Simulation of E-Cloud driven instability and its attenuation using a feedback system in the CERN SPS*

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The problem

- Transverse instability observed in SPS beams due to electron clouds
- Interaction between e-cloud and beam leads to large transverse oscillations
- Feedback system was proposed to control the beam transverse motion
- We use the Particle-In-Cell framework Warp-Posinst to investigate dynamics of instability as well as feasibility and requirements of feedback
Our simulation framework encompasses the Warp and Posinst PIC codes

Warp quasistatic model similar to HEADTAIL, PEHTS, QuickPIC.

2-D slab of electrons

3-D beam

parallelized using pipelining

Mesh refinement provides higher efficiency

Secondary emission from Posinst:
- enables self-consistent multi-bunch calculations.

Example:
- 2 bunches separated by 25 ns in SPS

E-cloud feedback simulations - Vay et al.
Physics of electron interaction with bunches

1. Electrons injected here from Posinst dump

3D view

Beam direction

t=0 (bunches 35-36 = buckets 176-181)
Physics of electron interaction with bunches

Electron density \( (x10^{12} \text{m}^{-3}) \) at turn 500 (bunches 35-36 = buckets 176-181)

2. Electrons are focused by bunch
Physics of electron interaction with bunches

3D view

3. High-density spikes eject electron jets

Electron density \((x10^{12} m^{-3})\) at turn 500 (bunches 35-36 = buckets 176-181)
Physics of electron interaction with bunches

4. Secondary emission from impact of e-jets on walls

Electron density \((x10^{12} \text{m}^{-3})\) at turn 500 (bunches 35-36 = buckets 176-181)
Physics of electron interaction with bunches

Electron density ($x10^{12}m^{-3}$) at turn 500 (bunches 35-36 = buckets 176-181)

5. Electrons fill the chamber
Physics of electron interaction with bunches

Electron density (x10^{12} m^{-3}) at turn 500 (bunches 35-36 = buckets 176-181)

6. Electrons interact with next bunch
Electrons after 500 turns

Electron density \((x\times10^{12} \text{m}^{-3})\) at turn 500 (bunches 35-36 = buckets 176-181)
Bunches 35 and 36 after 500 turns

Beam density \((x10^{15}\text{m}^{-3})\) at turn 500 (bunches 35-36 = buckets 176-181)
Comparison with experimental measurements

- Separation in two parts, core and tail, with tune shift in tail higher than in core
- Similar tune shift for the core of the beam but higher with simulations for tail
- More experimental results at poster WEPEB052, J. D. Fox et al, “SPS Ecloud instabilities - Analysis of machine studies and implications for ecloud feedback”, Wednesday, May 26, 16:00-18-00.
Both expt. and sim. show activity level inversely proportional to frequency

Interesting difference: instability grows in simulation but is already there at turn 0 in experiment
Bunches transverse internal structure has fairly long wavelength component

- Can a feedback system resolving the bunch control the instability?
- What characteristics are needed, (amplitude, frequency range, noise level, delay, …)?
Simulated feedback model

- \( E_f \) is set from estimated velocity offset \( v_y \):  
  \[
  E_f = g \, v_y \left( \frac{\gamma m}{q} \right) \frac{v_z}{L_f} \quad (0 < g \leq 1)
  \]

- predicts \( y'(t) = v_y / v_z \) from records of centroid offsets at two previous turns \( y_{i-1} \) and \( y_i \) using linear maps, ignoring longitudinal motion and effects from electrons

\[
y'_{i+\xi} = (cc_\xi - ss_\xi) y_i - cy_{i-1}
\]

with

\[
\begin{align*}
  c &= \cos(2\pi Q_y) & c_\xi &= \cos(2\pi \xi Q_y) \\
  s &= \sin(2\pi Q_y) & s_\xi &= \sin(2\pi \xi Q_y)
\end{align*}
\]

In following results, \( \xi = 1 \).

(for \( \xi = 0 \), same as Byrd PAC95 and Thompson et al. PAC09)
Emittance history with feedback on/off, with gains $g=0.1$ and 0.2

Feedback very effective at damping instability.

Better with $g=0.2$ for bunch 36.

Run with bunch 35 frozen.

Effect of bunch 35 on 36 is weak.
Tests with finite bandwidth

Runs with 5 different digital filters with cutoffs (-3 dB) around 250, 300, 350, 450 and 575 MHz.

With these filters, cutoff>450 MHz needed for maximum damping.
Multi-bunch simulations:
beware of electron injection procedure.

Why is emittance of 36 >> 35?

Run of bunch (36,37) gives same emittance histories as (35,36).

Is it because \( <n_e> \) raises by ~8%?

Source of inconsistency?

Single bunch runs with electron load
(a) Uniform
(b) Random refreshed at each time step
(c) Random using load from t=0

=> Bunch 36 experienced more noise than 35 because of random secondary electron generation.
Summary and future work

- Beam-ecloud self-consistent simulations are now within reach, allowing detailed understanding of the dynamics and control of beam instability via feedback systems.

- Improvements to Warp-Posinst quasistatic model
  - mesh refinement,
  - secondary emission, gas ionization,
  - better feedback model.

- Multi-bunch simulations are now possible (thanks in part to parallelism).

- Good qualitative and semi-quantitative agreement with experiment.

- Modeling of bunches 35 and 36 in SPS at 26 GeV show effective damping from simulated feedback, provided that bandwidth cutoff > 450 MHz.

- Care must be exercised with interpretation due to statistical implications of electrons injection procedures.

- A lot more work is needed, including: implementation of planed feedback n-tag prediction, filtering, etc; better control of numerical noise issue in simulations, eventually using as proxy to emulate real machine noise; replace smooth focusing with linear optics, etc.