Studies at CesrTA of Electron-Cloud-Induced Beam Dynamics for Future Damping Rings

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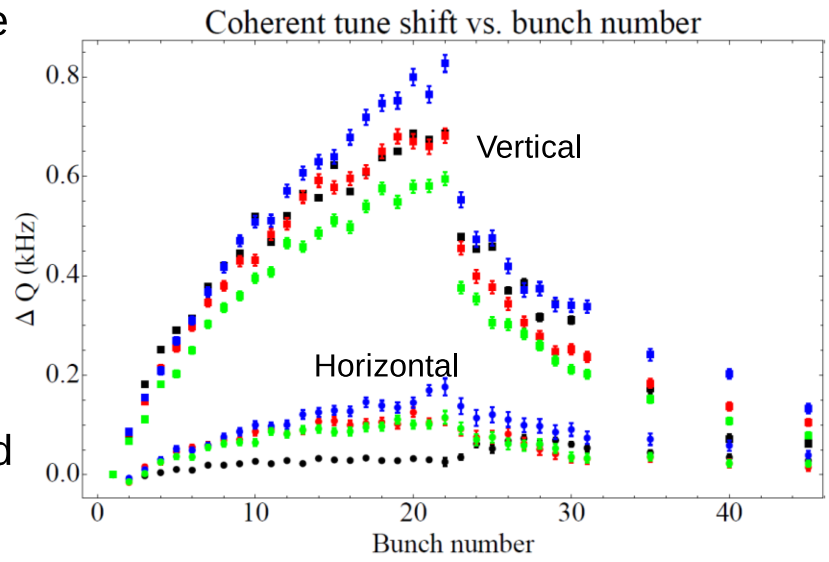
Electron cloud studies at CesrTA

- Electron clouds can adversely affect the performance of accelerators, and are of particular concern for the design of future low emittance damping rings.
- Studies of the impact of electron clouds on the dynamics of bunch trains in Cesr have been a major focus of the Cesr Test Accelerator (CesrTA) program.
- In this presentation, we report measurements along bunch trains of
  - coherent tune shifts,
  - coherent instability signals,
  - coherent damping rates, and
  - emittance growth.
- The measurements were made for a variety of bunch currents, train configurations, beam energies and transverse emittances, similar to the design values for the ILC damping rings.
- The measurements will be compared with simulations which model the effects of electron clouds on beam dynamics, to extract simulation model parameters and to quantify the validity of the simulation codes.

Coherent tune measurements

- A large variety of bunch-by-bunch coherent tune measurements have been made, using one or more gated BPM's, in which a whole train of bunches is coherently excited, or in which individual bunches are excited.
- These data cover a wide range of beam and machine conditions.
- The change in tune along the train due to the buildup of the electron cloud has been compared with predictions based on the electron cloud simulation codes (POSINST and ECLOUD).
- Quite good agreement has been found between the measurements and the computed tune shifts. The details have been reported in previous papers and conferences.
- The agreement constrains many of the model parameters used in the buildup codes and gives confidence that the codes do in fact predict accurately the average density of the electron cloud measured in CesrTA.

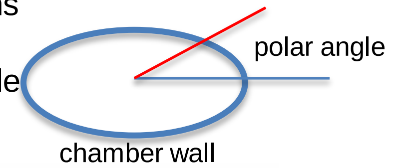


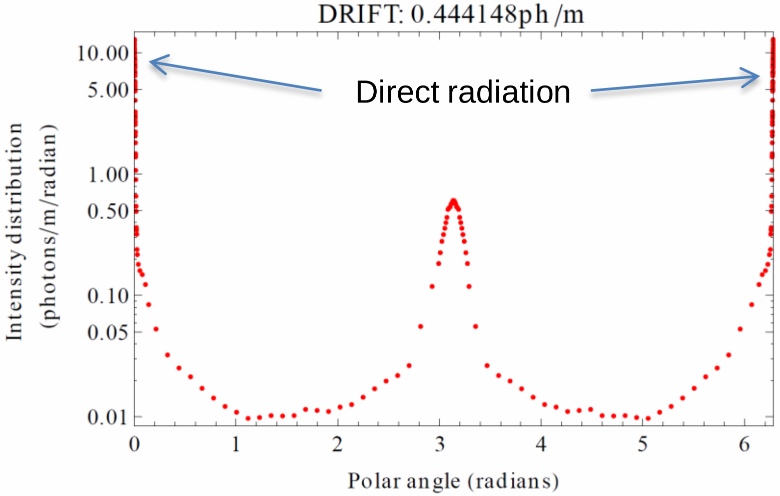
2.1 GeV positrons, 0.5 mA/bunch
Black: data
Blue, red, green: from POSINST simulations, varying total SEY by +/-10%

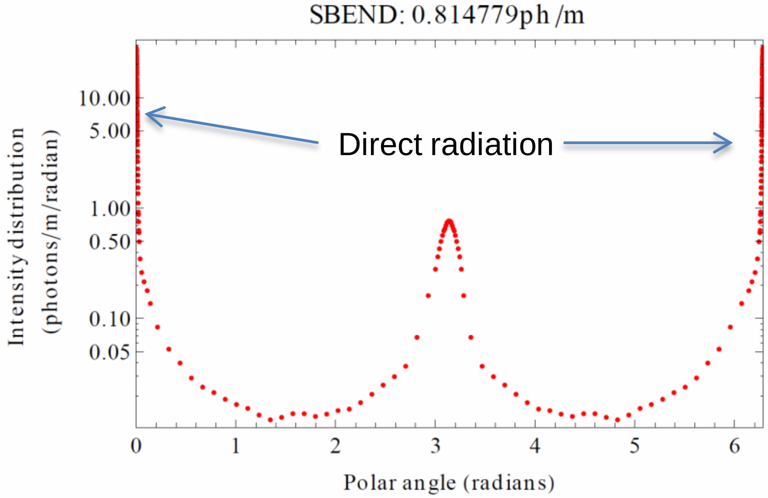
Photon reflectivity simulations (1)

- Since synchrotron radiation photons generate the photoelectrons which seed the cloud, the model predictions depend sensitively on the details of the radiation environment in the vacuum chamber. To better characterize this environment, a new simulation program, SYNRAD3D, has been developed.
- This program predicts the distribution and energy of absorbed synchrotron radiation photons around the ring, including specular and diffuse scattering in three dimensions, for a realistic vacuum chamber geometry.
- The output from this program can be used as input to the cloud buildup codes, thereby eliminating the need for any additional free parameters to model the scattered photons.

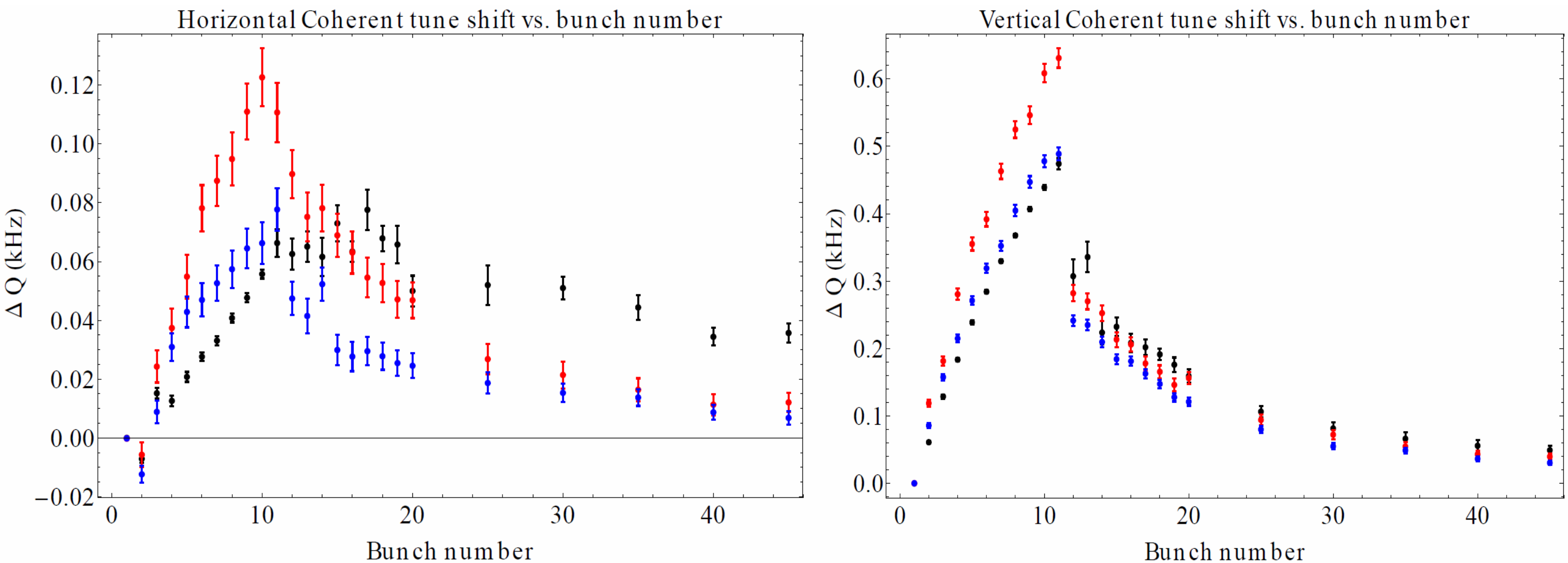
SYNRAD3D predictions for distributions of absorbed photons on the CesrTA vacuum chamber wall for drift and dipole regions, at 5.3 GeV.







Photon reflectivity simulations (2)



Measured tune shifts (black points) vs. bunch number, for a train of 10 0.75 mA/bunch 5.3 GeV positron bunches with 14 ns spacing, followed by witness bunches.

Red points are computed (using POSINST) based on direct radiation and a uniform background (free parameter) of scattered photons.

Blue points are computed using results from SYNRAD3D (with no free parameters for the radiation) as input to POSINST.

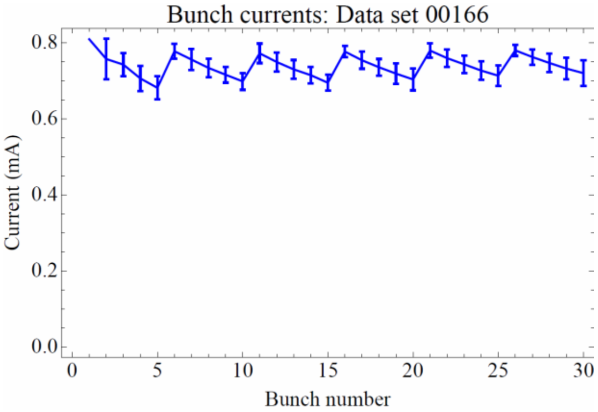
Bunch-by-bunch frequency spectra

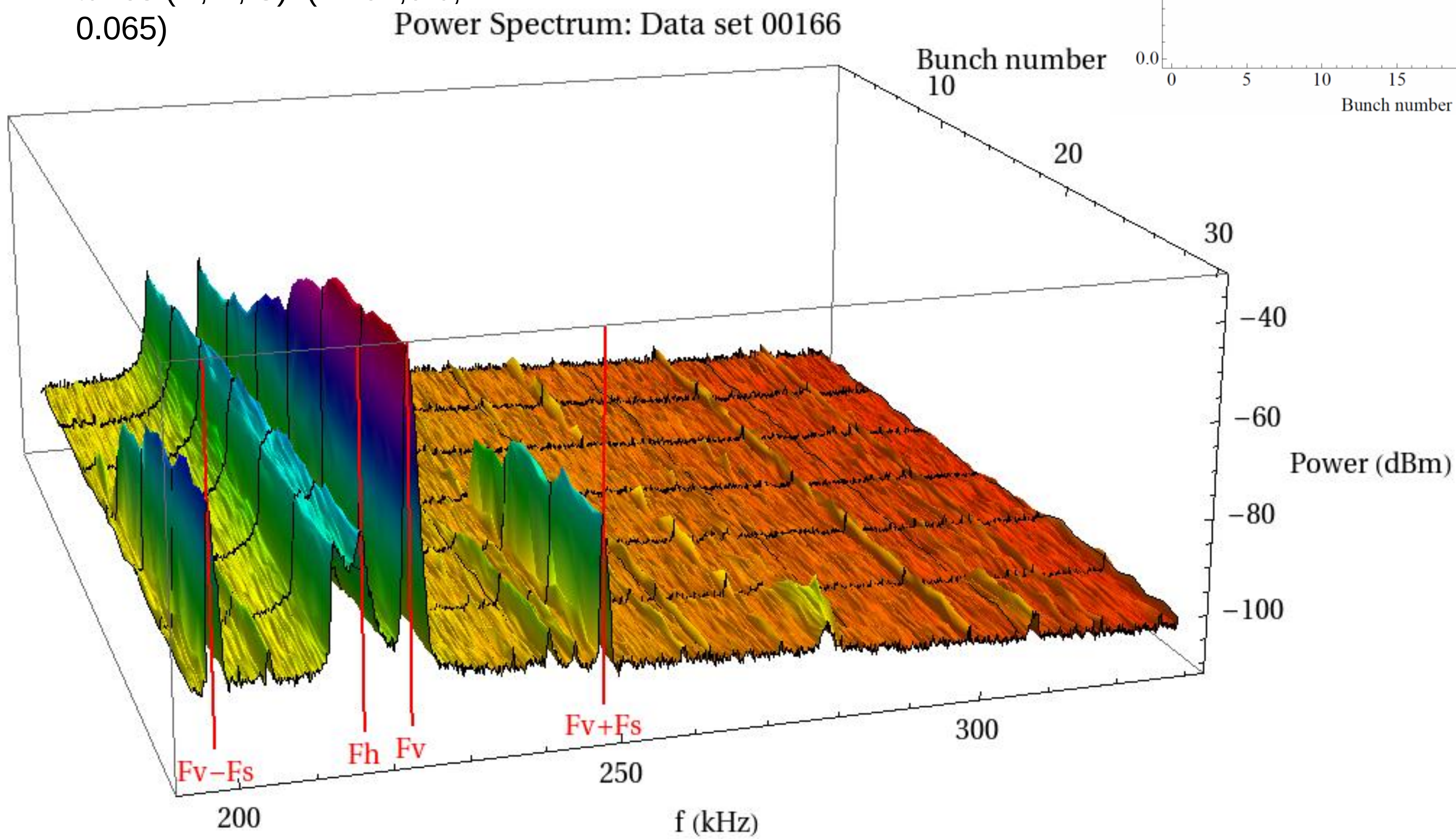
- Using a high-sensitivity, filtered and gated BPM, and a spectrum analyzer, bunch-by-bunch frequency spectra have been collected for a variety of machine and beam conditions, to detect signals of single-bunch instabilities which develop along trains of positron bunches.
- Under conditions in which the beam is transversely self-excited via the electron cloud, these frequency spectra exhibit the vertical m = +/- 1 head-tail (HT) lines, separated from the vertical betatron line by approximately the synchrotron frequency, for many of the bunches along the train. The amplitude of these lines typically (but not always) grows along the train.
- We attribute the presence of these lines to a vertical head-tail instability induced by the electron cloud.

30 bunch train: bunch by bunch spectra

Beam parameters:

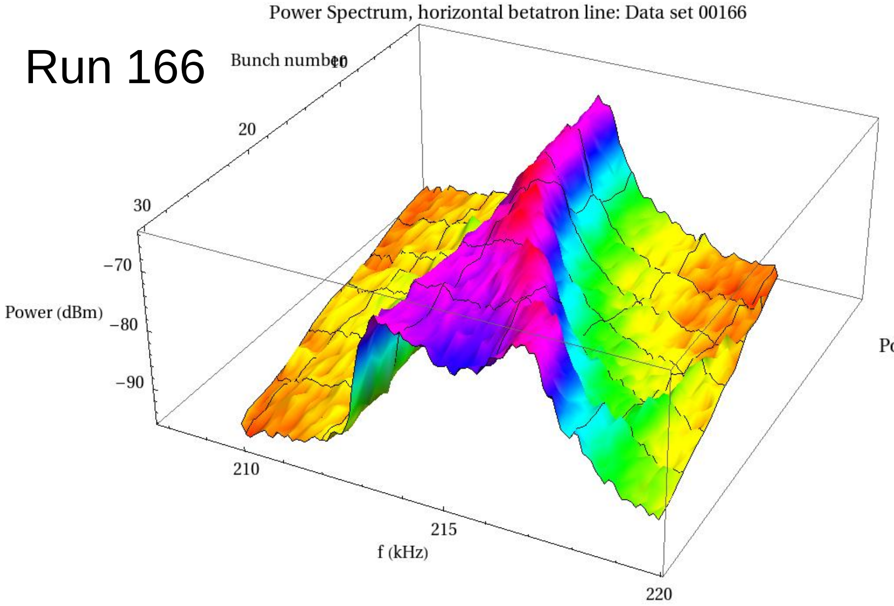
- 2.1 GeV;
- H (V) emittance: 2.6 nm (20 pm);
- bunch length 10.8 mm;
- tunes (H, V, S): (14.57,9.6, 0.065)
- momentum compaction 6.8x10^{-3}
- (H,V) chrom = (1.33,1.155)
- Avg current/bunch = 0.74 mA.
- L-FBK off; H-, V-FBK at 20%



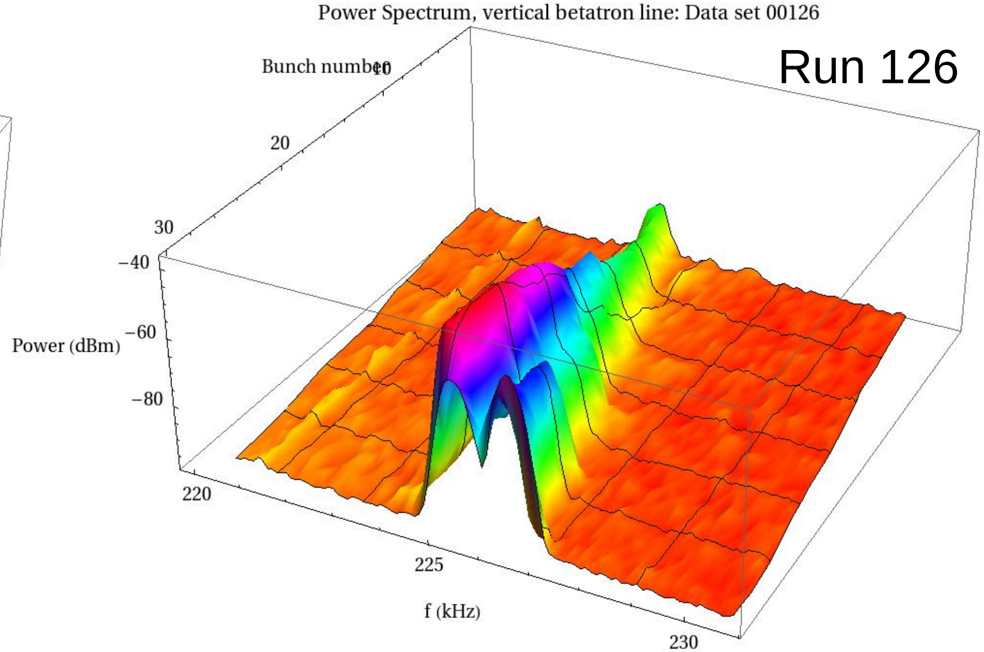


Detailed features of horizontal and vertical lines

Run 166



Run 126

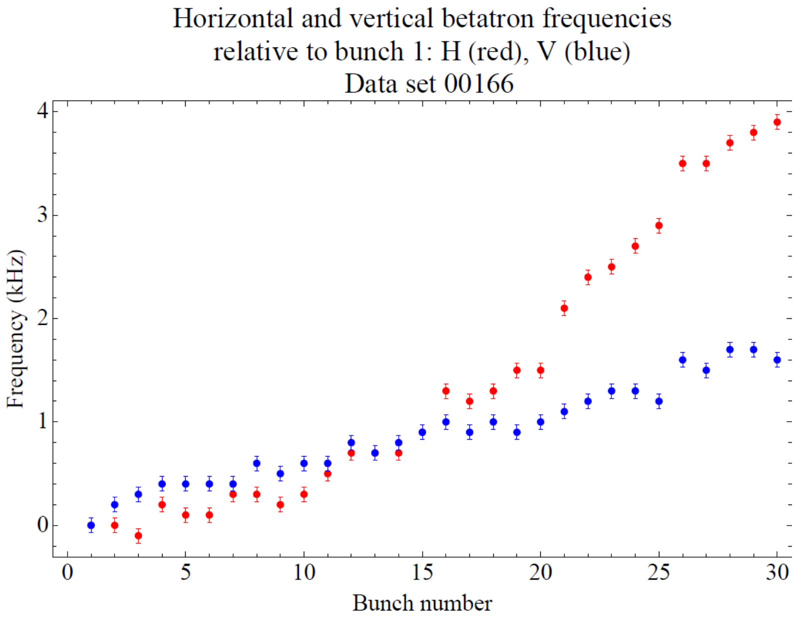


A lower frequency (~3 kHz) shoulder in the horizontal tune spectrum is attributable to the known dependence of horizontal tune on the multibunch mode.

In many cases, there is bifurcation of the vertical tune spectrum, which starts to develop at the same bunch number as the head-tail lines, and is not well understood.

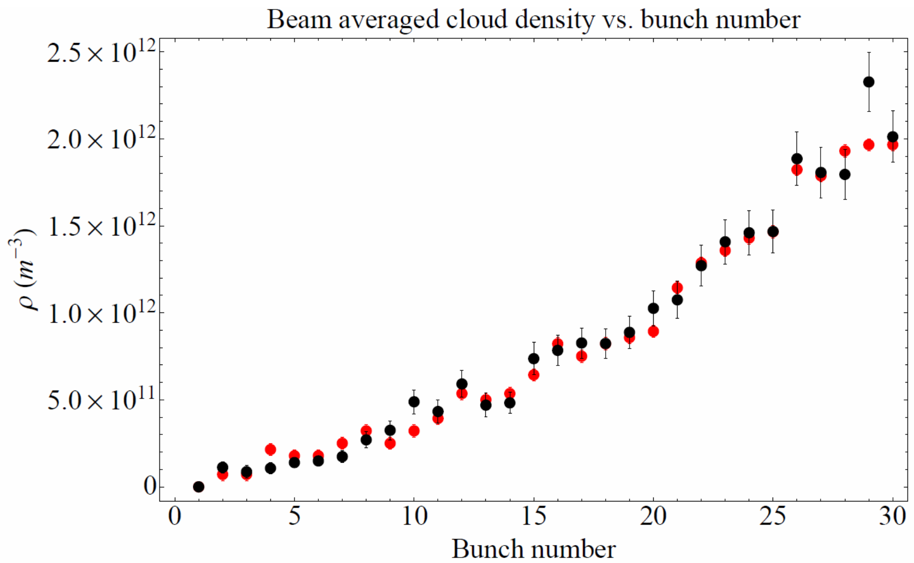
Horizontal and vertical betatron tune shifts

Horizontal and vertical betatron tunes shift along the train due to the buildup of the electron cloud.

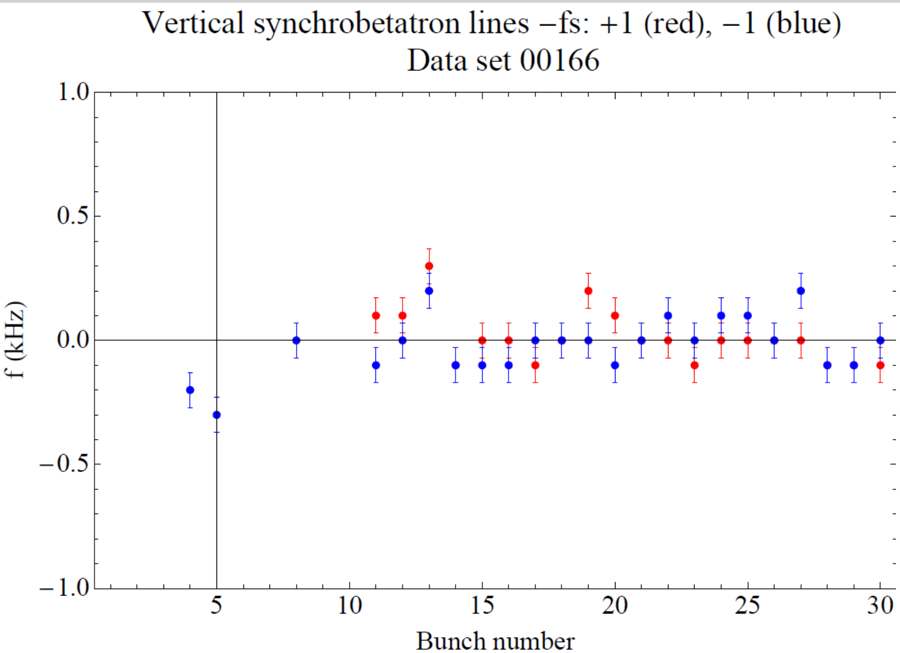


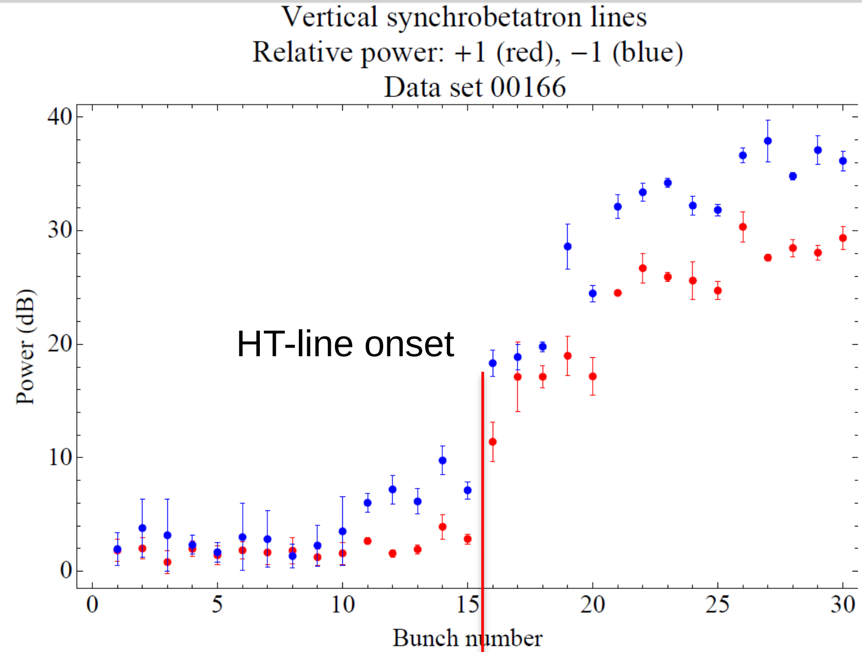
The electron cloud density can be inferred from the tune shifts (directly calculated: red. From simulation: black).

$$\langle \rho_c \rangle = \gamma \frac{\Delta Q_x + \Delta Q_y}{r_e \langle \beta \rangle C}$$

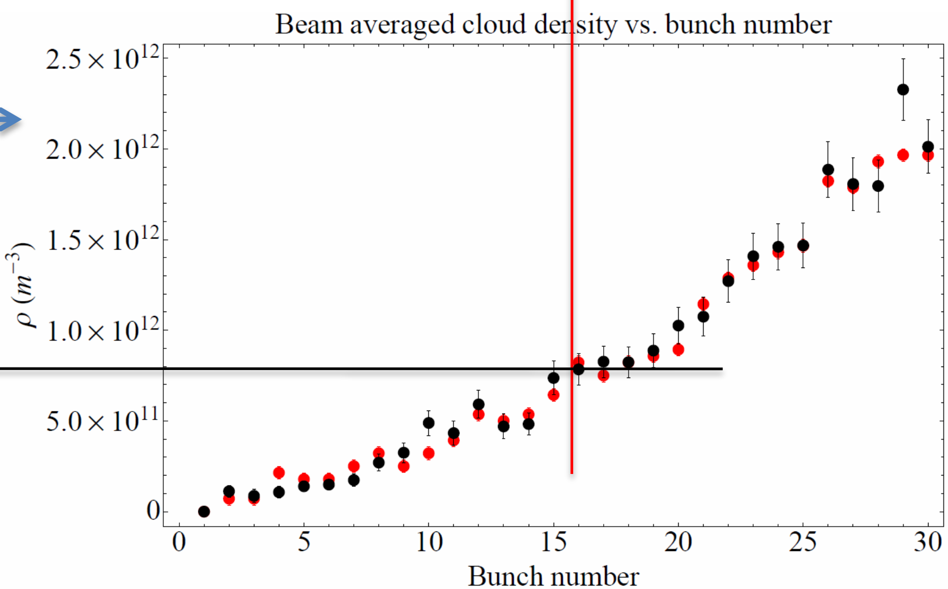


Vertical head-tail lines: correlation with cloud density at 2.1 GeV



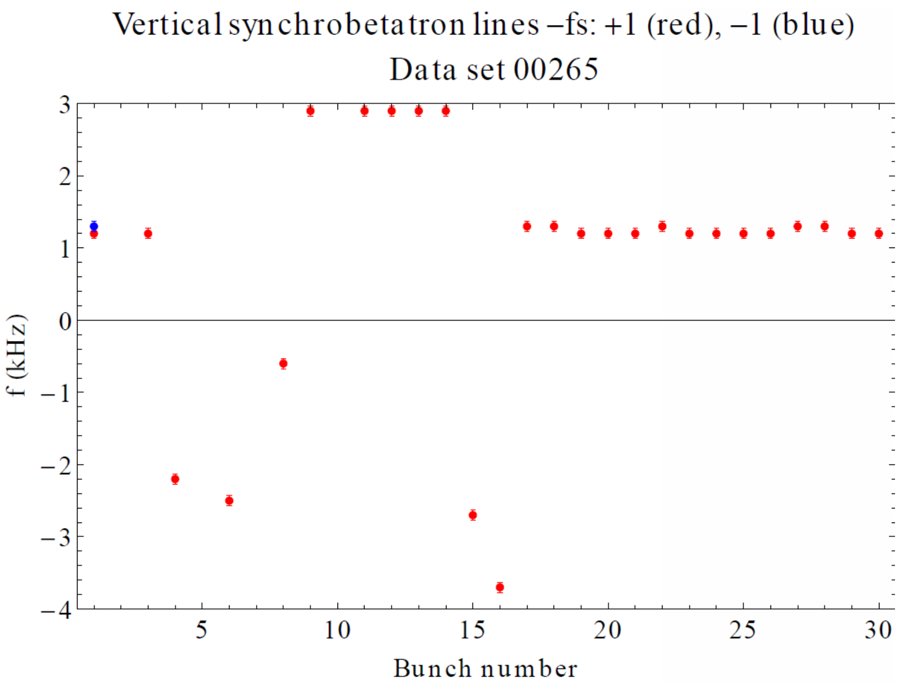


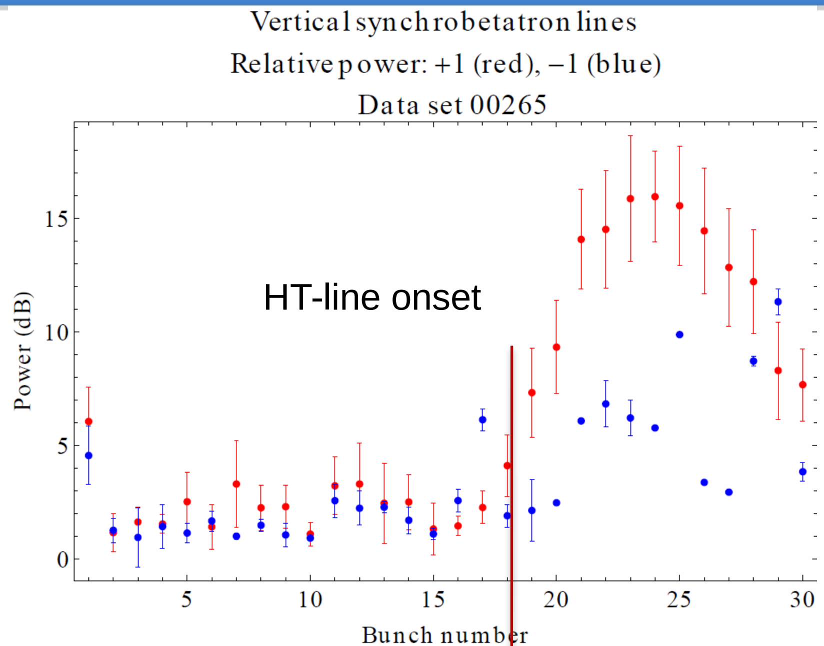
Cloud density inferred from tune shifts (directly calculated: red. From simulation: black).



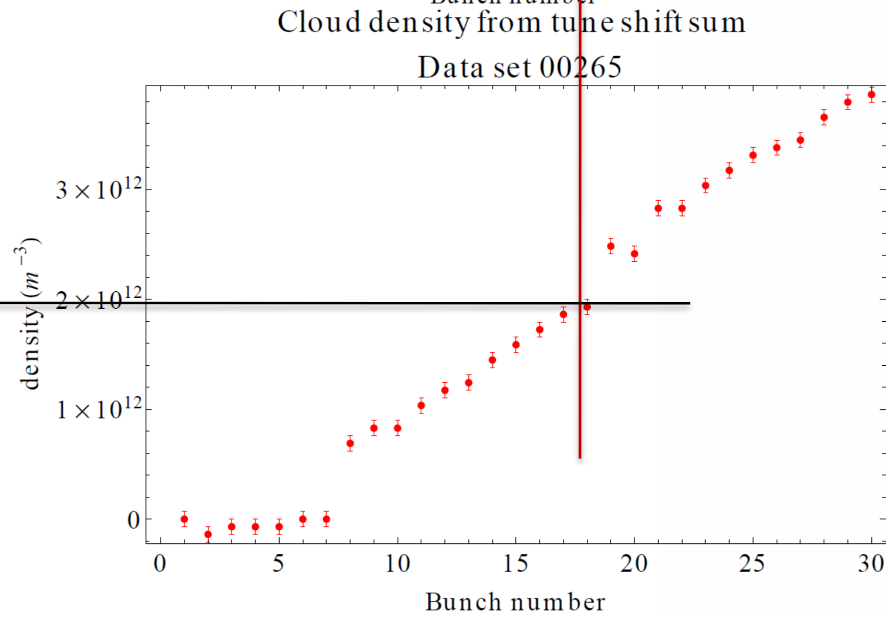
Cloud density at HT-line onset: ~$8\times10^{11}/m^3$

Vertical head-tail lines: correlation with cloud density at 4 GeV



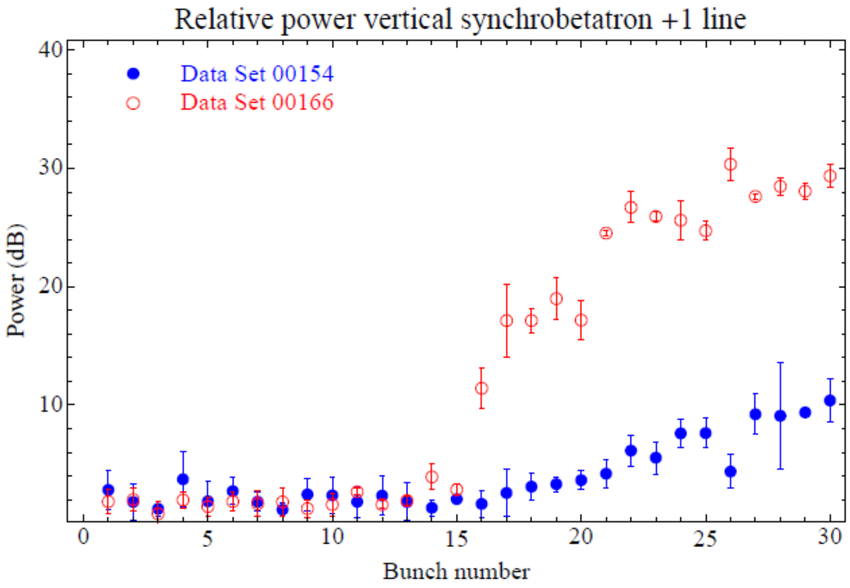


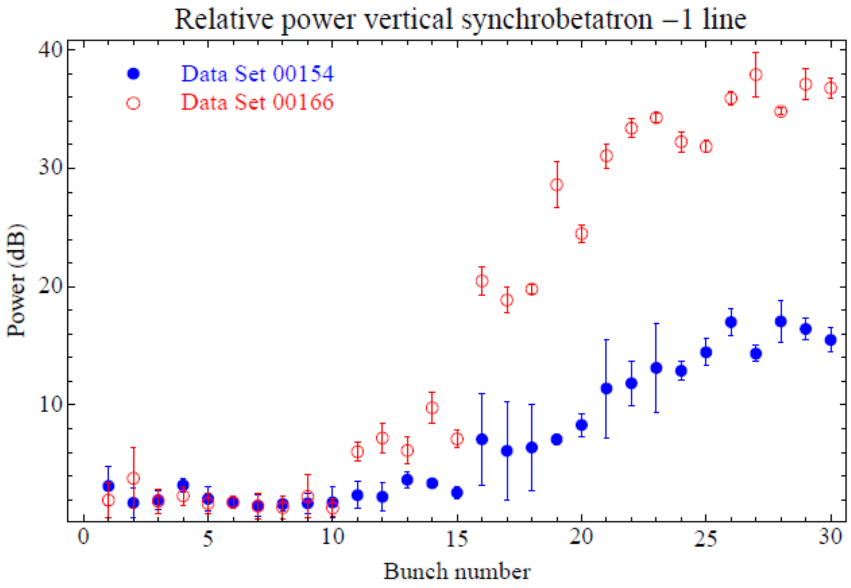
Cloud density inferred from tune shifts (directly calculated)



Cloud density at HT-line onset: ~$2\times10^{12}/m^3$

Vertical head-tail lines: species dependence at 2.1 GeV



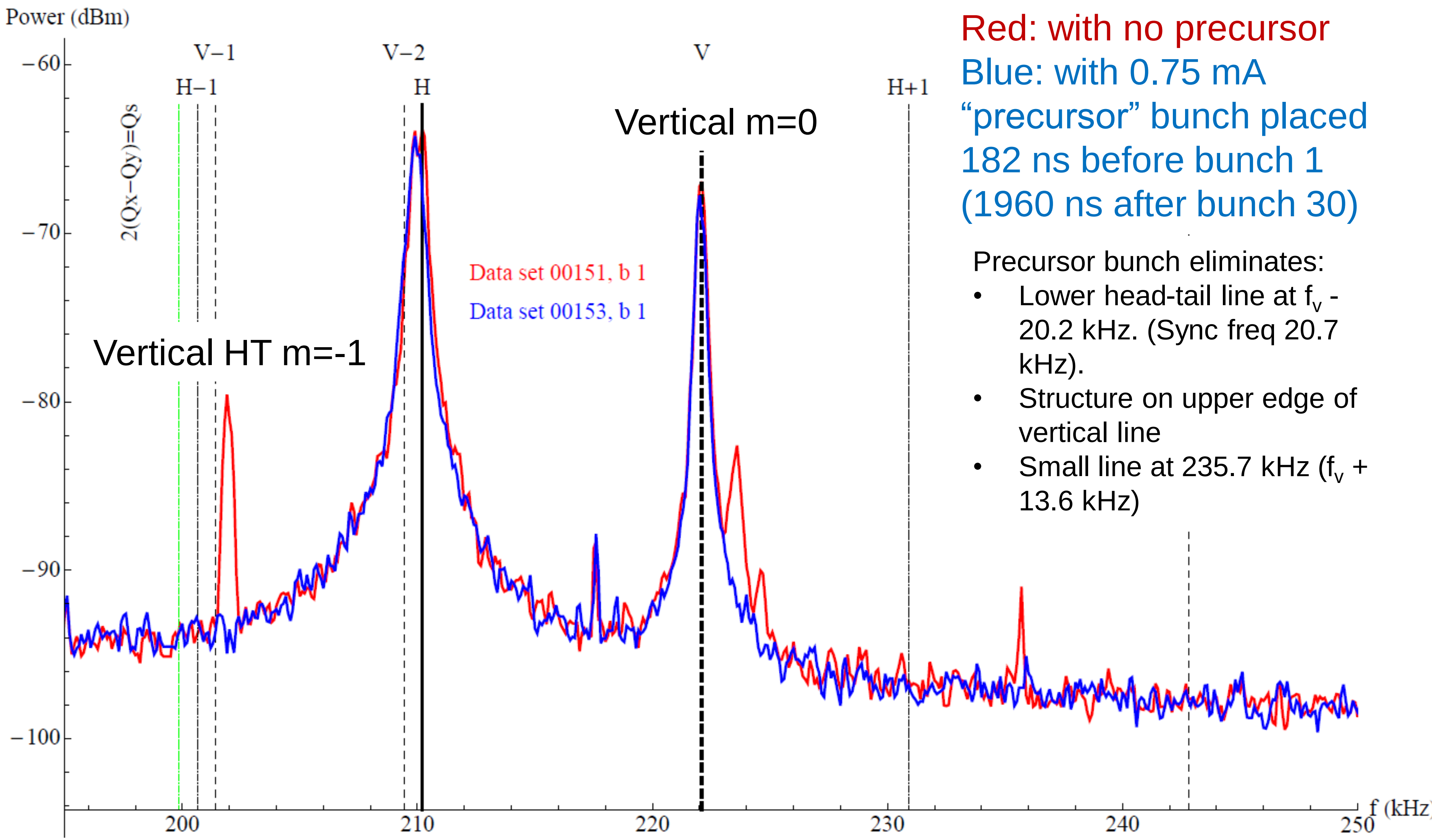


Vertical head-tail line excitation for positrons and electrons compared. 30 bunch trains of 0.75 mA/bunch electrons (data set 154) and positrons (data set 166) with the same settings for the chromaticity, single bunch emittance, bunch length, and other beam parameters.

Additional observations from the frequency spectra

- The amplitude of the HT lines depends strongly on the vertical chromaticity, the beam current and the number of bunches
- For a 45 bunch train, the HT lines have a maximum power around bunch~30; the line power is reduced for later bunches.
- There is a weak dependence of the onset and amplitude of the HT lines on the synchrotron tune, the single-bunch vertical emittance, and the vertical feedback.
- Under some conditions, the first bunch in the train also exhibits a head-tail line (usually m=-1 only). The presence of a ``precursor'' bunch a few hundred ns before the start of the train can eliminate the m=-1 signal in the first bunch.
  - One explanation is that there may be a significant ``trapped'' cloud density near the beam which lasts long after the bunch train has ended, and which is dispersed by the precursor bunch. Indications from RFA measurements and simulations indicate this ``trapped'' cloud may be in the quadrupoles and wigglers.

Precursor bunch effect: 2 GeV, 0.75 mA/bunch 30 bunch train



Bunch 1 spectrum

Red: with no precursor

Blue: with 0.75 mA "precursor" bunch placed 182 ns before bunch 1 (1960 ns after bunch 30)

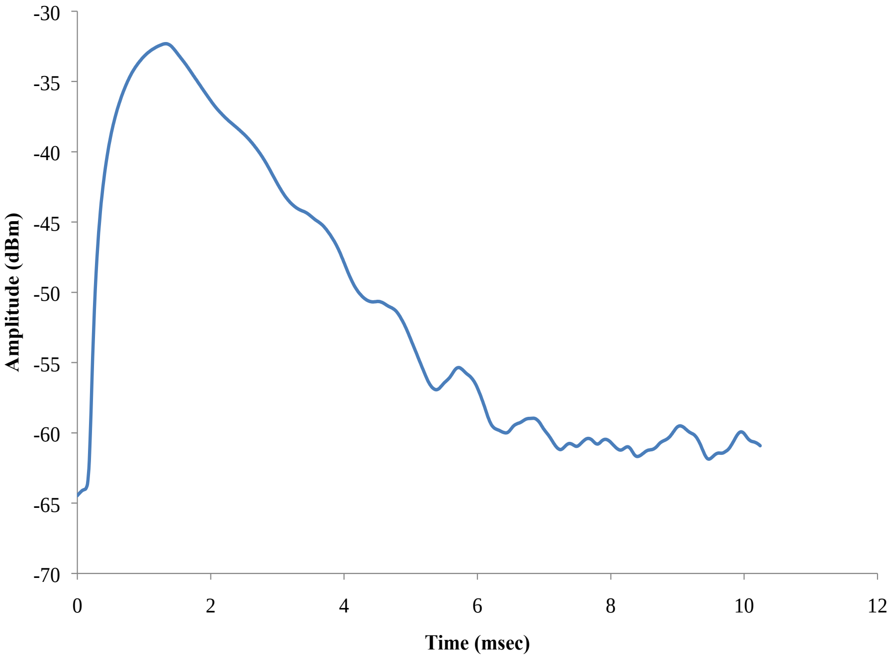
Precursor bunch eliminates:

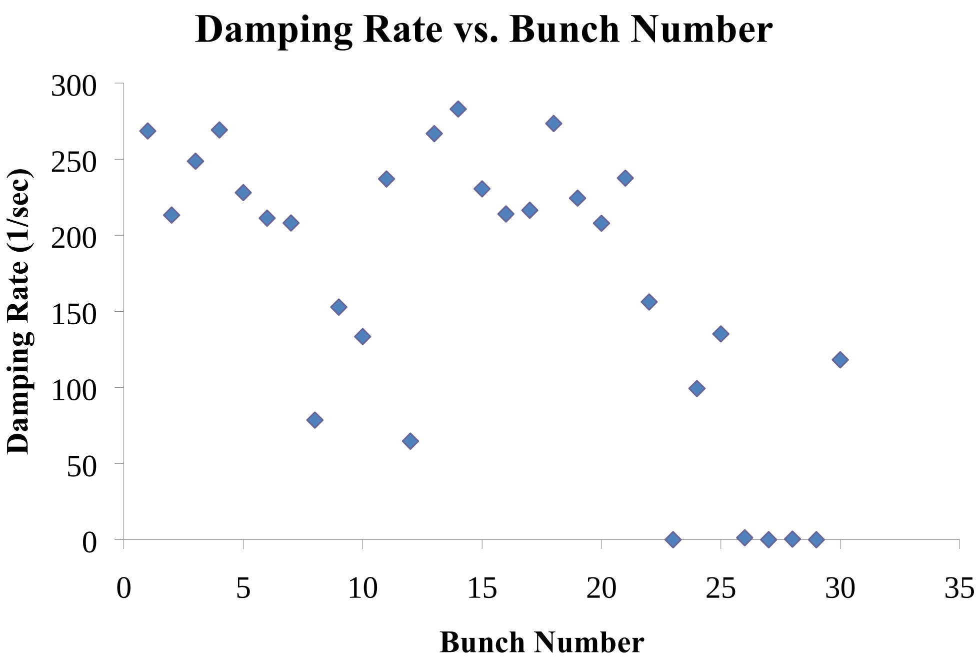
- Lower head-tail line at f_v - 20.2 kHz. (Sync freq 20.7 kHz).
- Structure on upper edge of vertical line
- Small line at 235.7 kHz (f_v + 13.6 kHz)

Measurements of bunch-by-bunch damping rates

- As the electron cloud builds up along a train, it will modify the coherent damping rates of each bunch, as well as producing tune shifts. Measurements of bunch-by-bunch damping rates provide additional information on the nature of the effective impedance of the cloud.
- Bunch-by-bunch damping rate measurements have been done for
  - betatron line:
    - Drive a single bunch via the transverse feedback system's external modulator.
    - Observe the output from a button BPM, gated on the same bunch, using a spectrum analyzer in tuned-receiver mode set to the betatron line frequency.
    - Measure the damping rate of the betatron line's power after the drive is turned off.
  - m=+/-1 head tail lines:
    - Same technique as for the betatron line, but the tuned receiver is set to the head-tail line frequency.
    - In addition, a CW drive is applied to the RF cavity phase to provide the longitudinal excitation necessary to observe the head-tail line below the instability threshold.

Betatron line drive-damp measurements

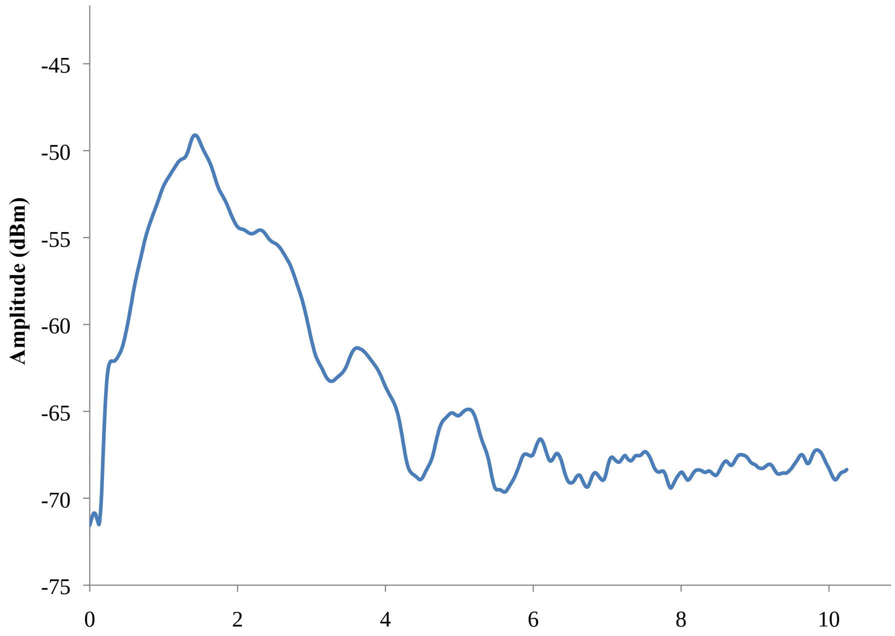


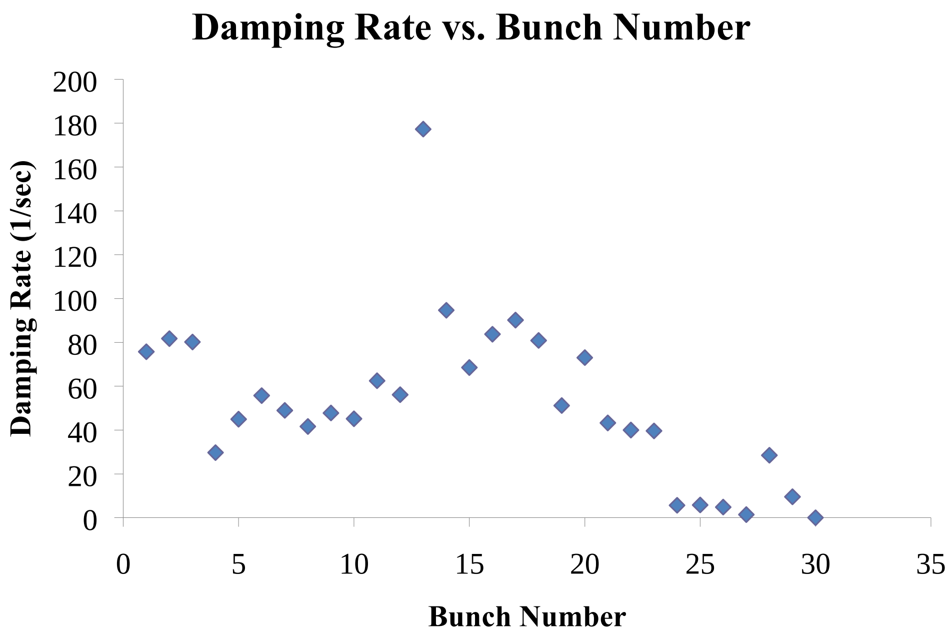


Amplitude vs time for one of the bunches

Damping rate vs. bunch number for a 30 bunch train of positrons at 2.1 GeV, 0.72 mA/bunch. (Estimated single bunch damping rate: 200/s).

m=-1 head-tail line drive-damp measurements



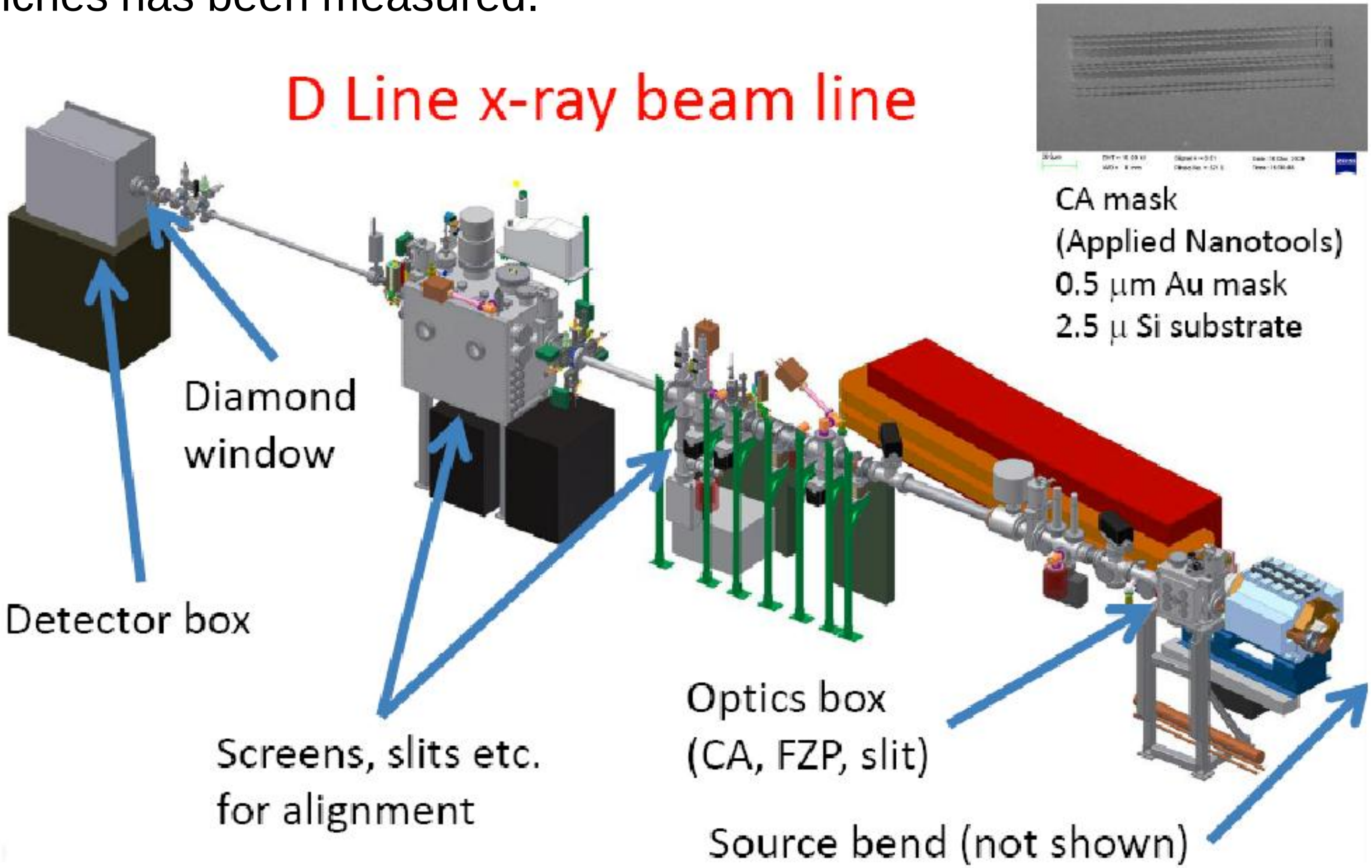


Amplitude vs time (in ms) for one of the bunches

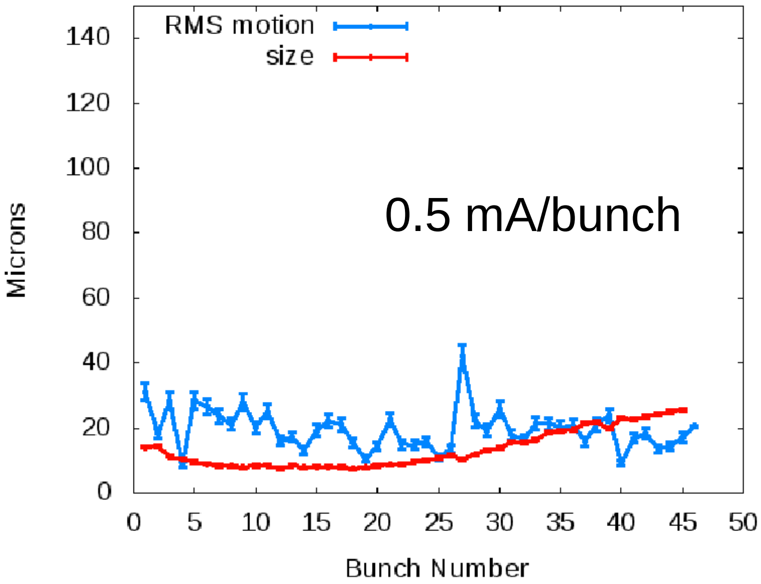
Damping rate vs. bunch number for a 30 bunch train of positrons at 2.1 GeV, 0.72 mA/bunch.
(Estimated single bunch damping rate: 110/s).

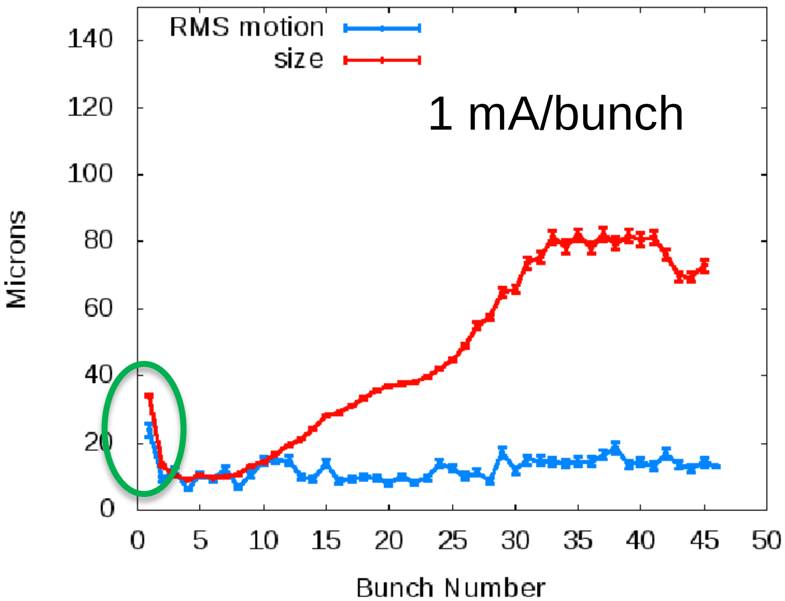
Bunch-by-bunch beam size measurements

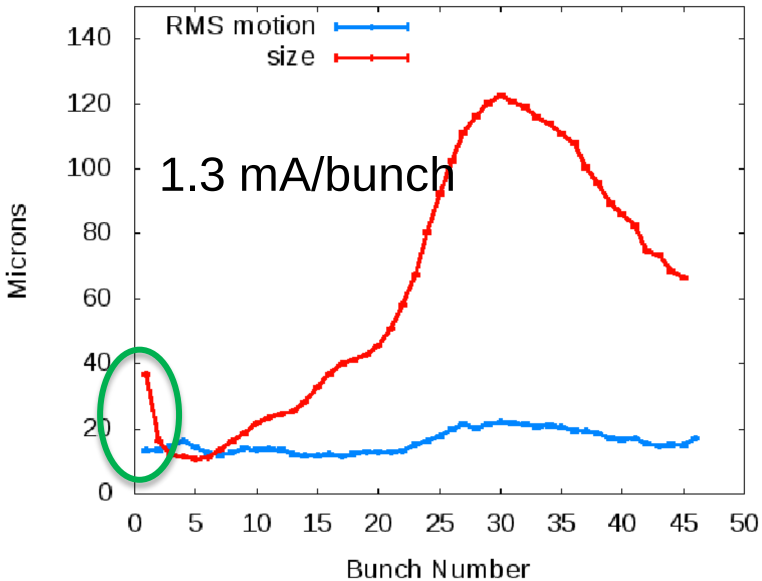
Using an x-ray beam size monitor (XBSM), bunch-by-bunch beam position and size measurements have been made on a turn by-turn basis for positron beams. From the beam size measurements, the evolution of the beam emittance along trains of bunches has been measured.



Beam size evolution along the train for different bunch currents





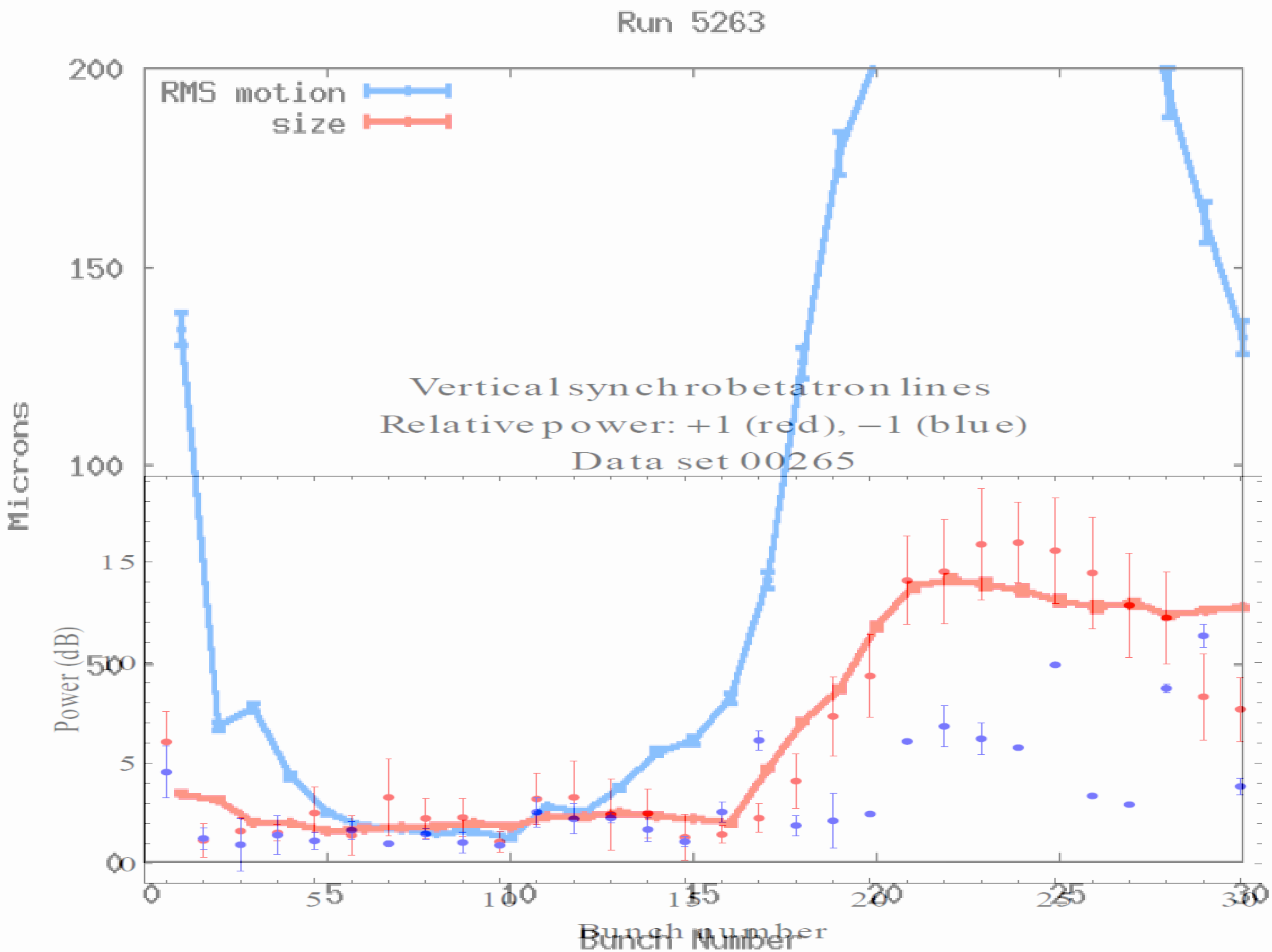


45 bunch train of positrons, 2.1 GeV, 14 ns spacing

Note enhancement of bunch 1 size

For fixed bunch current, beam size growth along the train is not very sensitive to the chromaticity, the bunch spacing, the initial beam size or the feedback gain.

Comparison of HT line power and beam size growth under identical conditions

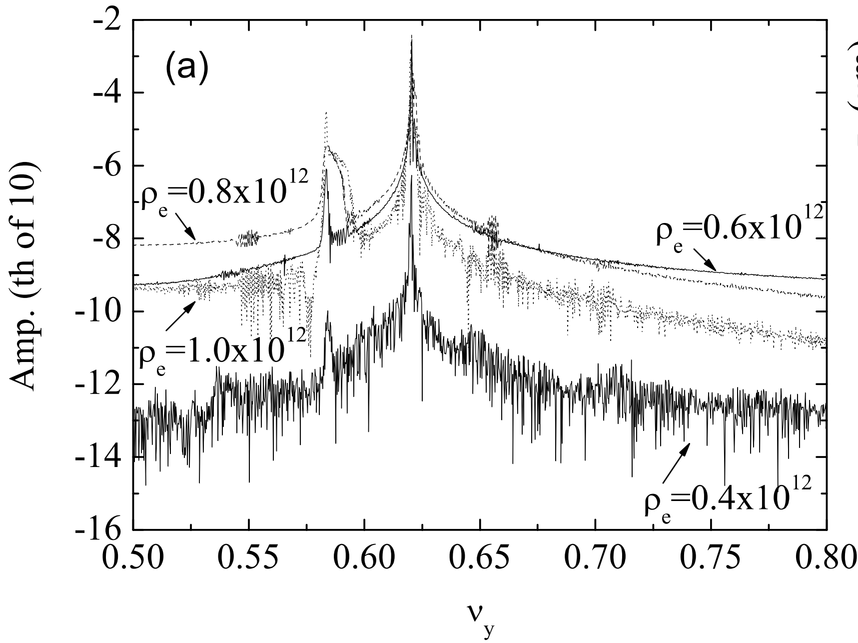


30 bunch train of positrons, 4 GeV, 1.1 mA/bunch, chromaticity (H,V) = (1.3, 1.4).

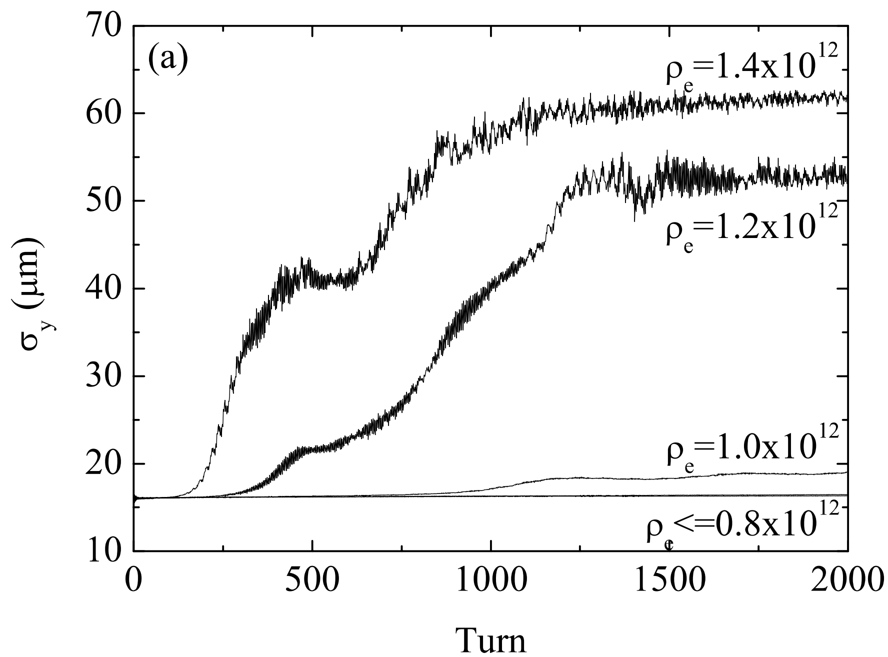
4 GeV beam size plot overlaid on HT line power plot from slide 11

Comparisons with PEHTS simulations

- PEHTS simulations



Fourier spectrum of dipole motion
Simple lattice, CesrTA beam parameters, 2 GeV

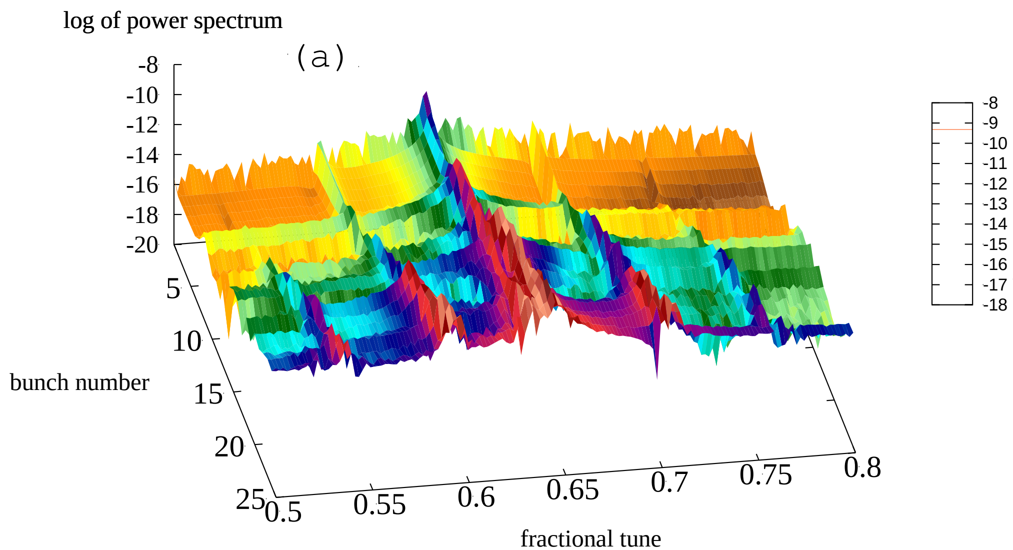


Evolution of beam size
Realistic lattice (83 int. pts.), CesrTA beam parameters, 2 GeV

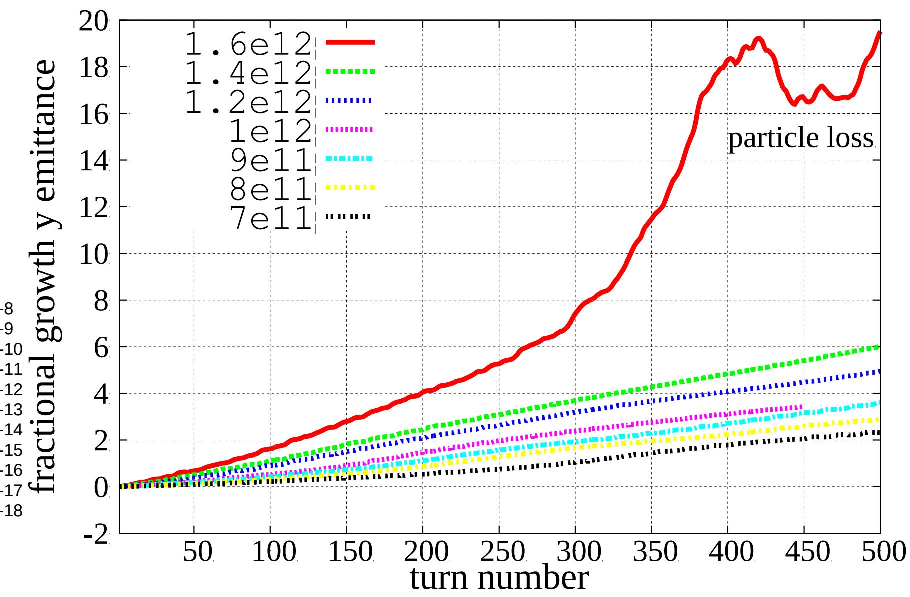
Beam energy (GeV)	2	4	5
Observed instability threshold ($\times10^{12}/m^3$)	0.8	2	
PEHTS predicted instability threshold ($\times10^{12}/m^3$)	1.2		5

Comparisons with CMAD simulations

- CMAD simulations



Fourier spectrum of dipole motion
CesrTA beam parameters, 2 GeV

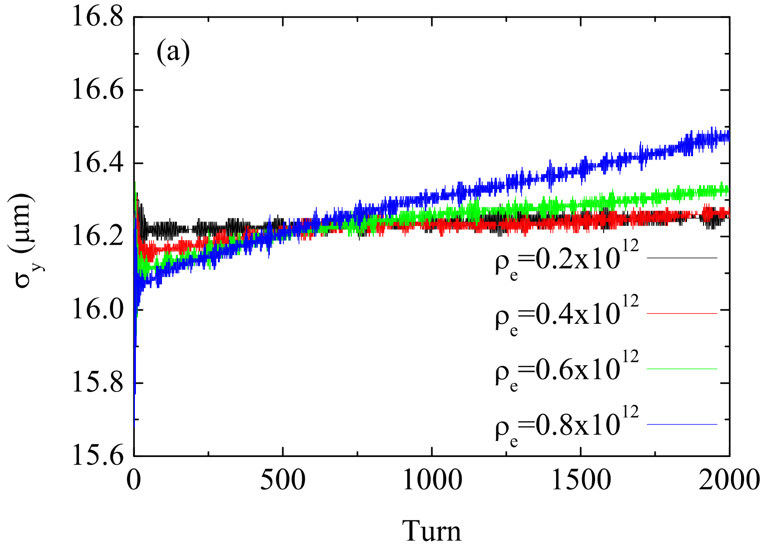


Evolution of emittance
CesrTA beam parameters, 2 GeV

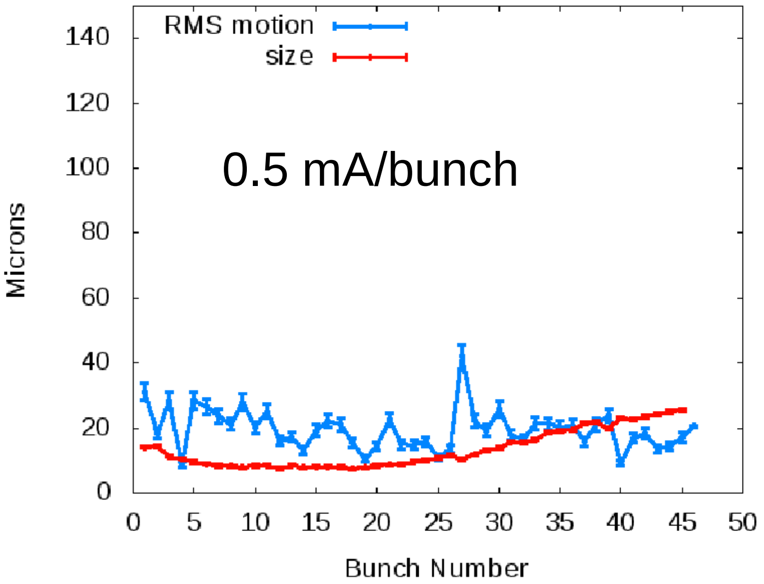
Beam energy (GeV)	2	4
Observed instability threshold ($x10^{12}/m^3$)	0.8	2
CMAD predicted instability threshold ($x10^{12}/m^3$)	1.6	

Sub-threshold (incoherent) emittance growth

- PEHTS simulations, below the coherent instability threshold



Evolution of beam size below the instability threshold.
Realistic lattice, CesrTA beam parameters, 2 GeV.
-suggests 20% growth in equilibrium emittance at a cloud density of $0.8 \times 10^{12}/m^3$



2 GeV beam energy

Observed (XBSM) beam size growth below the instability threshold may be due to incoherent effects

Summary and Conclusions

- The CesrTA research program has investigated the dynamics of trains of positron bunches in the presence of the electron cloud through measurements of bunch-by-bunch coherent tune shifts, frequency spectra, and beam size.
- Coherent tune shifts have been compared with the predictions of cloud buildup models (augmented with a new code to characterize the photoelectrons) in order to validate the buildup models and determine their parameters.
- Frequency spectra have been used to determine the conditions under which signals for electron-cloud-induced head-tail instabilities develop.
- Drive-damp measurement techniques are being developed to characterize the stability of bunches in the train before the onset of the head-tail instability.
- An X-ray beam size monitor has been used to determine the conditions under which beam size growth occurs, and to correlate these observations with the frequency spectral measurements.
- Simulation codes have been used to model the cloud-induced head-tail instability. The predicted features of the instability agree reasonably well with the measurements.
- The success of the cloud buildup and head-tail instability codes in modelling the observations gives confidence that these codes can be used to accurately predict the performance of future storage rings.