APS RFA studies and modeling:

Findings vs. open issues

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Advanced Photon Source

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Cesr-TA electron cloud simulation
WebEx meeting
APS EC study origins: circa 1997

Transverse multibunch instabilities at CESR discovered to be due to trapped electrons in DIP leakage field [T. Holmquist, J.T. Rogers, PRL 79, 3186 (1997)]

SLAC PEP-II and KEKB B-factories both under development; became concerned about ECEs:
Separate, first-generation codes developed to model EC generation and instabilities (M. Furman, K. Ohmi, F. Zimmermann, and colleagues)

LHC: Calculated predictions of a BIM resonance resulted in a crash program at CERN to study ECEs.

We were asked: why don’t we observe EC effects at the APS with Aluminum chambers (high $\delta$) and positron beams? Started experimental program in 1997-98 first with e+ beam, then 1998-2004 with e- beam. Collaborator: R. Rosenberg.
Retarding field analyzer (RFA) distribution

FIG. 1. Modified vacuum chamber (top view) showing locations of RFA detectors 1–10 and BPMs a, b, and c. The top numbers and letters indicate those detectors or BPMs mounted above the chamber midplane; the bottom numbers indicate those mounted below. The end absorber EA intercepts high-energy photons.

Mounting on 5-m-long APS chamber, top view, showing radiation fan from downstream bending magnet. Pressure measured locally (3.5 m upstream of EA).
Retarding field analyzer (RFA)†

RFA measures distribution of EC colliding with walls, transmission efficiency ~50%

Radiation fan at det. #6 for $E_{\gamma} \geq 4$ eV

Mounting on APS Al chamber behind vacuum penetration (42 x 21 mm half-dim.)

† Designed by Richard Rosenberg

FIG. 3. Schematic of APS planar retarding field analyzer (RFA). The collector is graphite coated to lower $\delta$ and biased at +45 V to enhance the collection efficiency. The grounded, outer grid is mounted behind a slotted vacuum penetration to shield the RFA from beam-induced rf noise. The penetration slot area is approximately 1.25 cm², and approximate distances between the chamber wall (1.6 mm thick), grids, and collector are indicated.
# Machine parameters for APS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>7</td>
</tr>
<tr>
<td>Circumference</td>
<td>m</td>
<td>1104</td>
</tr>
<tr>
<td>RF frequency</td>
<td>MHz</td>
<td>351.9</td>
</tr>
<tr>
<td>Minimum bunch spacing</td>
<td>ns</td>
<td>2.84</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>–</td>
<td>1296</td>
</tr>
<tr>
<td>Chamber semi-axes ((a, b))</td>
<td>mm</td>
<td>42.5, 21</td>
</tr>
<tr>
<td>Antechamber height</td>
<td>mm</td>
<td>10</td>
</tr>
<tr>
<td>Chamber material</td>
<td>–</td>
<td>Al</td>
</tr>
<tr>
<td>Distance from dipole magnet end to RFA (#6)</td>
<td>m</td>
<td>9.25 (e+/e-)</td>
</tr>
<tr>
<td>Dipole bend angle</td>
<td>rad</td>
<td>0.07854</td>
</tr>
<tr>
<td>Dipole length (80) (fill fraction ~0.2)</td>
<td>m</td>
<td>3.06</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>cm</td>
<td>1</td>
</tr>
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</table>
# Posinst modeling, SE input params (v8)

<table>
<thead>
<tr>
<th></th>
<th>Copper (CERN)</th>
<th>Stainless steel (LBNL)</th>
<th>Aluminum (APS msrd/fit)</th>
<th>Aluminum (APS model)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total SEY</strong></td>
<td>E_tot_pk</td>
<td>eV</td>
<td>271</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td>( \delta _\text{tot}_\text{pk} )</td>
<td></td>
<td>2.1</td>
<td>2.05</td>
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<tr>
<td><strong>True secondary</strong></td>
<td>( \delta _\text{ts}_\text{pk} )</td>
<td></td>
<td>1.88</td>
<td>1.22</td>
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<tr>
<td></td>
<td>E_0_ts_pk</td>
<td>eV</td>
<td>276.8</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>s</td>
<td>eV</td>
<td>1.54</td>
<td>1.813</td>
</tr>
<tr>
<td></td>
<td>t1, t2, t3, t4</td>
<td></td>
<td>0.66, 0.8, 0.1, 1</td>
<td>0.66, 0.8, 0.1, 1</td>
</tr>
<tr>
<td><strong>Rediffused</strong></td>
<td>P1_r</td>
<td>( \infty )</td>
<td>0.2</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>E_r</td>
<td>eV</td>
<td>0.041</td>
<td>40</td>
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<tr>
<td></td>
<td>r</td>
<td></td>
<td>0.104</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>q</td>
<td></td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>r1, r2</td>
<td></td>
<td>0.26, 2</td>
<td>0.26, 2</td>
</tr>
<tr>
<td><strong>Elastic</strong></td>
<td>P1_e</td>
<td>( \infty )</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>P1_e_pk</td>
<td>( \delta(0) )</td>
<td>0.496</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>E_0_e_pk</td>
<td>eV</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>eV</td>
<td>60.86</td>
<td>100</td>
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<tr>
<td></td>
<td>p</td>
<td>eV</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>( \sigma _e )</td>
<td></td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>e1, e2</td>
<td></td>
<td>0.26, 2</td>
<td>0.26, 2</td>
</tr>
</tbody>
</table>

**Note:**
- Rediffused parameters are input values.
- Elastic parameters are calculated from the input values.

**Source:**
- K. Harkay, APS RFA studies and modeling, CesrTA Webex, Nov 13 2008
**Secondary electron emission**

- Universal $\delta$ curve [1], peak values surface dependent
  \[ D(x) = \frac{sx}{s - 1 - x^s} \]
  - $\delta_{\text{max}} \sim 1$-3 metals, $>10$ non-metals
  - $E_{\text{max}}$ 250-400 eV
  - $E_1 \sim 20$-50 eV
  - $E_2 \sim 1$ keV but much higher at grazing incidence

- EC lifetime depends strongly on $\delta_0 \sim 0.5$ (CERN, PSR)

- APS Al chamber secondary emission measured (R. Rosenberg) and fit to universal curve: $\delta_{\text{max}} 2.8$, $E_{\text{max}}$ 330 eV, $s=1.86$ (L. Loiacono) [2]. Dependence below 50 eV can be estimated in posinst and/or scaled to CERN data.

Secondary electron distribution function

- Emission has 3 components [1]
  - True SE peaks at 1-3 eV, surface independent
    \[ f_{ts} \propto E^{p_n-1} e^{-E/\varepsilon_n} \]
    \( p_n=2, \varepsilon_n=1 \)
  - Rediffused varies/sensitive to surface
  - Elastic depends on prim. energy

RFA distribution fitted to a Lorentzian func: \( \langle E \rangle \) 2.5eV, width 5 eV (10 bunches, 128 rf bunch spacing, 2 mA/bunch) [K. Harkay et al, Proc. 2003 PAC, 3183].

True secondary and rediffused components [1] using APS parameters (p. 6)

Photoemission params

- Effective photoelectron yield: 0.1
- Number photons per e+: 0.07
- Photoelectron $\sigma_y$: 5 mm (for det 6)
- Reflectivity $\neq 0$
- Dilution: 1 (reflectivity %?)
Positron beam: dependence on bunch spacing

Measured (RFA 6) electron wall current ($I_c$) as a function of bunch spacing, normalized to the total beam current ($I_b$) (10 bunches; total current shown).

The inset shows a conditioning effect of more than a factor of two reduction after 60 Ah of beam operation.
Multipacting resonance (RFA vs. bunch spacing)

Comparison (RFA det 6) with simulated normalized electron wall current as a function of bunch spacing (10 bunches).

**RFA vs. POSINST:**

- Peak at 20 ns bunch spac. (7 bkt) sensitive to true secondary electron spectrum
- Amplitude (max current) sensitive to \( \delta_{\text{max}} \)
- Peak width sensitive to rediffused component

\[ f_{\text{ts}} \propto E_p e^{-E/E_R} \]
Modeled effect of space charge, 20 ns bunch spacing

Surface conditioning: Wall flux at APS reduced 2x after 60 Ah of surface conditioning (inset, left), equivalent to $10^{-3}$ C/mm² dose, consistent with CERN data (Cu). Conditioned Aluminum chamber RFA data consistent with $\delta_{\text{max}} 2.2$. 
Cloud build-up and saturation

EC saturates after 20-30 bunches (middle of straight)

Level varies nonlinearly with bunch current ($7\lambda_{rf}$ bunch spacing)

Associated pressure rise (shown later)

Calculated EC density at saturation (e+ beam)

- KEKB 6e11 m$^{-3}$ (no solenoid) (H. Fukuma, E CLOUD02)
- APS 10e10 m$^{-3}$ ("")
- PEPII 10e10 m$^{-3}$ (between solenoids) (A. Kulikov)
Buildup over bunch train

Measured (RFA det 1,6) and simulated (dashed line, $\delta_{\text{max}}=3.0$) electron wall current as a function of bunch train length, 20 ns bunch spacing, comparing RFAs 65 cm apart. Anomalous pressure rise P is also shown.
Energy distribution

- Energy distributions from differentiated RFA (det6) signals as a function of bunch spacing (units of \( \lambda \)) (10 bunches, 2 mA/bunch).
- Low-energy part is well fit by a Lorentzian with \( \langle E \rangle \) 2.5 eV and width 4 eV.
- Long exponential tail on all but 128 \( \lambda \).
- Energy bumps observed for 2 \( \lambda \) and 4 \( \lambda \), but not on longest tail for 7 \( \lambda \).
- Avg energy \( \sim \)100 eV for e+ beam at 20 ns spacing; \( \sim \)10 eV for e- beam at 30 ns spacing.
Energy distributions

- Simulated energy distributions similar to RFA data
- Simulation results may show similar energy bumps but not explored in detail
- Computed histograms up to 300 eV also
Open issues
Dramatic Z-dependence

Measured peak RFA current as function of bunch number, spacing, and distance from photon absorber (2 mA/bunch) (after conditioning).
Dependence on RFA position and bunch spacing

- 10 bunches, 20 mA
- Det 1,2 likely dominated by photoelectrons
- Det 6-8 similar multipacting response
- Det 3-5 current much smaller (multipacting suppressed?)
- Det 9-10 current small (smaller radiation fan)
**APS electron-cloud driven instability, e+**

Acquired near end (9/28/1998) of positron beam operation: max e-cloud amplification with 7 $\lambda_{rf}$ bunch spacing (head of bunch trains at left)

60 bunches, 96 mA, streak camera, x-t

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**50 bunches, 90 mA, stripline $\Delta x$**

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Electron beam: weak multipacting effect

Measured (RFA 3,6) and simulated (dashed line) wall current vs. bunch spacing. The peak appears at 30-ns bunch spacing (11 \( \lambda \)). There is additional conditioning of 100 Ah for these data compared to positron data, main plot.
Electron beam: weak cloud buildup

- Measured wall current as a function of bunch train length, 30 ns spacing. The signal near EA (RFA 1) is always higher than RFA 6.
- No anomalous pressure rise is observed for these uniformly-spaced bunch trains.
- Pressure rise and beam lifetime degradation was observed for certain 100-mA fill patterns, but quickly conditioned away.
Electron beam: energy distributions

To be plotted…
### Summary: RFA data vs. simulations

<table>
<thead>
<tr>
<th></th>
<th>Positrons RFA (det6)</th>
<th>Positrons posinst8</th>
<th>Electrons RFA</th>
<th>Electrons posinst8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch spacing at max current</td>
<td>$\lambda_{rf}$</td>
<td>7</td>
<td>7</td>
<td>11-12</td>
</tr>
<tr>
<td>Max normalized collector current</td>
<td>nA/mA</td>
<td>3.0 (broad)</td>
<td>2.9 (broad)</td>
<td>0.17 (det6)</td>
</tr>
<tr>
<td>(no sharp)</td>
<td></td>
<td>5.1 (sharp)</td>
<td>(no sharp)</td>
<td>0.4 (det3)</td>
</tr>
<tr>
<td>Width broad peak</td>
<td>$\lambda_{rf}$</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>(vs. bunch spacing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ave. collision energy</td>
<td>eV</td>
<td>88</td>
<td>111</td>
<td>8</td>
</tr>
</tbody>
</table>

Used posinst params for conditioned chamber (matched to positrons) to model electron beam. Electron beam operation 4-6 wks after shutdown to switch modes (no chambers vented).
Impulse kick not valid near beam; but \( n_{kick} = 1 \) vs. 21 similar ave wall collision rate

For 40-ps-long (12-mm) positron APS bunches, cloud electrons that are within about 500 \( \mu m \) of the beam center oscillate several times in the bunch potential (calculations are for vertical plane). The transverse rms beam size is 350 \( \mu m \) (horizontal) and 50 \( \mu m \) (vertical).

[Courtesy L. Loiacono, from K. Harkay, R. Rosenberg, L. Loiacono, ICFA BD Newsletter 33, Apr 2004]
Summary

- Measured electron cloud distribution in APS for bunch trains vs current; positron and electron beam
- Modeling benchmark focused on positron data, det6: near center of drift, far from end absorber
- EC generation depends strongly on true secondary distribution $f_{ts}(E)$ and rediffused components
- Wall conditioning effect: $\delta_{\text{max}}$ started at 3.1, conditioned to 2.2
- Wall current, collision energy distributions, broad multipacting resonance peak match model well at det6, reasonable surface parameters for Aluminum
Open issues

- Never able to explain (model) sharp resonance peak
- Detector position-dependence rich in physics, not yet modeled to satisfaction (tried case w/o antechamber, inconclusive)
- What predicts CB instability threshold? (more than EC density)
- Weak multipacting effect for electron beam reproduced qualitatively, but details not understood
- Energy distribution different for positrons vs electron beams, confirms expected beam-cloud dynamics. Modeling results not yet understood (photoelectron component? nkicks?)