Overview of New Developments on the PSR Instability

(Robert Macek, 2/16/99)

Collaborators

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- **PPPL**
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This is the list of collaborators who participated in various aspects of the studies that lead to our present understanding of the PSR instability. Five other national laboratories are participating.

Outline

- Introduction: Main Characteristics of the PSR Instability
  - Strong, fast (50-100 μs), transverse (vertical) instability, thought to be e-p, and controlled mainly by sufficient rf Voltage
- Tests of Dual Harmonic RF in December 1998
- New Studies of the Mechanism or Causes
  - Electron cloud studies
  - Suppression of electron cloud
- New Tests of Potential Remedies
  - X,Y Coupling via a Skew Quadrupole
  - Multipoles
  - Inductive Inserts
- Some Key Issues
- Conclusions from the Work to Date
- Plans for Future Work

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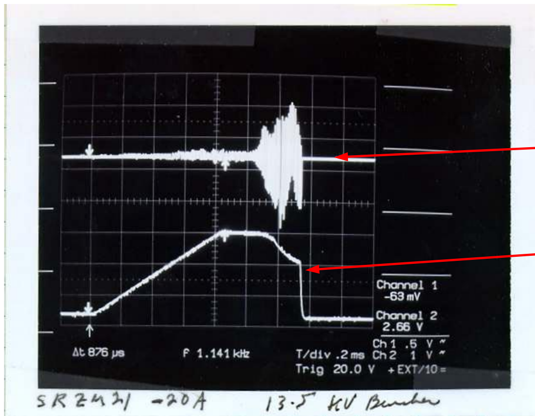
This will primarily be an experimental talk covering what has been learned from various experiments at PSR. By way of introduction, I will summarize the main and well-established characteristics of this instability.

The picture we had 2 years ago suggested that the addition of a second harmonic buncher would be the best next step in controlling it well enough for the goals of the PSR intensity upgrade. The 1998 improvements to the existing buncher were very successful and permitted us to modify it to support tests of dual harmonic rf, albeit at reduced drive in the fundamental. The, results which I will summarize show that it was of no help in controlling the instability.

This lead us to rethink our approach to controlling the instability. We have proceeded on two fronts, 1) new studies into the causes and 2) tests of potential cures or controls. Results from the these experiments and test will constitute the bulk of my presentation and the one by A. Browman that follows.

If time permits I would say a word or two about plans for future work.

Unstable Beam Signals



BPM ΔV signal

CM42 (4.2 µC)
(Circulating Beam
Current)

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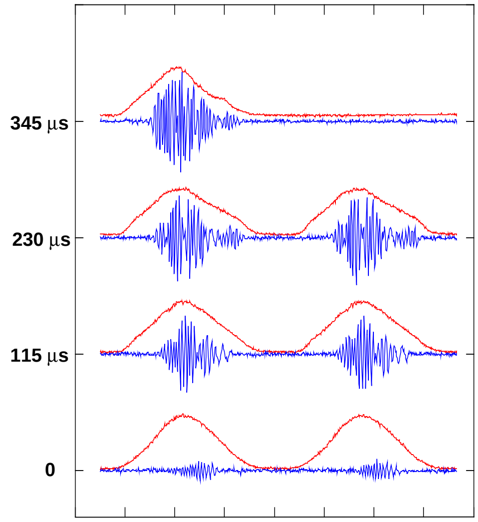
We typically observe the instability at threshold in a situation where beam is stored for 4 or 500 microseconds after the end of injection as shown in this oscilloscope trace of the stored current. The rf buncher voltage is lowered until the instability shows up at the end of the store as a rapid loss of a good fraction of the beam. If you also observe the beam centroid motion on a short stripline BPM you will see a rapidly growing vertical difference signal shortly before the beam loss.

Vertical Oscillations Compared with Beam Density

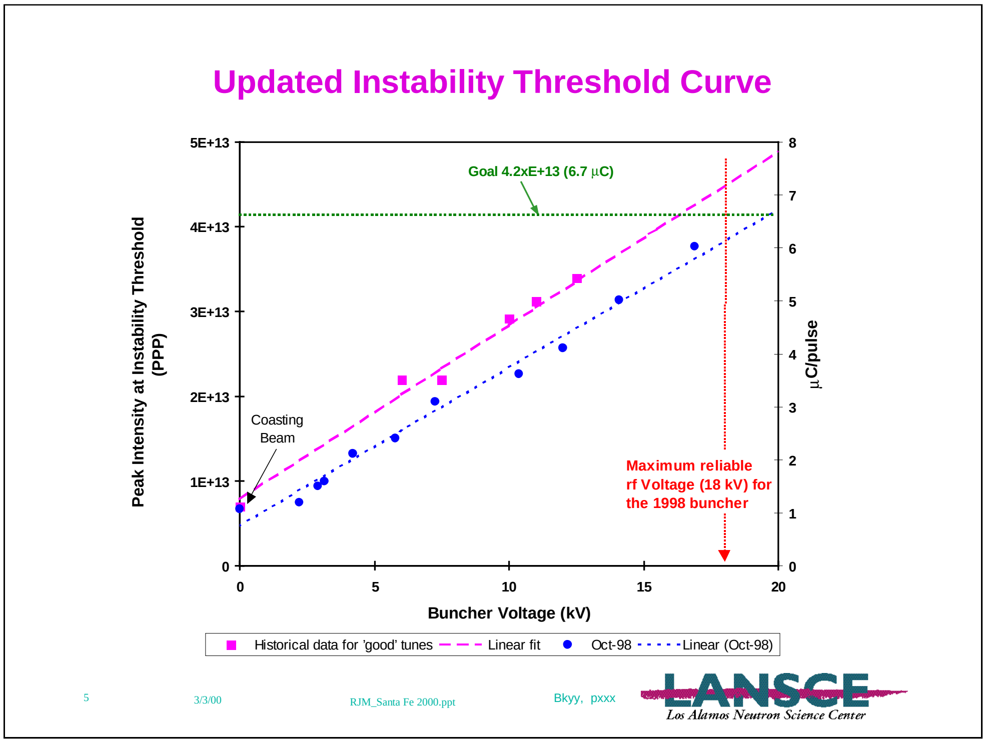


- Vertical difference signals (**blue**) from a short stripline BPM and beam pulses from a wall current monitor (**red**).
  - WM41VD.4B
  - WC41.4B
  - Data taken Apr. 14, 1997
  - Data at t, t+115 µs, t+230 µs, t+345 µs

A. Alexandrov's talk will cover a more detailed analysis of BPM signals and the question of obtaining absolute values of the beam centroid motion.

This is what you see looking turn by turn at various points in the growth of the instability. Here the vertical difference signal is compared to the wall current monitor trace at various points in time during the growth of the instability. The beam motion starts on the backside of the pulse and broadens out as it grows in strength. At the last turn before extraction you see there has been some evidence of beam loss from the red trace.

The raw vertical difference signal shown here is not a true position signal but is closer to the time derivative of position times intensity. Never-the-less it reveals the frequency content and growth in amplitude of the unstable motion. Sasha Alexandrov in his talk will discuss, among other things, how position information can be recovered from the short stripline BPM.



RF buncher voltage is the main means of control at present operating currents. This graph of threshold intensity as a function of buncher voltage shows just how effective it is. The magenta curve is historical data for good tunes showing the strong and remarkably linear dependence of threshold intensity on RF buncher voltage. This consistent with Landau damping in the e-p model to be discussed shortly.

The blue curve is the new data which show that the instability got worse after the injection upgrade. It slowly improved to the historical values after 6-8 weeks of operation. This “conditioning” effect, perhaps some kind of beam scrubbing of vacuum surfaces, has been observed on two other occasions after coming off a long shutdown where much of the ring was up to air.

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**

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

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

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

  - **Growth rate**

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

*Neuffer etal,"Observations of a fast transverse instability in the PSR", NIM A321(1992) 1-12

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Our present picture or working model is the e-p instability as put together by Dave Neuffer around 1990. He used the uniform DC coasting beam solutions of the coupled equations of motion to describe the situation for the long bunch beam in PSR. He assumed a small amount of beam in the gap as the means for trapping electrons during the passage of the gap in the beam.

Some formula's we will refer to later are listed. The bounce frequency of electrons in the field of the proton beam and the frequency of the protons in the fields of the electrons are shown as functions of N, the number of protons; $\eta_{e,}$ the ratio of the number of electrons to protons;a and b the beam transverse dimensions.

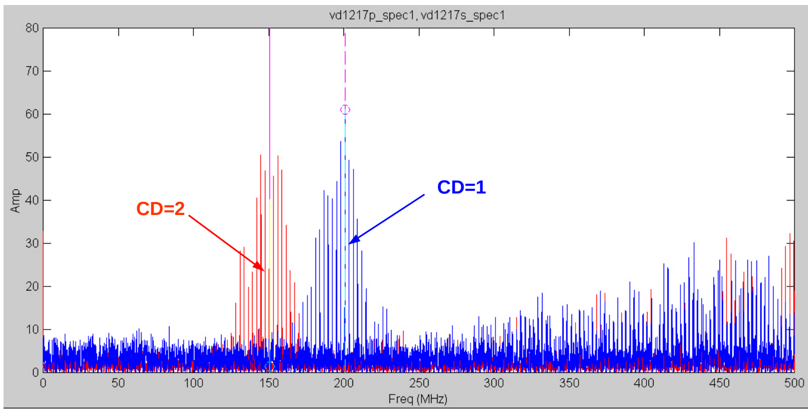
Unstable modes occur when the mode number n minus Q is close to Qe and the threshold condition is satisfied. The threshold condition when the Landau damping regime holds is shown along with the usual tune spread formula for mode n.

Frequency Spectra at Threshold for Unstable, Bunched-Beam Motion

- ~ 6.1 μC (for CD =1), 3 μC (CD=2)
- Results expected in Neuffer's picture: √2 in frequency ratio, as observed

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

$f \approx 230$ MHz (6.1μC)



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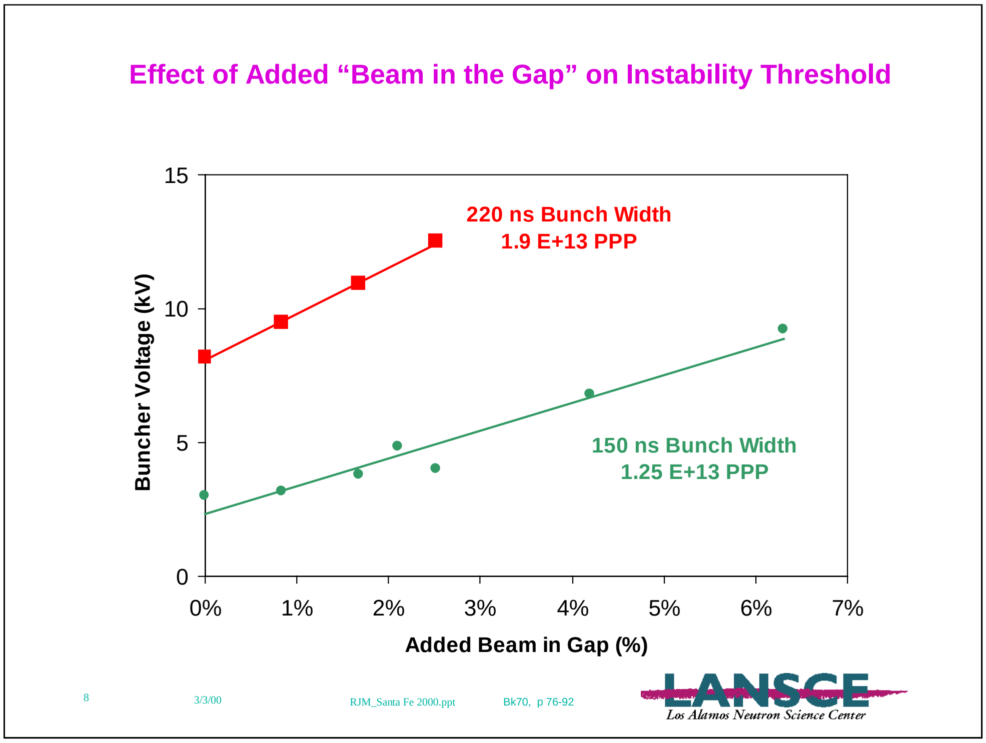
Perhaps the best evidence for e-p comes from the frequency spectra of the BPM vertical difference signal shown here for two intensities that differ by a factor of 2. The lines in the peaks are the n-Q betatron side bands. The peak for 6.1 μC centers around 200 MHz which close to the value expected for the electron bounce frequency. When the intensity is changed by a factor of 2 (injected pulse counted down of 2) the mean frequency of the peak shifts by a factor of 0.7 as expected.



Another feature of Neuffer’s model was the importance of beam in the gap for trapping e’s. The graph here shows the result of an experiment where controlled amounts of beam were added to the gap by injecting a number of unchopped pulses. The threshold voltage for a fixed accumulated charge increased with added beam in the gap as expected in Neuffer’s hypothesis.

Ring/Beam Parameters and their Effect on the Threshold Intensity

Noticeable Effect

- **rf Buncher Voltage**
- **"Position" in the fixed-frequency rf bucket**
  - **ΔE (departure from synchronous energy)**
  - **ΔR (departure from synchronous orbit radius)**
  - **$\Delta\Phi$ (rf Phase relative to center of injected beam bunches)**
- **Bunch Width**
- **Phase Slip Factor, η**
- **Size (emittance) of stored beam**
- **Betatron Tune (Increase of ν_y from 2.16 to 3.16 increases threshold ~40%)**
- **Multipole fields (sextupoles and octupoles)**
- **Injected beam momentum spread (for coasting beams)**

Little or No Effect

- **Vacuum pressure**
- **Beam Losses**

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Systematic studies of the effect of numerous ring and beam parameters were carried out. The list of those producing a noticeable effect on the threshold intensity are shown in the left column. They divide mainly into two classes: 1) those that affect Landau damping I.e.change the momentum or tune spread, such as buncher voltage, η, betatron tune change, and multipole fields. Or 2) those that affect beam in the gap such bunch width and including the parameters beam energy, dipole fields, buncher phase that affect position in the fixed frequency rf bucket. The injected bunch width also affects the momentum spread of the stored beam.

The e-p picture is qualitatively consistent with all of these effects. The fact that large changes in the vacuum pressure or beam losses show little effect is consistent if other sources of electrons are dominant. We will have more on that point later.

This picture, with the apparent importance of keeping the gap free of beam leakage, lead to the belief that adding a second harmonic buncher would be an effective control. Simulations indicated it would help keep beam from leaking into the gap. It would also improve the bunching factor which would help lower the transverse space charge tune shift.

Dec 1998 Tests of Dual-Harmonic RF

Validate the proposal to add a Second Harmonic RF Buncher to raise the Instability Threshold for PSR.

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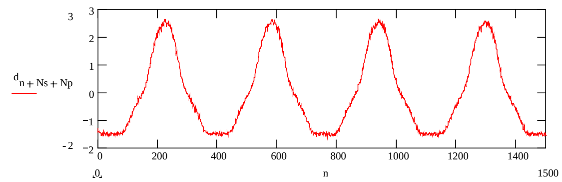
As mentioned earlier, the improvements made in 1998 to the existing bunch allowed us to modify the the buncher for a test of dual harmonic rf which we carried out in Dec of 1998. It did everything it was supposed to except help with the instability.

Comparison of Bunch Shape for Single & Dual Harmonic rf

Time profile of beam bunch shortly after the end of accumulation

Single Frequency



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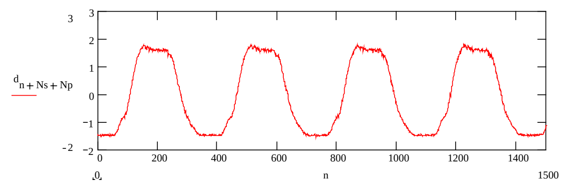
Dual Frequency,
2:1 Amplitude ratio



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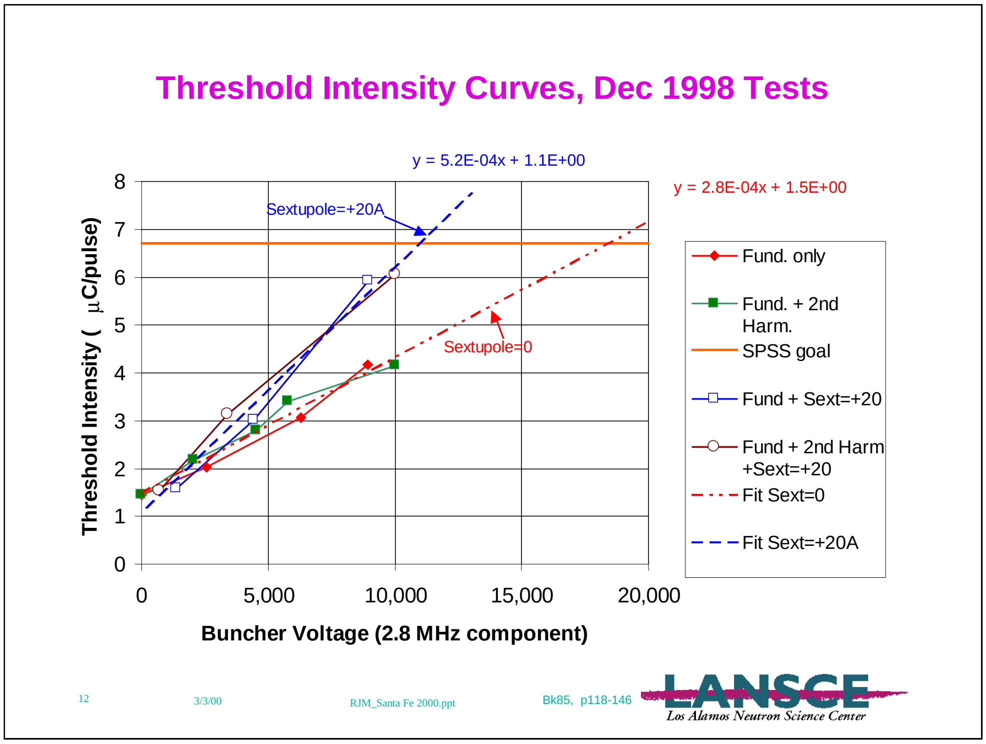
This data shows the improvement in bunching factor with dual harmonic rf. These are traces from a current transformer in the ring and show the time profile of the beam bunches in the ring shortly after the end of accumulation. The top trace is what we usually see with the usual single frequency rf. The bottom trace shows the change with dual harmonic rf with a 2:1 amplitude ratio for fundamental to second harmonic. Note the flattening of the bunch. Both traces have the same average current within 3-4%.



The effect of dual harmonic rf on the instability threshold was nil as shown here for two different values of a sextupole setting. In each we plot the threshold intensity as a function of the amplitude of the 2.8 MHz component of the rf. When the second harmonic was added with an amplitude 50% of the fundamental and zero relative phase no change in the threshold intensity was observed with either sextupole setting.

Another surprise was the highly beneficial effect of turning on a sextupole magnet. The effect of the sextupole field was surprising in that we tried them 8 years ago with significantly less effect. For Landau damping, the change in chromaticity is not enough to explain the size of the effect.

Another puzzle is the fact that -20A had about the same effect on the instability despite the fact that the vertical chromaticity went to zero.

Later, I will show evidence that suggests the bulk of the effect of a single sextupole is from X,Y coupling brought about by the skew quad component introduce by vertical closed orbit offsets at the sextupole.

These results caused us to rethink spending 5 million dollars to build and implement a second harmonic buncher. We thought it prudent to gain a better understanding of the root cause of this instability and to test other possible controls.

Summary of Electron Cloud Studies

Summary of the main results of 1999 studies to be presented by Andrew Browman in the next talk.

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Reliable information on the electron cloud responsible for the e-p instability has been the most uncertain piece of the puzzle. Fortunately we were able to make good progress thanks to some superb electron detectors from our ANL collaborators and from an unexpected opportunity for ample beam studies time this past summer and fall.

Main Results from the 1999 Electron Cloud Studies in PSR

- **Electrons hit the wall in a pulse near the end of the beam pulse passage**
- **Energy spectrum for electrons goes beyond 250 ev**
- **Very strong dependence of electron flux (in most locations) on beam intensity for stable beams**
- **Strong variation of electron flux with location**
- **Numerous electrons observed in a dipole and a quadrupole**
- **High electron fluxes observed even for stable beams**
  - **Line density of electrons observed at the wall is comparable to average line density of protons in certain locations**
- **Electron flux increases during unstable beam motion**
- **Electron flux ~ linear in local losses and vacuum pressure**
- **TiN coating suppresses e-flux by factor ~ 100 in section 5**

Richard Rosenberg's talk tomorrow will describe the very useful ANL e-detector that we used and Andrew Browman's talk will cover the various experiments at PSR.

I will just mention the main results of our electron cloud studies. Richard Rosenberg will describe the detector and Andrew Browman will more fully discuss the various experiments and results.

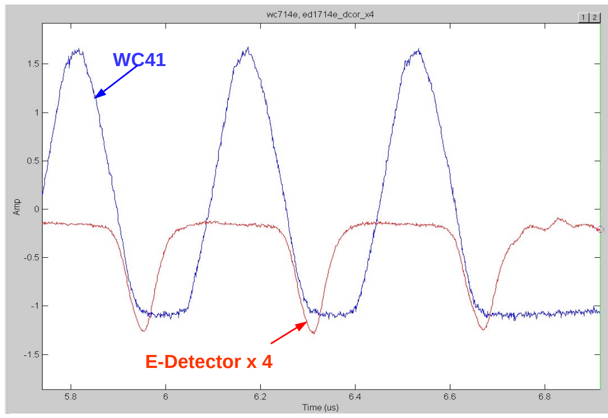
The ANL detector and Andrew's electronics enable us to measure the electron flux hitting the wall and get information on the electron energy spectrum and time structure, without perturbing the beam-wall environment. See next slide 15.

Other important results are listed: energy spectra out beyond 250 ev, very strong dependence on beam intensity, dependence on location, numerous electrons in dipoles and quad magnets and an increase during unstable motion. It is also interesting that the electron flux ~ linear in local losses and vacuum pressure as if there is an amplification process on "seed" electrons generated by these two sources.

Finally I want to mention the very promising result from TiN coatings where a factor of ~ 100 suppression of the electron flux was observed in the one section tested. It is tempting to conclude that TiN is the cure for this instability, but is it sure to work. We have been fooled before and the cost and downtime for coating every chamber in PSR as a retrofit is steep. Go to slide 17

Electron Signals at the End of a 500 µs Store of Stable Beam)

- Detector in vertical plane in Section 4, repeller voltage = 5 V
- 3.8 µC of accumulated protons, stable beam
- ~2 pC/cm^2/pulse of electrons hitting wall or ~ 60 pC/cm/pulse line density (compare with 420 pC/cm average proton line density)



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A turn by turn picture of the electron signal in relation to the circulating beam pulse is shown here at the end of a 500 µs store of stable beam. The timing between electrons and proton beam is good to a few ns. The repeller voltage of 5 volts means e's above 5 eV get through to the collector.

Electrons start to appear after the peak of the beam pulse has past and the peak of the electrons appears at the end of the beam pulse. Higher repeller voltage shows a smaller, and narrower pulse. From this one picture one cannot deduce how much electron multipacting is occurring on the backside of the beam pulse without additional data and assumptions.

The electron flux hitting the wall is sizeable, about 25 µA/cm^2 at the peak or ~ 2 pC/cm^2/pulse or 60 pC/cm/pulse integrated over the circumference of the 4" beam pipe. It is interesting to compare this with the 420 pC/cm ave line density of the proton beam. One cannot deduce with any precision the neutralization of the beam without additional information or assumptions on how long the electrons were captured by the beam before hitting the wall. I will leave these speculations for another time.

A Concern: Will Suppressing the Electrons Cure the Instability?

- **More electrons from factors of 2 - 3 increase in losses or a very large increase in vacuum pressure did not change the threshold by more than 10-15%.**
  - **From recent studies, one expects that the number of e's would have increased substantially throughout the ring and therefore η_e should increase**
  - **Neuffer model implies that the threshold intensity should go down**
- **Simultaneous suppression of e's by clearing fields etc (in several sections in 1996) had a weak effect (~20%) on bunched beam and no effect on coasting beam thresholds.**
- **What portion of the electron cloud is important for e-p?**
  - **The simple theory we have assumes all electrons are involved.**
  - **What would a more complete theory predict?**

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Before concluding with a resounding yes we need to address a couple of lingering doubts.

We have seen that that the electrons increase more or less linearly with losses and with vacuum pressure. Yet, factors of 2-3 increase in total losses have little effect on the threshold. Likewise a factor of ~100 change in the vacuum pressure had only a small effect on the threshold. Based on our recent studies, one would expect the the number of e's to have increased substantially and therefore the threshold intensity to go down. Of course, we really don't measure the neutralization of the beam only the flux of those that hit the wall.

Instead of increasing the number of electrons we have also tried clearing electrons with clearing fields and other measures. When we tried this simultaneously in several sections it had a weak effect on the bunched beam threshold and none on the coasting beam threshold intensity. This may be easier to get out of. Go to slide 17

Back to the question of will TiN cure the instability? It is plausible but not assured by what we know. We don't know, for example, what fraction of the electrons participate most strongly in the instability. I hope Ron Davidson and Hong Qin have more to say on this point. Go to slide 20.

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)	?	?
	>8-11+?	>3.5-6+?

- The last item for 5 μC could be ~0.05 - 1 e's/proton/turn (at the wall) for ~500 turns, implying 25 - 500 e's/proton, well above all other sources.
- Estimates of the electron density function in the region of the proton beam are even more uncertain and require a detailed model of electron production and motion.

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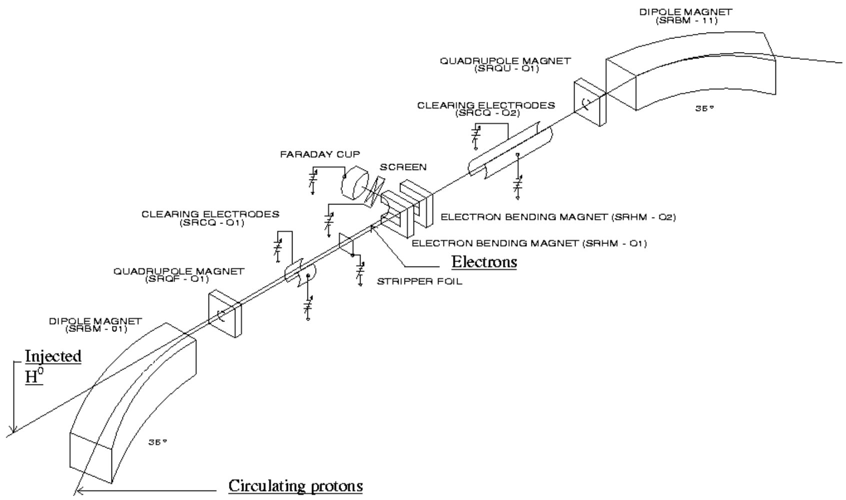
This list of various sources was what were examining a few years ago to come up with ways of suppressing the main sources of electrons. We directed convoy electrons to a bias absorber, biased the stripper foil at up to 10 kV and put clearing electrodes in 5 or so straight sections for a minor effect on the instability. In light of our recent data on beam induced multipactor we might expect this source to overwhelm all other sources and produce electrons everywhere. Since the total length of clearing electrodes was about 15% of the ring circumference perhaps this is why we got the results we did. (Back to previous slide)

Electron Clearing Devices in Injection Section (Pre H^- Injection Upgrade)



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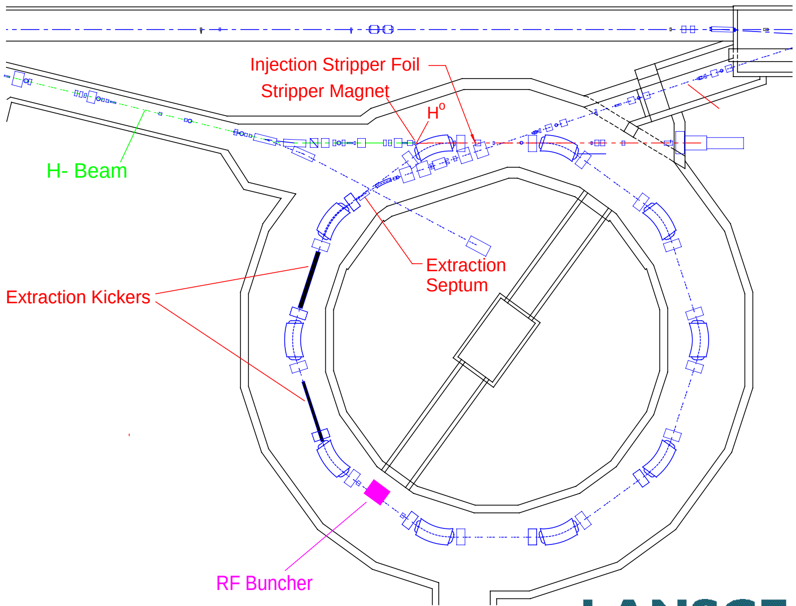
Layout of PSR Pre- H^- Injection Upgrade



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Tests of Potential Remedies

- **X,Y coupling via skew quadrupole**
- **Sextupoles**
- **Inductive Inserts**

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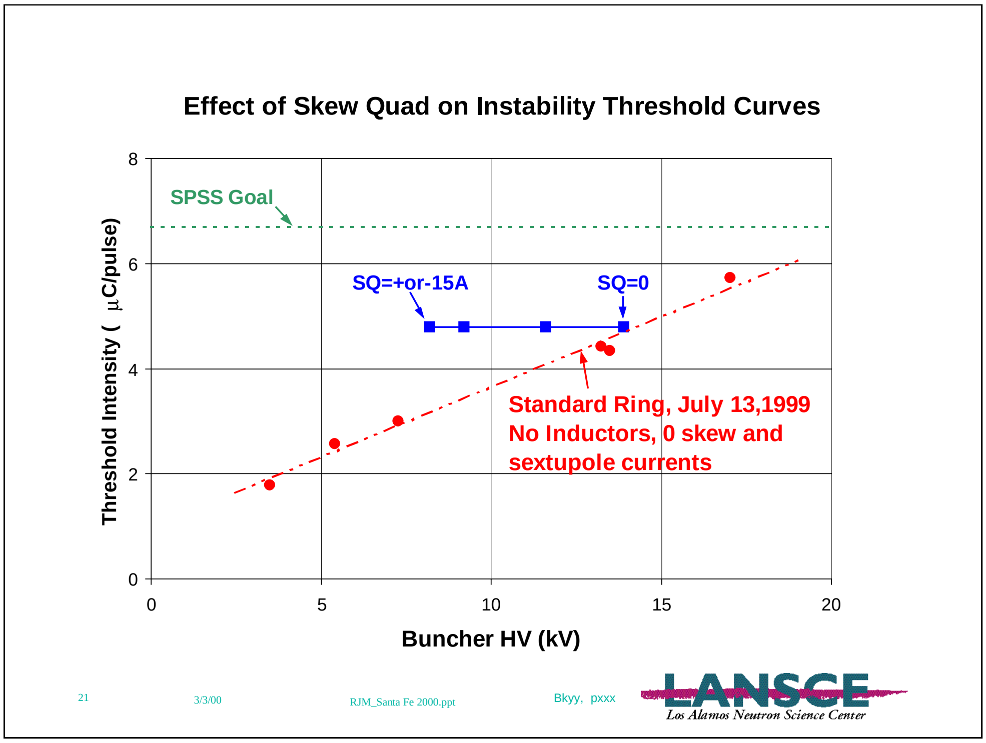
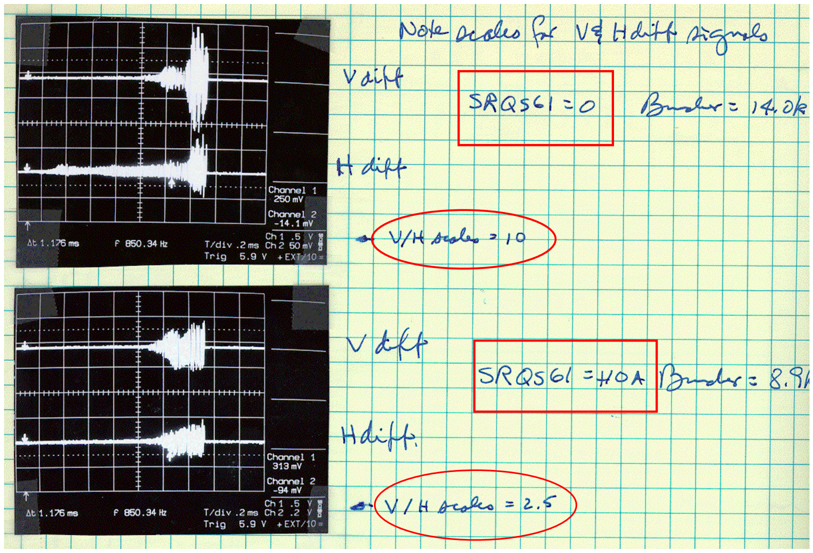
Now I will discuss results of new tests of some potential remedies. I have already showed some of the gain with sextupoles. We have also carried out tests of damping from X,Y coupling and more tests of inductive inserts.



We found a strong effect on the instability threshold using a skew quad and sitting on the coupling resonance as shown here. For a fixed stored charge, the buncher voltage at threshold was reduced 45 % by energizing a single small skew quad to either + or - 15A (the effect is symmetric). The other two intermediate points are at 3 and 8 A respectively. One down side is an increase in beam losses which is not surprising given that emittance is being exchanged. We do not yet have a good quantification of the losses. It depends on how much room is left in the ring transversely after injection painting. A reduction in the painting amplitude reduced the losses from coupling. We still have an optimization to carry out.

Skew Quad Coupling

BPM signals



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At the instability threshold one can observe the effect of the skew quad coupling on the unstable motion. The top traces are the case for the skew quad set to 0A. At the end of the trace where the unstable motion occurs on sees the usual result where the horizontal motion is 5-10% of the vertical. (note the ratio of scope gains, the vertical scale is 1/10th of the horizontal). When the skew quad is set to +10 A, the horizontal amplitude increased to about 30-35% of the vertical.

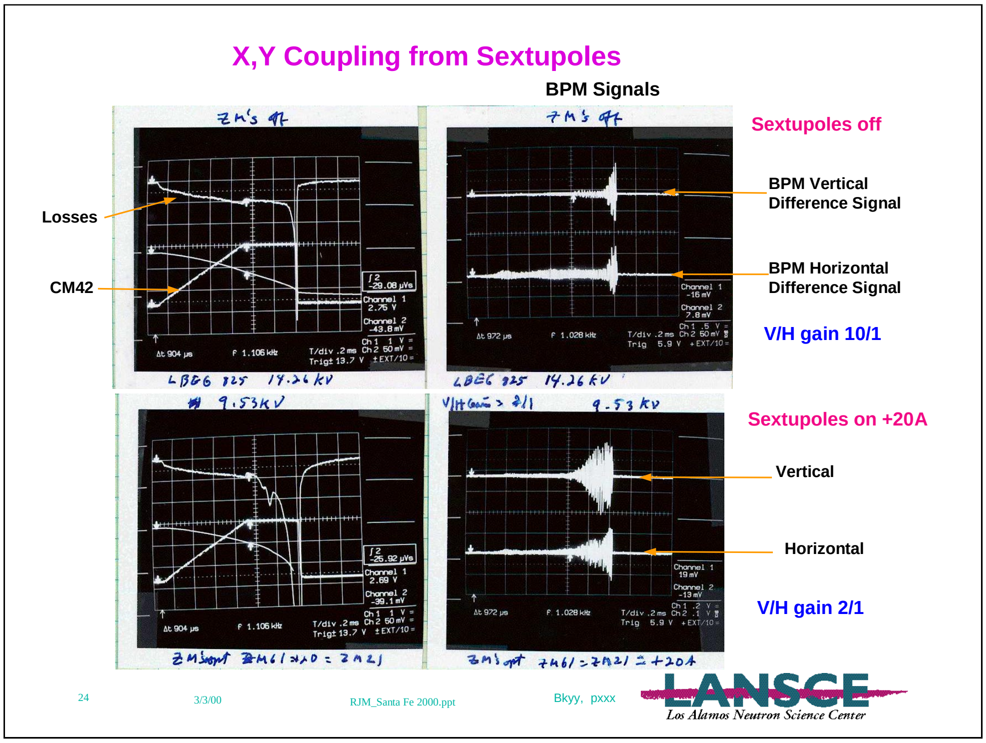
Coupled Landau Damping

- **Theory has been worked out by E. Metral* (CERN) and tested on a resistive instability at the CERN PS.**
- **Basically, X,Y coupling permits a sharing of the stabilizing tune spread in both planes for extra damping.**
- **Depends on two parameters, Δ, the distance from the coupling resonance and K the strength of the coupling field.**
- **There is benefit even if far from the coupling resonance.**
- **In general, optimum $\Delta \neq 0$.**

* E. Metral, "Theory of Coupled Landau Damping", Particle Accelerators, vol. 62(3-4,p.259, January 1999 also PS/CA/ Note 98-16 on measurements at the PS.

The effect of coupled Landau damping has been recently worked out by Metral at CERN and verified experimentally at the CERN PS. Basically, X,Y coupling produces a sharing of stabilizing tune spread in both planes for extra damping.

Another result, which we have also observed is that there is benefit even considerably off the coupling resonance. We have not done detailed scans of Δ,K space to find the precise optimum. For one thing, set point reproducibility of the accelerator and ring probably would ned to be improved.



After seeing the strong benefit of coupling it occurred to us that coupled Landau damping might explain the somewhat puzzling results for sextupoles. I remind you that a vertical closed orbit offset in a sextupole produces a skew quad component of the field at the beam center. These scope traces show the X,Y mixing of unstable motion when the sextupoles are turned on. The horizontal amplitude goes from 10% of the vertical to 40% or so.

Was the orbit offset sufficiently to produce the needed skew component? I can't say since we don't have BPM's that give a reliable measure of the closed orbit at the end of accumulation. I estimate we need 4-5 mm of offset to produce enough skew component. That is plausible, but not definitive, given the uncertainties in knowledge of the closed orbit at high intensities. One more reason to improve our BPM's which only work on the 200 MHz component of the beam.

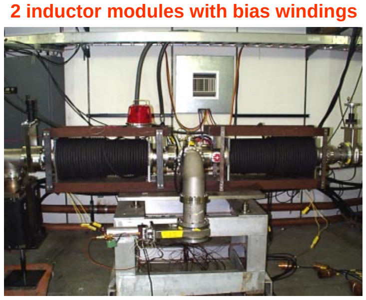
Use of Inductive Inserts

- Idea is to add ferrite to increase wall inductance to cancel longitudinal space charge voltage per turn
- Net voltage per turn from space charge self-voltage and inductive wall impedance (below transition) is:

$$V_s = \frac{\partial \lambda(s)}{\partial s}\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \Omega_0 L\right] e\beta c R$$

- In collaboration with FNAL in 1999, we installed enough inductance (3 modules) to fully cancel space charge

2 inductor modules with bias windings



Expect improvements from two effects:

1. Less beam leaking into the gap.
2. Inductor removes the reduction of rf bucket height from space charge thereby increasing the momentum spread and producing more Landau damping.

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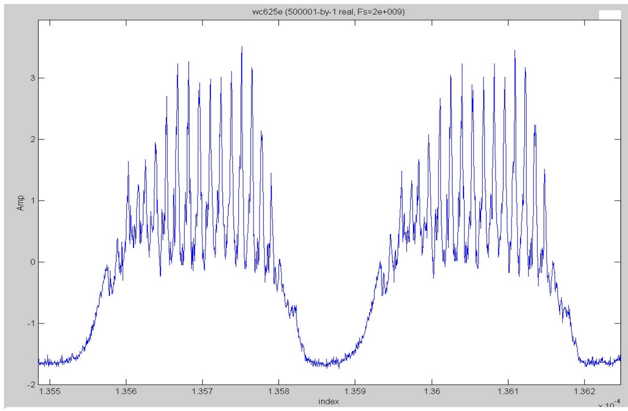
Inductive inserts were an idea from our FNAL colleagues that we first tried in 1997 with results that were encouraging. The idea is to add enough wall inductance to passively compensate longitudinal space charge. Choose L to make the net voltage per turn from space charge and the inductive wall zero. Our focus was on the benefit expected from reduced leaking into the gap in the beam pulse. In 1999 we installed 3 modules enough for full compensation.

Longitudinal Resonance with Inductors Installed

Wall Current Monitor for two turns of coasting beam (RF off) is displayed.

RF off, Injected PW = 250 ns, accumulate 125 μs, 500 μs store, Inductor Bias=0, 3 modules installed



See longitudinal modulation at 72.7 MHz, close to the estimated beam-driven, ferrite-loaded cavity resonance.

The first surprise was a strong longitudinal resonance for a coasting beam. The frequency of ~73 MHz is close to what one would estimate for a beam-driven, ferrite loaded cavity.

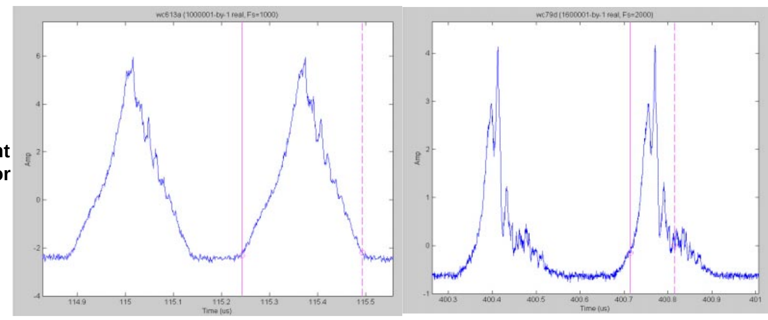
Effect of Inductors on Bunched Beam Pulse

- Injected bunch width = 250 ns (standard injection width)
- Longitudinal modulation may be tolerable at 250 ns bunch width.

- Injected bunch width = 100 ns
- Here beam pulse is too badly distorted to be very useful for potential short-pulse applications.

3 modules used, bias =0, room temperature

Wall Current Monitor



Bk86, p78

Bk87, p56

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The resonance also showed up for bunched beams with the rf on as shown here for a250 ns injected bunch width and for 100 ns bunch width. We could probably live with the modulation on the standard 250 ns bunch but the effect on potential short pulse applications would not be acceptable.

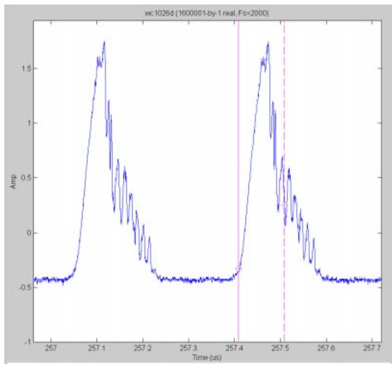
What to do? Abandon the idea? Fortunately the FNAL folks hit on the idea of heating the ferrite. Offline tests showed that this would detune the resonance and incidentally increase the inductance.

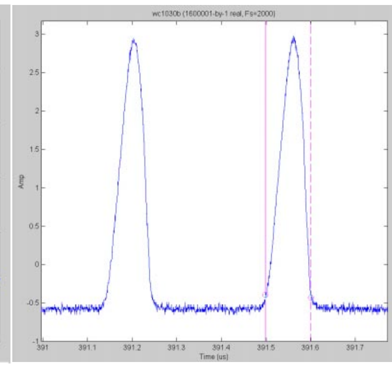
Effect of Heating the Inductor Ferrite

- Ferrite Inductor (2 modules) at room temperature
- 3.3 μC accumulated

- Ferrite at 130º C
- 3.3 μC accumulated
- Longitudinal signal at cavity resonance down 30db from room temperature case

Wall Current Monitor





Bk91, p150

Bk92, p10

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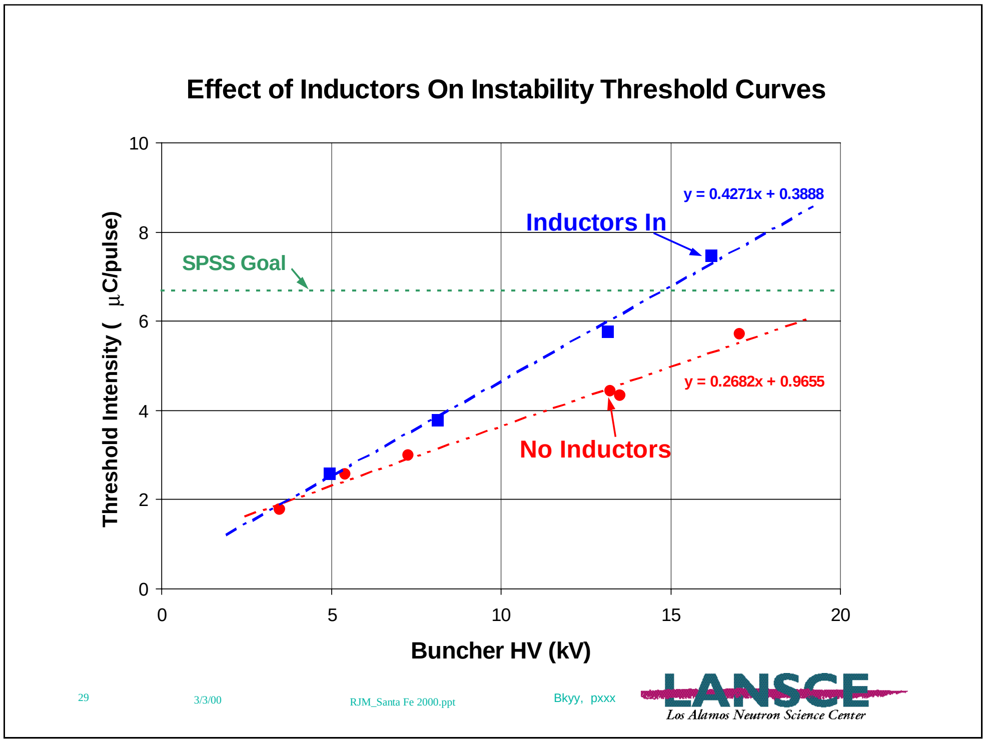
The improvement with the beam is readily apparent from these before and after traces for 100 ns bunch width. Here we have only two inductor modules installed. The longitudinal resonance is down 30 db when the ferrite was heated to 130 degrees C.



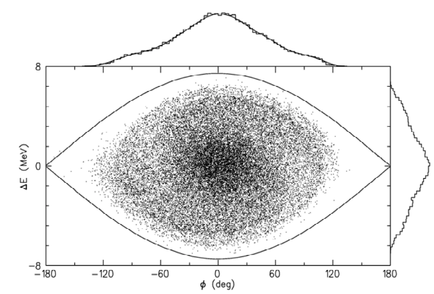
The effect of inductors with full compensation on the threshold intensity for our standard beam is shown in this graph. These are actually for room temperature ferrite when we had 3 modules installed. The benefit is significant and can be explained from the amount of added rf from the ferrite. This will increase the momentum spread and thereby provide more Landau damping.

Estimation of the Change in Bucket Height with Inductors

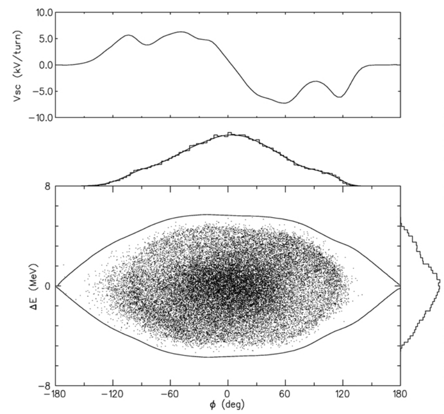
- **ACCSIM simulations show expected change in bucket height (or of momentum spread) of ~ 24% for 7.3 μC with 13 kV rf,**
  - **equivalent to a 42% change in rf voltage and in line with observations (~32% on threshold voltage).**
- **Can also estimate analytically, which gives the same number as the simulation results.**

$$A_{sp.c} / A = \left[1 - g_c ehN/(4\pi\varepsilon_0\gamma^2 V)\right]^{1/2} \approx 0.75$$

No longitudinal space charge (7.3 μC)



Including longitudinal space charge (7.3 μC)



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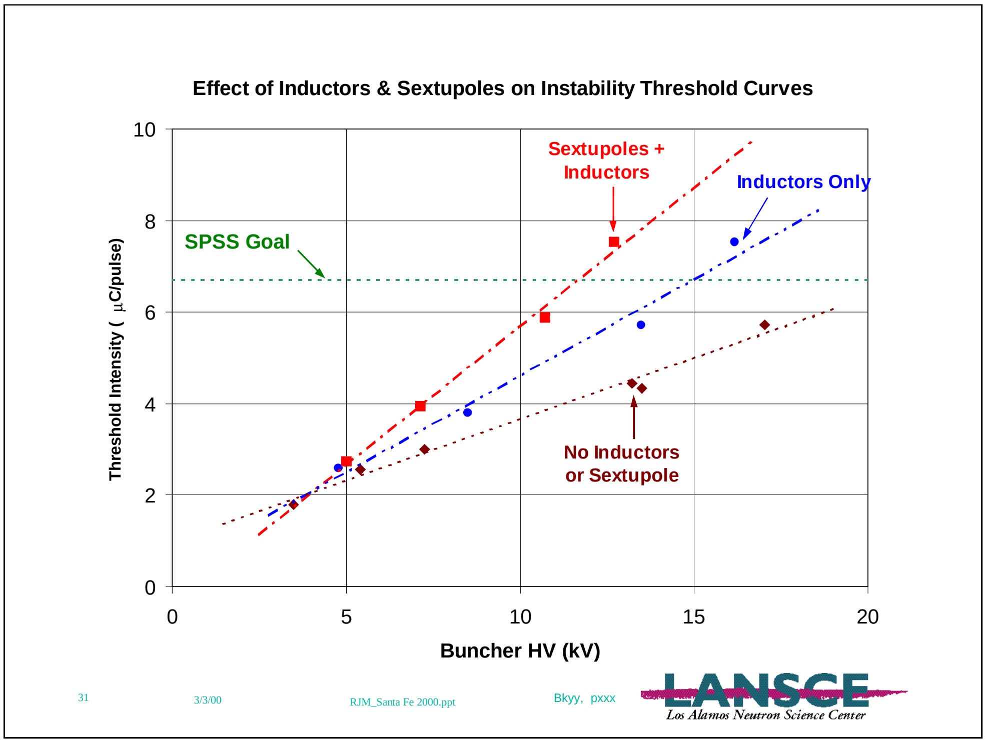
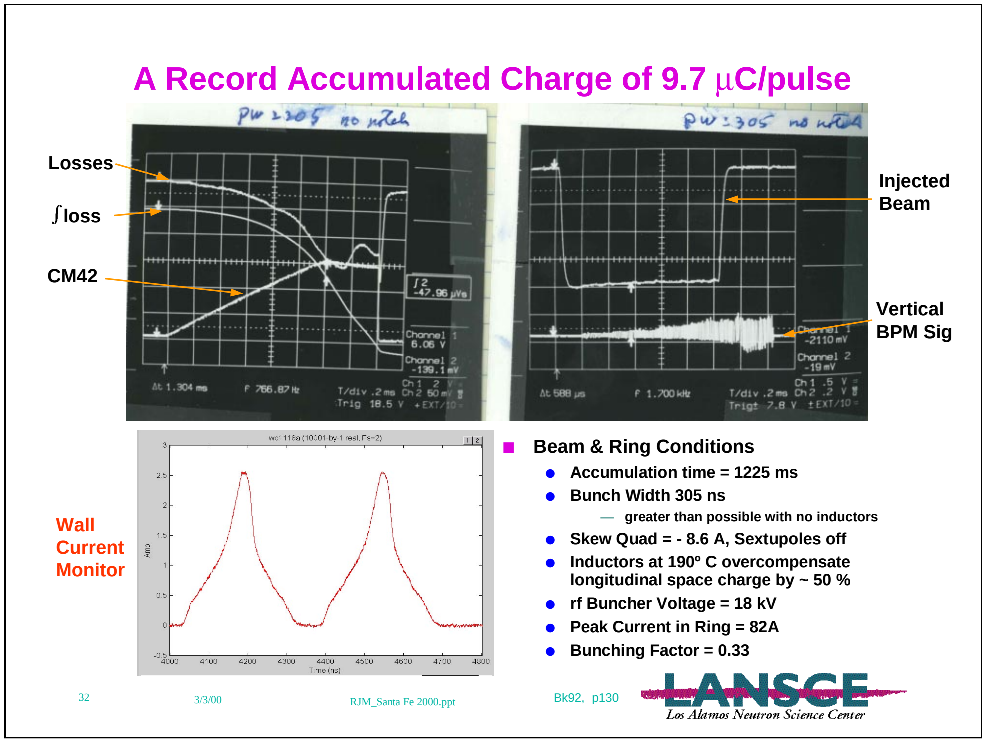
The effect of the inductors on Landau damping can be estimated from the change in bucket height with inductors. From ACCSIM simulations for identical situations except with out without longitudinal space charge we see a 24% change which is equivalent to a 42% change in rf voltage in terms of our threshold intensity curves. This is reasonable agreement with the observed 32% effect. You can also see from longitudinal space charge graph that the inductors would added 5 or 6 kV of rf voltage with the wave form shown. You can also estimate it analytically from a formula in Bovet's handbook with a similar result. In any case, it appears that the effect inductors is understood.



The benefits of inductors and sextupoles seem to be additive as shown here. Once again, this data was obtained with the earlier setup of 3 modules at room temperature but with some bias current which helped damp the longitudinal resonance. Heating the ferrite did not significantly change these results.



We recently put it all together and were able to stabily accumulate and store a record 9.7 µC/pulse which is all that the linac could deliver.

We accumulated the maximum length pulse, 1225, ms that could be obtained at 1 Hz from the linac. Inductors were at 190 degrees C which over compensates longitudinal space charge by ~ 50%. RF was at the maximum of 18 kV and we used the skew quad but no sextupole fields.

To get this intensity we had to stretch the bunch width out to 305 ns, something we were never able to do before without reducing the threshold intensity. Of course, a 55 ns gap is not enough for clean extraction in routine operations but it did help get more intensity for this demonstration.

Beam losses during accumulation were high ~5% for a variety of reasons. The long accumulation time is one reason. (We need that new ion source to reduce the accumulation time). The stripper foil was in poor shape and had to be run into the beam several mm to get good stripping efficiency. The was no doubt significant emittance growth that can be attributed to the very high, peak beam current of 82 A. We clearly have our work cut out to reduce the beam losses to sustainable levels at these peak intensities.

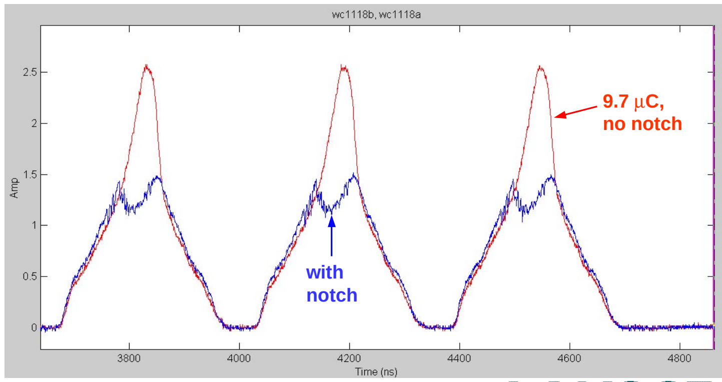
The self bunching from the extra inductance (above that needed for full compensation) seem to do no great harm but probably contributes to the center spike in the beam pulse. It may help keep the beam gap cleaner than other wise.

At this time we were also able to test another idea for improving the bunching factor, I.e a notch in the middle of the injected pulse, a poor man's dual harmonic rf.

Comparison to Beam Injected with 50 ns Notch

- Inductors at 190º C, enough inductance to over-compensate longitudinal space charge by ~ 50%
- Use 50 ns notch in 305 ns injected pulse
- Stored intensity down 16%
- Bunching factor up ~ 50%
- Losses down a factor of ~ 2
- Electrons up 10-20%

Wall Current Monitor



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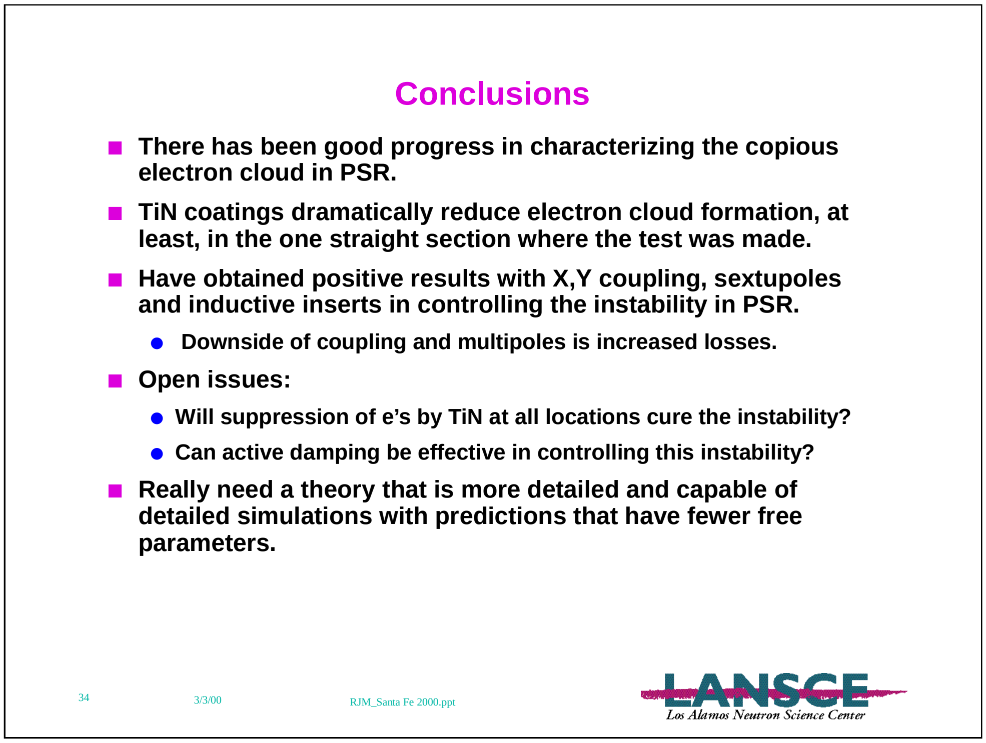
We used the same beam as in the last slide but this time chopped out a 50 ns notch in every injected ring pulse. The before and after effect on the stored beam pulse profile is shown in the graphic where the two signals are superimposed. Several results are of note: The bunching factor improved ~ 50%, the beam intensity went down by 16% as expected and the beam losses went down factor of 2. Some what surprising, the electrons hitting the wall actually went up a bit. From the strong dependence on intensity seen in other situations this is somewhat unexpected. As Andrew will show the electrons are generally quite sensitive to the shape of the beam pulse. This is another example. When we get a detailed model of electron production perhaps these effects will be better explained.

I have now presented an overview of the results of our recent work. What do we conclude from this?



I would brag that we have made good progress in characterizing the copious electron cloud in PSR although I must point out that we only measured the electrons hitting the wall not the electron distribution function in the beam.

TiN coatings dramatically reduce electron cloud formation and as such show good promise as a potential cure.

We have obtained positive results with X,Y coupling, sextupoles and inductive inserts in controlling the PSR instability. However, the skew quad and multipoles do increase beam losses. We have not strong evidence that the inductors cause increase losses, although an increase in momentum spread will do so at some level.

We still have some open questions (see slide)

Since Landau damping seems to be our only remedy so far why not consider active damping? Bob Kustom, when he spent a few months with us, did look into it fairly carefully. He concluded that it was a very difficult problem given the fast growth time and wide frequency range of the unstable motion. It would definitely tax the resources and capabilities at PSR. Still, I would think the SNS project would be advised to at least leave the hooks in for active damping should the TiN remedy fail. I think we can have a good debate on this issue.

Lastly I would make the strong pitch for improvements to the theory. We need some predictions that don't leave a lot of room to wiggle out of.

Plans for Future Work at PSR

- **Improve BPM diagnostics for measuring unstable motion.**
- **Electron cloud studies at more locations and with higher frequency electronics.**
- **Implement multipoles, skew quad(s) and inductors as operational devices in the present PSR Upgrade Project.**
- **Try TiN coatings of chambers where largest electron fluxes are observed or presumed.**
  - **Injection straight section (0)**
  - **Straight section 4 which has some small ceramic pieces**
  - **High loss regions, (sections 9 and 1)**
- **Exploit the new ion source when it comes on line in about a year**
- **Theory and simulations**
  - **Simulation of electron cloud formation**
  - **Simulations of e-p characteristics**

Plans for future work are outlined here.

We are planing a better BPM for measuring unstable motion. We want a direct measure of position over a wide frequency span.

We plan more electron cloud studies at more locations and with higher frequency electronics. We hope that we might get better evidence for beam induced multipactor.

As part of the PSR upgrade project we will make the multipoles, skew quad and inductors into operational devices.

We plan to try TiN coatings of chambers where the largest electron fluxes are observed or presumed as indicated.

A higher intensity ion source is being develop as part of the SPSS upgrade project. We will exploit its capabilities when it comes on line in about a year.

With help from the SNS project we hope to develop a better theory. I would judge that experimental development are well ahead of theory for the PSR instability. I believe the time is ripe, for a detailed simulation of electron cloud formation. There is much data with which to test the model.

Stay tuned for the next installment of this saga.