Observations of Electron Cloud Effects at the PSR

Robert Macek, 4/11/02, ICFA Workshop

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with acknowledgement to the PSR e-p instability collaboration from LANL, ANL, BNL, FNAL, LBNL, ORNL, &PPPL

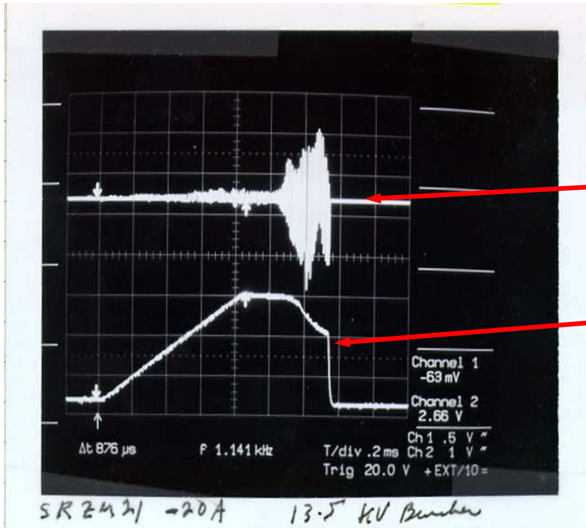
For more information see the website for the
8th ICFA Mini Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings, Santa Fe, NM Feb 16-18, 2000
http://www.aps.anl.gov/conferences/icfa/two-stream.html

Also see the website for the
International Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings, KEK Tsukuba, Japan, Sept 11-14, 2001
http://conference.kek.jp/two-stream/

Outline

- Principal e-cloud effects
  - Two-stream e-p instability
  - Interference with some beam diagnostics in the ring and extraction line
- Basic features of the e-p instability at PSR
- Observations of electron cloud at PSR
  - Diagnostics for measuring electrons
  - Key observations
  - Estimates of electron neutralization of the beam
- Tests of Potential Cures
  - Suppression of electron generation
  - Various methods for increased Landau damping
  - Inductive Inserts
- Conclusions

Well Established ep Instability Characteristics at PSR

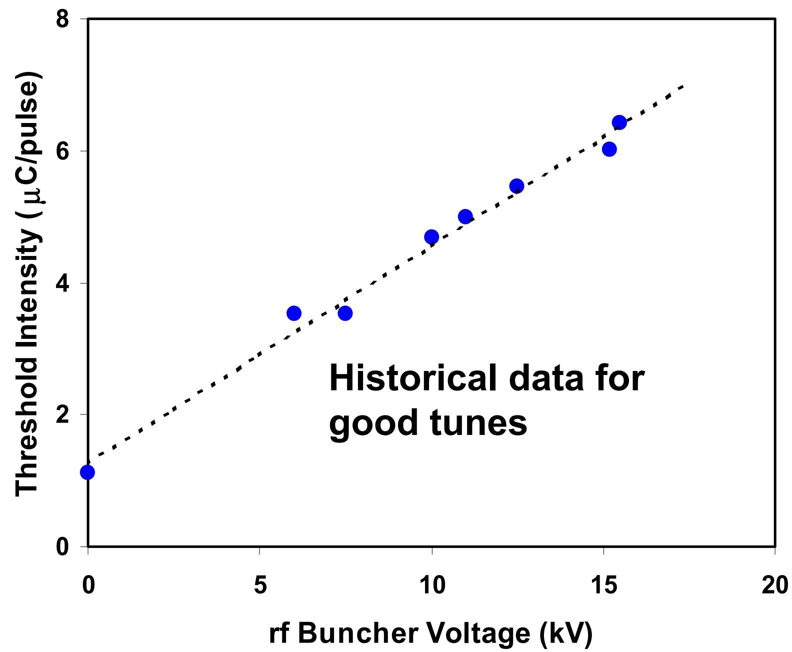


Instability Signals

BPM ΔV signal

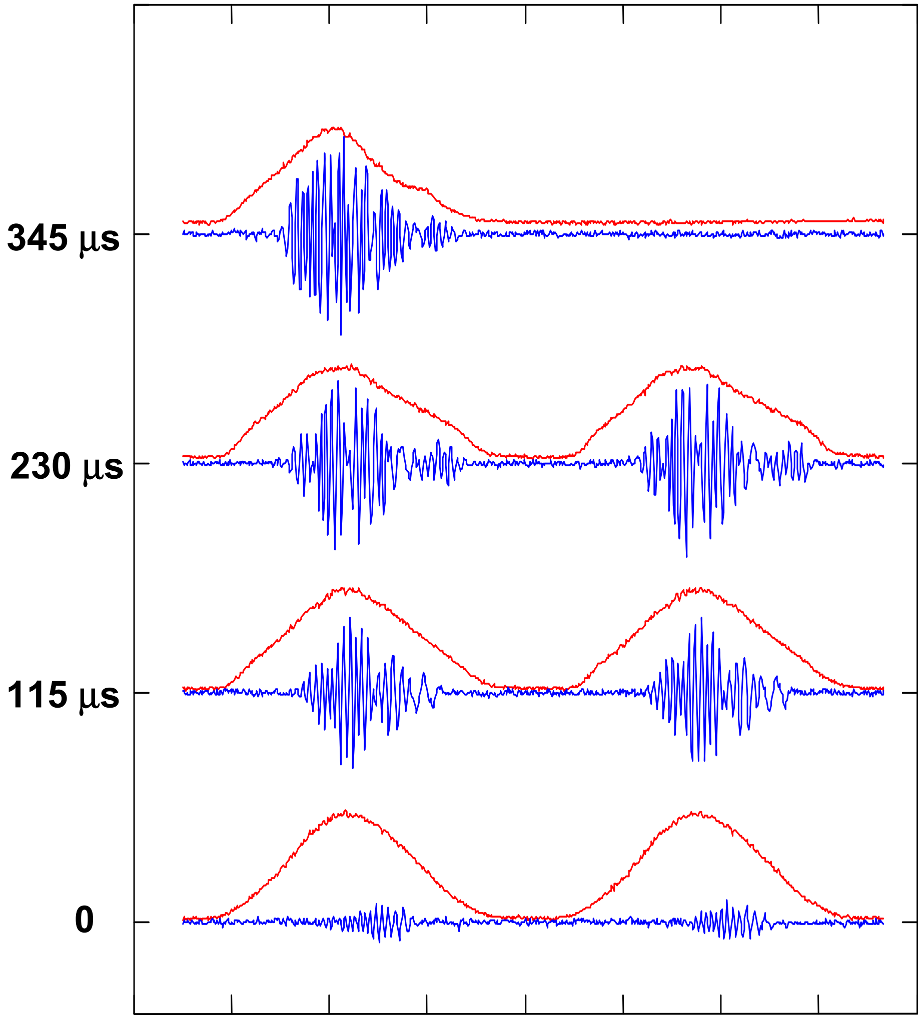
CM42 (4.2 μC) (Circulating Beam Current)

Control by rf buncher voltage



- **Growth time ~ 75 μs or ~200 turns**
- **High frequency ~ 70 – 200 MHz**
- **Controlled primarily by rf buncher voltage**
- **Requires electron neutralization of ~ 1% (from centroid model)**

Turn-by-turn vertical oscillations compared with beam profile during evolution of unstable motion



- **Vertical difference signals (blue) from a short stripline BPM and beam pulses from a wall current monitor (red).**
  - **WM41VD.4B**
  - **WC41.4B**
  - **Data taken Apr. 14, 1997**
  - **Data at t, t+115 μs, t+230 μs, t+345 μs**

Bk70, p16

Simplified centroid model is our working picture for e-p

- **Rigid, uniform coasting beam, centroid model of coupled e and p dipole oscillations with linear motion near threshold***

$$\frac{d^2 y_p}{dt^2} + (\omega_\beta^2 + \omega_p^2) y_p = \omega_p^2 \bar{y}_e, \qquad \frac{d^2 y_e}{dt^2} + \omega_e^2 y_e = \omega_e^2 \bar{y}_p$$

$$\omega_e^2 = \frac{2 N_p r_e c^2 (1 - f_e)}{\pi b (a + b) R}, \qquad \omega_p^2 = \left(\frac{f_e m_e}{\gamma m_p (1 - f_e)} \right) \omega_e^2, \quad Q_x = \frac{\omega_x}{\omega_0}$$

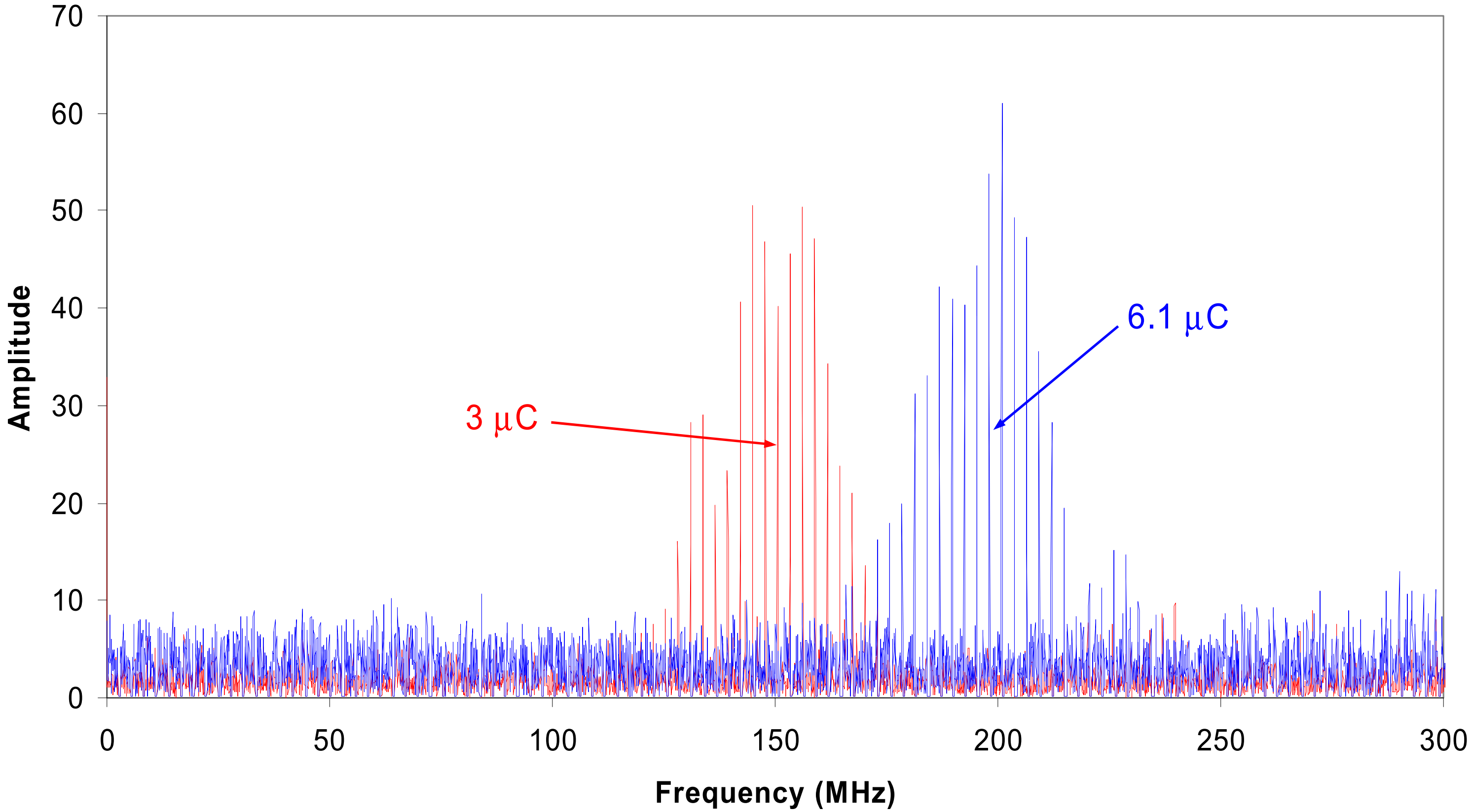
- **Some Features**
  - **Unstable modes (n-Q_β) close to Q_e (ratio of electron bounce frequency to ω_0)**
  - **Ratio of e/p amplitudes large for unstable motion**
  - **Threshold condition with Landau damping can explain threshold curves vs buncher voltage assuming ~ constant $f_e \approx 1\%$ and $\Delta Q_e / Q_e \approx 10\%$**

$$\frac{Q_p^2}{Q_\beta^2} \geq \frac{64}{9\pi^2} \cdot \frac{\Delta Q_\beta}{Q_\beta} \cdot \frac{\Delta Q_e}{Q_e}, \qquad \Delta Q_\beta = \left| (n - Q_\beta)\eta - \xi Q_\beta \right| \cdot \frac{\Delta p}{p} + \text{N.L.}$$

*Keil and Zotter 1971, also Neuffer, Wang, Channell, M Blaskiewicz in last decade

Frequency spectra of unstable motion agrees with model

$$\omega_e = Q_e \Omega_0 = 2\pi f = \sqrt{\frac{2 N r_e c^2 (1 - f_e)}{\pi b (a+b) R}}, \qquad f \approx 230 \text{ MHz } (6.1 \mu C)$$



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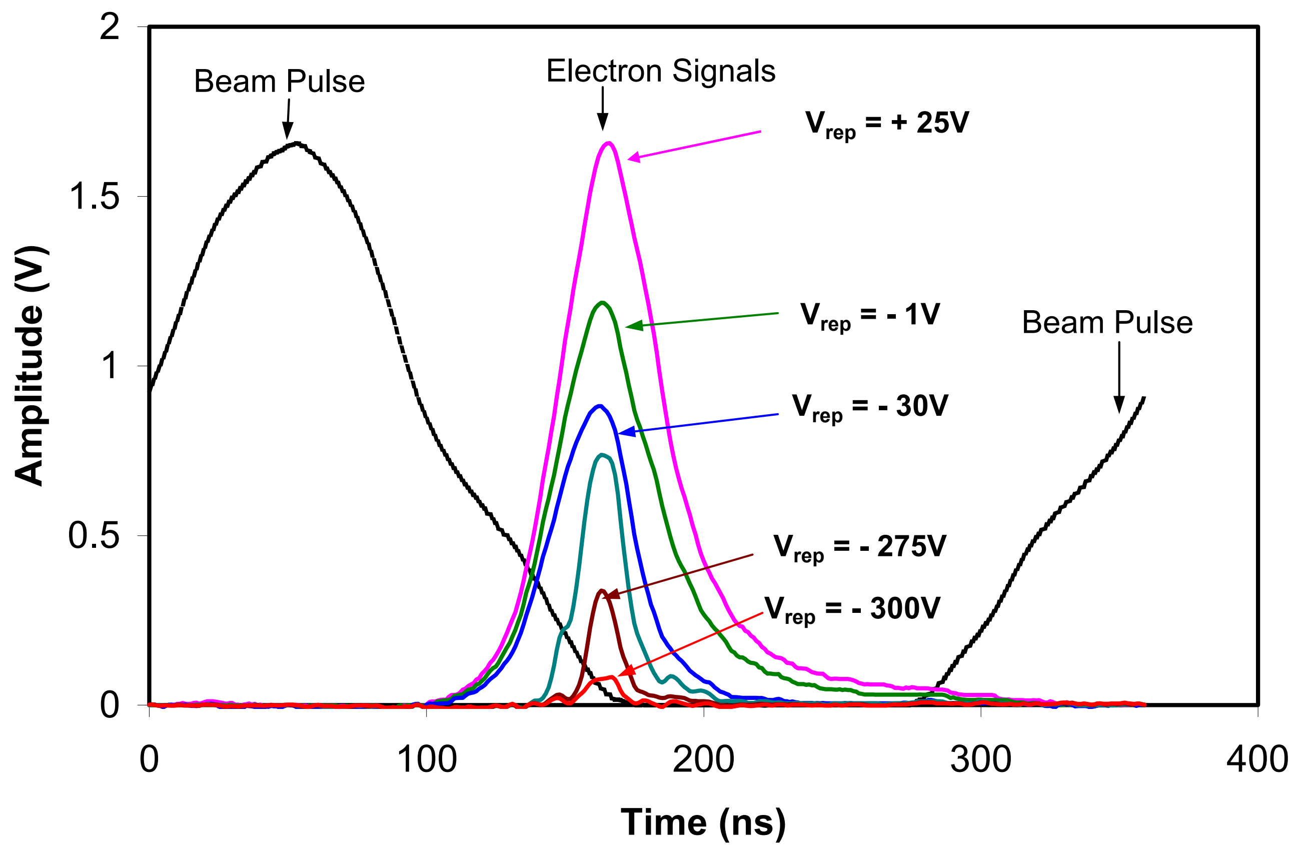
Electron Cloud Diagnostics

- Biased collection plates
  - Provided some evidence for large numbers of electrons just before beam went unstable
  - Slow because of filtering to suppress induced signals from the beam
  - Perturbs the beam wall environment
  - Only device we have for measuring electrons in magnets
- Retarding Field Analyzer (RFA) developed at ANL measures electron flux striking the wall with minimal perturbation of the beam wall environment and can provide energy spectra and time structure
- Electron sweeper developed at PSR to measure electrons remaining in the pipe

Electron signals from RFA in straight section 4



- **RFA signal has contributions from "trailing edge multipactor" and "captured electrons" released at end of beam pulse plus their secondaries**
- **Key issue is how many electrons survive the gap to be captured by the beam**

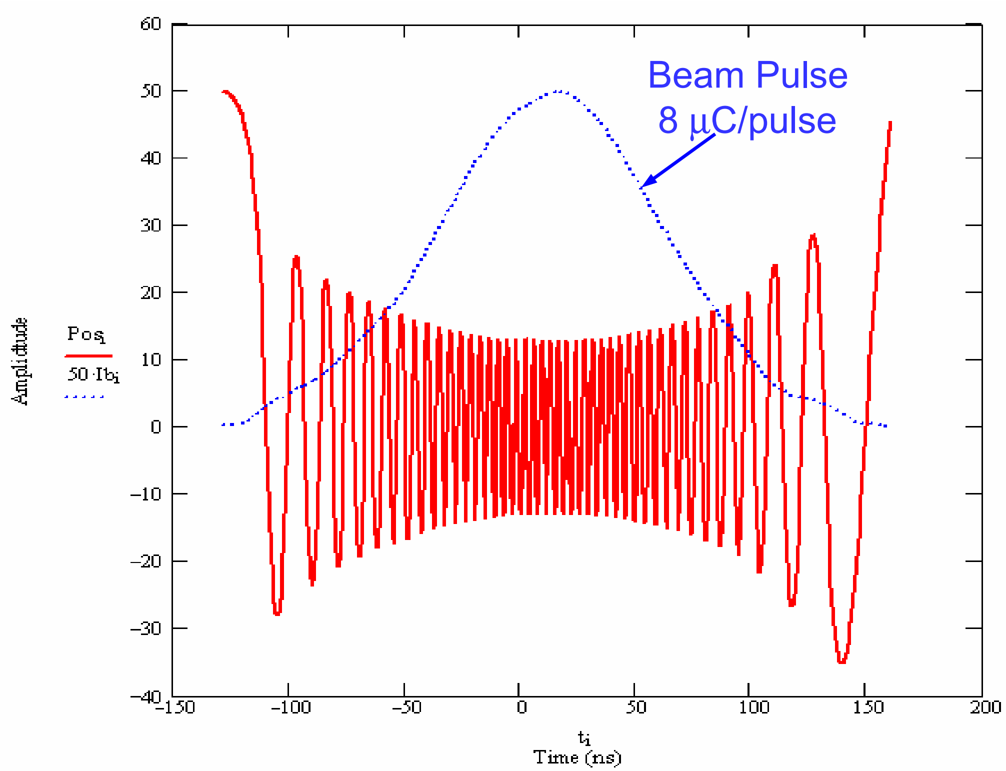
Signals averaged for 32 beam macropulses, ~ 8 μC/pulse beam intensity, device is labeled ED42Y, Transimpedance = 3.5 kΩ, opening ~1 cm^2

Bk95, p6-12

Motion of "captured" electrons

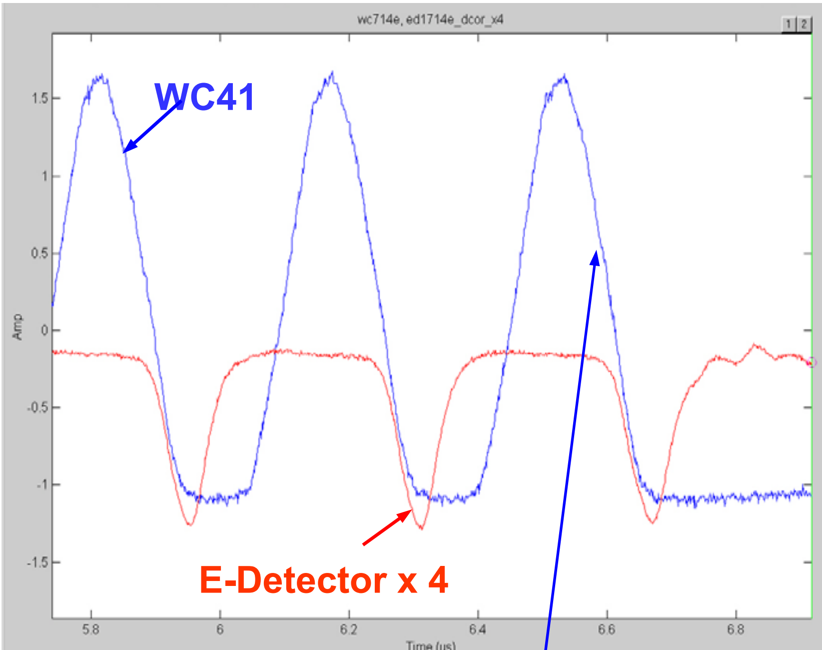
- Captured electrons are the ones that drive the e-p instability
  - Oscillate against the beam during the entire passage of the beam pulse (~40 oscillation periods)
  - Confined to the beam region for almost all of the beam pulse
- Released at the end of the beam pulse with energy that depends on initial conditions and pulse shape but can reach ~ 100 eV and produce secondary electrons

Electron radial position (mm) vs time (ns)



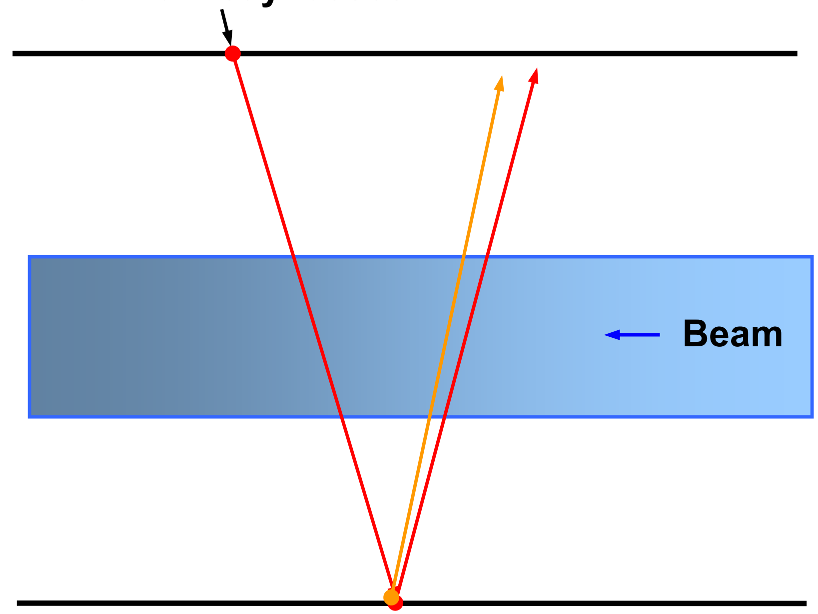
Electrons initially at zero velocity in the gap before arrival of the beam pulse

Mechanism #2: “trailing edge” multipactor



Energy gain is possible in wall-to-wall traversals on trailing part of beam pulse

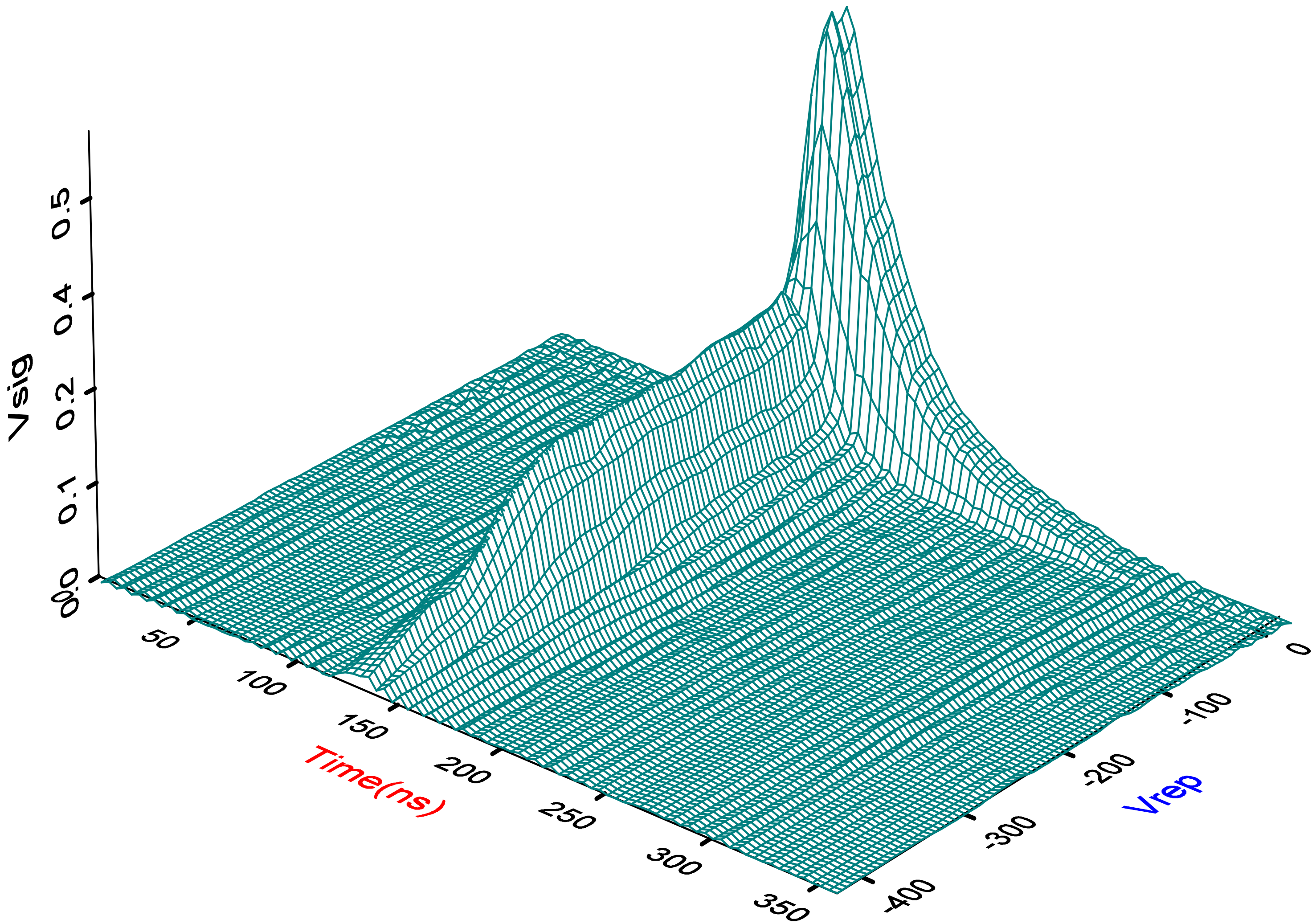
Electron born at wall from say losses



Energy gain in one traversal is high enough for multiplication

Bk87, p111

Electron energy cumulative spectrum (3D profile)



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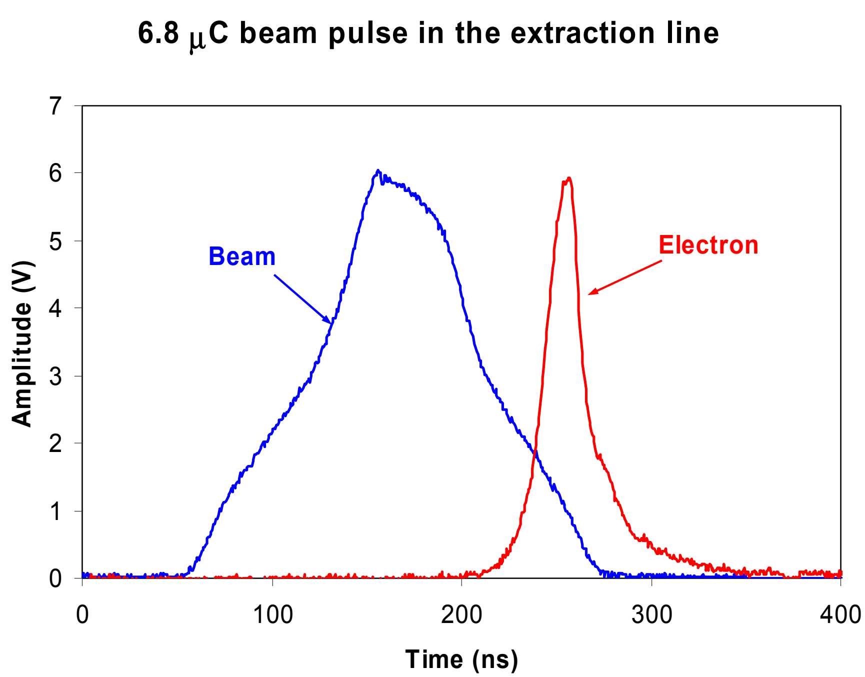
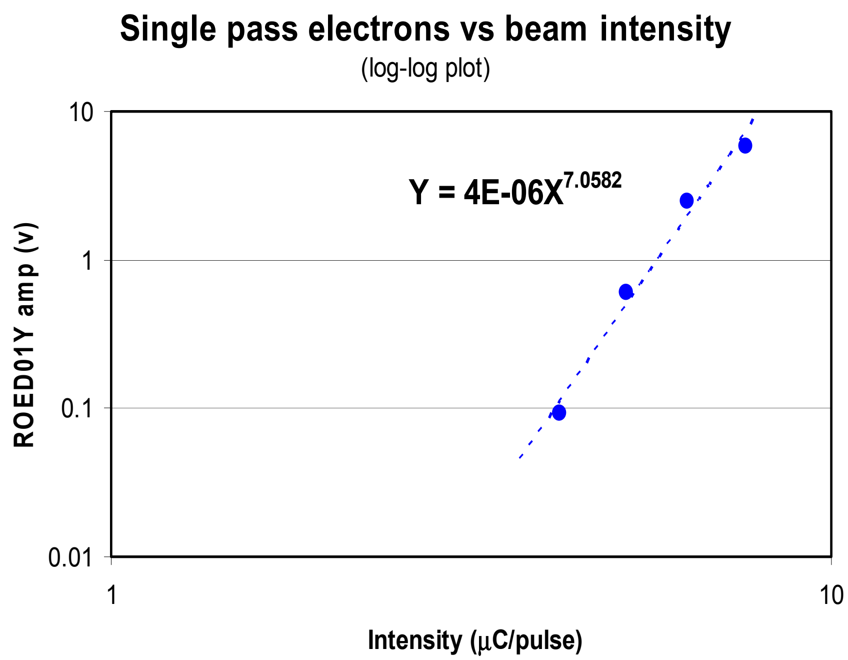
Electron signals in a single pass experiment





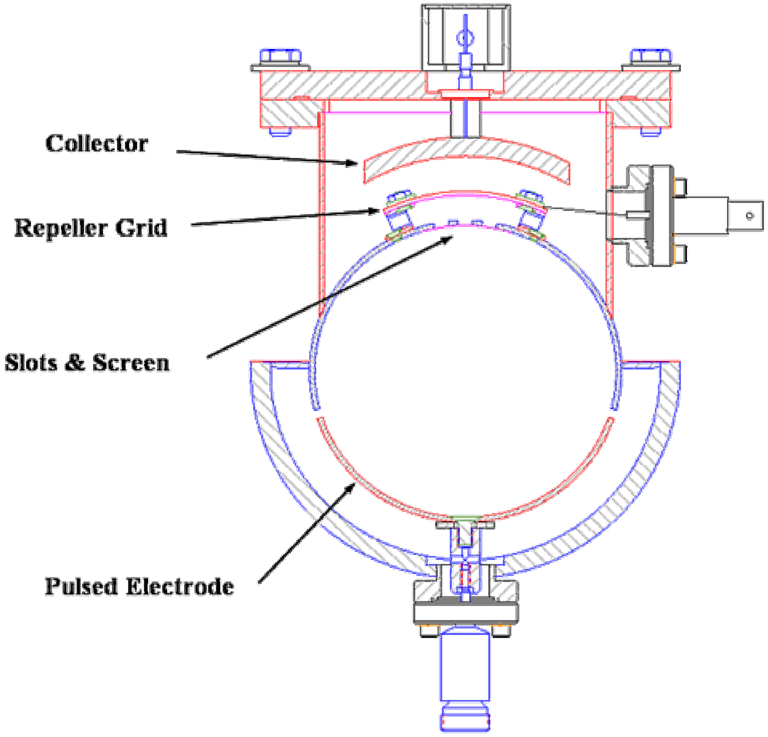
- Electron signal is very similar to signals in the ring wrt e-flux, time structure, energy spectra and dependence on beam intensity

Bk 96, p 16

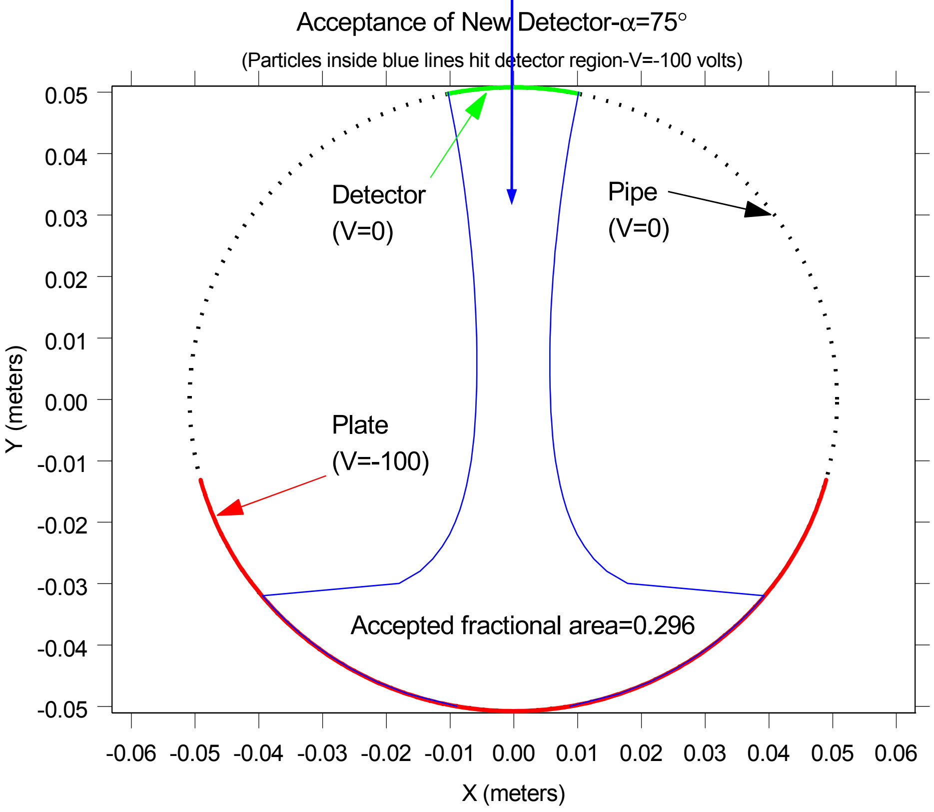
Electron Sweeping diagnostic

- Designed by A. Browman to measure e-cloud surviving passage of the gap
- Short HV (~1kV) pulse is applied to electrode to sweep electrons into RFA

Cross-section

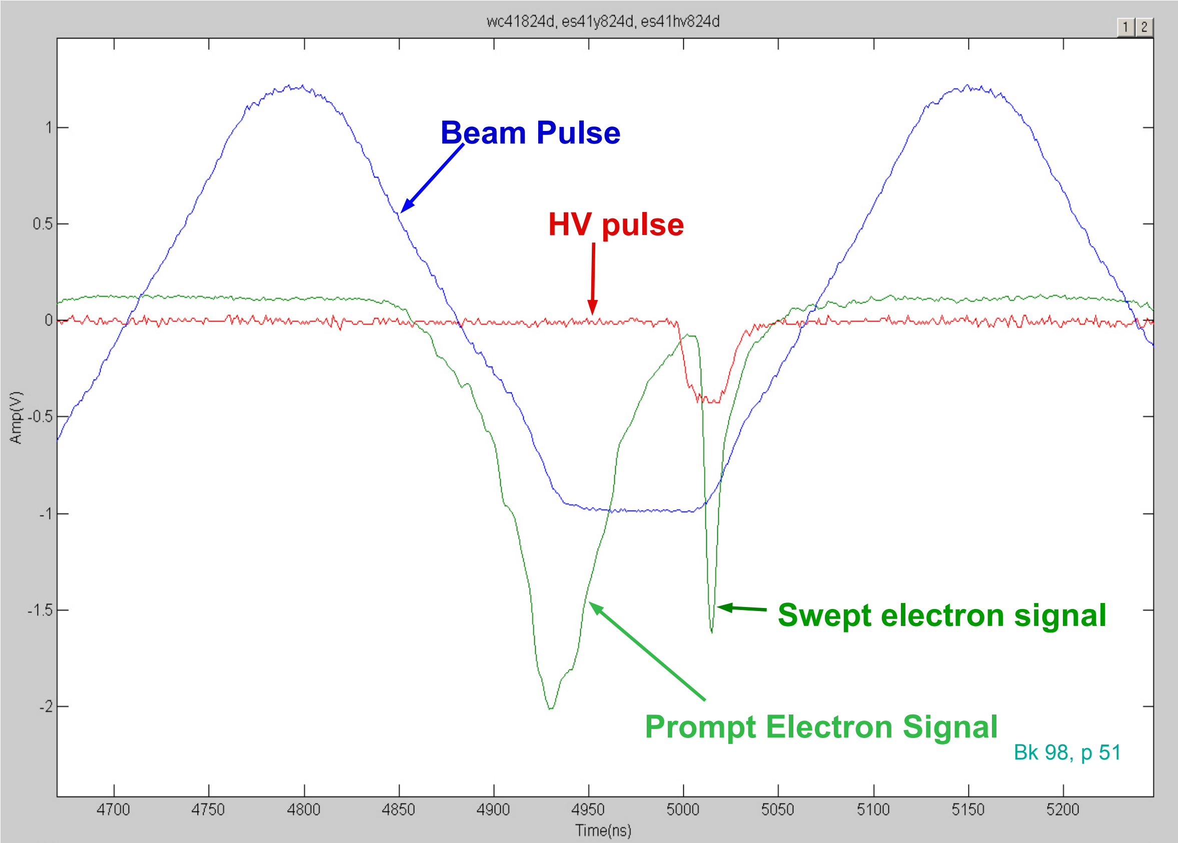


Collection Region



Sample Electron Data from Electron Sweeper

- Signals have been timed correctly to the beam pulse
- "Prompt" electrons strike the wall peak at the end of the beam pulse. Contributions from:
  - Trailing edge multipactor
  - Captured electrons released at end of beam pulse
- Device basically acts a large area RFA until HV pulse applied
- ~10 ns transit time delay between HV pulse and swept electron signal is expected
- "Swept" electron signal is narrow (~10 ns) with a tail that is not completely understood



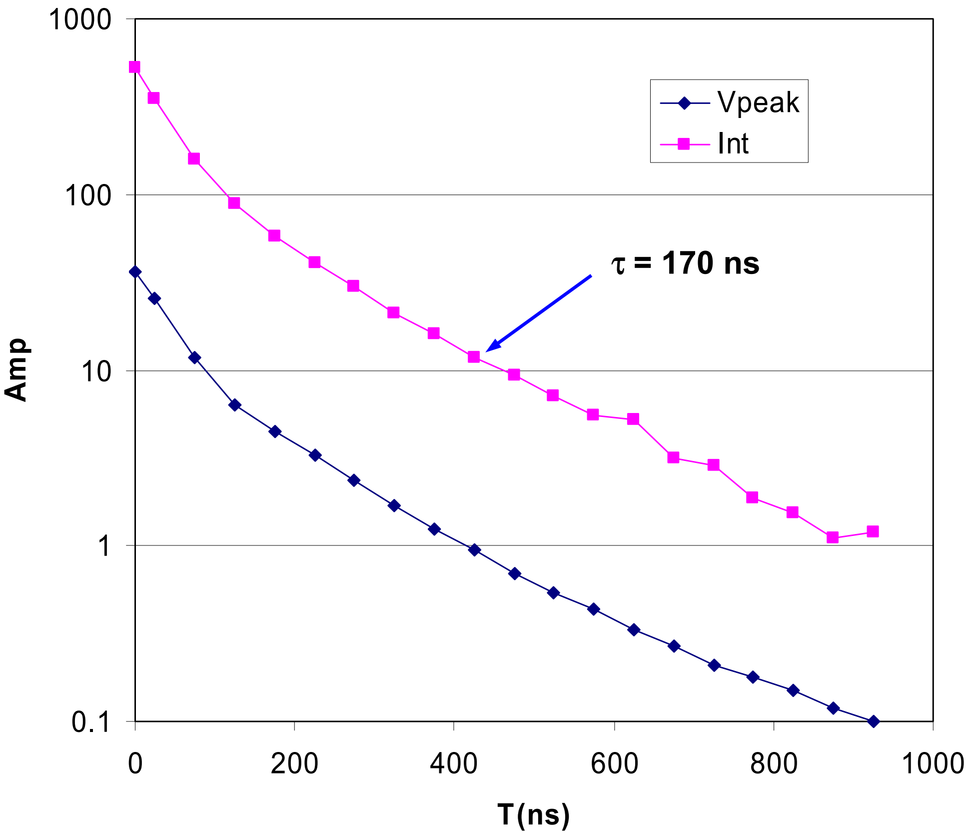
7.7 μC/pulse, bunch length = 280 ns, 30 ns injection notch, signals averaged for 32 macropulses, repeller = - 25V, HV pulse = 500V

Swept Electrons in pipe vs time after end of beam pulse

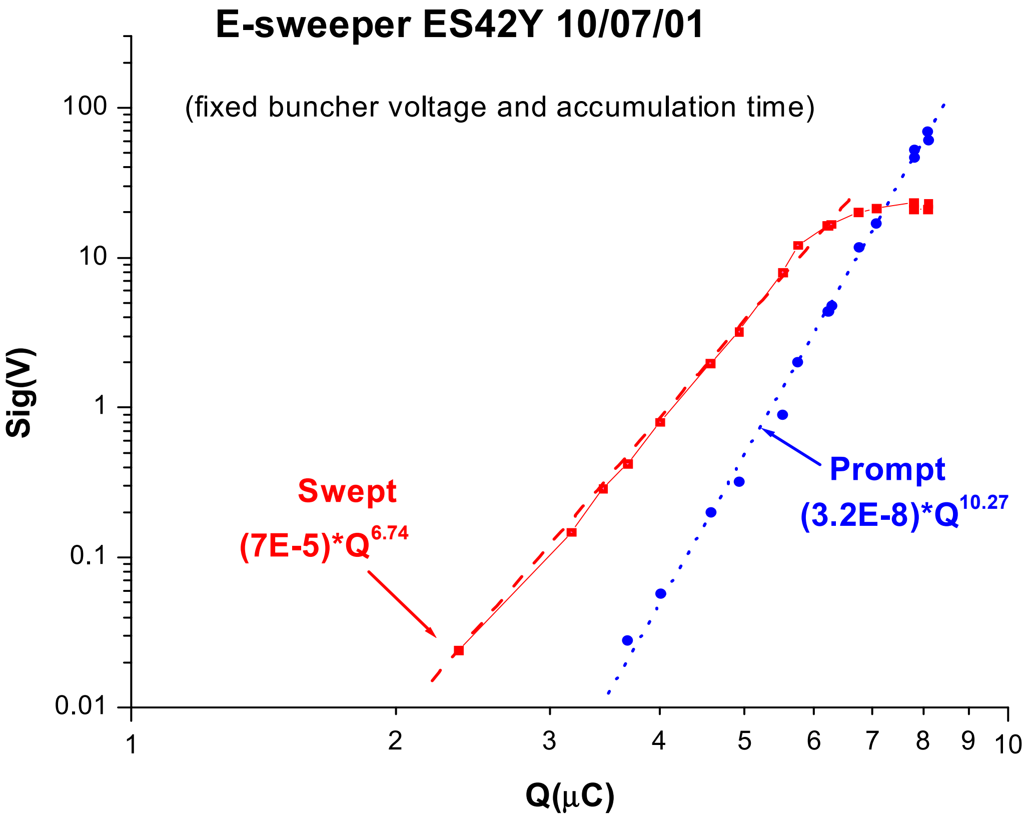
- **Early results from electron sweeper for 5μC/pulse looking just after extraction**
- **Peak signal or integral have essentially the same shape curve**
- **Long exponential tail seen with ~170 ns decay time**
- **Still see electrons after 1 μs**
- **Implies a high secondary yield (reflectivity) for low energy electrons (2-5 eV)**

$$\delta_{eff} = \exp\left[-\frac{\mathbf{d}}{\mathbf{c}\cdot\tau}\cdot\sqrt{\frac{\mathbf{m_e}\cdot\mathbf{c}^2}{2\mathbf{E}}}\right] \approx 0.5$$

- **Implies neutralization lower limit of ~1.5% based on swept electrons signal at the end of the ~100ns gap**



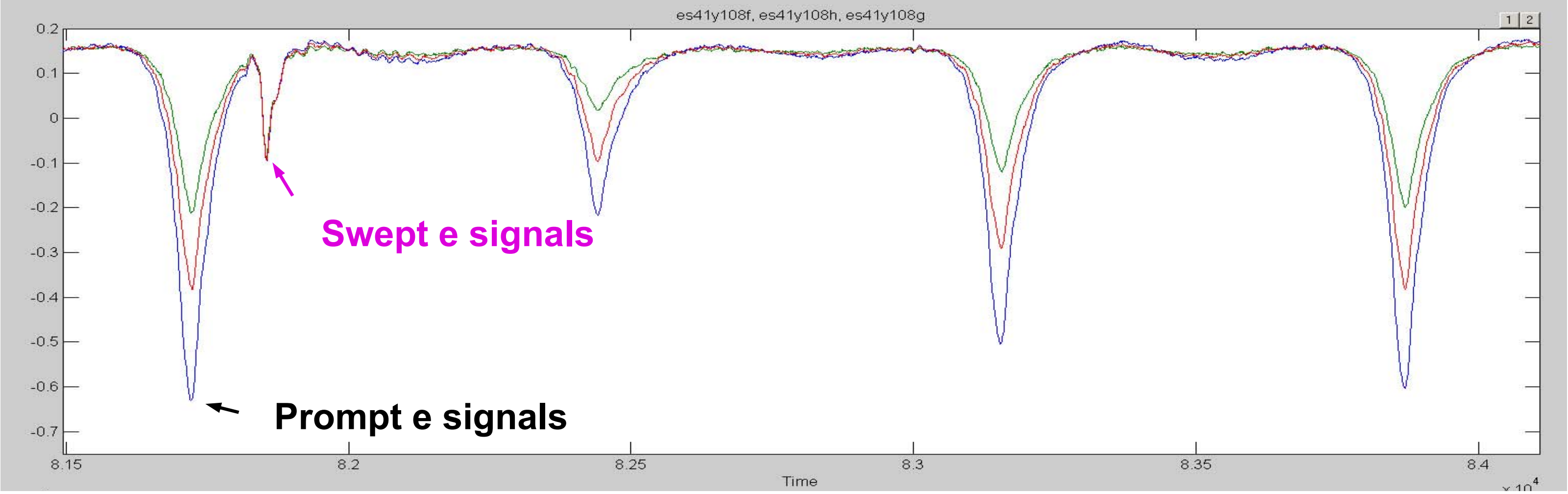
Prompt and Swept Electrons vs Beam Intensity



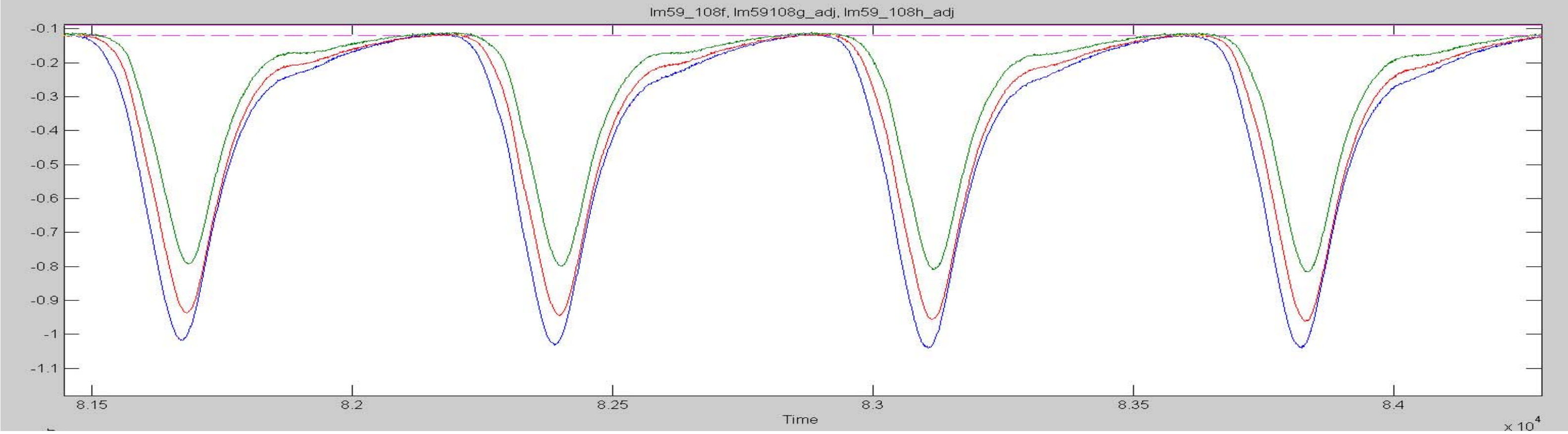
- The saturation of swept electrons above 5 µC/pulse is not restricted to variations of beam intensity but includes other variables that affect the prompt signal such as:
  - Variation in beam loss
  - Bursts
  - Changes in pulse shape
- Saturation explains several puzzles:
  - Why instability threshold is unchanged by increases in losses or vacuum pressure
  - Why the threshold intensity curves vs buncher voltage do not plateau at some intensity

"Saturated" Swept and Prompt e's vs local losses

Averaged (16 macro pulses) ES41Y signals for three different bumps and local losses



Loss Signals (LM59) for the three bumps (0, +2, +4 mm in section 4)



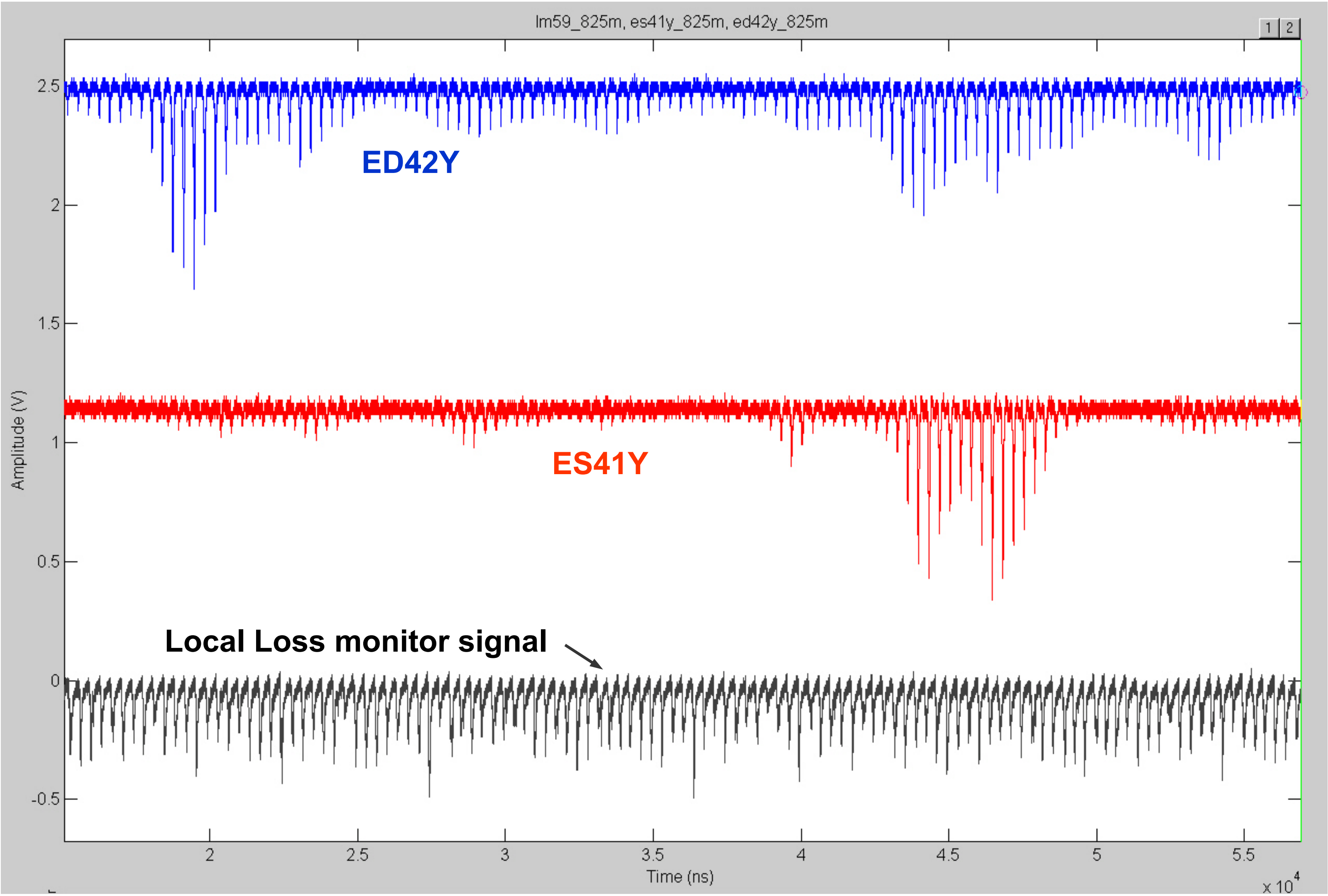
Present picture of electron cloud in PSR

- Electrons captured by the beam pulse from the “cold” electron cloud surviving the gap oscillate against the protons within the confines of the beam and drive the instability
  - Emerge at the end of the beam pulse with significant energy and contribute to the “prompt” signal
- Multipacting electrons from trailing edge multipactor strike the wall and produce much of the “prompt” signal observed in an RFA or e-sweeping detector
  - Wall to wall trajectories
  - Short dwell time, don’t drive the instability directly
  - These feed secondaries to the low energy cloud that lingers in the gap
- Low energy cloud (gap electrons) that lingers in the gap but dies away in time with an exponential tail
  - Created by secondary emission at the end of the pulse but not accelerated by the proton beam
  - Cloud expands from space charge but partially replenished by “scattering” back from the wall
  - Shows a definite saturation value depending on length of gap
  - Measured using the e-sweeping detector (“swept” e’s)

Electron cloud at other locations in the ring

- **Sections 4 and 9 are rather similar**
- **Section 0 near the stripper foil has the most e-flux but**
  - **intensity dependence of the prompt e's is much different**
    - varies as the 1.5 to 2nd power of intensity and not as $n \geq 7$
  - **bursts are greatly reduced at this location**
  - **Many more 'seed" electrons from the processes at the stripper foil**
- **Lots of e's seen in dipoles and quads using biased collection plates but lacking the details obtained from RFA or e-sweeper**
- **Highest pressure rise associated with inductive inserts of section 5**
- **Seems reasonable to assume that line density of e's surviving the gap in section 4 represent a lower limit on the average density around the ring**

“Electron burst” phenomenon (110 turns)



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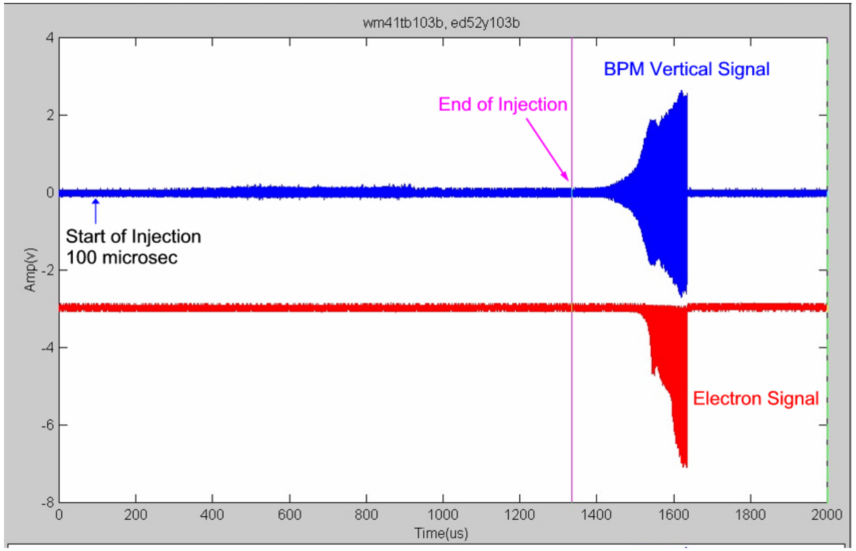
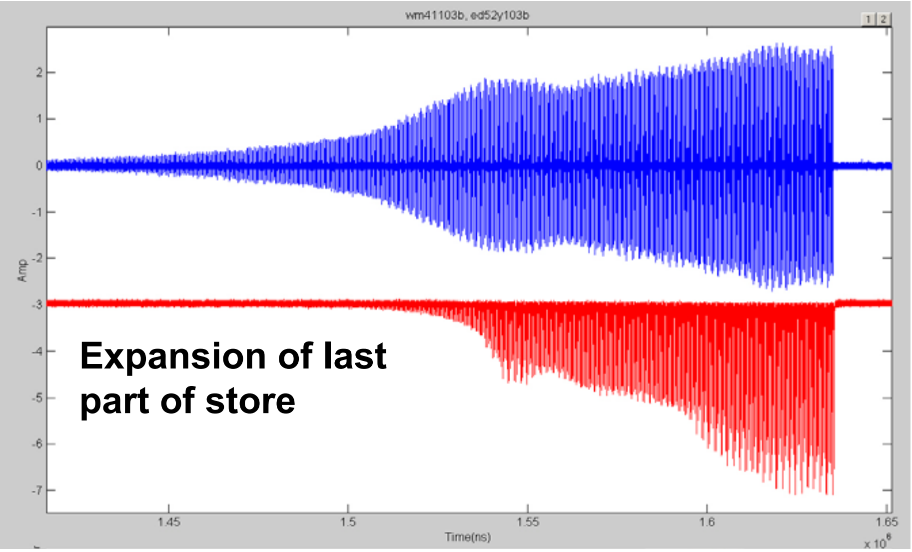
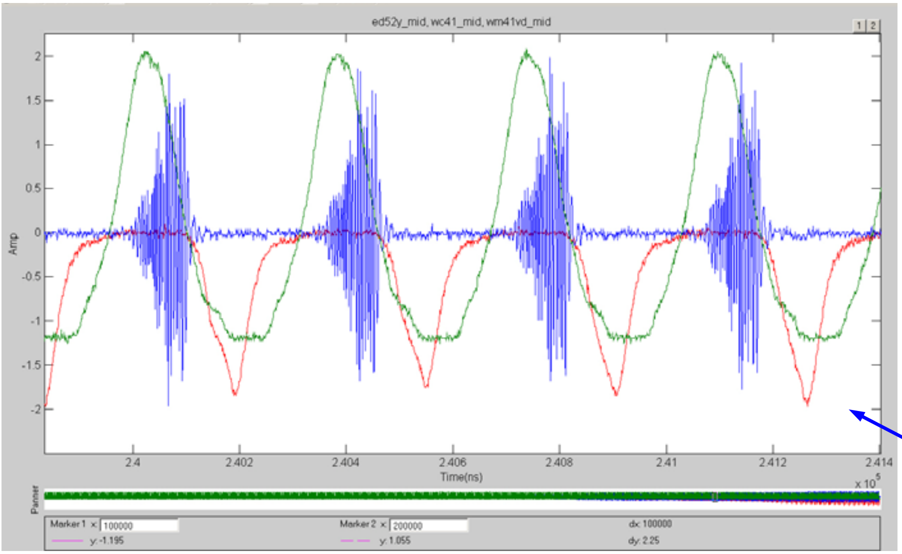
Prompt electron signals for unstable beam







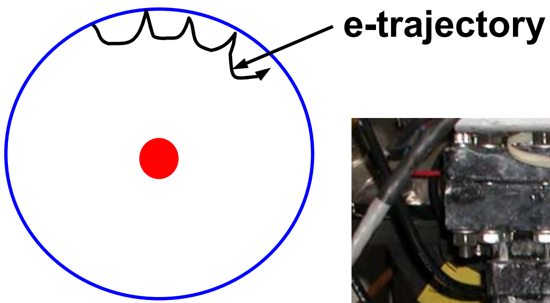
- Data (1999) for 4.4 μC store, higher intensity saturated RFA electronics
- E-signal much larger (>10) than for stable beam of same intensity
- Electron pulse shape (at end of each turn) is similar to stable pulses

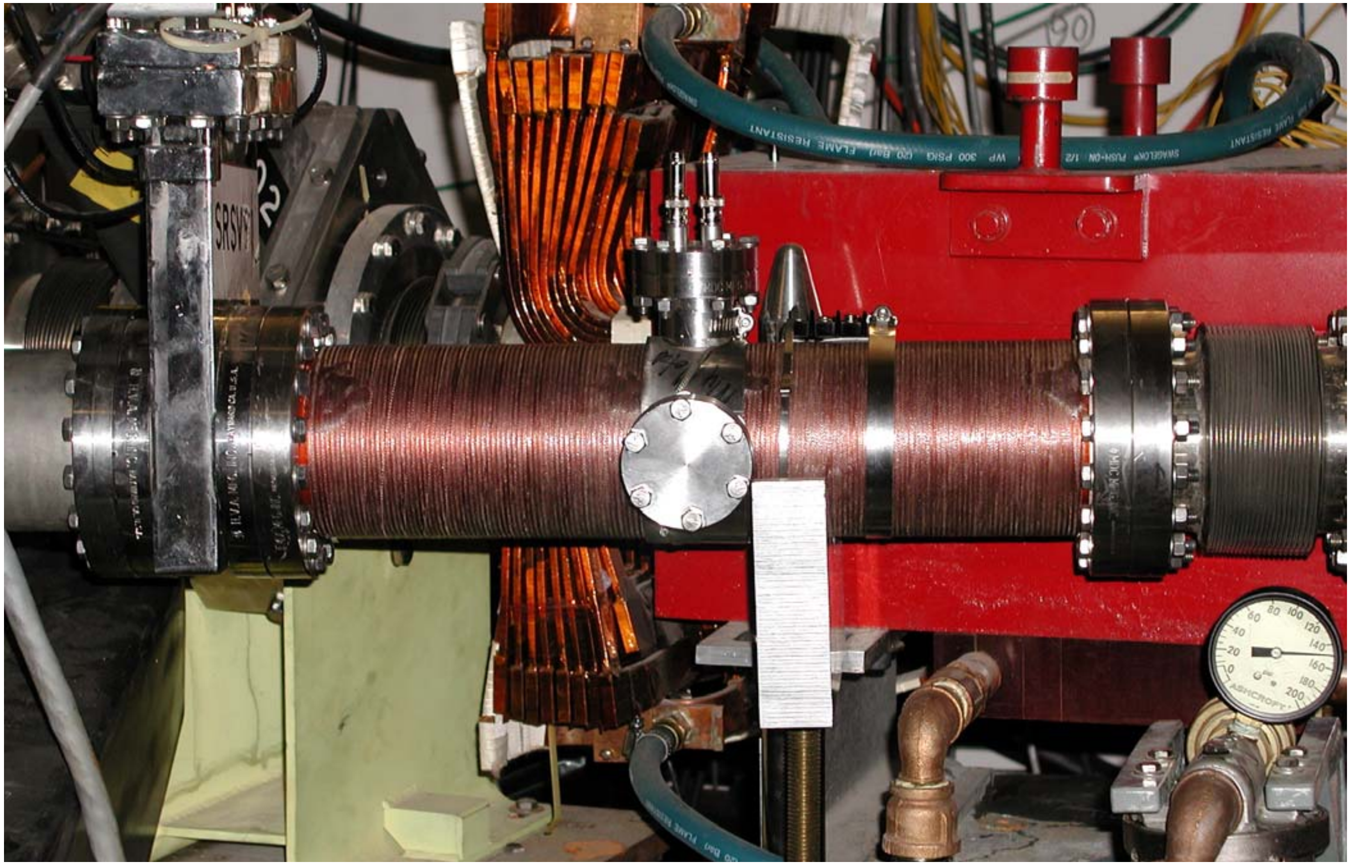
Beam pulse, BPM and e-signal turn by turn

Methods of suppressing electron generation

- **TiN coatings suppressed "prompt" electrons by a factor of 100 or more in tests in section 4 of PSR**
- **Weak solenoid magnetic field suppressed prompt electrons by factor of ~ 50 in a 0.5 m section in PSR**
- **Lower beam losses and better vacuum ?**
- **Beam conditioning over time reduced prompt electron signals and improved the instability threshold curves**
  - **Do the swept electrons change with conditioning?**

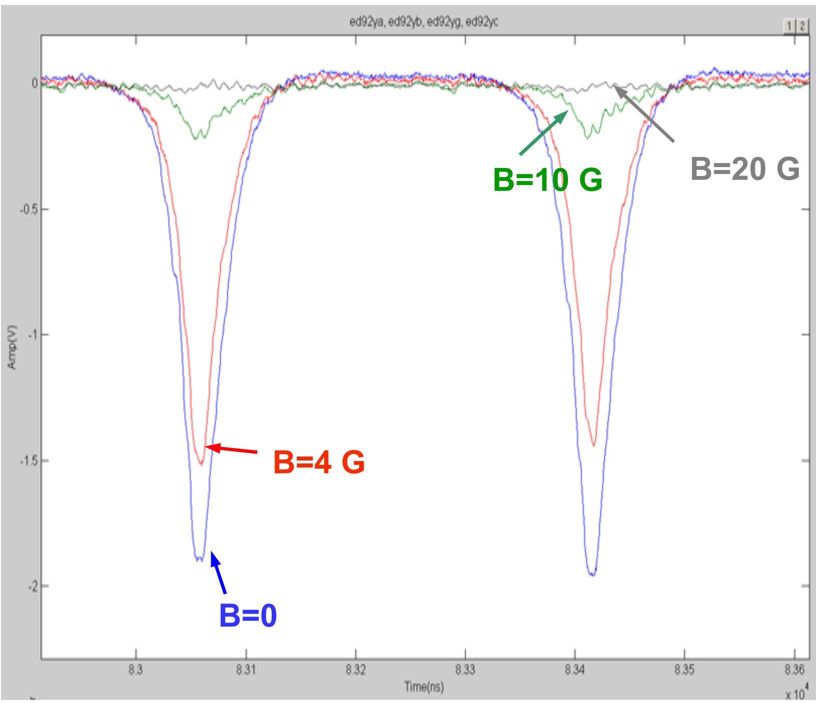
Picture of Solenoid Section with RFA

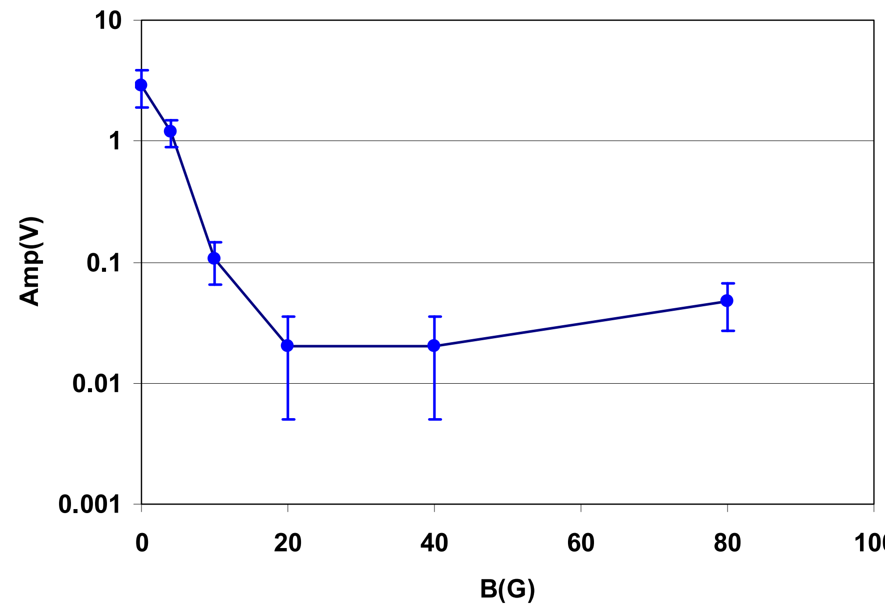




Suppression of prompt e's in a weak solenoid field

RFA signals in a weak solenoid fields





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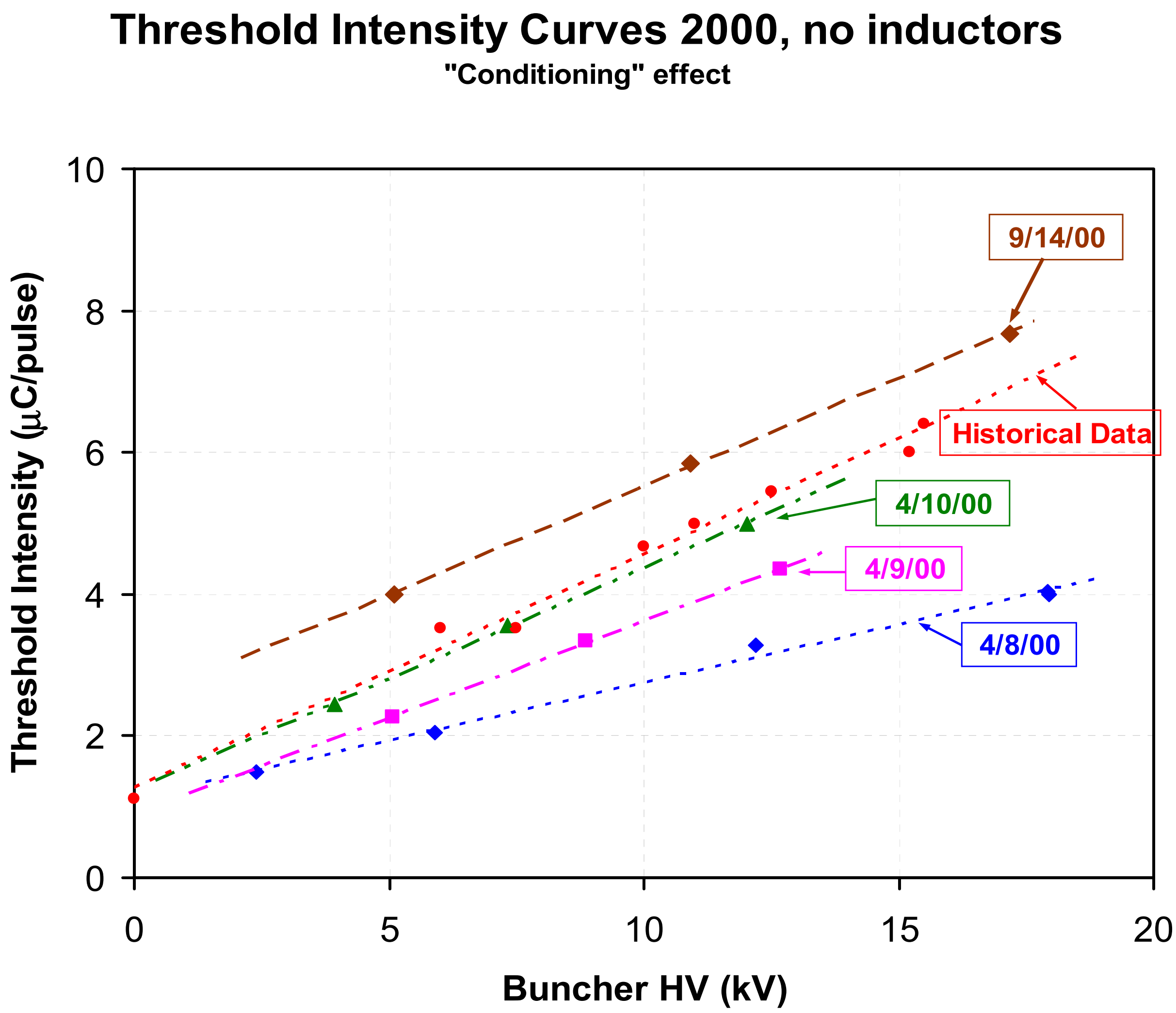
Conditioning effect

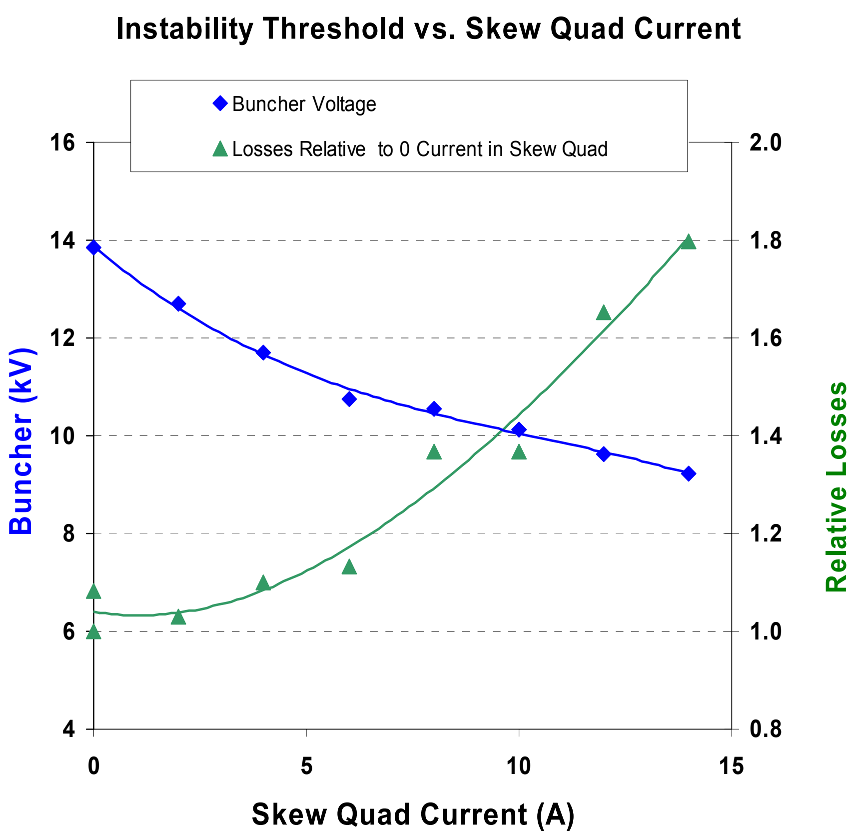


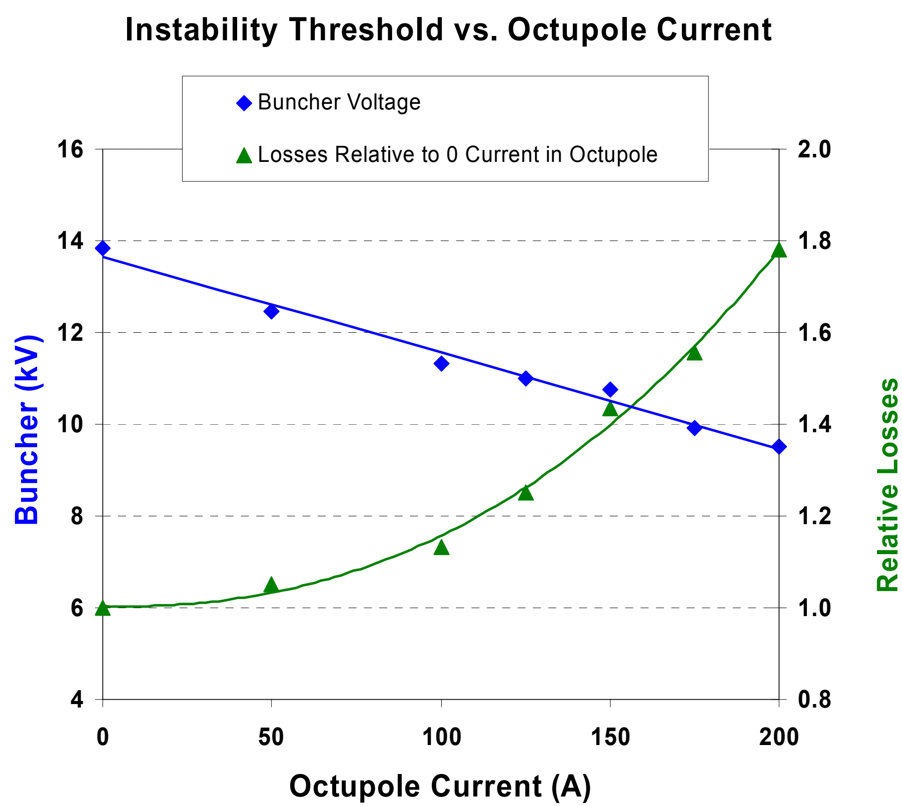
Demonstrations of various “controls” for the instability

- **Conditioning effect**
- **Traditional Landau damping from multipoles**
- **Coupled Landau damping via a skew quad**
  - X,Y coupling permits sharing of the stabilizing tune spread and growth rates in both planes thereby providing extra damping
- **Inductive inserts**
  - Equivalent to more rf with suitable harmonics which passively compensate longitudinal space charge voltage
  - Helps prevent leakage of beam into gap
  - Increased bucket height i.e., increased momentum spread for more Landau damping

Effects of skew quad and octupole on instability and losses

Results for 5 μC/pulse peak beam intensity





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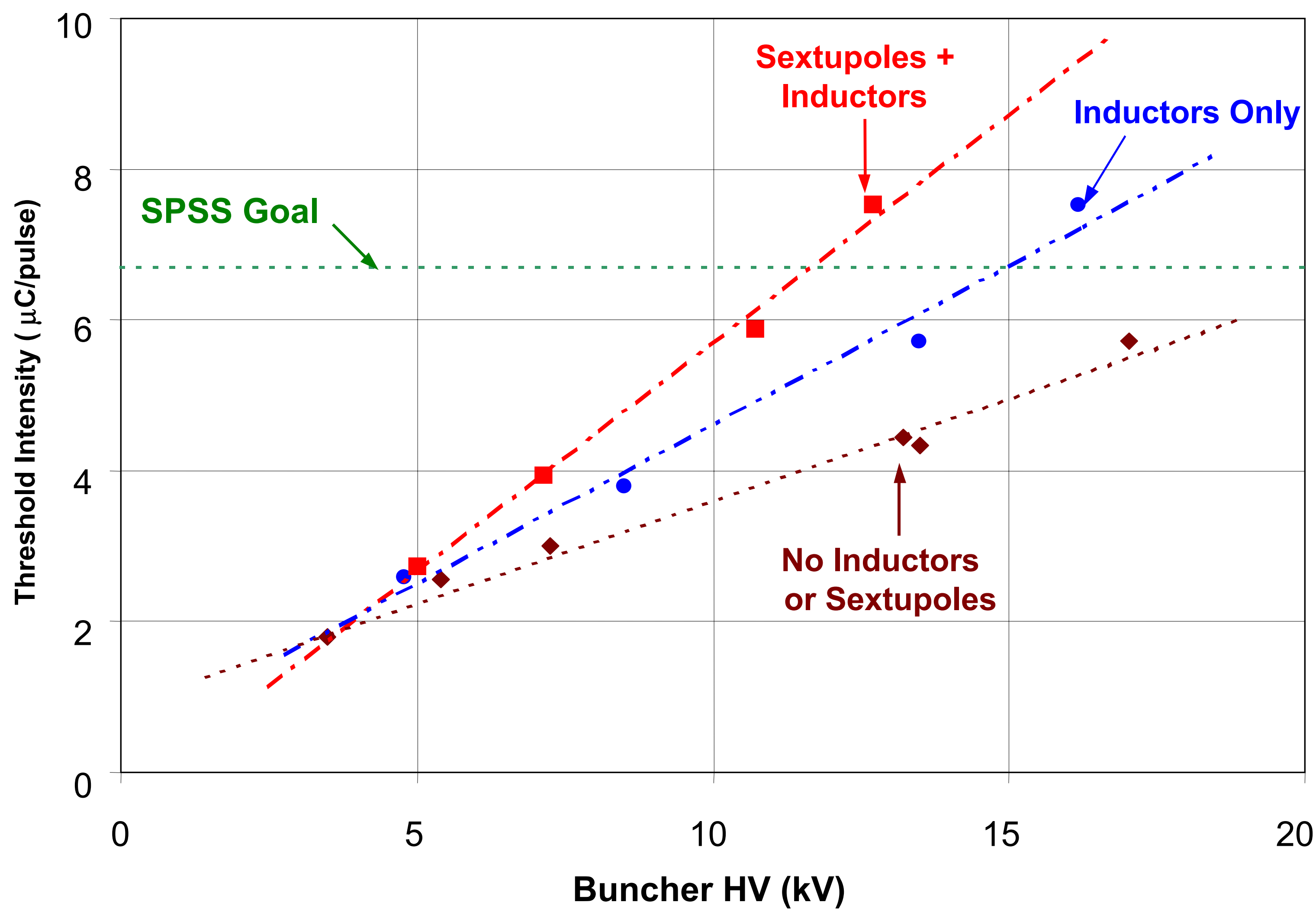
Effect of Inductors & Sextupoles on Instability Threshold Curves



Summary and Main Conclusions

- Good progress on understanding and characterizing the electron cloud
  - Electron multiplication by trailing edge multipactor and captured electrons creates a copious source of prompt electrons
  - Sufficient numbers survive the gap to account for the instability thresholds
- TiN coatings offer the prospect of a cure with no increase in losses but not yet shown that it suppresses the e's surviving the gap.
  - Tests planned this summer using TiN coated electron sweeper
- Landau damping by increased rf voltage, (X,Y) coupling, multipoles and inductive inserts significantly raises the instability threshold but with some increase in beam losses
- Open issues:
  - How is the electron cloud generation modified in dipoles and quadrupoles?
  - What causes the electron burst behavior?
  - Will TiN coatings of all vacuum surfaces cure the instability?
  - Can active damping be effective in controlling this instability?
  - Why is the e-p instability not seen at ISIS?