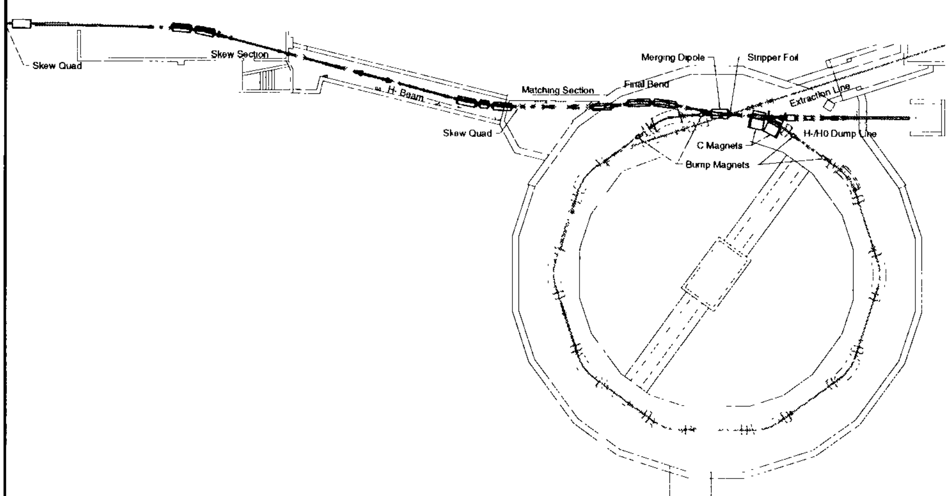
Status of the PSR e-p Instability

(R. Macek, BNL, 6/28/99)

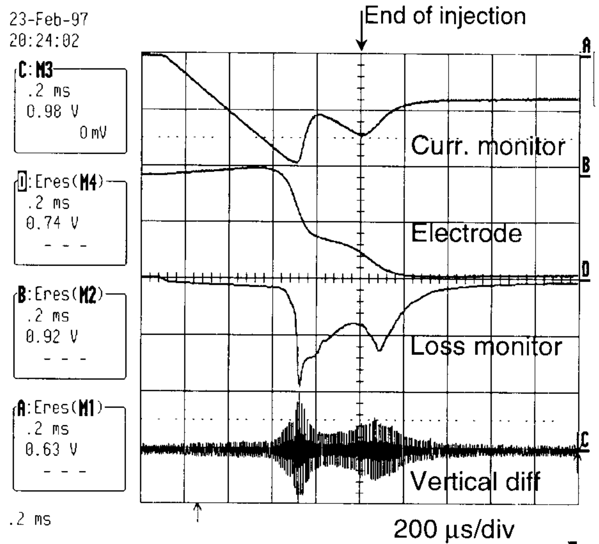
Outline

- Introduction
- Main Characteristics of the Instability
- Present Picture/Model of the e-p Instability at PSR
- Issues and Experimental Tests Motivated by the Model
  - Manifestations of Landau damping
  - Evaluation of electron sources
  - Electron trapping during passage of the gap
- Methods of Control
- Plans for Future Work
- Conclusions

PSR After Upgrade (1999)



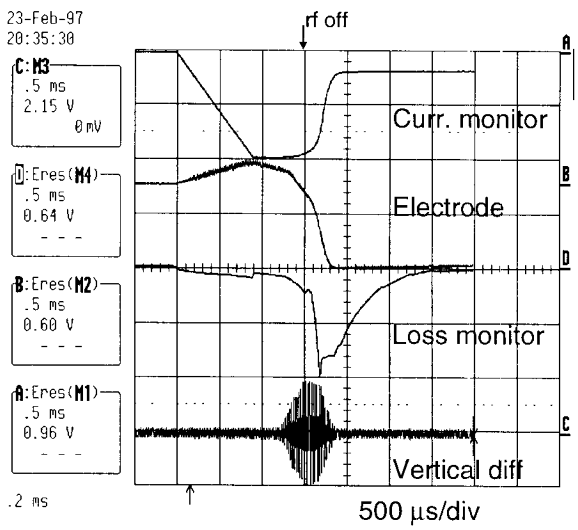
Coasting beam instability signals



3.0 µC injected
(2.0 µC before instab.)
925 µs injection
250 ns PW
rf off

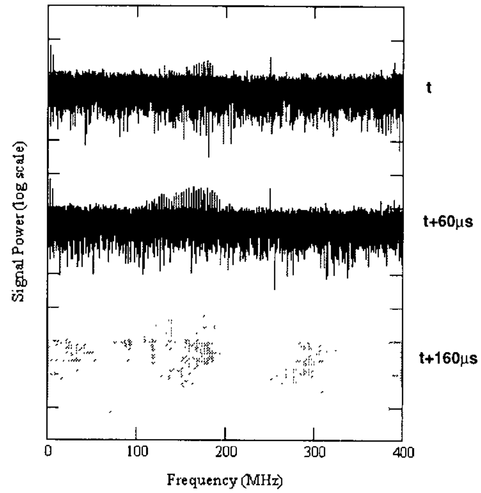
Bunched beam instability signals

(during beam studies)



3.0 µC
925 µs injection
250 ns PW
6 kV rf
-1900 V opp. elec.

Frequency Spectra vs. time

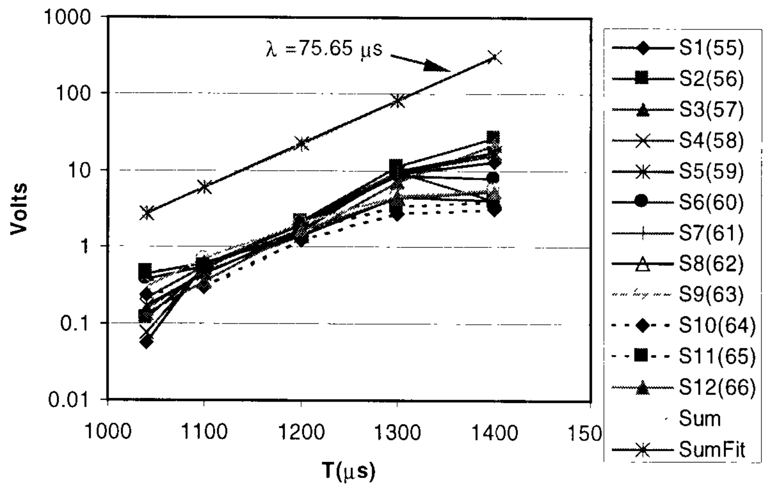


- Signal power at t, t + 60 µs, and t + 160 µs from wide band stripline beam position monitor.
- Power begins at about 175 MHz, then spreads in width and amplitude.

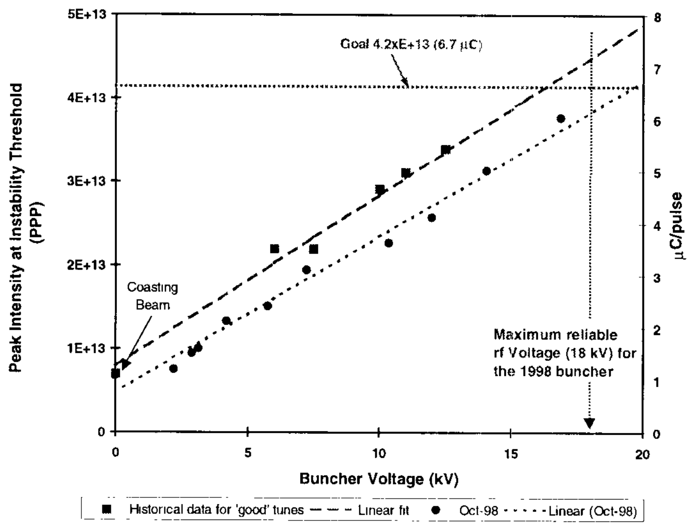
$$f = \frac{1}{2\pi}\sqrt{\frac{2Nr_ec^2(1-\eta_e)}{\pi b(a+b)R}}$$

Data from SRWM41 ΔV, 4/7/97. WM41VD.ON2

Growth Rates of n-ν Lines for Beam at the Threshold of Instability



Updated Instability Threshold Curve



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Present picture: e-p instability as described/modeled by Neuffer *

- Uniform coasting beam model of coupled e and p oscillations and
- Trapping of e's from beam in the gap ala Schonauer**
- Some useful formulas/features of model
  - Bounce frequencies

$$Q_e\Omega = \sqrt{\frac{2Nr_ec^2(1-\eta_e)}{\pi b(a+b)R}}, \quad Q_p\Omega = \sqrt{\frac{2\eta_e Nr_pc^2}{\pi b(a+b)\gamma R}}$$

  - Coupled equations of motion

$$\left(\frac{\partial}{\partial t}+\Omega\frac{\partial}{\partial \theta}\right)^2 y_p + \left(Q^2+Q_p^2\right)\Omega^2 = Q_p^2\Omega^2\bar{y}_e$$

$$\frac{\partial^2 y_e}{\partial^2 t} + Q_e^2\Omega^2 y_e = Q_e^2\Omega^2\bar{y}_p$$

  - Dispersion relation for single frequency

$$\left[Q_e^2 - x^2\right]\cdot\left[Q^2+Q_p^2-(n-x)^2\right] = Q_e^2Q_p^2$$

*Neuffer etal,"Observations of a fast transverse instability in the PSR", NIM A321(1992) 1-12
**Schonauer "Neutralization of Bunched Proton Beams", PAC 1973, NS-20 (1973) 866

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Present picture of e-p (cont'd)

- Unstable modes (n-Q) close to Q_e
- Threshold condition (for unstable beam) from dispersion relation (for case when frequency spreads overlap)

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

$$\frac{\Delta p}{p} = \pm \frac{1}{\beta_0} \sqrt{\frac{eV}{\pi \eta_0 \gamma_0 m_p c^2}} \sqrt{1 - \cos(BW/2)}$$

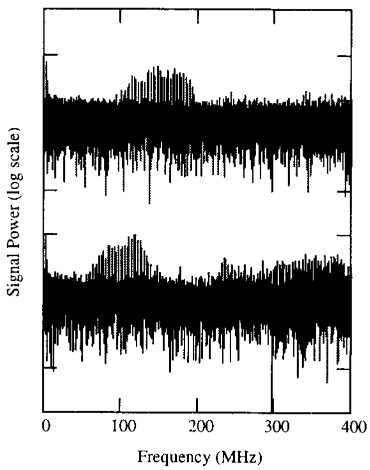
- Growth rate

$$\tau^{-1} = \frac{\Omega Q_p}{2} \cdot \sqrt{\frac{Q_e}{n - Q_e}}$$

Additional Evidence and Tests of the Model

- Mode spectrum (BPM signal frequency spectrum) varies with beam intensity as expected from the model
- Instability threshold increases with increasing beam size
- Various methods of increasing betatron tune spread produce Landau damping
- Data on various electron sources and attempts at suppression of electron production
- Data on the possibility of electron trapping by "beam in the gap"

Peak frequency vs. intensity



- The peak in the signal spectrum depends on the beam intensity.
- Top spectrum is twice the intensity of the bottom spectrum
- Beam conditions for the top and bottom spectra are the same except for the beam intensity and the buncher voltage.

$$f = \frac{1}{2\pi}\sqrt{\frac{2Nr_e c^2(1-\eta_e)}{\pi b(a+b)R}}$$

SRWM41 ΔV from 13/Apr/97 data
WM41VD.4C SRWM41VD.4F

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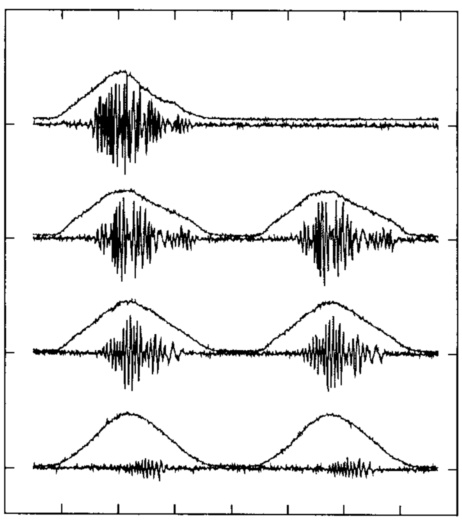
Vertical oscillations and beam profile



- WM41VD.4B
- WC41.4B
- Data taken Apr. 14, 1997
- Data at t, t+115 μs, t+230 μs, t+345 μs

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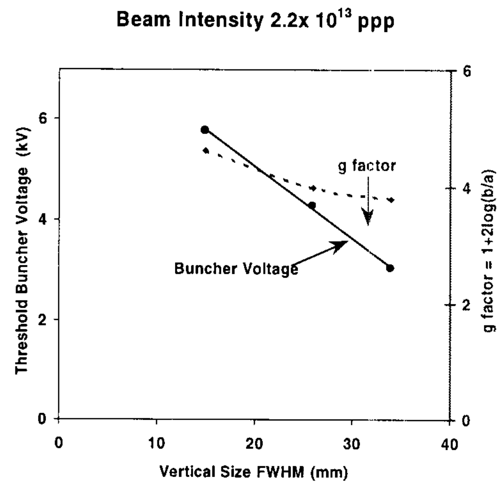
Effect of Vertical Beam Size (Emittance)



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Influence of Tune Spread (Landau Damping)

- Buncher voltage - large effect
- $\Delta P/P$ sweeping in linac - large effect on coasting beam threshold
  - 0.6×10^{13} ppp for $\Delta p/p \simeq 0.002$ to 1.8×10^{13} ppp for $\Delta p/p \simeq 0.008$
- Sextupoles - larger effect (at highest intensity) in recent tests
  - 42% increase in threshold for +20A (vertical chromaticity = -3.2)
  - 35% increase in threshold for -20A (vertical chromaticity = -0.2)
- Octupoles - last tried in late 1980's
  - Bunched beam - additional 13% lower buncher voltage (sextupoles on)
  - Coasting beam - 2.5 x higher threshold (sextupoles off)
- Increase of vertical tune from 2.14 to 3.16 raised "threshold" significantly i.e., lowered needed buncher voltage by 40%
- η (phase slip factor) variation from - 0.19 to -0.065 by changing γ_{TR} lowered threshold 45%.

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“Explanation” of the linear threshold vs rf voltage curves

- Threshold condition when frequency spreads overlap (Landau damping applicable)

$$\frac{Q_p^2}{Q^2} = \frac{1}{\Omega^2 Q^2}\frac{2\eta_e N r_p c^2}{\pi b(a+b)\gamma R} \geq \frac{64}{9\pi^2}\cdot\frac{\Delta Q}{Q}\cdot\frac{\Delta Q_e}{Q_e}$$

- R.H.S and L.H.S. for $\Delta Q_e/Q_e$ constant

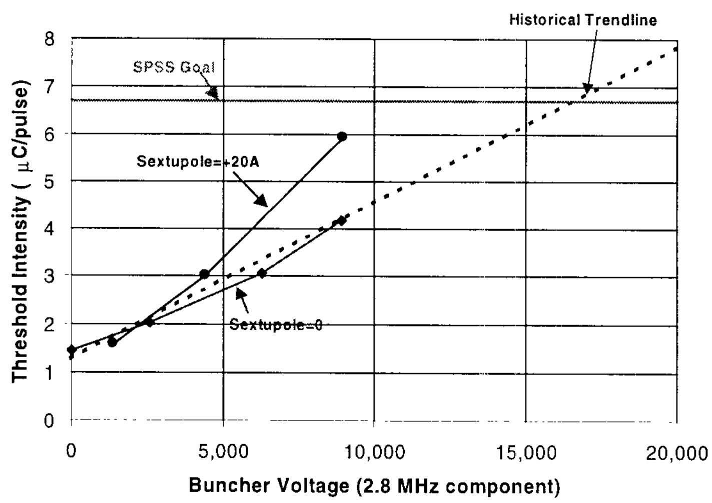
$$\frac{Q_p^2}{Q^2} \propto N \qquad \Delta Q = \left|(n-Q)\eta - \xi Q\right|\cdot\frac{\Delta p}{p} + N.L. \;\propto \left|Q_e \eta\right|\sqrt{V} \propto \sqrt{N}\sqrt{V}$$

$$\frac{\Delta p}{p} = \pm\frac{1}{\beta_0}\sqrt{\frac{eV}{\pi\eta_0\gamma_0 m_p c^2}}\sqrt{1-\cos(BW/2)}$$

- Finally, the threshold condition becomes

$$N \geq \text{const}\sqrt{N}\sqrt{V} \quad \text{or} \quad N \geq \propto V$$

Effect of Sextupole on Threshold Intensity



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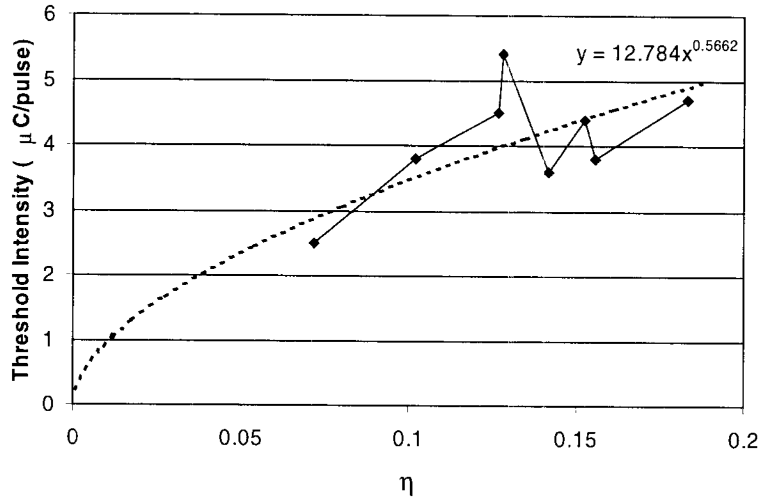
Effect of varying η (phase slip factor)



Sources of e's at PSR

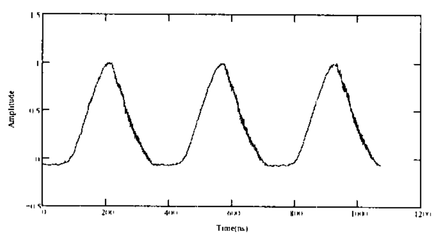
Source	H^0 inj (≤1997) e's/proton	H^- inj (1998) e's/proton
• 400 keV "convoy" electrons from H^0 stripping	1	2
• Secondaries from convoy e's	0.1 - 1	0.2 - 2
• Secondary emission from foil (0.02/traversal)	~6	~1
• Knock-on electrons from foil	~1	~0.3
• Thermionic emission from foil	<0.1	<0.1
• Secondary emission from beam losses (1-200/ lost proton)	0.01- 2	0.003 - 0.7
• Residual gas ionization (2-4x10^{-8} torr)	<0.01	<0.01
• Beam induced multipactoring (bunched beam)	>0.1?	>0.1?
	>8-11+?	>3.5-6+?

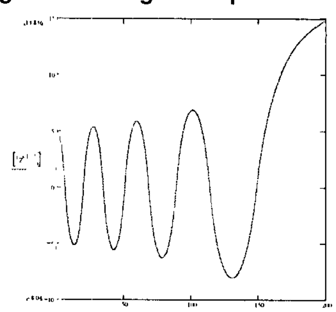
Electron Production/Control Experiments

- Vacuum Experiment
  - Increased residual gas pressure by factor of 30-100 without any detectable effect (at the 10% level) on threshold for bunched beams, maybe up to 20 % on coasting beams
- Electron suppression of most copious sources (section 0,3,4,7&8) has only modest and not very reproducible effect (~10-30%) on threshold
- Beam scraping and extra beam loss show only small effect (~10%)
- Large amounts of charge collected (on biased plates) for unstable beams
  - Electron flux growing before significant beam loss
  - For unstable beam, electrons appear where ever we have diagnostics (section 0,3 and now 5)
  - Beam induced multipactor is the most plausible explanation

Beam Induced Multipactor

- Ought to occur for bunched beam when SEY > 1. Driven by decreasing beam intensity on trailing side of long beam pulse.





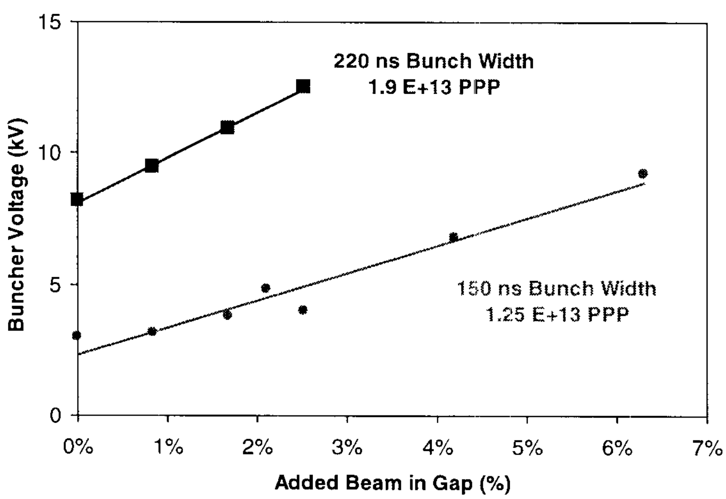
- Additional driving force when motion is unstable (from e-p). Blaskiewicz * estimates energy of > 100ev when electron hits the wall.
  - Could explain multipactor for DC coasting beam

M Blaskiewicz, "Instabilities in the SNS", PAC 99

Tests of the Influence of "Beam in the Gap"

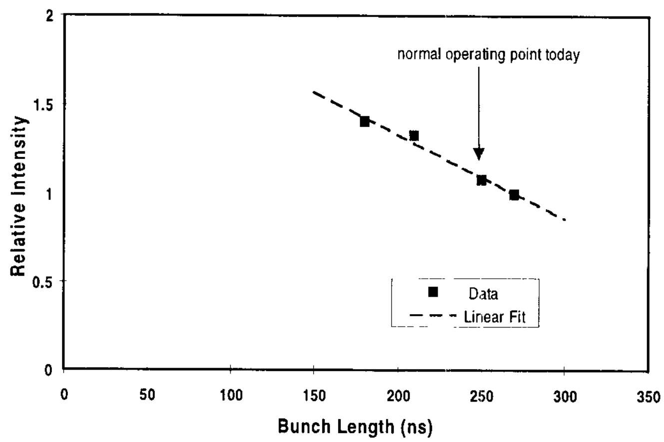
- Injection with some beam in the gap lowered threshold significantly (see graph)
- Influence of buncher voltage & bunch width is a strong effect
- Off center buncher phasing can put noticeable beam in the gap and lowers stability threshold
- "Extract the gap" to measure beam in the gap with a special beam current transformer
  - ~0.01% for stable, well tuned beam
- Tested inductive insert for longitudinal space charge compensation
  - initial result encouraging but not conclusive
  - evidence for longitudinal instability from inductor cavities
- Dual harmonic rf had no measurable effect on the instability threshold

Effect of Added "Beam in the Gap" on Instability Threshold



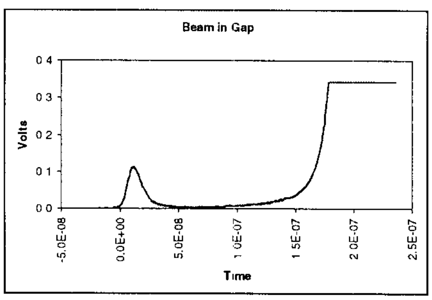
Threshold Intensity vs Bunch Width

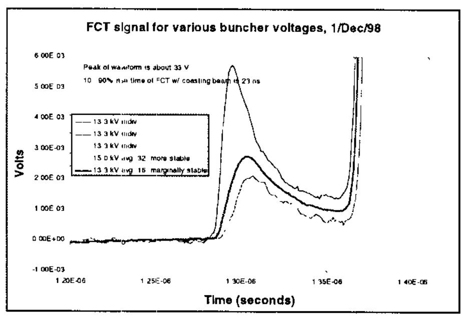
(1989 Data)



Measurement of Beam in the Gap

"Extract the Gap".
10 - 15 volt is the peak of the pulse.





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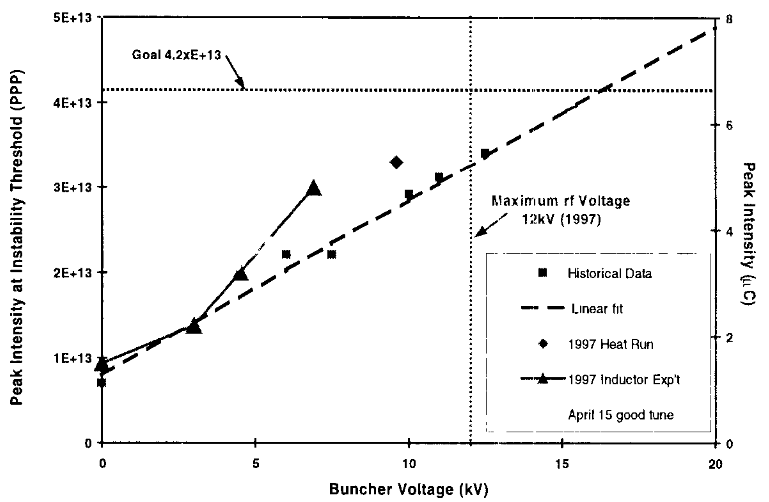
Effect of Inductor on Instability Threshold



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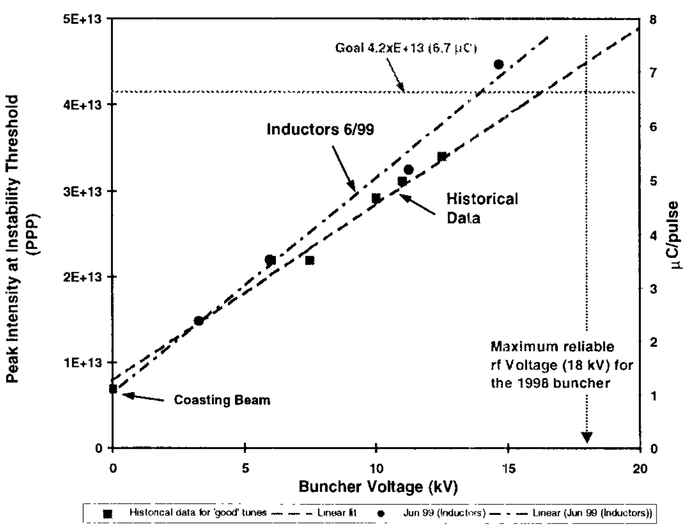
Effect of Inductors (6/99)



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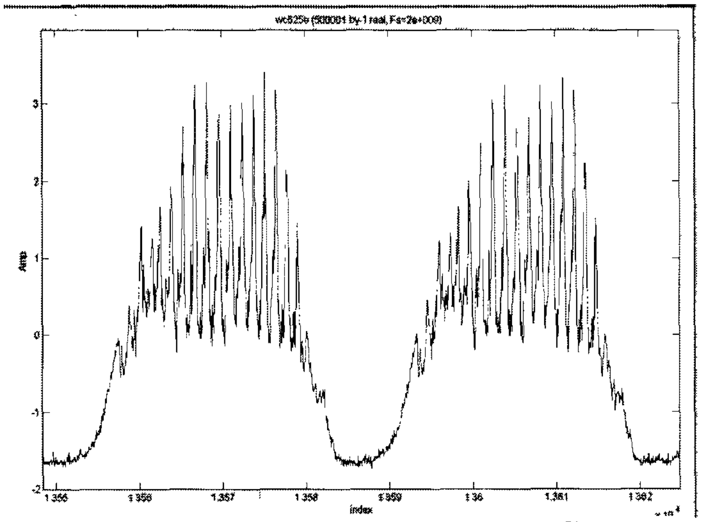
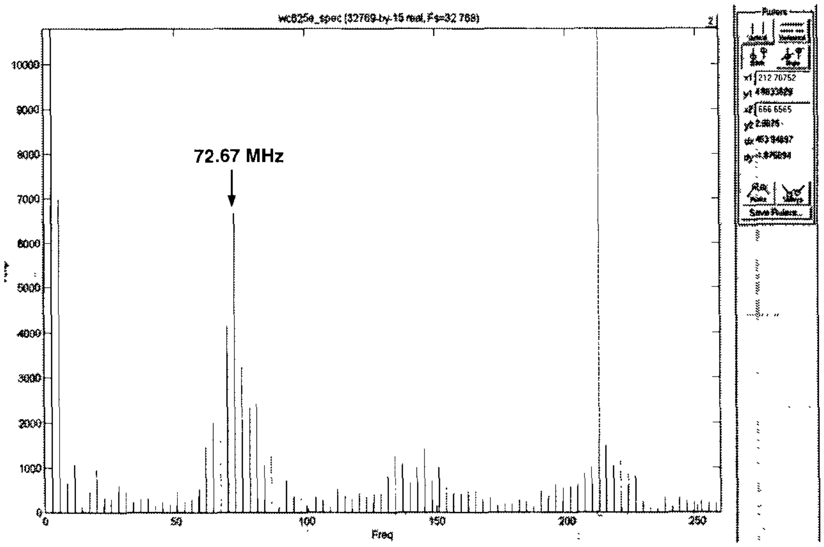
Longitudinal Instability

Two turns displayed



RF off, Injected bunch width 250 ns, accumulate 125 μs, 500 μs store, Inductor Bias=0

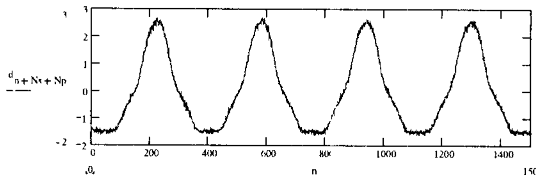
Frequency Spectrum



Comparison of Bunch Shapes for Single and Dual Harmonic RF

Time profile of beam bunch shortly after the end of accumulation

Single Frequency



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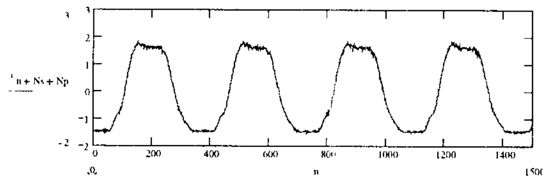
Dual Frequency,
2:1 Amplitude ratio



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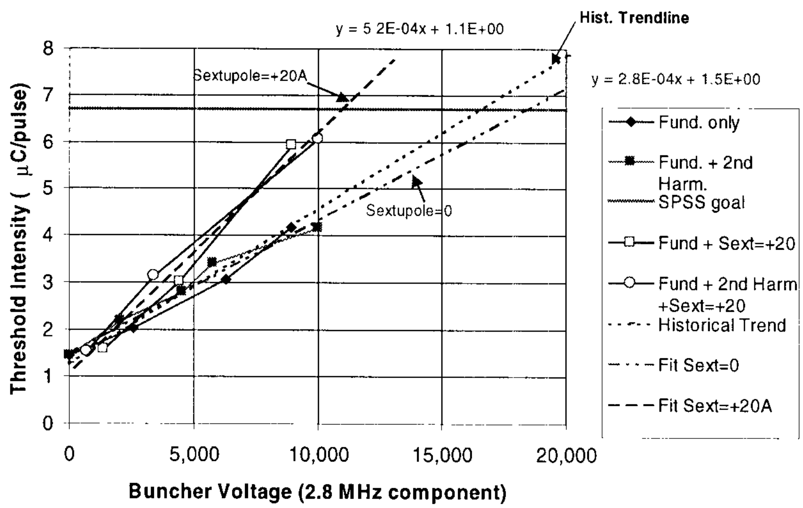
Threshold intensity curves for Dec. 1998 tests



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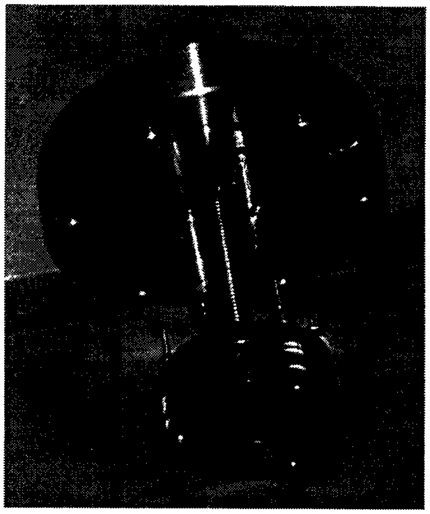
Methods of Control

- Landau Damping
  - Increase momentum spread
    - rf voltage
    - momentum painting
  - Multipoles
- Active Damping
  - Difficult given growth times and frequency range
- Suppression of electron production
  - Clearing fields
  - TiN coatings
- Suppression of electron trapping by beam in the gap
  - Longer gap
  - Inductive inserts

Plans for Future Work

- More tests of promising methods of control
  - Finish inductor tests
  - Optimize sextupoles
  - Tests of suppressing beam induced multipactor by TiN coatings
- Studies aimed at basic understanding
  - Characterize electron flux and energy spectra at the wall at various locations around the ring
    - Refine the ANL e-detector with goal of measuring e-flux and energy spectra as functions of time with good time resolution (possibly 25-50 MHz or better)
    - Resolve the role of beam induced multipactor
  - Improve the theory and carry out simulations of e-p
  - Incorporate electron generation and trapping in the simulations

ANL e-analyzer



- Diagnostic layout
  - Grounded grid at entrance
  - Repeller grid
  - Collector plate
- Detector with promise of measuring:
  - electron flux incident on vacuum chamber wall,
  - electron energy spectra by biasing grid,
  - time structure at relatively high frequency,
  - all without perturbing fields from the beam

Figure 1. ANL electron analyzer for PSR.

Summary/Conclusions

- e-p continues to explain the PSR instability.
- We understand it well enough for near-term PSR goals but not well enough to extrapolate to ESS or SNS.
- More information (theory and experiment) on sources of electrons and their trapping is essential.
- Data on electron flux and energy distributions as functions of time are in sight using the ANL e-detector.
- Need to resolve the role of beam-induced multipactor.
- Beware of beam-driven cavity modes with inductive inserts.