SPEAR3 Commissioning
J. Safranek for the SPEAR3 commissioning team

- SPEAR built 1972 e+/e- collider at Stanford/SLAC
- 1989 became dedicated light source
- 2003 – SPEAR3 installation
  - Complete rebuild, maintaining geometry for photon beamlines
  - Low emittance optics, $\varepsilon_x = 18$ nm
  - $I = 500$ (100) mA
  - 11 beamlines; 7 insertion devices
Commissioning milestones

- **2003:**
  - 1 April, SPEAR2 removal begins
  - 9 December, Transport line commissioning begins
  - 10 December, First beam to SPEAR
  - 15 December, First accumulation

- **2004:**
  - 22 January, 100 mA stored
  - 8 March, First photons
  - 15 March, Start of operations
# Commissioning Team

<table>
<thead>
<tr>
<th>SSRL:</th>
<th>PAL:</th>
<th>DESY:</th>
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<tbody>
<tr>
<td>S. Allison</td>
<td>M. Yoon</td>
<td>W. Decking</td>
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<td>P. Bellomo</td>
<td>ALS:</td>
<td>SLS:</td>
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<td>W.J. Corbett</td>
<td>J. Byrd</td>
<td>M. Boege</td>
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<td>M. Cornacchia</td>
<td>D. Robin</td>
<td>ESRF:</td>
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<tr>
<td>E. Guerra</td>
<td>T. Scarvie</td>
<td>A. Ropert</td>
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<td>R. Hettel</td>
<td>C. Steier</td>
<td>Australian Synch. Proj.:</td>
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<tr>
<td>D. Keeley</td>
<td>SOLEIL:</td>
<td>M. Boland</td>
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<tr>
<td>N. Kurita</td>
<td>L. Nadolski</td>
<td>E. Tan</td>
</tr>
<tr>
<td>D. Martin</td>
<td>NSRRC:</td>
<td>CAMD:</td>
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<td>P. McIntosh</td>
<td>NSLS:</td>
<td>APS:</td>
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<tr>
<td></td>
<td>S. Krinsky</td>
<td>K. Harkay</td>
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<td>B. Podobedov</td>
<td>V. Sajaev</td>
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... + SSRL staff
Matlab Software Tools

Matlab Toolboxes for Accelerator Simulation and Control:

- AT – Accelerator Simulation
- Middle Layer Software – Accelerator Control + Physics Functions
- MCA – Matlab to EPICS Library
- LOCO – Accelerator Calibration
MATLAB commissioning tools

- GUls
  - Orbitgui
  - Plotfamily
- Fast scripting language for commissioning shifts
- Numerical algorithms and graphics for fast data processing
Electronic logbook

- Web-based, interactive browser
- Accepts graphics and text
- Searchable
- Backed up
- Authors: Kay Rehlich, Raimund Kammering, DESY
- Courtesy: Patrick Krejcik, SLAC
Diagnostics

- Bergoz DCCT, 1 μA in 1 second
- Bergoz on 54 BPMs
  - 4 kHz update
- Stripline tune driver
- Coming soon:
  - 112 BPMs
    - Echotek digital receivers
    - Turn-by-turn data
  - X-Ray pinhole camera
  - UV synchrotron light monitor
  - Scraper

Orbit measurement:
- 20 nm in 0.5 second
- ~5 μm at 4 kHz
BPM IF frequency issue

- **BPM troubles** –
  - Fill-to-fill orbit not reproducible
  - Fill pattern dependence
  - Orbit dependence on RF phase

- **Solution:** unlock IF from RF frequency
Find rf frequency that centers average orbit in sextupoles.
RF frequency, 60 days

- RF frequency included in orbit correction/feedback
- In March temperature up, RF frequency down.

![Graph showing RF frequency change over 60 days](image)

-3 kHz = +1.5 mm

![Graph showing tunnel temperature change](image)

magnets off
Closed orbit, steering magnets off

$|y| < 2 \text{ mm}, |x| < 4 \text{ mm}$
Beam-based alignment
Beam-based alignment repeatability
Orbit interlock

\[ \frac{|y|}{y_{\text{trip}}} + \frac{|y'|}{y'_{\text{trip}}} < 1 \]
SPEAR orbit stability

- **Orbit stability specs.**:
  - ~3-5 \( \mu m \) vertical
  - ~16-40 \( \mu m \) horizontal
- **Girder frequencies** ~20 Hz
- **Invar struts supporting BPMs**
- **Most synchrotron radiation hits H2O-cooled masks**
- **Tight power supply stability specs.**
- **Bergoz BPM electronics**
  - Low current dependence
  - Low fill pattern dependence
- **Alignment < 150 \( \mu m \)**

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Table 3.23 RMS source point beam dimensions and stability requirements for SPEAR 3 (rms, 1% coupling).

<table>
<thead>
<tr>
<th>Source</th>
<th>Electron</th>
<th>Photon</th>
<th>10%</th>
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<tbody>
<tr>
<td>( \sigma_x (\mu m) )</td>
<td>160</td>
<td>160</td>
<td>16</td>
</tr>
<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>236</td>
<td>mrad</td>
<td>&lt; mrad</td>
</tr>
<tr>
<td>( \sigma_x (\mu m) )</td>
<td>51</td>
<td>51</td>
<td>5</td>
</tr>
<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>11</td>
<td>136</td>
<td>14</td>
</tr>
<tr>
<td>( \sigma_x (\mu m) )</td>
<td>435</td>
<td>435</td>
<td>43</td>
</tr>
<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>43</td>
<td>2-20 mrad</td>
<td>&lt; mrad</td>
</tr>
<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>30</td>
<td>30</td>
<td>3†</td>
</tr>
<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>6</td>
<td>136</td>
<td>14</td>
</tr>
<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>435</td>
<td>435</td>
<td>43</td>
</tr>
<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>43</td>
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<td>4</td>
</tr>
<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>30</td>
<td>30</td>
<td>3†</td>
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<tr>
<td>( \sigma_y (\mu rad) )</td>
<td>6</td>
<td>15</td>
<td>1.5</td>
</tr>
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† This requirement can be relaxed to 5 \( \mu m \) due to 50 \( \mu m \) minimum vertical spot size achieved from present focusing mirrors.
Orbit drift over 10 hours, feedback off

BPM time

x(mm)

0.15 mm

-0.1 mm

y(mm)

0.04 mm

-0.06 mm
x(100mA)-x(50mA), BPM intensity dependence

- $\Delta x_{\text{rms}} = 3.4 \, \mu\text{m}$
- $\Delta x_{\text{peak}} = 7 \, \mu\text{m}$
- $\Delta y_{\text{rms}} = 3.0 \, \mu\text{m}$
- $\Delta y_{\text{peak}} = 18 \, \mu\text{m}$
$x(84\text{mA}) - x(1\text{mA})$, BPM intensity dependence
476 MHz rf noise on $\frac{1}{2}$ BPMs

- $\Delta x_{\text{rms}} = 69 \text{ \mu m}$
- $\Delta x_{\text{peak}} = 190 \text{ \mu m}$
- $\Delta y_{\text{rms}} = 84 \text{ \mu m}$
- $\Delta y_{\text{peak}} = 310 \text{ \mu m}$
BPM fill pattern dependence
\( x(16\text{mA, single bunch}) - x(16\text{mA, multibunch}) \)

- \( \Delta x_{\text{rms}} = 18 \ \mu\text{m} \)
- \( \Delta x_{\text{peak}} = 70 \ \mu\text{m} \)
- \( \Delta y_{\text{rms}} = 18 \ \mu\text{m} \)
- \( \Delta y_{\text{peak}} = 60 \ \mu\text{m} \)
BPM PSD

Blue: orbit motion
Red: BPM noise floor
BPM PSD with $\nu_s$ noise
Fast orbit feedback

- Digital feedback
- Includes electron and photon BPMs.
- 4 kHz cycle rate.
- ~200 Hz bandwidth
LOCO optics analysis code

- Calibrate/control optics using orbit response matrix
- Determined quadrupole gradients
  - $\beta$ functions, $\eta$
  - Found $0.017\,\nu_y$ error from excess dipole focusing
- Corrected coupling
- Calibrated BPM gains, steering magnets
- Measured local chromaticity and transverse impedance

New MATLAB version of code
- rewritten from FORTRAN
- linked to control system
- linked to AT simulator

G. Portmann
Linear optics calibration method

The orbit response matrix is defined as

\[
\begin{bmatrix}
\bar{X} \\
\bar{Y}
\end{bmatrix} = M \begin{bmatrix}
\bar{\Theta}_x \\
\bar{\Theta}_y
\end{bmatrix}
\]

The parameters in a computer model of a storage ring are varied to minimize the \( \chi^2 \) deviation between the model and measured orbit response matrices (\( M_{\text{mod}} \) and \( M_{\text{meas}} \)).

\[
\chi^2 = \sum_{i,j} \frac{(M_{ij}^{\text{meas}} - M_{ij}^{\text{model}})^2}{\sigma_i^2} \equiv \sum_{k=i,j} E_k^2
\]

The \( \sigma_i \) are the measured noise levels for the BPMs; \( E \) is the error vector.

The \( \chi^2 \) minimization is achieved by iteratively solving the linear equation

\[
E_k^{\text{new}} = E_k + \frac{\partial E_k}{\partial K_l} \Delta K_l = 0
\]

\[-E_k = \frac{\partial E_k}{\partial K_l} \Delta K_l
\]

For the changes in the model parameters, \( K_p \), that minimize \( ||E||^2 = \chi^2 \).
Before

After

ID focusing correction
Coupling & $\eta_y$ correction, LOCO

Minimize $\eta_y$ and off-diagonal response matrix:

- Lifetime, 19 mA, single bunch
  - Correction off: 4.5 hours
  - Correction on: 1.5 hours
Measured dispersion

Dispersion Function

$\eta_x$ [m] vs BPMx Position [meters]

$\eta_y$ [m] vs BPMy Position [meters]
Chromaticity

Nonlinear $\xi$:

$(\nu_x, \nu_y)$ vs. $f_{rf}$ agrees with model.

Local chromaticity calibrated with LOCO shows no sextupole errors:
Dynamic aperture vs. $\Delta p/p$

- Dynamic aperture measured with single injection kicker for varying rf frequency.
- $x_\beta(\Delta p/p)$ for different straight sections. (From model.)
- RF acceptance

**Graphs:**
- **IDs open**
  - Dynamic aperture
  - RF aperture
  - $x_\beta(\Delta p/p)$

- **IDs closed**
  - Dynamic aperture
  - RF aperture
  - $x_\beta(\Delta p/p)$
Dynamic energy aperture, 2

- Lifetime vs. $V_{\text{gap}}$, rf
- 8 mA, single bunch
  - Touschek regime
  - $\tau^{1/3} \sim$ rf acceptance

Energy aperture

rf acceptance
Dynamic aperture vs. tune

- Resonant lines:
  - $v_x - v_y = 9$
  - $3v_x + v_y = 48$
  - $4v_x + v_y = 62$

- Resonances offset from tune shift with amplitude.

- * = operating tunes (14.19, 5.23)

- Data gathered automatically on owl shift.
Lifetime vs. tunes

- Resonant line: \( v_x - v_y = 9 \)
- \( * \) = operating tunes (14.19, 5.23)
- Data gathered automatically on owl shift.

Data gathered automatically on owl shift.
Aperture scans

- $\tau$ vs $y$ in small gap ID
  - Poor man’s scraper
- Determine minimum gap for future IDs
  - 12 mm $\rightarrow$ 8 mm
  - Smaller still for reduced $\beta_y$
- Complications
  - Vacuum degrades with beam bump
  - Coupling, $\eta_y$ degrades with beam bump
  - Need scraper
Low emittance optics test

- $\eta = 10 \text{ cm in IDs}$
- $\varepsilon_x: \ 18 \text{ nm} \rightarrow 12 \text{ nm}$
- Good lifetime, injection
- Reserved for later upgrade

LOCO fit $\eta$: nominal optics  low emittance optics
Low $\beta_y$ optics

- Reduced $\beta_y$ in long straight
  - For future ID, small gap
  - $\beta_y$: 10 m  2 m
- Good dynamic aperture

LOCO fit: $\beta_y = 10$ m

$\beta_y = 2$ m
Momentum compaction measurement

linear fit is $f_s^2 = 45.7463 \cdot v_{rt} + -16.8233$

Alpha = 0.0014
SPEAR3: Longitudinal Dynamics

<table>
<thead>
<tr>
<th>Sextupoles on</th>
<th>Sextupoles off</th>
</tr>
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<tbody>
<tr>
<td>$\alpha_1 = 1.19 \times 10^{-3}$</td>
<td>$\alpha_2 = 37.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\alpha_2 = -2.1 \times 10^{-3}$</td>
<td>$\alpha_2 = 37.4 \times 10^{-3}$</td>
</tr>
</tbody>
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4D tracking using AT

$-\frac{\alpha_1}{2\alpha_2} = -0.0158$

$-\frac{\alpha_1}{\alpha_2} = -0.0317$
$\alpha_2$ measurement

- $|\alpha_2|$, sextupoles off $\gg$ $|\alpha_2|$, sextupoles on
- Energy aperture much reduced with sextupoles off
Impedance, instabilities

- 25 mA single bunch limit ($\xi_{x,y} = 1$)
- Multibunch $\nu_y$ oscillations
  - Ion driven
  - Decreasing as vacuum improves
- $\nu_s$ oscillations driven by 360 Hz harmonics
- 200 mA tests ongoing
- Transverse impedance measurements
Transverse impedance measurement

*see V. Sajaev, PAC03.
Lifetime (at 90 mA) vs. Integrated Current

![Graph showing lifetime vs. integrated current](image-url)
Acknowledgements

I would like to express my appreciation for all the help SSRL received with the commissioning effort from accelerator physicists worldwide. I would also like to commend the SSRL staff. The speed at which commissioning proceeded is a testimony to the fine work that went into designing and building SPEAR3. Finally, thanks to the SSRL operations group. Their experience, expertise and energy was a great help.