Preliminary Design of Injector Complex

NSLS-II Accelerator Systems Advisory Committee

October 8th, 2007

T. Shaftan for NSLS-II team
Outline

• Introduction
• NSLS-II injection requirements
• Top-off
• Injection system overview
• Linac
• Booster
• Transport lines
• Cost
• Schedule
• Summary
Introduction

• CD-1: in-tunnel booster → most economical solution
• Support from technical reviews
• Concerns expressed by Lehman review regarding booster-ring cross-talk and impact on installation schedule and troubleshooting
• Recommendation from Lehman review to develop injector with a “compact” booster
• Given short schedule: linac and booster are semi-turnkey procurements
• Transport lines and ring injection straight are by BNL
• Maximum energy for the injector is 3.1 GeV
Requirements for NSLS-II Injection

• High reliability
• Reasonable initial fill time
• Low losses

• Lifetime 3 hours (with 3\textsuperscript{rd} HC)
• Top-off
  ▪ Stability of current <1 \%
  ▪ Time between top-off injections >1 min
  ▪ Bunch-to-bunch variations of charge <20\%
## Ring Parameters Related to Injection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, GeV</td>
<td>3</td>
</tr>
<tr>
<td>Circulating current, A</td>
<td>0.5</td>
</tr>
<tr>
<td>Circumference, m</td>
<td>792</td>
</tr>
<tr>
<td>Revolution period, μs</td>
<td>2.6</td>
</tr>
<tr>
<td>RF frequency, MHz (wavelength, m)</td>
<td>500(0.6)</td>
</tr>
<tr>
<td>Circulating charge, μC</td>
<td>1.3</td>
</tr>
<tr>
<td>Total number of buckets</td>
<td>1320</td>
</tr>
<tr>
<td>Number of filled buckets</td>
<td>1320⋅4/5≈1080</td>
</tr>
<tr>
<td>Charge per bucket, nC</td>
<td>1.25</td>
</tr>
<tr>
<td>Lifetime, hours</td>
<td>3</td>
</tr>
<tr>
<td>Interval between top-up cycles, min</td>
<td>1</td>
</tr>
<tr>
<td>Current variation between top-up cycles, %</td>
<td>0.55%</td>
</tr>
<tr>
<td>Charge variation between top-up cycles, nC</td>
<td>7.3</td>
</tr>
</tbody>
</table>
Injection Scenario

- Many (~1000) bunches in the ring → multi-bunch injection
  - \( N_M \) bunches in the injected train
  - Filling \( N_M \) consecutive buckets in the ring
  - Sequentially shift the injection timing
- 1 Hz repetition rate suffices with pulse train injection
- 1 minute between top-off cycles
- Kickers duration are 2 turns long (5.2 \( \mu \)sec) or can be even longer
- Considered in ALS top-off (10 bunches)
Top-off formats and bunch patterns

Nominal

Fall-back

Top-off formats

NSLS-II Baseline

Future upgrades:

“Camshaft”

“Complex”

Bunch patterns

Accelerator Systems Advisory Committee, October 8th 2007
NSLS-II Injector Complex
Linac

- NSLS-II: 200 MeV, 15 nC/train, ~0.5% energy spread
- 100 MeV linac from THALES is in operations for SOLEIL
- Achieved parameters:
  - 10 nC/pulse in LPM
  - 0.5nC/pulse in SPM
- Close to NSLS-II requirements

<table>
<thead>
<tr>
<th></th>
<th>LPM</th>
<th></th>
<th>SPM</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Specified</td>
<td>Measured</td>
<td>Specified</td>
<td>Measured</td>
</tr>
<tr>
<td>Pulses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse length (ns)</td>
<td>300</td>
<td>286</td>
<td>&lt;2</td>
<td>1.3</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>&gt;=100</td>
<td>108</td>
<td>&gt;=100</td>
<td>110</td>
</tr>
<tr>
<td>Charge/Pulse (nC)</td>
<td>8</td>
<td>9.3</td>
<td>0.5 and 2</td>
<td>0.52</td>
</tr>
<tr>
<td>Emittance (mm.mrad)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal (4\theta)</td>
<td>200</td>
<td>47</td>
<td>200</td>
<td>64</td>
</tr>
<tr>
<td>Vertical (4\theta)</td>
<td>200</td>
<td>52</td>
<td>200</td>
<td>67</td>
</tr>
</tbody>
</table>
| Energy spread (%)   | ±1.5      | ±0.5    | ±1.5     | ±0.50   | ±0.82
Booster Layout

- C = 158.4 m (1/5 of SR)
- E = 0.2 $\rightarrow$ 3 GeV
- Q = 10 nC
- $\varepsilon_x = 125 \rightarrow 30$ nm rad
- $\sigma_\gamma/\gamma = 0.5 \rightarrow 0.1\%$
- $N_b = 40-150$ bunches
- $F_{rep} = 1$ Hz
- 4-quadrant lattice
- 60 combined-function magnets
- 1 straight $\rightarrow$ injection
- 1 straight $\rightarrow$ RF (Two 499.68 MHz PETRA-type cavities)
- 1 straight $\rightarrow$ extraction
- Low magnet peak field of 1 T
- 200 MeV injection energy
Booster Lattice

- ASPb-like solution
- Cost-effective design
- Periodicity of 4
- Combined function FODO lattice
- B, K₁, K₂ in dipoles
- Matching triplets (additional quad family for flexibility)
- Low dispersion in long straights
- Discrete sextupoles for eddy-current compensation (+0.5 x, -1.4 y max at 1Hz)
- Preliminary design

\[ \delta x / \rho \circ c = 0. \]

Table name = TWISS
# Booster parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ASP booster</th>
<th>NSLS-II booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emittance, nm</td>
<td>34.4</td>
<td>26.6</td>
</tr>
<tr>
<td>Circumference, m</td>
<td>130.2</td>
<td>158.4</td>
</tr>
<tr>
<td>Revolution time, ns</td>
<td>434</td>
<td>528</td>
</tr>
<tr>
<td>RF frequency, MHz</td>
<td>499.654</td>
<td>499.68</td>
</tr>
<tr>
<td>RF voltage, MV</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>217</td>
<td>264</td>
</tr>
<tr>
<td>X/Y tune</td>
<td>9.2/3.25</td>
<td>10.91/6.69</td>
</tr>
<tr>
<td>X/Y Chromaticity</td>
<td>-8.83/-11.5</td>
<td>-13.8/-18.9</td>
</tr>
<tr>
<td>X/Y coupling</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Corrected chromaticities</td>
<td>+0.83/+0.87</td>
<td>+1.7/+1.7</td>
</tr>
<tr>
<td>Momentum Compaction</td>
<td>0.0098</td>
<td>0.0072</td>
</tr>
<tr>
<td>Energy loss per turn, keV</td>
<td>743</td>
<td>625</td>
</tr>
<tr>
<td>X/Y/Z damping time, ms</td>
<td>2.7/3.5/2.0</td>
<td>5.4/5.1/2.5</td>
</tr>
<tr>
<td>Damped energy spread, %</td>
<td>0.094</td>
<td>0.078</td>
</tr>
<tr>
<td>Damped bunch length, mm</td>
<td>19</td>
<td>13.9</td>
</tr>
</tbody>
</table>
Flexibility of NSLS-II booster

NSLS-II booster

ASP booster
Booster injection and extraction

• Considering booster injection system be able to allow stacking of the low-energy beam at the maximum linac repetition rate of 10 Hz.

• Calculations are in progress of attempting to stack two consecutive (separated by 0.1 seconds) bunch trains transversely in the booster by injecting them with ½ of the nominal kicker strength.

• Combination of DC strong septum and pulsed weak kicker is preferable and will be explored for both injection and extraction.
# Part Count / Magnetic element properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ASP</th>
<th>NSLS-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number, BF/BD</td>
<td>28/32</td>
<td>28/32</td>
</tr>
<tr>
<td>Length, BF/BD</td>
<td>1.35/1.15 m</td>
<td>1.35/1.4 m</td>
</tr>
<tr>
<td>Angle, BF/BD</td>
<td>3.43/8.25°</td>
<td>3.43/8.25°</td>
</tr>
<tr>
<td>Injection energy</td>
<td>100 MeV</td>
<td>200 MeV</td>
</tr>
<tr>
<td>Field, BF/BD (inj)</td>
<td>0.015/0.042 T</td>
<td>0.030/0.069 T</td>
</tr>
<tr>
<td>Field, BF/BD (ext)</td>
<td>0.443/1.25 T</td>
<td>0.443/1.00 T</td>
</tr>
<tr>
<td>Quadrupole K1, BF/BD (ext)</td>
<td>0.82595/-0.66977 m⁻²</td>
<td>0.82800/-0.63831 m⁻²</td>
</tr>
<tr>
<td>Sextupole K2, BF/BD (ext)</td>
<td>3.54/-4.925 m⁻³</td>
<td>4.10/-5.65 m⁻³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ASP</th>
<th>NSLS-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number, QF/QD/QG</td>
<td>8/8</td>
<td>8/8/8</td>
</tr>
<tr>
<td>Length, QF/QD/QG</td>
<td>0.25/0.15 m</td>
<td>0.45/0.15/0.15 m</td>
</tr>
<tr>
<td>K1, QF/QD/QG (inj)</td>
<td>-0.0784/0.0133 m⁻²</td>
<td>0.123/0.058/-0.0869 m⁻²</td>
</tr>
<tr>
<td>K1, QF/QD/QG (ext)</td>
<td>-2.351/0.0400 m⁻²</td>
<td>1.84/0.871/-1.30 m⁻²</td>
</tr>
<tr>
<td>Number, SF/SD</td>
<td>8/8</td>
<td>8/8</td>
</tr>
<tr>
<td>Length, SF/SD</td>
<td>0.2/0.2 m</td>
<td>0.15/0.15 m</td>
</tr>
<tr>
<td>K2, SF/SD (ext)</td>
<td>50/-30 m⁻³</td>
<td>40/-40 m⁻³</td>
</tr>
</tbody>
</table>

**Focusing and defocusing dipole pole tips**

Thanks to S. Mikhailov (Duke Univ.)

26th 8th 2007
Orbit correction and tolerances

- Tolerances
  - Dipole length: 0.1%
  - Dipole field: 0.1%
  - Dipole ∥ displ.: 1mm
  - Dipole ⊥ displ.: 0.1mm
  - Dipole roll: 0.5mrad
  - Quad ⊥ displ.: 0.2mm
  - Quad gradient: 0.02%

Uncorrected and corrected orbits
(red - X, blue - Y)

Corrector maximum angles <1mrad
## Diagnostics and Instrumentation for Booster

### Measured parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>30 mA</td>
<td>0.1%</td>
</tr>
<tr>
<td>Fill pattern</td>
<td>40-150 bun.</td>
<td>1%</td>
</tr>
<tr>
<td>Closed orbit</td>
<td>&lt;30 m</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>Beta-functions</td>
<td>&lt;35 cm</td>
<td></td>
</tr>
<tr>
<td>Dispersion</td>
<td>10.9/6.7</td>
<td>0.01</td>
</tr>
<tr>
<td>X/Y Tunes</td>
<td>~30 nm·rad</td>
<td>10%</td>
</tr>
<tr>
<td>X geom. emittance</td>
<td>-13.8/-18.9</td>
<td>0.3</td>
</tr>
<tr>
<td>X/Y chromaticities</td>
<td>&lt;10%</td>
<td>1%</td>
</tr>
<tr>
<td>Coupling</td>
<td>16 ps RMS</td>
<td>2 ps</td>
</tr>
<tr>
<td>Synchrotron Frequency</td>
<td>~20 kHz</td>
<td>1 kHz</td>
</tr>
</tbody>
</table>

### Continuously monitored beam parameters:

- Current
- X/Y Tunes
- Orbit
- Beam shape

### Diagnostics:

- 20 X-Y BPMs
- 1 DCCT
- 2 striplines
- 6 Fluorescent Screens
- Fast Current Transformer
- Synchrotron Light Monitor
- Tune Measurement System
- Bunch cleaner

### Comments:

- Booster is a turnkey procurement; diagnostics to be supplied by vendor according to our requirement
- Libera BPM receivers are functional at two revolution frequencies therefore the same modules suitable for both ring and booster
Layout of LB TL

- Diagnostics:
- Gun: 3 Wall Current Monitors
- Linac
  - 4 Fluorescent Screens
  - 2 Current Transformers
- Linac to Booster Transfer Line
  - 5 Fluorescent Screens
  - Integrating Current Transformer
  - 3 Four-Button pick-ups
- E = 200 MeV
- Q = 15 nC
- $\varepsilon_n = 50$ mm mrad
- $\sigma_\gamma / \gamma = 0.5\%$
- $N_b = 40-150$ bunches
- LB TL will allow fast linac commissioning

Booster

Linac

Accelerator Systems Advisory Committee, October 8th 2007
Layout of BSR TL

- $E = 3$ GeV
- $Q = 10$ nC
- $\varepsilon_x = 30$ nm rad
- $\sigma_{\gamma}/\gamma = 0.1\%$
- $N_b = 40-150$ bunches

Diagnostics:
- 6 Fluorescent Screens
- Integrating Current Transformer
- 6 Four-Button Pick-ups with Libera receivers
- Two Cameras with external trigger
Storage ring injection straight

- Quad-to-quad distance increased from 7.6 m (CD-1) to 9.3 m (CD-2)
- Pulsed magnets for up to 3.1 GeV max
- Combination of strong DC pre-septum with pulsed septum
- Closed bump of 15 mm
- Kickers with 5.2 μs long pulse powered separately
- Pulsed magnets are within vendors capabilities
- Proposal on development and optimization of pulsed magnets and PS (total of 13 magnets for NSLS-II) in-house: Pulsed Magnet Lab
## Injector cost

<table>
<thead>
<tr>
<th>Activity</th>
<th>Labor, hr</th>
<th>Bare Cost, M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac</td>
<td>4087</td>
<td>9.963</td>
</tr>
<tr>
<td>Booster</td>
<td>16139</td>
<td>17.23</td>
</tr>
<tr>
<td>L-B TL</td>
<td>7163</td>
<td>1.345</td>
</tr>
<tr>
<td>B-SR TL</td>
<td>9796</td>
<td>1.808</td>
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<tr>
<td>Injector utilities</td>
<td>5015</td>
<td>0.871</td>
</tr>
<tr>
<td>Injector installation</td>
<td>16644</td>
<td>1.107</td>
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<tr>
<td>Injector testing</td>
<td>9308</td>
<td>0.731</td>
</tr>
<tr>
<td>Injector commissioning</td>
<td>9659</td>
<td>0.743</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>44.62 FTE</strong></td>
<td><strong>33.754</strong></td>
</tr>
</tbody>
</table>

- Large procurements: Linac (~9M$) and Booster (~15M$)
### Schedule

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Design</td>
<td></td>
<td>Booster Procurement</td>
<td></td>
<td>Booster Building BOD</td>
<td></td>
<td>Booster Building BOD</td>
<td></td>
<td></td>
<td></td>
<td>Linac Comm. Start</td>
<td></td>
<td>Booster Building BOD</td>
<td></td>
</tr>
<tr>
<td>Booster Installation</td>
<td></td>
<td>B-SR Transport Line Design</td>
<td></td>
<td>Early project complete</td>
<td></td>
<td>Early project complete</td>
<td></td>
<td></td>
<td></td>
<td>SR Comm. Start</td>
<td></td>
<td>Early project complete</td>
<td></td>
</tr>
<tr>
<td>Injection System Integration and Test</td>
<td></td>
<td>Injection System Commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Summary

- NSLS-II full energy injector will support top-off operations in presence of short beam lifetime
- Multi-bunch injection with high charge per bunch train
- Linac and booster are semi-turnkey procurements
- NSLS-II booster is based on existing ASP design with some modifications
- We choose low-emittance cost-effective solution for NSLS-II booster
- We developed design of injection straight and transport lines
- Injector cost and schedule are developed
- Preliminary level of design
Acknowledgements

Back-up
Previous ASAC comments

Injection System with a Booster in Separate Tunnel (T. Shaftan)

- The committee is pleased with the injection tracking studies and recommends their continuation, including all insertion device effects and lattice errors.
- From experience elsewhere, the committee is not fully convinced that the present high beta straight for injection is long enough to accommodate injection equipment, and in particular is fully compatible with state of the art top-up requirements. In order to assess the adequacy of available space, an engineering layout of the injection straight of the storage ring should be generated. It is the feeling of the committee that a longer straight for injection could easily be accommodated in the lattice (see comments above).
- A possible operation at a 3.6 GeV energy was mentioned several times and the committee recalls that if NSLS-II intends to run at this energy, it should be included in the specifications of all systems such as magnets, absorbers, RF, Booster, and injection/extraction systems.
- The committee recommends a horizontally movable septum magnet at the ring injection point in order to ease commissioning through a near on-axis injection configuration as well as to optimize the kicker currents in relation to the final horizontal aperture.
- The Australian Light Source booster lattice design which is used as a reference design for the proposed booster lattice presents the drawback of limited flexibility in the tunes. The committee recommends the investigation of solutions which increase the accessible tune range.
- The proposed lattice for the booster synchrotron is pretty tight and the committee ask for an engineering layout in order to check that there is enough space for the correctors, diagnostics, vacuum pumps, etc. The committee recommends that the space required and the positioning of injection and extraction magnets inside the booster lattice be investigated (in particular the impact of the high value of the dispersion function in the injection and extraction straights has to be evaluated as well as the low beta values).
- The committee notes that there is no definite requirement yet for hybrid filling modes, but nevertheless recommends including this capability from the outset, since a need is almost certain to arise in the future.
- Regarding the issue of whether or not to use a single power supply for all storage ring injection kicker magnets, the committee believes that there will inevitably be differences from kicker to kicker (due to mechanical tolerances, thickness of ceramic coating, etc.). So the committee recommends that individual power supplies be used in order to optimize the bump closure and hence minimize the disturbance of the stored beam, in view of top-up operation.
Multi-bunch Injection

- Short lifetime → multi-bunch mode
- SLS experience: feedback for enhancement of the bunch pattern purity
- “Hunt&Peck” mode: is it necessary for NSLS-II?
- Studies at ALS on pattern evolution

Studies at NSLS and ALS (in progress)
“Hunt & Peck”: Adjusting Average Value

- Measure charge in the ring buckets
- Every top-off cycle adjust gun grid voltage → adjust charge per bunch
- Inject macropulse (N bunches) with average charge equal to missing charge in N-bunches in the ring
- Eliminates all bunch-bunch variations on $N_b > N_{\text{MICRO}}$ scale
- Can be done in “sequential” or “hunt & peck” modes
- Reducing harmonics of SR bunch pattern: requires R&D
“Hunt & Peck”: Fast modulation of macropulse

- Measure charge in the ring buckets
- Modulate gun voltage (laser intensity) with inverse of the charge/bunch in the pattern
- or
- Stack bunches in the booster via multiple injections
- Inject “premodulated” macropulse into the ring
Alternative version by H. Nishimura (ALS)

- Circumference = 158.40000 [m]
- Betatron Tunes X/Y = 9.26706/4.19942
- Momentum Compaction = 7.51991E-003
- Chromaticity H = -11.46993
  V = -7.17248
- Radiation Loss = 8.33737E+002 [keV]
- Natural Energy Spread = 1.45518E-003
- Natural Emittance = 1.61981E-008
- Radiation Damping H = 1.67192 [msec]
  V = 3.80238 [msec]
  E = 5.23937 [msec]
- Periodicity of 2 (racetrack)
- Combined function FODO lattice
- B, K₁ in dipoles
- 2 sₓ₁, 2 sᵧ sextupoles per cell
- Booster Dynamic Aperture gives about ±30 mm in both planes (in middle of straight)
- Needs more realistic chromaticity correction
- Preliminary design
DA and Emittance scan

- Maximum of DA is ±10 mm in both planes
- Emittance of 26 to 100 nm·rad within tune footprint
- Broad range of optics solutions
Diagnostics in Linac & Linac-to-Booster Transport Line

- **Measured parameters (at Linac exit):**
  - Charge: 15 nC, 0.2%
  - Fill pattern
  - Energy: <270 MeV, 0.5%
  - Energy spread: <0.5% RMS, 0.05%
  - Beam positions: 0.1 mm
  - Beam sizes: ~2 mm, 0.1 mm
  - Norm. emittances: ~50 mm·mrad, 5%

- **Continuously monitored beam parameters:**
  - Charge
  - Energy
  - Beam positions
  - Bunch train pattern

- **Diagnostics:**
  - **Gun:**
    - 3 Wall Current Monitors or Fast Current Transformers
  - **Linac:**
    - 4 Fluorescent Screens
    - 2 Integrating Current Transformers
  - **Linac to Booster Transfer Line:**
    - 5 Fluorescent Screens
    - Integrating Current Transformer
    - 3 Four-Button Pick-ups with Libera BPM receivers

- **Comments:**
  - Linac is a turnkey procurement; diagnostics to be supplied by vendor according to our requirement; transport line we are developing ourselves.
  - Diagnostics suite must enable early commissioning of Linac and demonstration beam parameters required for lossless injection into Booster.
  - Charge monitoring will be used for interlocks.
Diagnostics in Booster-to-Storage Ring Transport Line

- Measured parameters (at Booster exit):
  - Charge 10 nC 0.2%
  - Fill pattern
  - Energy 3 GeV 0.5%
  - Energy spread <0.1% RMS 0.05%
  - Beam positions 0.1 mm
  - Beam sizes <1 mm 0.1 mm
  - Geom. emittances ~30 nm-rad 5%

- Continuously monitored beam parameters:
  - Charge
  - Energy
  - Beam profile and position
  - Bunch train pattern

- Diagnostics:
  - 6 Fluorescent Screens
  - Integrating Current Transformer
  - 6 Four-Button Pick-ups with Libera receivers
  - Two cameras with external trigger capability

- Comments:
  - Transport Line we are developing ourselves
  - Diagnostics suite must enable early commissioning of Booster and demonstration of beam parameters required for lossless injection into Storage Ring
  - Charge monitoring will be used for interlocks
Injector Service Area

1. Booster Service Area (20 m x 8 m) 160 m²
2. L-B TL Service Area (3 m x 10 m) 30 m²
3. B-SR TL Service Area 57 m²
4. AC power disconnects/switch gear 24 m²
5. 2 entry labyrinths 2· (3 m·3 m) 18 m²
7. Bathroom 25 m²
8. Local Injection System Control room 54 m²
10. Equipment storage area (spare parts and test instruments) (9 m ·9 m) 81 m²
11. Electronic/Mechanical Workshop 100 m²
12. Water and air distribution area 36 m²
Total square footage 585 m²
Walkways and corridors: 80 m²
Total for building: 665 m²