Intrabeam scattering studies at CESR-TA

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• Description of CESR and CesrTA program
• Two beam size monitors
• Intrabeam scattering (IBS) modeling
• Results of IBS experiments
  – Size vs. current at various energies and vertical emittances
  – Size vs. RF voltage
  – Size vs. damping time
• Vertical data with puzzling current dependence
• Directions and conclusion
CESR-TA program
- 768 m ring
- Twelve 1.9 T damping wigglers
- Independently powered quadrupoles
- 1.8 to 5.3 GeV
-  $\varepsilon_x=3$ nm·rad,  $\varepsilon_y=\sim 10$ pm·rad

Emittance measurement tools
- X-ray beam size monitor (xBSM)
  - Measure vertical beam size
  - Bunch-by-bunch turn-by-turn
- Visible-light beam size monitor (vBSM)
  - Measure horizontal beam size with interferometry

Intrabeam scattering effect
Electron cloud studies
Fast Ion
X-ray beam size monitor (xBSM)

Optics
Slits, Fresnel zone plate, coded aperture

Detector & Data acquisition
Magnification ~ 2.5, resolution ~ 10 μm

Detector
- Linear array
- 32 InGaAs diodes
- Pitch = 50 μm
- Width = 400 μm
- Fast response

Vertical beam size growth along the train due to electron cloud

Detector & Data acquisition
Magnification ~ 2.5, resolution ~ 10 μm

Pinhole image

Counts

Channel

Bunch = 1
Turn = 7
Centroid = 17.42
Image Size = 1.07 pixels
Beam Size = 15.01 microns

N.T. Rider et al. Proc. Of IBIC 2012, WECD01
Visible-light beam size monitor (vBSM)

- Be mirror: 16x12 mm² (HxV)
- Adjustable iris: 3.0 - 22 mm
- Replaceable sets of double slits
  - Horizontal D=2.0, 2.5, 3.0 mm
  - Vertical D=5, 8, 10 mm
- Motorized stages to control the positrons of iris and slit sets

**Optics box in the tunnel**

Outside the tunnel:
- Splitter
- Lens 2 (f=1 m)
- Polarizer
- CCD camera
- Filter (500±5nm)
- Lens 3
- Streak Camera

**Horizontal beam size**

\[ \sigma_x = 275 \mu m \]

**Vertical beam size**

**S.T. Wang et al. NIMA 703 (2013) 80-90**
What is IBS?

- Occurs when particles in a single beam collide with each other.
- Causes emittance to increase as current is added.
- Single bunch effect.

**Thermalization**

Low currents: $p_x$, $p_y$, $p_z$ each dominated by separate processes.

$$\langle p_x^2 \rangle \neq \langle p_y^2 \rangle \neq \langle p_z^2 \rangle$$

Higher current: collisions between particles couple $p_x$, $p_y$, and $p_z$

**Diffusion in J due to changes in momentum**

- Scattering Event
- Jump in reference trajectory due to change in momentum
  - Suddenly, $J$ is bigger
  - “Negative Temperature” effect
• IBS emittance rise time on the order of milliseconds, competes with radiation damping.
• Lower bound on emittance and/or upper bound on current.
• Relevance to modern $e^-/e^+$ machine design:
  – Higher energies: roughly, $\gamma^{-3}$ dependence
  – Damping wigglers
  – Roundish beams
  – Drives optics design (IBS suppression lattices)
  – Adds uncertainty to expected machine performance
    • Due to ill-defined cut-offs in impact parameters (Coulomb Log), IBS theory has an error of about 20%
    • Vertical behavior can be strongly dependent on details of lattice imperfections
There are several methods for calculating IBS growth rates. As part of CesrTA, we have implemented and compared many of them. Over a wide range of parameters, we find all give very similar predictions. We treat the Coulomb Log the same for each method we have implemented. Piwinski’s formulas modified to take impact parameters.
Cornell’s BMAD Simulation Suite

- Element-by-element model of CesrTA lattice including multipole terms and field-map wiggler models
- IBS blow up calculated by Kubo & Oide formalism
- Potential well distortion (PWD) calculated by Billing’s effective impedance formalism
  - Current-dependent effective RF voltage
- Beam sizes obtained from beam $\Sigma$-matrix
- Simulation has 3 significant free parameters
  1. Zero-current horizontal emittance
  2. Zero-current vertical emittance
  3. Effective longitudinal inductive impedance

M.P. Ehrlichman et al. PRSTAB 16 (2013) 104401
• **Machine Setup**
  - 6 or 12 wigglers powered
    - 100 ms or 50 ms damping time (500 ms without wigglers)
  - 6.3 MV RF provided by four 500 MHz superconducting cavities
    - Adjustable down to ~1 MV
    - ~10 mm bunch lengths
  - Single-bunch charges from $\sim 10^9$ up to $\sim 10^{11}$ particles
    - Lifetime dominated by Touschek scattering

• **Beam Physics**
  - Intrabeam Scattering
    - $\varepsilon_x$ increase of $\sim 200\%$ ($\sim 1$ m horizontal dispersion)
    - $\varepsilon_y$ increase of $< 10\%$ (very low vertical dispersion and coupling)
  - Potential Well Distortion
    - Impedance effect that changes apparent RF voltage.
  - Coherent Tune Shift -0.5 kHz/mA
    - Resonance lines up To 6$^\text{th}$ order observed
  - Vertical Behavior at high current is Puzzling
• Working point is selected
  – Vertical coherent tune changes by ~4 kHz from low current to high current
• Apply optics corrections
  – Orbit
  – Phase and coupling
  – Dispersion
• If desired, increase $\varepsilon_{y0}$ using closed coupling and dispersion bumps
• Charge single bunch to $> 10^{11}$ particles
• Cut injection and take beam size measurements as the beam decays
  – Vertical by x-ray beam size monitor
  – Horizontal by visible light beam size monitor
  – Longitudinal by streak camera
• Decay due to Touschek lifetime
  – Experiment takes about 30 minutes
7 skew quads are used to create a closed coupling and dispersion bump.
Bands come from systematic uncertainty in measurement of zero-current vertical beam size

| Run ID   | \( \varepsilon_{y0} \) (pm) | \( \varepsilon_{x0} \) (nm) | \( \varepsilon_{x} \) (7.5 \( 10^{10} \) part) (nm) |
|----------|-------------------------------|-------------------------------|-----------------------------------------------------|
| Low \( \varepsilon_{y0} \) | 9.6 – 13.9                   | 3.6                           | 7.25                                                 |
| Med \( \varepsilon_{y0} \) | 54.2 – 63.8                   | 3.6                           | 6.55                                                 |
| High \( \varepsilon_{y0} \) | 163.6 – 179.9                 | 3.5                           | 5.18                                                 |

\*7.5 \( 10^{10} \) part. \( \approx 12 \) nC \( \approx 5 \) mA
### Input Parameters

| Run ID | \( \varepsilon_0 \) (pm) | \( \varepsilon_0 \) (nm) | \( \varepsilon_x \) \( \times 10^{10} \) (nm) |
|--------|----------------|----------------|------------------|
| Low \( \varepsilon_0 \) | 4.9 – 8.1 | 5.7 | 10.4 |
| High \( \varepsilon_0 \) | 52.3 – 61.8 | 5.7 | 7.62 |

\*7.5 \times 10^{10} \text{ part.} \approx 12 \text{ nC} \approx 5 \text{ mA}
### Input Parameters

| Run ID  | \( \varepsilon_{y0} \) (pm) | \( \varepsilon_{x0} \) (nm) | \( \varepsilon_x \) (7.5 \( \times 10^{10} \)) (nm) |
|---------|-----------------------------|----------------------------|---------------------------------|
| Low \( \varepsilon_{y0} \) | 17.29 – 23.0 | 4.6 | 6.6 |
| High \( \varepsilon_{y0} \) | 58.1 – 68.1 | 4.6 | 5.84 |

\[ \ast 7.5 \times 10^{10} \text{ part.} \approx 12 \text{ nC} \approx 5 \text{ mA} \]
Combined Results vs. Energy

**Low $\varepsilon_y$ Conditions**

| Energy  | Blowup Percentage |
|---------|-------------------|
| 2.1 GeV | 101 % $\varepsilon_x$ |
| 2.3 GeV | 82 % $\varepsilon_x$ |
| 2.5 GeV | 43 % $\varepsilon_x$ |

**~ 50 um Vertical Beam Size Conditions**

| Energy  | Blowup Percentage |
|---------|-------------------|
| 2.1 GeV | 81 % $\varepsilon_x$ |
| 2.3 GeV | 33 % $\varepsilon_x$ |
| 2.5 GeV | 27 % $\varepsilon_x$ |
• The tail-cut is a modification to IBS theory that excludes from the rise time those scattering events that occur less frequently than once per particle per damping period.

\[
\frac{1}{\tau_{\text{IBS}}} \propto \log \frac{b_{\text{max}}}{b_{\text{min}}}
\]

• Weak application of the central-limit theorem.

• Significant in machines with strong damping.

• Without the tail-cut, IBS theory can significantly over-estimate the equilibrium beam size

\[M.P. \ Ehrlichman \ et \ al. \ PRSTAB \ 16 \ (2013) \ 104401\]
• In e⁻/e⁺ rings of a few GeV energy, emittance growth due to IBS is similar to emittance growth due to photon emission.

• Photon emission creates emittance growth when $\mathcal{H}_x$ is large in the bends.

• IBS creates emittance growth when $\mathcal{H}_x$ is large when the beam is small.

$$\mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x \eta'_x^2$$
• Not consistent with IBS model
  – IBS size vs. current plot would be “log like”
• Species-independent
• Sensitive to betatron and synchrotron tunes
• Not sensitive to chromaticity
• FFT of vertical centroid and size does not show a strong signal above noise
• Energy spread measured to be constant, no threshold behavior seen in energy spread vs. current.
• Seen even in large beams
• Coupling (Cbar12) vs. current measured to be constant
• Coherent tune shift plays a part, but not the whole story
• Incoherent tune shift is a suspect, cannot be whole story
Size vs. RF Voltage

100 ms damping time
Crabbed beam
50 ms damping time

\[ \varepsilon_x = 3.0 \text{ to } 5.2 \text{ nm} \]
\[ \varepsilon_y = 4.6 \text{ to } 17.9 \text{ pm} \]

M.P. Ehrlichman et al. arXiv:1311.1763
• Beam size vs. current with different damping rates.

• Measurements on beams with global coupling.
  – Significant vertical IBS growth rate.

• Measurements at 1.8 GeV.
  – Requires instrumentation development.

• Understanding vertical behavior at high current.
  – Impedance model with wake fields.
  – Model higher current behavior.

• Lower emittances.
• IBS data has been gathered over a range of energies, particle densities, and RF voltages.
• Model developed that gives good agreement with horizontal and longitudinal data.
  – Incorporates IBS and PWD effects
• High-current vertical data is interesting and lacks a model.
• Directions: global coupling, various damping rates, 1.8 GeV, and lower vertical emittance