BEAM PHYSICS AT THE
ADVANCED PHOTON SOURCE

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CASA Seminar, JLab
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Accelerator and FEL Physics Group

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Outline

• Introduction
• Near-term issues
  o Instabilities
  o Impedance Database
• Related R&D
  o Lattice characterization
• Mid- to far-term R&D
• Summary
# Basic APS Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Energy [GeV]</td>
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<tr>
<td>Circumference [m]</td>
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<td>Nominal RF voltage [MV]</td>
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<td>Momentum compaction</td>
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<tr>
<td>Synchrotron tune</td>
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<tr>
<td>Emittance H [nm·rad]</td>
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<td>Coupling [%]</td>
<td>3 %</td>
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<tr>
<td>Nom. chromaticity,$\xi^1$ H / V</td>
<td>5 / 7</td>
</tr>
<tr>
<td>Damping time H/V/L [ms]</td>
<td>9.5 / 9.5 / 4.7</td>
</tr>
</tbody>
</table>

$^1\xi = \Delta \nu / (\Delta p / p)$
25 of 40 sectors are occupied with photon beamlines: bending magnet and insertion device (ID) synchrotron radiation
Typical APS storage ring sector
Insertion Device (undulator magnet) with ID chamber

Small-gap ID chamber (8-mm or 5-mm vertical height, 5 m long)
Small-gap ID chambers are located in 5-m straight sections (total no.: 22 with 8-mm gap, 2 with 5-mm gap, 1 with 19.6-mm gap)
A word on SR User operation

- Standard (~75%) ($\tau \sim 7-9$ h)
  - 100 mA
  - Low emittance lattice (2.4 nm-rad)
  - 23 bunches spaced at h/24 (one missing) (4.3 mA/bunch)
  - Top-up

- Special operating modes (typ. 1-2 weeks ea. per run)
  - High emittance, non-top-up (7.7 nm-rad) ($\tau \sim 20$ h)
  - Hybrid mode (1 or 3 + 56) ($\tau \sim 20$ h)
  - Many-bunch mode (324 bunches) ($\tau \sim 100$ h)
Near-term Issues

- Typically deliver 100-mA electron beam in 23 bunches (4.3 mA/bunch) for normal operation for users.

- Horizontal instability (centroid oscillations) observed above about 5 mA/bunch – this is above the transverse mode-coupling instability (TMCI) threshold.

- Normal operation with high positive chromaticity allows a single-bunch intensity limit > TMCI limit: up to about 10 mA. However, beam properties degraded (effective emittance).

- Addition over time of small-gap insertion device chambers, our major source of coupling impedance, has
  - lowered single-bunch instability and intensity limit
  - required operation with higher chromaticity and smaller beta functions to restore

- Need to understand physics and how to control instability in order to
  - satisfy anticipated future user requirement for higher bunch current
  - anticipate effect of additional small-gap insertion device chambers and influence design
  - mitigate instability while preserving beam quality, in particular, beam lifetime (e.g., effect of high chromaticity)
**Single-bunch instability: transverse mode coupling instability**

Force due to transverse wake defocuses beam, i.e., detunes betatron frequency.

When $\nu_\beta$ crosses $(\nu s)$ modulation sidebands, synchrotron motion can couple to transverse plane and beam can be lost unless chromaticity is sufficiently large/positive.

Tune slope increases with no. of small gap chambers: mode merging threshold decreases.

\[ \xi_x > 1.3, \xi_y \approx 4 \]

\[ \Delta \nu_x / \Delta I = -8 \times 10^{-4} / \text{mA} \]

\[ \Delta \nu_y / \Delta I = -2.6 \times 10^{-3} / \text{mA} \]

(data courtesy of L. Emery [K. Harkay et al., Proc. of 1999 PAC, 1644])
Transverse Mode-Coupling Instability
(a.k.a. strong head-tail, fast head-tail, transverse turbulence)


\[ BB: \quad Z^\perp_1(\omega) = \frac{2c}{b^2\omega_0} R_0 \left| \frac{\omega_0}{\omega} \right|^{3/2} [\text{sgn}(\omega) - j] \]

\[ Y' = \frac{N\rho c^2 R_0}{\sqrt{\gamma T_0 \omega_0 \omega_3 b^2}} \sqrt{\frac{\dot{z}}{cT_0}} \]

Tune slope, \( \Delta v/\Delta I \), from transverse reactive wake:

\[ \frac{\Delta v}{\Delta I} \propto \frac{v_0 \langle \beta \rangle R}{\sigma_z E/e} \bar{Z}^\perp_1(\omega) \]

where \( R = \) ring radius, \( \bar{Z}^\perp_1(\omega) = \) effective impedance

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Two instability modes observed above TBCI; not observed in any other ring with $\xi > 0$.

Early APS data using beam position monitor turn-by-turn histories showed horizontal centroid oscillations whose bunch intensity instability onset and mode (bursting vs. steady-state amplitude) varied with rf voltage (chromaticities: $\xi_x = 1.3$, $\xi_y = 3.9$) (2/15/1999)
Large $<x>$ oscillations above mode-merging threshold (V_{rf} 9.4 MV case shown): some Users will observe an effective emittance blowup, $\Delta\varepsilon_x$.

Note: bunch length $\sigma_z$, energy spread $\delta$, and emittance $\varepsilon_x$ also vary with current ($\varepsilon_x$ decoherence NOT 100% of $<x>$ oscillation amplitude; $\sigma_x = 220$ $\mu$m (7.5 nm-r lattice))
Variations with different machine parameters

7.5 nm lattice, Vrf = 7.3 MV, $\xi_{x,y} = (3,6)$

Peak-to-peak amplitude as a function of Vrf

Dual-sweep streak camera image of single bunch undergoing coherent horizontal oscillations in bursting mode: bunch does not completely decohere

[data courtesy of B. Yang; K. Harkay et al., Proc of 1999 PAC, 1644]
Measured bunch lengthening vs $V_{rf}$
(L. Emery, M. Borland, A. Lumpkin; no 5-mm ID chambers)
$Z_{il}/n \approx 0.5 \, \Omega$ (estimated) [Y.-C. Chae et al., Proc. of 2001 PAC, 1817]

Measured $\delta$ and $\varepsilon_x$ vs $I_b$ ($V_{rf}$ 7 MV, nominal $\xi_{x,y}$)
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Jan. 31, 2003


7 MV, 7-nm lattice
Main Sources of Impedance in the SR

Single-bunch instabilities

- small-gap ID chambers
  - resistive wall impedance
  - geometric impedance (transitions)
- other discontinuities: rf fingers, kickers, scraper “cavity”
- “trapped” chamber modes?

Multibunch instabilities

- rf cavity higher-order modes
- other discontinuities: scraper “cavity”
- “trapped” chamber modes?
**APS Storage Ring chambers**

**Standard**

antechamber  radiation slot  beam chamber

8-mm gap ID chamber

5-mm gap ID chamber
ID chamber transitions

[Fig. courtesy of S.-B. Song, formerly at APS (post-doc), unpublished]
Impedance and Instabilities Plan

- Machine impedance database (Chae et al.)
  - MAFIA calculations ($Z_{x,y}$, PAC01 – $Z_z$)
  - Local tune shift using lattice model (V. Sajaev, C.-X. Wang – $Z_{x,y}$)
  - Local bump method (PAC01 – $Z_y$)
- Characterize longitudinal instability experimentally – validate $Z_{\parallel}$
  - Apply $Z_{\parallel}$ calculated from MAFIA to model with *elegant* code to reproduce bunch lengthening, $\Delta\sigma_l/\Delta l$, and microwave instability, $\Delta\delta/\Delta l$
- Characterize transverse instability experimentally – validate $Z_{\perp}$
  - Instability threshold, growth rate, and saturation amplitude vs $V_{rf}$, $\zeta$, $\Delta\nu_x/N_x^2$, dispersion
- Instability photon diagnostics
  - Details of decoherence over bursts
- Other supporting studies
  - Nonlinear dynamics
  - Measure frequency spectrum evolution to look for mode-coupling and/or parametric resonance signatures
Impedance Database

- **Goal**

  Wakepotential (APS Storage Ring) =

  \[
  20 \times (8\text{-mm ID Chamber}) + 2 \times (5\text{-mm ID Chamber}) +
  
  400 \times \text{(BPM)} + 80 \times \text{(C2 Crotch Absorber)} +
  
  \ldots\
  \]

- **Standardize Wakepotential**

  1. Data in SDDS format
     - S, Wx, Wy, Wz

  2. Uniform simulation conditions
     - rms bunch length \( \Rightarrow \) SIGz = 5 mm,
     - mesh size \( \Rightarrow \) dz = 0.5 mm,
     - wakelength \( \Rightarrow \) SBT = 0.3 m

  3. Deposit the authorized wakepotentials in
     - \texttt{~aps/ImpedanceDatabase/SR}
     - \( \Rightarrow \) Available to everyone to read files

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Y.-C. Chae
Impedance Database (cont.)

Vacuum Chamber Components

- Old components (experience)
  - Insertion Device Chambers
  - RF Cavities + Transition
  - Crotch Absorbers
  - Horizontal/Vertical Scrapers
  - Septum Intrusion
  - Stripline Monitors .......

- New components
  - BPMs
  - SR absorber between rf cavities
  - Vacuum port (slotted rf screen)
  - Shielded bellow

Y.-C. Chae
Impedance Database (cont.)

Example: Insertion Device Chambers

- Insertion Device Chambers
  - 5-mm-gap chamber
  - 8-mm-gap chamber
  - 12-mm-gap chamber

- Steps taken for 3-D Wakepotential
  I. 2-D ABCI calculation for circular chamber (High confidence)
  II. 2-D ABCI vs. 3-D MAFIA for circular pipe (Compare)
  III. 3-D MAFIA for elliptical chamber (Final result)
Impedance Database (cont.)

2-D ABCI vs. 3-D MAFIA (Compare)

Geometry

Results

Y.-C. Chae
Impedance Database (cont.)

3-D MAFIA Results for Elliptical ID Chamber (Wakepotential & Impedance)

Y.-C. Chae
8-mm-gap ID vacuum chamber impedance

$Z_y$ (effective) estimated five ways:

1. $Z_y = (Z_{RW} + Z_{geom})$ determined experimentally from change in tune slope, $\Delta v/\Delta I$, as a function of no. of chambers [N. Sereno et al, Proc. of 1997 PAC, 1700]:

$$Z_y = 53 \text{k}\Omega/\text{m per chamber} \times 20 = 1.1 \text{M}\Omega/\text{m}$$

2. Simulations with $Z_y$ represented by broad-band resonator impedance model reproduced measured tune slope and intensity threshold for TMCI at low chromaticity [K. Harkay et al, Proc. of 1999 PAC, 1644]:

exp: $\Delta v_x/\Delta I = -8 \times 10^{-4}/\text{mA}$$

$\Delta v_y/\Delta I = -2.6 \times 10^{-3}/\text{mA}$

model: $0.2 \text{ M}\Omega/\text{m}$$

$1.2 \text{ M}\Omega/\text{m}$

$I_{TMCI}$ thresh: $4.4 \text{ mA}$$

$2.2 \text{ mA}$

3. Impedance calculated: resistive wall and geometric

a. resistive wall $\propto 1/b^3$

$$\frac{Z_{1,xy}^{\perp}}{L} = \frac{c}{\omega} \frac{1 + \text{sgn}(\omega)j}{\pi b^3 \delta \sigma} G_{1,xy} \Rightarrow Z_{1,xy}^{\perp} \left[ \frac{\text{k}\Omega}{\text{m}} \right] = \left(1 + \text{sgn}(\omega)j\right) \frac{25500}{b[\text{mm}]^3 \sqrt{f[\text{MHz}]}} G_{1,xy}$$

$f = \text{cutoff frequency} = c/2\pi b = 13 \text{ GHz}$

$G_{1y} = 0.825$ [Gluckstern and van Zeijts, CERN SL/AP 92-25, Jun 1992]

$Z_{RW}$ (per 8-mm chamber, $L = 5 \text{ m}$) = $3.4 \text{ k}\Omega/\text{m}$
b. geometric (transition): assuming a perfectly conducting circularly cylindrical tube of half-height $b=4$ mm, angle $\theta$ [Bane and Krinsky, Proc. of 1993 PAC, 3375]

$$W_{\perp} = \frac{Z_0 c}{\pi b} \left( \frac{2\theta}{\pi} \right)^{1/2} \frac{1}{\sqrt{2\pi} \sigma_s} \exp \left( \frac{-s^2}{2\sigma_s^2} \right) = 4 \times 10^{14} \, \Omega/\text{m-s per transition}$$

$$Z_{\theta} = 2 \times (\sigma_s/c) W_{\perp} = 26 \, \text{k}\Omega/\text{m} \quad (5\text{-mm}: Z_{\theta} = 55 \, \text{k}\Omega/\text{m})$$

$$Z_{\theta} = 20 \times 26 = 0.5 \, \text{M}\Omega/\text{m}$$

c. totals

8-mm chamber: $Z_y = Z_{RW} + Z_{\theta} = 3.4 + 26 = 30 \, \text{k}\Omega/\text{m}$

5-mm chamber: $Z_y = Z_{RW} + Z_{\theta} = 12 + (2.1 \times 26) = 70 \, \text{k}\Omega/\text{m}$

4. MAFIA calculations of wake potentials: $Z_{\theta}$ from extracted tune slopes for geometric component (Y.-C. Chae)

8-mm ID: 20 k$\Omega$/m

5-mm ID: 80 k$\Omega$/m


8-mm: $Z_y = 16 \, \text{k}\Omega/\text{m}$

5-mm: $Z_y [\text{k}\Omega/\text{m}] = 96 \pm 8 \, \text{k}\Omega/\text{m} (\text{ID}3); \ 78 \pm 14 \, \text{k}\Omega/\text{m} (\text{ID}4)$


Work in progress: prelim. results agree with methods 4 & 5

K. Harkay, ANL

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Related R&D

• AP Group is developing tools to characterize lattice
  o Response matrix fit (V. Sajaev)
  o Model-independent analysis (C-X. Wang)
• Beta function correction and betatron phase advance
  o Lower sextupole strength for chromaticity correction
  o Local impedance
Increasing brightness of x-rays

• Brightness is the main single parameter characterizing a synchrotron light source. It is inversely proportional to the electron beam emittance.

• Over the last one and a half years, APS has made two big steps toward increasing the brightness:

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
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<tbody>
<tr>
<td>7.7 nm×rad</td>
<td>3.3 nm×rad</td>
<td>2.4 nm×rad</td>
</tr>
<tr>
<td>11/7/2001</td>
<td>10/15/2002</td>
<td></td>
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</tbody>
</table>

Response matrix fit allowed us to perform these changes quickly and ensured that the delivered beam parameters corresponded to the designed ones.

V. Sajaev
Orbit response matrix fit

- The orbit response matrix is the change in the orbit at the BPMs as a function of changes in steering magnets.

\[
\begin{pmatrix}
x \\
y
\end{pmatrix} = M_{\text{measured}} \begin{pmatrix}
\theta_x \\
\theta_{\text{model}}
\end{pmatrix}
\]

- The response matrix is defined by the linear lattice of the machine; therefore it can be used to calibrate the linear optics in a storage ring.
- Modern storage rings have a large number of steering magnets and precise BPMs, so measurement of the response matrix provides a very large array of precisely measured data.
Exploitation of the model

- Improving the performance of the existing machine
  - Beta function correction – to improve lifetime, injection efficiency and to provide users with the radiation exactly as specified
  - BPM gain calibration

- Creation of new lattices
  - Increasing brightness of x-rays by decreasing the beam emittance
  - Exotic lattices:
    - Longitudinal injection to decrease beam motion during injection
    - Converging beta function to increase x-ray flux density

V. Sajaev
Model-Independent Analysis

- MIA is a statistical analysis (principal composition analysis) of spatial-temporal modes in beam centroid motion recorded by the BPMs
- Mostly independent of detailed machine models
- Inclusive rather than exclusive – various other data analysis methods such as Fourier analysis, map analysis, etc. (even machine modeling) are being incorporated
- Not a recipe for a specific measurement, but rather a paradigm that facilitates systematic measurements and analysis of beam dynamics

Advantage: High sensitivity, model-independent, noninvasive, systematic

Basic requirement: A large set of reliable turn-by-turn BPM histories

Phase changes due to a 0.5% quadrupole current change near 56th BPM

Phase changes due to a current-dependent wakefield (single bunch)
Other R&D topics (sample)

• Collaboration of Accelerator Research at Argonne (CARA) (Kwang-Je Kim)
  o APS
  o ATLAS (Rare Isotope Accelerator)
  o Advanced Wakefield Accelerator
  o Intense Pulsed Neutron Source
• Electron-cloud-induced multipacting resonance
• Ionization cooling
• Interleaved SR/FEL operation
• Injector development
• Ultrafast Thompson source, gamma source
• Frequency-Resolved Optical Gating (FROG) FEL analysis
• CSR microbunching at SURF
• Beam halos
The APS SASE FEL Schematic

The Low-Energy Undulator Test Line System

Present Configuration

APS SASE Project Goals

- Characterize the SASE FEL output and perform experiments with it
- Assess the challenges associated with producing a SASE FEL in preparation for an x-ray regime machine

S. Milton
## Basic Parameters for the APS FEL

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Regime 1</th>
<th>Regime 2</th>
<th>Regime 3</th>
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<tbody>
<tr>
<td>Wavelength [nm]</td>
<td>530</td>
<td>120</td>
<td>51</td>
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<tr>
<td>Electron Energy [MeV]</td>
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<td>457</td>
<td>700</td>
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<tr>
<td>Normalized rms Emittance ($\pi$ mm-mrad)</td>
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<td>3</td>
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<td>Energy Spread [%]</td>
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<td>0.1</td>
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<tr>
<td>Peak Current [A]</td>
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<td>500</td>
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<tr>
<td>Undulator Period [mm]</td>
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<td>Magnetic Field [T]</td>
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<td>Undulator Length [m]</td>
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<td>9 x 2.4</td>
<td>10 x 2.4</td>
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</table>

S. Milton
SPIRIT will use the high VUV pulse energy from LEUTL to uniquely study –

- **Trace quantities of light elements:** H, C, N, O in semiconductors with 100 times lower detection limit
- **Organic molecules with minimal fragmentation**
  - cell mapping by mass becomes feasible polymer surfaces
  - modified (carcinogenic) DNA
  - photoionization thresholds
- **Excited states of molecules**
  - cold wall desorption in accelerators
  - sputtering of clusters

Coming 2002
Gun test stand status & future plans
Higher-Order-Mode Gun
High-Power Prototype Design
$\text{TM}_{0,1,1}$ Photoinjector Design

$\text{TM}_{0,1,1}$
π-Mode Gun with Needle Cathode
On-Axis Field Comparison

200-µm flat top radius, 300-µm needle radius

“Effective” needle height is ~ 1.3mm
Summary

- AP Group pursuing accelerator physics R&D in a number of areas
- Highest-priority topics address near-term anticipated User requirements
  
  e.g., characterize and mitigate single-bunch instability

- Also pursuing general accelerator physics topics for far-term light source development
  
  e.g., lattice characterization tools and source development