Measurements and simulations of electron-cloud-induced tune shifts and emittance growth at CESRTA

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Electron Cloud (EC) can cause instabilities and emittance growth, and can be a limiting factor in accelerator performance.

An increase in vertical beam size due to electron cloud has been seen in many e+ rings:
- PEPII, KEKB, DAPHNE, CESR

EC has been studied at CESRTA (Cornell Electron-Positron Storage Ring Test Accelerator) since 2008:
- Local and ring-wide EC measurements
- EC mitigation techniques
- Inform ILC damping ring design

Emittance growth has been measured along trains of positron bunches, and compared to simulations.
• This talk will present our measurements, describe the simulations, and compare results

• Focus on recent developments:
  – Improved tune shift measurements
  – Fitting e-cloud model to tune shift measurements at various bunch currents & beam energies
  – Improved modeling of photons from synchrotron radiation & generation of primary electrons
    ★ (Jim Crittenden’s talk Wednesday morning)
  – Effect on emittance growth simulations

• These improvements greatly enhance the predictive power of the model
  – Can be applied to any storage ring given a lattice and vacuum chamber information
• Buildup of electrons hitting the vacuum chamber wall and generating secondary electrons
• Main source: photoelectrons from synchrotron radiation
  – Also beam-gas ionization or stray protons hitting the wall
• Bunches accelerate the electrons as they pass
• Positron bunches pull the cloud towards it ("pinch effect")
• EC builds up along a train of bunches
• CESR (Cornell Electron-Positron Storage Ring)
  • 768 m in circumference
• Starting in 2008, CESR was reconfigured into a low emittance damping ring as a Test Accelerator (CESRTA) for the ILC Damping Ring specifically, and future high intensity, ultra low emittance storage rings in general
• The goal was to:
  – Characterize the build-up of EC in each of the key magnetic field regions
  – Study the most effective methods of suppressing EC in each region
• Electron and positron beams
• 1.8 – 6 GeV
• Flexible bunch patterns
• 12 Superconducting wigglers at low energy (2 GeV)
  – Generate 90% of the synchrotron radiation
• Beam:
  – 2.1 GeV positrons or electrons (5.3 GeV for additional tune shifts)
    ★ Horizontal emittance: 3.2 nm, fractional energy spread: 8x10^-4, bunch length: 9 mm
  – 30 bunch train, 0.4 mA/b and 0.7 mA/b, 14 ns spacing
    ★ (0.64x10^{10} and 1.12x10^{10} bunch populations)
  – 1 witness bunch, 0.25 to 1.0 mA, bunch positions 31 to 60
    ★ Witness bunch position probes cloud as it decays
    ★ Witness bunch current controls strength of pinch effect (cloud pulled in to e+ bunch)

• Measure:
  – Betatron tunes: using digital tune tracker
    ★ Drive an individual bunch via a gated kicker that is phase locked to the betatron tune
  – Vertical bunch size: from X-ray beam size monitor
    ★ Bunch-by-bunch, turn-by-turn
  – Horizontal bunch size: from visible light gated camera
    ★ Bunch-by-bunch, single-shot

• Bunch-by-bunch feedback on to minimize centroid motion
  – Disabled for a single bunch when measuring its tunes
• Vertical emittance growth along a train of positron bunches above a threshold current of 0.5 mA/b
• Trains of e- bunches do not blow-up
  – Indicates e+ emittance growth is due to EC, not another effect
• Horizontal beam size also blows-up in 0.7 mA/b e+ train
• One witness bunch to a 30 bunch 0.7 mA/b e+ train
  – Start with witness at bunch #60, vary current, eject bunch, move to #55…
  – For a given witness bunch #, the cloud it sees is the same
  
  ★ Emittance growth strongly depends on current (pinch effect)

### Graph

- **Y-axis**: Vertical Bunch Size [µm]
- **X-axis**: Bunch Number
- **Legend**:
  - Witness Bunch Current [mA]
    - 1.0
    - 0.75
    - 0.5
    - 0.25

The graph shows the relationship between witness bunch beam size and bunch number for different currents, illustrating the pinch effect on emittance growth.
Tune shifts can be measured various ways:

1. “Pinging”: Coherently kicking entire train once, measuring bunch-by-bunch, turn-by-turn positions, and peak-fitting the FFTs
   - Fast measurement (whole train at once)
   - Multiple peaks from coupled-bunch motion contaminate signal
   - Unable to measure horizontal tune shifts from dipoles (vertical stripe of cloud moves with train)

2. “Single bunch”: Feedback on all bunches except one. FFT its turn-by-turn position data
   - Cleaner signal if kicking the single bunch with gated kicker
   - Measures horizontal tune shift

3. “Digital tune tracker”: Enhancement on above technique, driving the bunch transversely in a phase lock loop with a beam position monitor
   - Best method; used here
• Tune shifts measured at 2.1 and 5.3 GeV at various currents:

2.1 GeV

5.3 GeV
• Simulations involve four codes which feed into each other

1. Tracking photons from synchrotron radiation (Synrad3D)
   ➔ Information on photons absorbed in vacuum chamber

2. Photo-electron production (Geant4)
   ➔ Quantum efficiencies
   ➔ Photo-electron energies

3. Electron cloud buildup (ECloud)
   ➔ Space-charge electric field maps

4. Tracking of beam through the lattice with EC elements (Bmad)
   ➔ Betatron tunes
   ➔ Equilibrium beam size

• The separation of steps 3 and 4 makes this a “weak strong” simulation
  – More on this later
1) Photon tracking

- **Synrad3D**
  - Simulates photons from synchrotron radiation
  - Tracks photons through vacuum chamber including specular & diffuse reflections
  - Input: lattice, 3D vacuum chamber profile, material
  - Output: information on absorbed photons:
    ★ Azimuthal angle
    ★ Energy
    ★ Grazing angle with vacuum chamber wall
• Geant4
  – Input: Absorbed photons
    ★ Azimuthal angle
    ★ Energy
    ★ Grazing angle with vacuum chamber wall
  – Simulates electron production from photo-electric and Auger effects
  – Vacuum chamber material (Aluminum) and surface layer (5 nm carbon-monoxide)
  – Output:
    ★ Quantum efficiency vs azimuthal angle
    ★ Photo-electron energy distributions
  – QE depends on photon energy & grazing angle which vary azimuthally
  – Improvement on ECLOUD model
  – Big improvement to predictive ability

★ See Jim Crittenden’s talk Wednesday morning
• Start with EC buildup simulations with ECLoud in both dipole and field-free regions
• Use element-type ring-averaged beam sizes
  – Dipole: 730 x 20 um
  – Drift: 830 x 20 um
    ★ The large horizontal size is dominated by dispersion
• Obtain space-charge electric field maps from the EC for 11 time slices during a single bunch passage, in ±5σ of the transverse beam size
  – Δt = 20 ps

• Only ~0.1% of electrons are within this beam region
  – Necessary to average over many ECLoud simulations
ECLOUD simulations depend strongly on vacuum chamber secondary yield (SEY) parameters.

Direct SEY measurements provide a good starting point, but it’s hard to accurately determine all the parameters.

Still, the condition in the machine may be different.

To improve agreement between the ECLOUD model and our various measurements:

- Use a multi-objective optimizer to fit the SEY parameters to tune shift data
- At each iteration, run ECLOUD simulations in parallel varying each parameter by an adaptive increment
  
  ★ Calculate Jacobian & provide to optimizer

**TABLE I. Main parameters of the model.**

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<tr>
<th></th>
<th>Copper</th>
<th>Stainless steel</th>
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<tr>
<td></td>
<td>Emitted angular spectrum</td>
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<td></td>
<td>($\alpha$) $\rightarrow$</td>
<td>1</td>
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<td>($P_{1,\alpha}(\infty)$)</td>
<td>0.02</td>
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<td>($P_{2,\alpha}$)</td>
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<td>($E_{p}$ (eV))</td>
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<td>($W$ (eV))</td>
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<td>($p$)</td>
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<tr>
<td>($\sigma_{E}$ (eV))</td>
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<td>($e_{1}$)</td>
<td>0.26</td>
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<td>($e_{2}$)</td>
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<td>Backscattered electrons</td>
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<td>($P_{1,\sigma}(\infty)$)</td>
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<td>($P_{2,\sigma}$)</td>
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<td>($r$)</td>
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<td>($q$)</td>
<td>0.5</td>
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<td>($r_{1}$)</td>
<td>0.26</td>
<td>0.26</td>
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<td>($r_{2}$)</td>
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<td>2</td>
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<td>Rediffused electrons</td>
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<td>($s$)</td>
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<td>($t_{1}$)</td>
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<td>($t_{3}$)</td>
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<td>($t_{4}$)</td>
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<td>True-secondary electrons</td>
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<td>($\delta_{\sigma}$)</td>
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<tr>
<td>($E_{\sigma}$ (eV))</td>
<td>271</td>
<td>292</td>
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<tr>
<td>($\delta_{t}$)</td>
<td>2.1</td>
<td>2.05</td>
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• Tune shifts calculated from the cloud space-charge electric field gradients
• Gradient just before a bunch passage ➔ coherent tune shift
  – Demonstrated in witness bunch tune measurements (left)
• Gradient during pinch ➔ incoherent tune spread, emittance growth
  – Demonstrated in witness bunch size measurements (right)
• Results from fitting E CLOUD model to data
  • Simultaneously fit to:
    – 0.7 mA/b at 2.1 GeV
    – 2, 3, and 6 mA/b at 5.3 GeV (next slide)
  • Parameters varied include:
    – Peak energy of true secondary yield
    – True secondary yield 's' parameter
    – True secondary yield
    – Rediffused secondary yield
    – Elastic yield at 0 energy
  • Same SEY parameters used in simulations at all currents & energies

Simulated tune shifts at 2.1 GeV

(Revolution frequency: 390 kHz)
Simulated tune shifts at 5.3 GeV

- 2 mA/b
- 3 mA/b
- 4 mA/b
- 5 mA/b
- 6 mA/b
• Use the *time-sliced electric field maps* in EC elements at the dipole and drifts
• Track particles in bunch through the full lattice (using Bmad) for multiple damping times, with radiation excitation and damping
• “weak-strong” model: does not take into account effects on the cloud due to changes in the beam
  – Tracking: *Weak*: beam; *Strong*: EC
  – EC buildup simulations: *Weak*: EC; *Strong*: beam
  – Justification: EC buildup simulations are rather insensitive to vertical beam size
• Strong-strong simulations are too computationally intensive to track for enough turns
  – Damping times at CesrTA are ~20,000 turns
  – We want equilibrium beam sizes
• Bunch size from simulation is the average over last 10k turns (of 60k)
• See vertical emittance growth in 0.7 mA/b simulations
• See some horizontal emittance growth in 0.7 mA/b simulations compared to 0.4 mA/b but needs investigation.
• More emittance growth with:
  – shorter distances from train (more cloud)
  – higher witness bunch current (more pinch)
• Simulations show similar behavior
• We have obtained various measurements of tune shifts and emittance growth from electron clouds
• Our e-cloud model has been improved with precise modeling of synchrotron radiation photons & generation of primary electrons
• The model has been validated with improved tune shift measurements for a range of bunch currents at 2.1 and 5.3 GeV
• A witness bunch at a range of currents gives a direct measurement of the pinch effect
  – Vertical emittance growth scales with pinch
  – Coherent tune shift does not
• Our weak-strong incoherent model is consistent with this data
• The simulations can uncover the largest contributions to tune shifts and emittance growth
  – EC mitigation methods can be targeted to these regions and tested in simulation
• Future work:
  – Further investigate horizontal emittance growth in simulation
  – Use model to predict EC effects at future accelerators
  – Use model to understand underlying factors driving emittance growth
    ★ New approaches to mitigating emittance growth from EC
Thank you for your attention
Witness bunch to a 0.4 mA/b train (below threshold)

**e+**

**0.4 mA/bunch train**

- **Vertical Bunch Size [µm]**
- **Witness Bunch Current [mA]**
- **Witness Bunch**
- **31 35 40 60**

**e-**

**0.4 mA/bunch train**

- **Vertical Bunch Size [µm]**
- **Witness Bunch Current [mA]**
- **Witness Bunch**
- **31 35 40 60**

**e+**

**0.4 mA/bunch train**

- **Horizontal Bunch Size [µm]**
- **Witness Bunch Current [mA]**
- **Witness Bunch**
- **31 35 40 60**

**e-**

**0.4 mA/bunch train**

- **Horizontal Bunch Size [µm]**
- **Witness Bunch Current [mA]**
- **Witness Bunch**
- **31 35 40 60**