 0.0          | 1.1     | 0.0     | 0.0          | 1.1     | 0.0     |
| Long. kicker | 1.8          | 105     | 1.2     | -            | -       | -       |
| Groove pipe  | 0.1          | 5.7     | 0.9     | -            | -       | -       |
| Electrode    | 0.0          | 2.2     | 2.3     | -            | -       | -       |
| **Total**    | 19.2         | 1141    | 33.4    | 29.0         | 1677    | 62.1    |

Ref. D. Zhou et al., IPAC14, TUPRI021
5. Impedance issues: MWI: LER

➤ Simulations with input of Pseudo-Green wake:
  - Use Warnock-Cai’s VFP solver
  - Collimators are important sources in bunch lengthening
  - Simulated $\sigma_z \approx 5.9\text{mm}$ @Design bunch current
  - Simulated MWI threshold is around $\text{NP}_{th} = 1.2\times10^{11}$
  - Interplay between CSR and conventional wakes?

![Graphs showing impedance issues](image-url)
5. Impedance issues: MWI: LER

➤ Concern of MWI in LER:

- Unknown impedance source in KEKB LER
- Lum. inversely proportional to bunch length for SuperKEKB

\[ L = L_0 R_{H\theta} \]
\[ L_0 = \frac{N_e N_p f_0 N_b}{2\pi \sqrt{\sigma_{xe}^2 + \sigma_{xp}^2}} \]
\[ R_{H\theta} \approx \frac{1}{\sqrt{1 + \frac{\sigma_{ze}^2 + \sigma_{zp}^2}{\sigma_{xe}^2 + \sigma_{xp}^2} \tan^2 \theta}} \]
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➤ Summary and Future plan
6. Summary

➢ Interplay of various issues

- Luminosity <= Emittance <= Beam-beam, Lattice nonlinearity, Space charge, Impedances, Electron cloud, Intra-beam scattering, etc.
- => Dynamic aperture and lifetime => Beam commissioning => Injection, Detector back ground, Alignments, etc. => Tolerances for hardwares => ...

![Diagram showing interplay of various issues]

- Lattice nonlinearities
- Machine errors & correction
- Electron cloud
- Instabilities
- Beam-beam
- Luminosity
- Background
- Dynamic aperture
- Collimation
- Emittance
- Space charge
- Lifetime
- Linac, injection, e+/e-sources, damping ring, ...
- Intra-beam
- Impedance
- Alignment
7. Future plan

➤ Detailed analysis of lattice nonlinearity under an international collaboration program
  • Cornell Univ.: D. Sagan (Bmad+PTC)
  • SLAC: Y. Cai
  • IHEP: Y. Zhang
  • KEK: E. Forest, A. Morita, K. Ohmi, Y. Ohnishi, K. Oide, H. Sugimoto, D. Zhou, etc.
➤ Collaboration with CEPC and FCC-ee teams
➤ High-priority tasks:
  • Global or local correction schemes for latt. nonlin.
  • SC compensation schemes
  • Better understand the interplay of BB and LN
  • More careful study for crab waist scheme
  • ... ...
➤ Recommendations are welcome!
Thanks for your attention!
Backup
Lum. calculation: Detuned lattice

➤ Assume: $\varepsilon_x = 1.75\text{nm}$, coupling = 2%
➤ Space-charge is not important
➤ Lattice nonlinearity is not very important
➤ $L = 1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ is promising
➤ $L = 10 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ is possible by increasing beam currents
Lum. calculation: Detuned lattice

➤ Assume: $\varepsilon_x=1.75\text{nm}$, coupling = 1%

➤ Space-charge is not important at low currents

➤ Lattice nonlinearity is not very important

➤ Decreasing coupling => Lum. gain but beam-beam limit appears at lower beam currents
Space charge: LER: Tune shift

Linear SC tune shift along the ring

![Graph showing linear SC tune shift along the ring](sler_1689)
Intra-beam scattering: LER: SAD simulation

- Emittance growth due to IBS (w/ errors in sext.)
  - $\varepsilon_x$ decrease with increasing errors in sext.
  - Tolerance: $\sigma_{\Delta y} < 0.06 \text{ mm w/o IBS, } \sigma_{\Delta y} < 0.05 \text{ mm w/ IBS}$

![Graph showing emittance growth with IBS and without IBS.](image)
Intra-beam scattering: LER: SAD simulation

➤ Bunch lengthening and energy spread increase due to IBS (w/ errors in sext.)

- Both $\sigma_z$ and $\sigma_z$ slightly increase due to IBS
- Not negligible in LER
Bellows

- Bellows chamber with comb-type RF shield will be used in SKEKB.
  - There is no radial step on the inner surface.
    (There is a small step (~1 mm) in a conventional bellows chamber.)
  - RF is shielded by nested comb teeth.
    length : 10 mm
    radial thickness : 10 mm
- **Loss factor** ($\sigma_z = 6 \text{ mm}$)

  
  $k = 2.2 \times 10^{-3} \text{ V/pC}$

  ![Diagram showing KEKB and SKEKB points on a graph.]

  ▼ 1000 pieces in one ring

  $k_{\text{total}} = 2.2 \text{ V/pC}$

- **Impedance**

  It was found that there are trapped modes at 7.5 GHz and 25 GHz (over cut-off frequency (2.5GHz)). Effects of these trapped modes on the beams will be investigated.
- **TMCI in LER** (pointed out in last KEKB Review)
  - We estimated the threshold of the Transverse Mode Coupling Instability using actual $\beta$ value at location of each collimator with $\sigma_z = 6$ mm.
  - D02V1 is the main impedance source because it would be used with the narrow aperture ($d = \pm 2$ mm).
  - The threshold is about 1.71 mA/bunch (Design value: 1.44 mA/bunch) in the latest collimator design.

### TMC threshold (mA/bunch)

<table>
<thead>
<tr>
<th></th>
<th>All Closed</th>
<th>Actual apertures</th>
<th>Bunch current (design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>1.41</td>
<td>13.15</td>
<td>1.44 mA/bunch</td>
</tr>
<tr>
<td>Vertical</td>
<td>1.32</td>
<td>1.71</td>
<td></td>
</tr>
</tbody>
</table>

### Collimator Aperture List (mm)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D06H1</td>
<td>-16.0/+17.0</td>
<td>D03H1</td>
<td>-21.0/+20.0</td>
<td>D02H1</td>
</tr>
<tr>
<td>D06H2</td>
<td>-16.0/+16.0</td>
<td>D03H2</td>
<td>-18.0/+20.0</td>
<td>D02H2</td>
</tr>
<tr>
<td>D06H3</td>
<td>-16.0/+15.0</td>
<td>D03V1</td>
<td>-9.0/+9.0</td>
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</tr>
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<td>D06H4</td>
<td>-13.0/+13.0</td>
<td>D03V2</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>D02V1</td>
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