SuperKEKB as test and demonstrator of future $e^+e^-$ circular colliders

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Exploring the luminosity frontier with SuperKEKB

KEKB
$2 \times 10^{34}/\text{cm}^2/\text{s}$

SuperKEKB
$8 \times 10^{35}/\text{cm}^2/\text{s}$

- Future $e^+e^-$ circular colliders (FCCee, CEPC) use concepts tried for 1st time at SuperKEKB, e.g. nanobeam collision scheme
- Maximize luminosity $\leftrightarrow$ mitigate beam induced detector* backgrounds $\rightarrow$ major SuperKEKB challenge

Relevant to test / validate future collider designs!

* also some accelerator components
1) Phase 1: February → June, 2016
   - single beam commissioning, vacuum scrubbing
   - no luminosity (no final focus), no Belle II
2) Phase 2: February → July 2018
   - colliding beam commissioning, Belle II w/o vertex detector
   - first collisions + pilot run (0.5 fb⁻¹)
3) Phase 3.1: March 27 → July 1, 2019
   - Physics run with full detector (6.5 fb⁻¹), resume in October-December
Belle-II @ SuperKEKB physics motivation

Discover new physics via precision search for deviations from SM predictions induced by new particles appearing in higher order quantum corrections

- Precision measurements of CKM matrix elements
- Rare / forbidden B, D, τ decays
- Dark sector searches
- ....

1st B-B like event during 1st physics run

Luminosity projection

Talks on Belle II detector & physics at ICNFC 2019

1. P. Goldenzweig, “First look at CKM parameters from early Belle II data”
2. I. Komarov, “Dark sector physics with Belle II: first results and prospects”
3. L. Vitale, “Belle II experiment: status and prospects”
KEKB ↔ SuperKEKB parameters

<table>
<thead>
<tr>
<th></th>
<th>KEKB LER ($e^+$)</th>
<th>KEKB HER ($e^-$)</th>
<th>SuperKEKB LER ($e^+$)</th>
<th>SuperKEKB HER ($e^-$)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy ($E$)</td>
<td>3.5</td>
<td>8.0</td>
<td>4.0</td>
<td>7.007</td>
<td>GeV</td>
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<tr>
<td>Circumference ($C$)</td>
<td>3016.262</td>
<td></td>
<td>3016.315</td>
<td></td>
<td>m</td>
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<tr>
<td>Half crossing angle ($\theta_x$)</td>
<td>0(11(s))</td>
<td></td>
<td>41.5</td>
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<td>mrad</td>
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<tr>
<td>Piwinski angle ($\phi_{piw}$)</td>
<td>0</td>
<td>0</td>
<td>24.6</td>
<td>19.3</td>
<td>rad</td>
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<tr>
<td>Horizontal emittance ($\varepsilon_x$)</td>
<td>18</td>
<td>24</td>
<td>3.2(1.9)</td>
<td>4.6(4.4)</td>
<td>nm</td>
</tr>
<tr>
<td>Vertical emittance ($\varepsilon_y$)</td>
<td>150</td>
<td>150</td>
<td>8.64</td>
<td>12.9</td>
<td>pm</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.83</td>
<td>0.62</td>
<td>0.27</td>
<td>0.28</td>
<td>%</td>
</tr>
<tr>
<td>Beta function at IP ($\beta_x^* / \beta_y^*$)</td>
<td>1200/5.9</td>
<td>1200/5.9</td>
<td>32/0.27</td>
<td>25/0.30</td>
<td>mm</td>
</tr>
<tr>
<td>Horizontal beam size ($\sigma_x^*$)</td>
<td>147</td>
<td>170</td>
<td>10.1</td>
<td>10.7</td>
<td>$\mu$m</td>
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<tr>
<td>Vertical beam size ($\sigma_y^*$)</td>
<td>940</td>
<td>940</td>
<td>48</td>
<td>62</td>
<td>nm</td>
</tr>
<tr>
<td>Horizontal betatron tune ($\nu_x$)</td>
<td>45.506</td>
<td>44.511</td>
<td>44.530</td>
<td>45.530</td>
<td></td>
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<tr>
<td>Vertical betatron tune ($\nu_y$)</td>
<td>43.561</td>
<td>41.585</td>
<td>46.570</td>
<td>43.570</td>
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<tr>
<td>Momentum compaction ($\alpha_p$)</td>
<td>3.3</td>
<td>3.4</td>
<td>3.20</td>
<td>4.55</td>
<td>$10^{-4}$</td>
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<tr>
<td>Energy spread ($\sigma_s$)</td>
<td>7.3</td>
<td>6.7</td>
<td>7.92(7.53)</td>
<td>6.37(6.30)</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Beam current ($I$)</td>
<td>1.64</td>
<td>1.19</td>
<td>3.60</td>
<td>2.60</td>
<td>A</td>
</tr>
<tr>
<td>Number of bunches ($n_b$)</td>
<td>1584</td>
<td></td>
<td>2500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle/bunch ($N$)</td>
<td>6.47</td>
<td>4.72</td>
<td>9.04</td>
<td>6.53</td>
<td>$10^{10}$</td>
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<tr>
<td>Energy loss ($U_0$)</td>
<td>1.64</td>
<td>3.48</td>
<td>1.76</td>
<td>2.43</td>
<td>MeV</td>
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<tr>
<td>Long. damping time ($\tau_z$)</td>
<td>21.5</td>
<td>23.2</td>
<td>22.8</td>
<td>29.0</td>
<td>msec</td>
</tr>
<tr>
<td>RF frequency ($f_{RF}$)</td>
<td>508.9</td>
<td></td>
<td>508.9</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Total cavity voltage ($V_C$)</td>
<td>8.0</td>
<td>13.0</td>
<td>9.4</td>
<td>15.0</td>
<td>MV</td>
</tr>
<tr>
<td>Total beam power ($P_b$)</td>
<td>$\sim 3$</td>
<td>$\sim 4$</td>
<td>8.3</td>
<td>7.5</td>
<td>MW</td>
</tr>
<tr>
<td>Synchrotron tune ($\nu_s$)</td>
<td>-0.0246</td>
<td>-0.0209</td>
<td>-0.0245</td>
<td>-0.0280</td>
<td></td>
</tr>
<tr>
<td>Bunch length ($\sigma_z$)</td>
<td>$\sim 7$</td>
<td>$\sim 7$</td>
<td>6.0(4.7)</td>
<td>5.0(4.9)</td>
<td>mm</td>
</tr>
</tbody>
</table>

- $\times 1/20 \beta_y$
- $\sigma_y \approx 50-60$ nm
- (similar as ILC/ATF2)
- $\times 2$-$3$ beam currents
- similar beam-beam strength (tune-shift)
- $\rightarrow \times 40$ peak luminosity

Luminosity 

\[
L = 2.108 \times 10^{34} \quad \text{cm}^{-2}\text{s}^{-1}
\]

\[
\int L = 1.041 \quad \text{ab}^{-1}
\]
Nanobeam collision scheme

opportunities

✓ very small $\beta_y$ avoiding “hour-glass” limitation (effective bunch length $\approx$ depth of field of the optics)
✓ collide more charge @ tiny vertical beam size with similar beam-beam tune-shift strength parameter

challenges @ SuperKEKB

1. IP tuning to cancel optical aberrations essential to maintain tiny beam sizes (linear collider like ?)
2. control beam-beam tune-shift with more complex beam-beam dynamics + IP optics aberrations
3. continuously injected intense beams & strong IP optical magnification $\rightarrow$ backgrounds (linear collider like ?)

$$\xi_{xy} = \frac{r_e}{2\pi \gamma_{\pm}} \frac{N_{\pm} \beta_{xy}^*}{\sigma_{xy}^*(\sigma_x^* + \sigma_y^*)} R_{\xi_{xy}}$$

$$L = \frac{\gamma_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{\pm} \xi_{\pm}}{\beta_{y\pm}^*} \right) \left( \frac{R_L}{R_{\xi_{\pm}}} \right) \times 1/20 \beta_y$$

$$L = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y} R_L \times 2\sim 3 \text{ beam currents}$$

$$L = \frac{1}{20} \sigma_y$$
SuperKEKB commissioning history: Phase 2  
(March => July 2018)

- Belle II detector rolled in and first physics events measured
- Colliding beam commissioning, no vertex detector
- Progressively reducing $\beta_y$ from 8 mm to 3 mm (design value is 0.3 mm)
- Smallest beam size (at low intensity) $\sigma_y^* \approx 0.4 \mu m$
- Maximum luminosity: $L \approx 0.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$
SuperKEKB commissioning history: Phase 3 (March => June 2019)

- Belle II vertex detector installed
- Background decreased by factor 10 with improved collimation
- Lost one month due to linac fire accident (unrelated to SuperKEKB)
- Maintained stable operation with continuous injection and currents at $I \approx 500\ mA$
- Belle II data taking most of the period: accumulated $\sim 6.5\ fb^{-1}$ for early Belle II physics analyses
- Squeezed beta $\beta_y^*$ to 2 mm
- Luminosity milestone: $L = 1.0 \times 10^{34}\ cm^{-2}s^{-1}$
Good progress squeezing $\sigma_y$ with $\beta_y < \sigma_z$

→ shows “hour-glass” effect mitigated in nanobeam scheme

→ smallest $\beta_y$ achieved in storage ring

$\beta_y > \sigma_z$  $\beta_y \approx \sigma_z$  $\beta_y < \sigma_z$

$\beta_y = 2\text{ mm} \text{ achieved in June 2019}$

$L_{sp}$ is increased by squeezing $\beta_y^*$. ($\xi_{\pm y}$ can be kept while squeezing)

$$L = \frac{\gamma}{2e \tau_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{\pm y}}{\beta_y^*} \right) \left( \frac{R_L}{R_{\gamma y}} \right)$$
Reduced bunch overlap in nanobeam scheme also visible on Z distribution of reconstructed track vertices.

**Ordinary collision KEKB**

Z vertex distribution

**Nano-Beam (SuperKEKB)**

$2\phi = 83$ mrad

Z vertex distribution

Belle II case 1999 data

$\sigma = 4.5$ mm

Belle II case 2018 data

$\sigma_{68} = 0.055$ cm

$\int L dt = 24 pb^{-1}$

$\sigma = 550$ $\mu$m
IP optical aberrations blowing up the beam size are unavoidable
→ reliable measurement for correction only at the IP...

\[ \sigma_y^2 = \mu^2 \varepsilon_y \left( \beta_y + \frac{\Delta s^2}{\beta_y} \right) + \left\{ \frac{(R_2 + R_4 \Delta s)^2}{\beta_x} + \beta_x \left( R_1 + R_3 \Delta s \right)^2 \right\} + (\eta_y \sigma_\delta)^2 \]

+ higher order terms
  (geometric & chromo-geometric)

ideal spot  waist shift  linear x-y coupling  linear dispersion

Optical functions in LER ±27 m around IP

Quad strength tolerance for waist shift \(< \beta^* / L^* = 3 \times 10^{-4} \)

\[ \sigma_{\text{quad}} = 0.2 \text{ mm} \]

\( \sigma_{\text{IP}} \approx 60 \text{ nm} \)

Matching quads to select \( \beta^* \)

Propagate IP aberration in low-\( \beta \) insertion
→ no visibility (except, possibly, at a secondary waist)

Must tune directly at IP (luminosity...)

Integration with Belle II
LumiBelle2

Luminosity monitor that measures recoiling electrons, positrons, and photons from forward radiative Bhabha scattering

FEATURES:
• Single crystal CVD diamond sensors
• $4 \times 4 \times 0.5/0.14 \, mm^3$
• Fast amplifiers;
• Digital electronics.
• 4 of 6 channels online

GOALS:
1. Train integrated luminosity): 1% precision at 1kHz;
2. Bunch-by-bunch integrated luminosity): 1% precision at 1 Hz;
3. Cover SuperKEKB large luminosity range with high SNR: $L = 10^{30} - 10^{36} \, cm^{-2} s^{-1}$
Zero degree radiative Bhabha scattering

\[ E(e^-) = 7\,\text{GeV} \]

\[ E(e^+) = 4\,\text{GeV} \]

- Complementary reaction for \( e^+ \) spectator
- Large cross section \( \sigma \approx 250\,\text{mbarn} \) for \( E(\gamma) > 1\% E(\text{beam}) \)
- LumiBelle2 measures rates \( dN/dt \) of \( e^+ \) in the positron ring and \( \gamma \) in the electron ring

\[ L = \frac{1}{\sigma} \frac{dN}{dt} \text{ not known with precision} + \text{acceptance varies over time} \]

\[ L \propto \frac{dN}{dt} \]
Optimal position found at 11 m downstream of IP using SAD

Bhabha positrons are over-bent and hit the vacuum chamber

Special beam pipe with window + Tungsten radiator

Originally position at 30 m (2018)

I designed an original simulation to track photons inside the vacuum chamber. Photons generated with GUINEA PIG ++

Optimal position found at 28 m

New position has rate ~10 times higher (2019);
Fast monitoring with diamonds

- High charge carrier mobility
  - fast signal formation
- Wide band-gap (5.5 eV)
  - good radiation tolerance

SuperKEKB collision period = 4 ns

- To monitor bunch-by-bunch luminosity we need a pulse width smaller than 4 ns
- 140 μm thick diamond + fast current amplifier provides 2 ns FWHM
Signal processing algorithms

- 2ns FWHM signals are sampled every 1 ns
- Synchronization to RF clock -> continuous monitoring, averaging at 1 kHz
- Luminosity proportional to amplitude of signal peaks
  1. ADC is AC-coupled -> difference between peak and baseline recorded
  2. Raw sum of signal peaks is also recorded
ZDLM (Zero Degree Luminosity Monitor)

S. Uehara (KEK, IPNS/Belle II)

Improved version of KEKB fast luminosity monitor
- used as benchmark for many studies ↔ LumiBelle2

Shared supports and many activities for optimisation and evaluation
Different, complementary techniques (sensors, electronics and DAQ, ...)

- Cherenkov and scintillator detectors + PMT
- 15 × 15 × 64 mm³ LGSO non-organic scintillator and ES-crystal (quartz)
- Miniaturized versions
- Provides bunch-by-bunch and train integrated luminosities
- Analog electronics
First collisions (luminosity): 25 April, 2018

- Vertical and phase (longitudinal) scans were performed to find the optimal position of the beams
- Zero Degree Luminosity Monitor (ZDLM), present since KEKB, used as benchmark
- The 4 LumiBelle2 channels and the ZDLM work well and are in agreement
- Successfully measured and provided the luminosity on-line from the first collision up to this date
The ZDLM is a relative luminosity monitor located close to the LumiBelle2 diamonds.

The Electromagnetic Calorimeter (ECL) is part of the Belle II detector and can measure the absolute luminosity.

We observe good correlation on a day-by-day basis or shorter time scales;

Long term variations in slopes (sensitivities) due to changes in beam conditions and setups: gains, position of the sensors, thresholds, etc.
SIMULATION FEATURES:
- Bremsstrahlung, Coulomb, and Touschek scattering included
- Use of SAD for tracking and Geant4 for particle detection
- Detailed simulation of pressure profile and chemical composition of vacuum gas ($Z_{eff} \approx 4.2 - 4.5$) from previous study (J.Carter, M.Ady)

HER (e- ring):
- Dominant rate from Bremsstrahlung photons
- Electron rates from Bremsstrahlung, Coulomb, and Touschek scattering are negligible ($\ll 1\text{Hz}$)

LER (e+ ring):
- Dominant rate from Bremsstrahlung positrons
- $\sim 10\%$ of the rate from Touschek scattering
- Positron rate from Coulomb scattering is negligible

Total pressures at 1000, 10000 A*hrs, $I = 3.6\, \text{A}$
- Total indicates sum of $\text{H}_2$, $\text{CO}$, $\text{CO}_2$, and $\text{CH}_4$ partial pressures
- Asymmetric because of synchrotron radiation

Scattering position of Bremsstrahlung particles detected in LumiBelle2 / LER

Measurement vs Simulation

Simulated vacuum profile in IR

Touschek
Fast & slow beam position variations at IP require feedback corrections

- **Beam-beam deflection** for fast vertical motion

  \[ \Delta y \text{ at IP} = \sim 5\text{nm} \sim 1/10\sigma_y^* \]

- **Luminosity feedback** by “dithering” for slower horizontal motion

  Vertical vibration \sim 25-100\,\text{Hz}
  
  Sampling (BPMs) \sim 32\,\text{kHz}

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Horizontal motion \sim \text{few Hz}

- Modulation freq. \( f_0 \sim 79\,\text{Hz} \)
- Sampling (lumi. meas.) \sim 1\,\text{kHz}

- minimize \( f_0 \) output component
- dithering \times \text{lumi. signal } \rightarrow \text{phase}

---

**Equation:**

\[ L(t) = \frac{f_{\text{rev}} N_1 N_2}{4\pi \sigma_x \sigma_y} e^{-(\frac{[q + psin(2\pi ft)]^2}{4})} \]
1st dithering feedback test in Phase 2

• The e- beam was artificially given an offset, while the e+ beam was dithered

• The algorithm tries to minimize the Magnitude [V] of the luminosity FT calculated at the driving frequency $f_0$ to bring the beams back to the optimal position (unwanted offset $o=0$)

• These parameters are then sent to the magnet control system via EPICS to create a bump in the e- beam

• After first two attempts, optimization of the algorithm parameters, in the third one the feedback was able to smoothly minimize the offset

Further tests in Phase 2 & 3 have exhibited some coupling effects between X and Y feedback systems $\rightarrow$ to be solved for operation at design parameters
Beam size estimation with vertical offset scans

Analytical result integrating Gaussian distributions with vertical offset:

\[
\frac{L}{L_0} = \exp \left( -\frac{\Delta y^2}{2\Sigma_y^2} \right) \\
\Sigma_y^2 = \sigma_{1,y}^* + \sigma_{2,y}^* \approx 2\sigma_y^2
\]

assumes rigid beams

\[
\sigma_y^* \text{ estimation slightly biased due to non constant beam-beam blow-up during the scan}
\]

beam-beam simulation (S. Di Carlo & D. Zhou)
Sensitive luminosity monitor important to correct optical aberrations in vertical IP beam size

\[ \beta^*_y = 4 \text{ mm} \]

*very low intensity essential to avoid beam-beam effects:*

1. confusion from blow-up,
2. biased beam size estimates

---

**Phase 2**

\[ \beta^*_y = 4 \text{ mm} \]

**Adjustment of XY Coupling with QC1 Skew Quadrupoles**

**Before \( R_2 \) adjustment**

**After \( R_2 \) adjustment**

**LumiBelle2 is good performance!**

Very large beam size!

Estimation from X-Ray Monitor:

- \( \sigma^*_y = 0.4 \mu m \) (LER), 0.5 \( \mu m \) (HER)
- No change after adjustment of X-Y coupling \( (R_2) \) at IP

Measurement by beam-beam scan:

- \( \sigma^*_y = 1.253 \mu m \rightarrow 0.689 \mu m \)
  - Very small!
Sensitive luminosity monitor important to correct optical aberrations in vertical IP beam size

*very low intensity essential to avoid beam-beam effects: (1) confusion from blow-up, (2) biased beam size estimates*

Phase 2
$\beta_y^* = 3$ mm

S. Di Carlo (LAL)
Vertical offset scan

Y. Funakoshi (KEK), 1st SuperKEKB Beam Dynamics Mini Workshop, 17/7/2019

\[ \frac{\Sigma y^*/\sqrt{2}}{\beta_y} = 0.35/\sqrt{2} = 0.248 \text{ mm} \]

\[ \frac{\Sigma y^*/\sqrt{2}}{\beta_y} \text{ (XRM)} = \sqrt{0.3^2 + 0.25^2}/\sqrt{2} = 0.276 \text{ mm} \]

XRM & beam-beam scan beam size match → IP has no big x-y coupling

Phase 3

\[ \beta_y^* = 2 \text{ mm} \]
Bunch-by-bunch luminosities, folded vertical bunch sizes and relative offsets

8% spread mainly depends on bunch current differences

Bunch-by-bunch luminosity precision: 1-2% at 1Hz
dominated by spread in bunch-by-bunch currents

8nm RMS spread in bunch-by-bunch vertical offsets (2.3% of average bunch size)

2% RMS spread in bunch-by-bunch vertical beam sizes
Bunch-by-bunch luminosities at high current:

enhanced values for 1\textsuperscript{st} bunches in the train 
→ transient beam loading effect, other ???

$L = 1.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

1576 bunches
Present beam-beam performance

Y. Ohnishi (KEK), 1st SuperKEKB Beam Dynamics Mini Workshop, 17/7/2019

Specific Luminosity and Beam-Beam Parameter

- Luminosity improves squeezing $\beta_y$
- Beam-beam parameter remains constant $\sim 0.025$

$\Rightarrow$ need $\xi_y \sim 0.08$ @ 1.4 mA $\Leftrightarrow \xi_y \sim 0.04$ @ 0.7 mA
Example of **simulated** effect of high-order / chromatic optical aberrations on beam-beam performance

based on K. Ohmi (KEK), 1st SuperKEKB Beam Dynamics Mini Workshop, 17/7/2019

Magnitude of aberrations needed to explain beam-beam blow-up seems very / too large...

- Realism of simulation to quantitatively fully represent the beam-beam interaction and its interplay with optical aberrations, including the full non-linear ring lattice?
- Other effects specific to nanobeam scheme (large crossing angle) → “crab-waist” solution?
Is crab-waist the solution?

D. Zhou (KEK), 1st SuperKEKB Beam Dynamics Mini Workshop, 17/7/2019

2. BBWS simulation: Tune scan

➤ Tune scan to detect the beam-beam resonances
  - $\pm v_x + 4v_y + \alpha = N$ was recognized and respected in the choice of operational working point from Phase-2
  - $\pm v_x + 4v_y + \alpha = N$ plays an important role only without crab waist, which is the baseline design of SuperKEKB
  - $\pm v_x + 4v_y + \alpha = N$ was found to be important in SuperKEKB by D. Shatilov [Talk presented at IHEP, China on Apr.11, 2014]

This plot approximately corresponds to the scheme currently adopted for SuperKEKB

No crab waist

Strong beam is not crabbed

Both beams are crabbed

The power of crab waist is demonstrated.

Thanks to Y. Zhang for sending the slides

Investigation of beam-beam effects in the nano-beam scheme → central topic at SuperKEKB
Conclusion and prospects

- SuperKEKB is the only electron-positron collider operating with new concepts to reach very high luminosity
- Initial commissioning and operation shows good progress, also considerable challenges
  - tuning of many optical aberrations at the IP
  - beam-beam effects/limits and interplay with optical aberrations
  - beam induced background and trade-off wrt luminosity / $\beta^*$
  - ......
- Essential instrumentation to directly probe the beam size and luminosity performance at the IP
- Application to future high energy colliders: FCC-ee / CEPC, also ILC/CLIC...
  - unique training ground to prepare, test, validate future designs...
Backup slides