Longitudinal Dynamics in the Stanford Linear Collider Damping Rings

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BNL

Outline

- Introduction

  SLC, Damping Rings, BPM signals, Instability history

- Hardware

  BPM signal processing, Streak camera, Control system interface

- Experimental studies at high current

  Instability phase space structure, Linac correlation studies, Stored beam studies

- Impedance-related measurements

  Synchronous phase measurement, Low current streak camera measurements, Tune shifts with current

- Conclusion

Parameters for the SLC Damping Rings Related to Longitudinal Dynamics and Diagnostics

Parameter	Symbol	Value
Energy	E_0	1.19 GeV
Typical Population per bunch	N	4.5×10^{10}
Number of bunches		2
Store time (NDR, SDR)		8.3 ms, 16.6 ms
Orbit Circumference	C	35.27 m
Revolution Frequency	f_0, $\omega_0/2\pi$	8.5 MHz
RF Frequency	f_{RF}	714 MHz
Harmonic Number	h	84
Typical RF Voltage	V_{RF}	800 kV
Typical Synchrotron Frequency	f_s, $\omega_s/2\pi$	100 kHz
Energy Spread (in, out)	δ_{inj}, δ	3×10^{-3}, 9×10^{-4}
Bunch Length (in, out)	σ_{inj}, σ	7.4 ps, 20-25 ps
Zero Current Bunch Length	σ_0	17.8 ps
Energy Loss/turn from Synch. Radiation	U_0	79.2 KeV
Momentum Compaction	α	0.015
Energy Damping Time (NDR, SDR)	τ_d, γ_d^{-1}	1.91 ms, 1.78 ms

$$\frac{N r_0}{\delta_0^2 \alpha \gamma C} \frac{4\pi |Z_{\|\mathrm{eff}}|}{Z_0} \sim 6$$

Strong Longitudinal Single Bunch Effects Expected!

Instability History

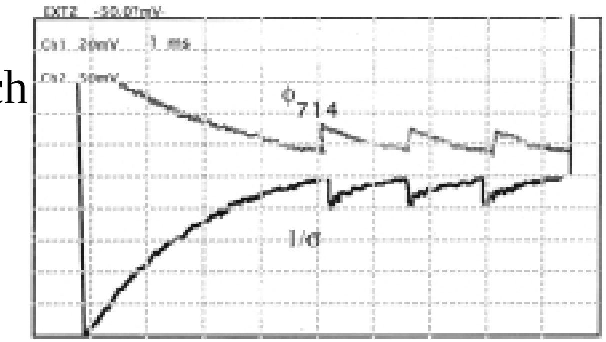
- 1992

  Attempt to raise current above 3×10^{10}/bunch

  Severe single bunch longitudinal instability

  Transient, "Saw-tooth" behavior

  Inability to operate the linac



P. Krejcik et. al., PAC-93

- 1993

  Solution - vacuum chamber replacement. Total inductance was reduced by a factor of 5.

  Simulations predicted threshold of 5×10^{10}/bunch

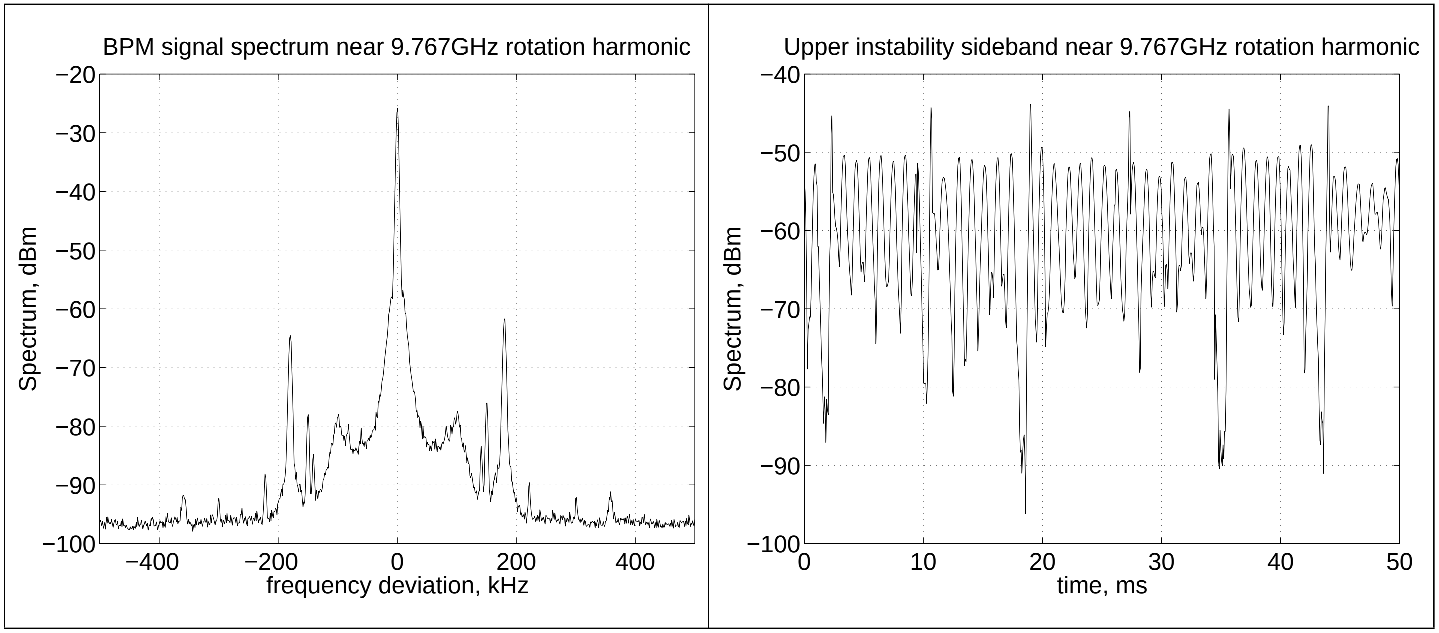
- 1994-1998

  The actual threshold went down ~2×10^{10}/bunch

  Instability less severe. Saturates at lower level. It is no longer the main limiting factor for the SLC

"New Saw-Tooth" Instability

BPM Signals on a Spectrum Analyzer



Other Measurements

- Wire scanner - energy spread growth above the threshold
- Streak Camera - no signs of instability other than bunch lengthening
- No measurable effect on the linac

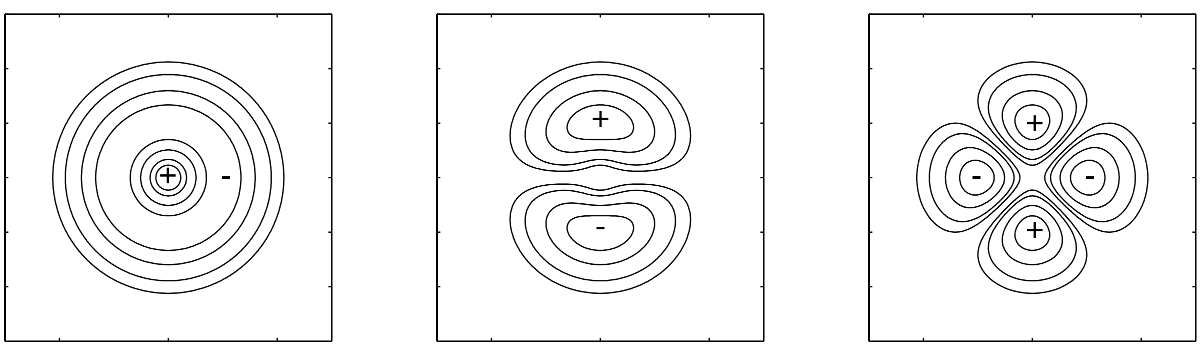
Something had to be there -> Need for new hardware

Collective Modes in Longitudinal Phase Space

- Canonical coordinates $x \equiv \frac{z}{\sigma_0}$, $p \equiv -\frac{\delta}{\delta_0}$, time normalized to synchrotron period $\tau \equiv \omega_{s0} t$, index denotes zero current
- Action-angle variables (usually from the steady state Haissinski solution) $\rho_H(p, x) \Rightarrow \rho_H(J)$
- In the limit of low intensity $J \rightarrow \frac{p^2}{2} + \frac{x^2}{2}$, $\varphi \rightarrow \operatorname{asin}\left(\frac{p}{x}\right)$
- Beam phase space density is Fourier transformed into sum over azimuthal modes

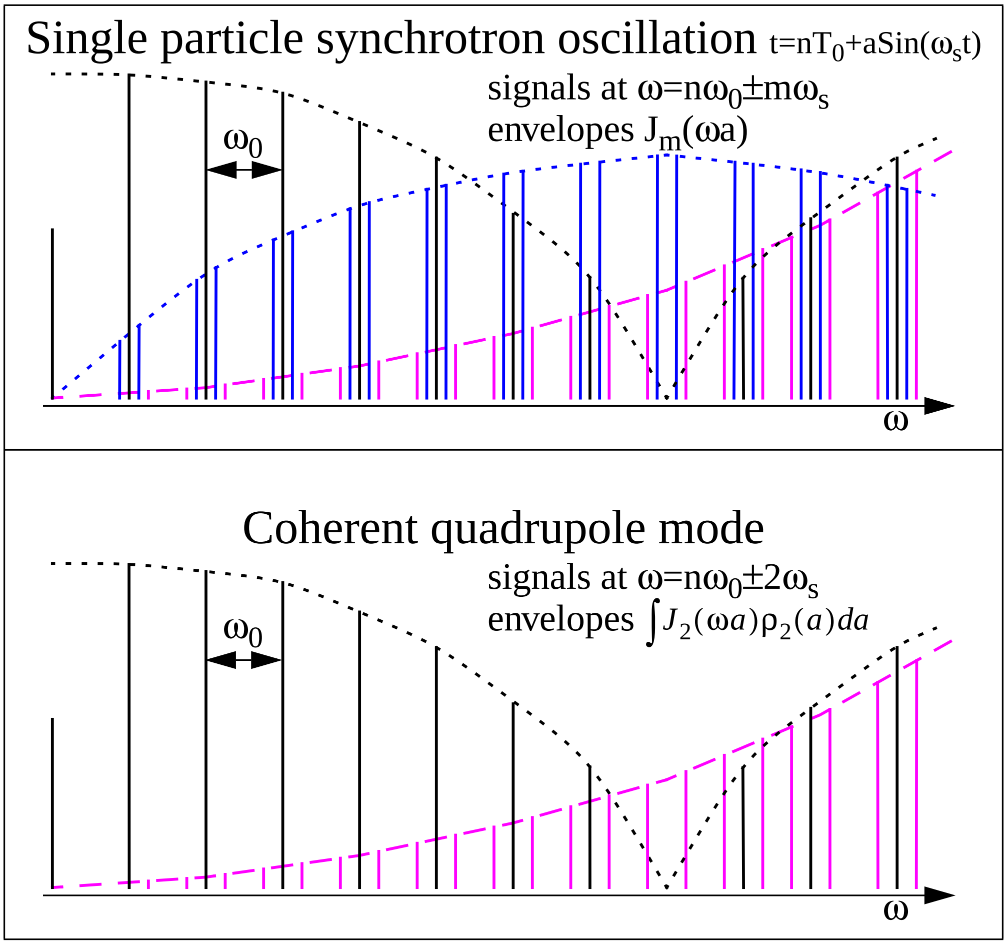
$$\rho(J, \varphi, t) = \sum_m \rho_m(J) e^{i\Omega\tau - im\varphi}$$

Example of the first three azimuthal modes



Monopole, m=0 Dipole, m=1 Quadrupole, m=2

BPM Signal Spectra and Longitudinal Phase Space



- m-th sideband suggests collective mode with m-fold azimuthal symmetry
- Need to go to high frequency ω~m/σ
- Spectrum completely describes beam phase space
- Radial structure is in the envelope
- Azimuthal orientation is in phase of any sideband

Experimental Goals

of our studies was to answer the questions

- What was the effect of the instability on the beam?
- What was the effect (if any) on the SLC performance?

Problems with Old Hardware

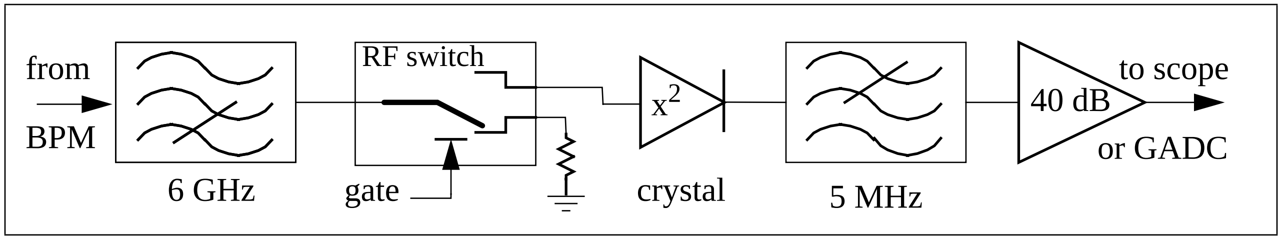
- Most instruments (wire scanner, streak camera) allowed only integrated measurements averaged over many injection cycles
- Spectrum analyzer shows instability presence within one injection cycle but not much else. It does not measure phase
- Studies of a single bunch instability require BPM signal from a single bunch
- Linac correlation studies require differentiation between bunches and stores

Ideas for New Apparatus

- We can distinguish two bunches employing fast RF switch
- Instability information resides mainly in sidebands to high frequency revolution harmonics. It can be demodulated from those sidebands
- Low frequency (less than a few GHz) BPM signal is not useful and too high in amplitude. It should be filtered out

Detecting Instability Signal I

Detector Schematics



Cuts RF power

Separates two bunches

Detects instability signal

Removes higher frequency products

Switch is gated at revolution frequency of 8.5 MHz and gate delay is adjusted to separate two bunches

RF Switch and Crystal Specifications

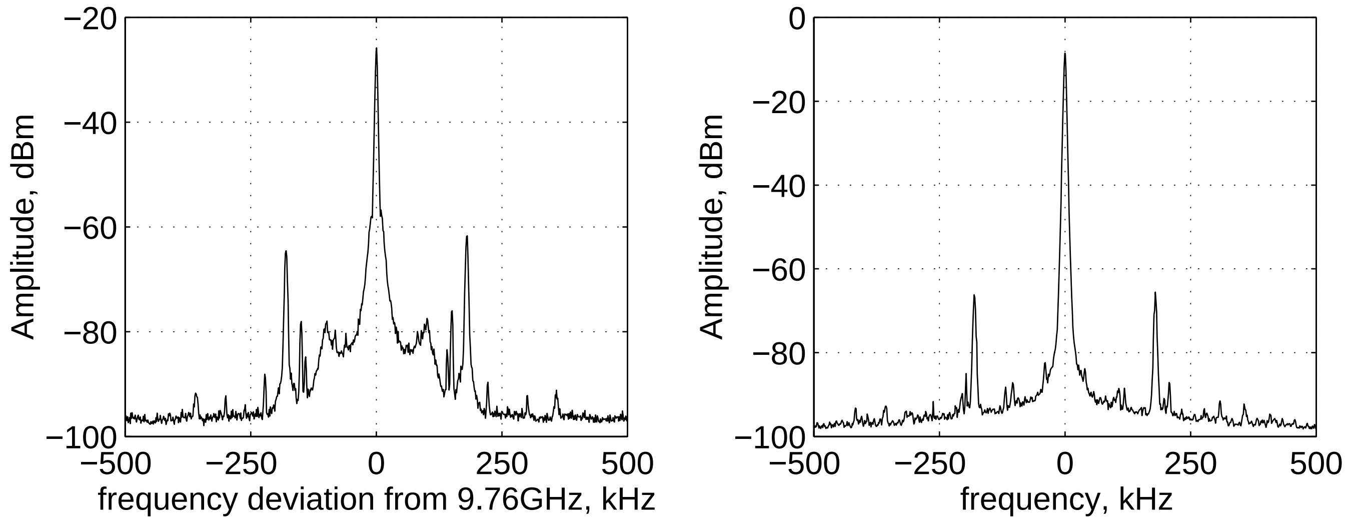
	WJ-MSE203	MITEQ-S138B	ACTP-1506N
Type	SPDT Reflective	SPST Absorptive	Square Law Detector
Bandwidth	2-18 GHz	2-18 GHz	8-18 GHz
Switching time	25 ns	20 ns	N/A
Isolation	~60 dB	80 dB	N/A
Video Bandwidth	N/A	N/A	2 MHz

Detector

- provides single bunch “instability signal”
- the phase of this signal relates to the azimuthal orientation of the instability-induced phase space structure

Detecting Instability Signal II

Spectrum Analyzer Traces before and after the Crystal



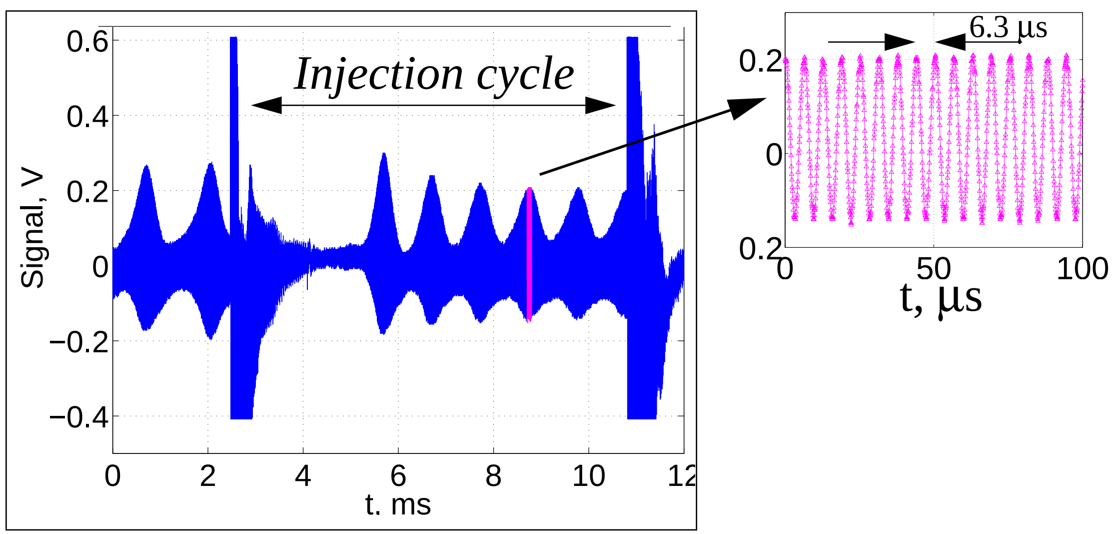
Signal after the Detecting Circuit

Instability frequency

160 kHz <~ 2 f_s

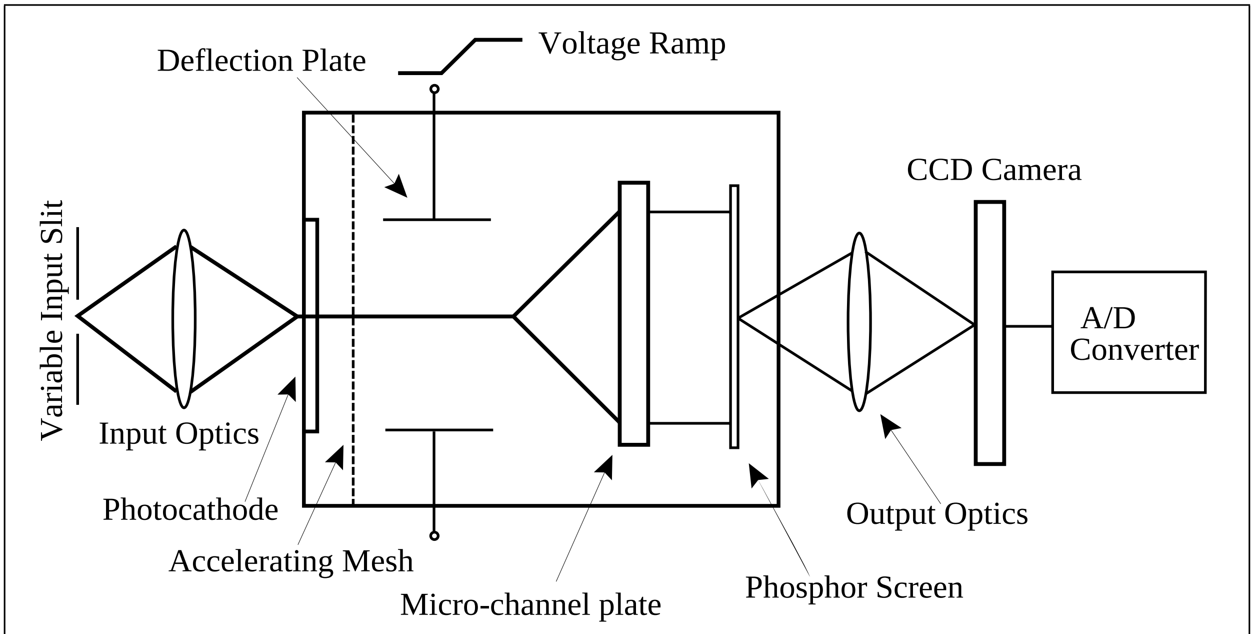
Envelope frequency

1 kHz ~ γ_d



Streak Camera

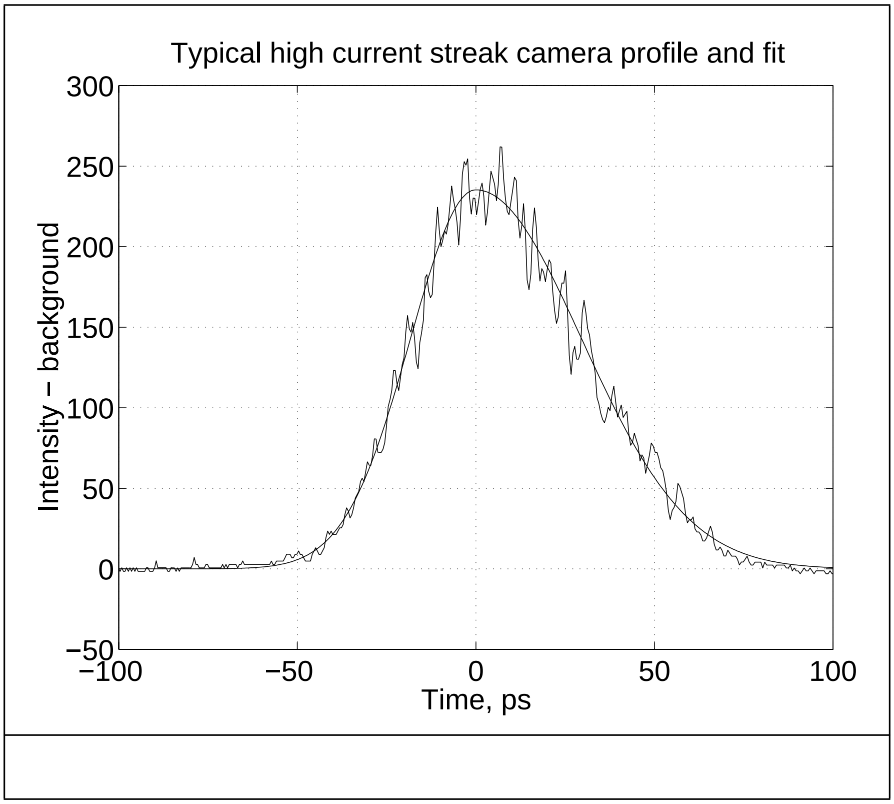
Layout and Major Specifications



HAMAMATSU FESCA-500 STREAK CAMERA & CCD SYSTEM	
Type	Single Sweep
Time Resolution	< 700 fs
Spectral Response	400-800 nm
Streak Rate	60-1200 ps/10 mm
Trigger Jitter	< 30 ps
Trigger Rate	< 1 kHz
CCD # of Pixels	1000 by 1018
CCD Readout time	> 4 s

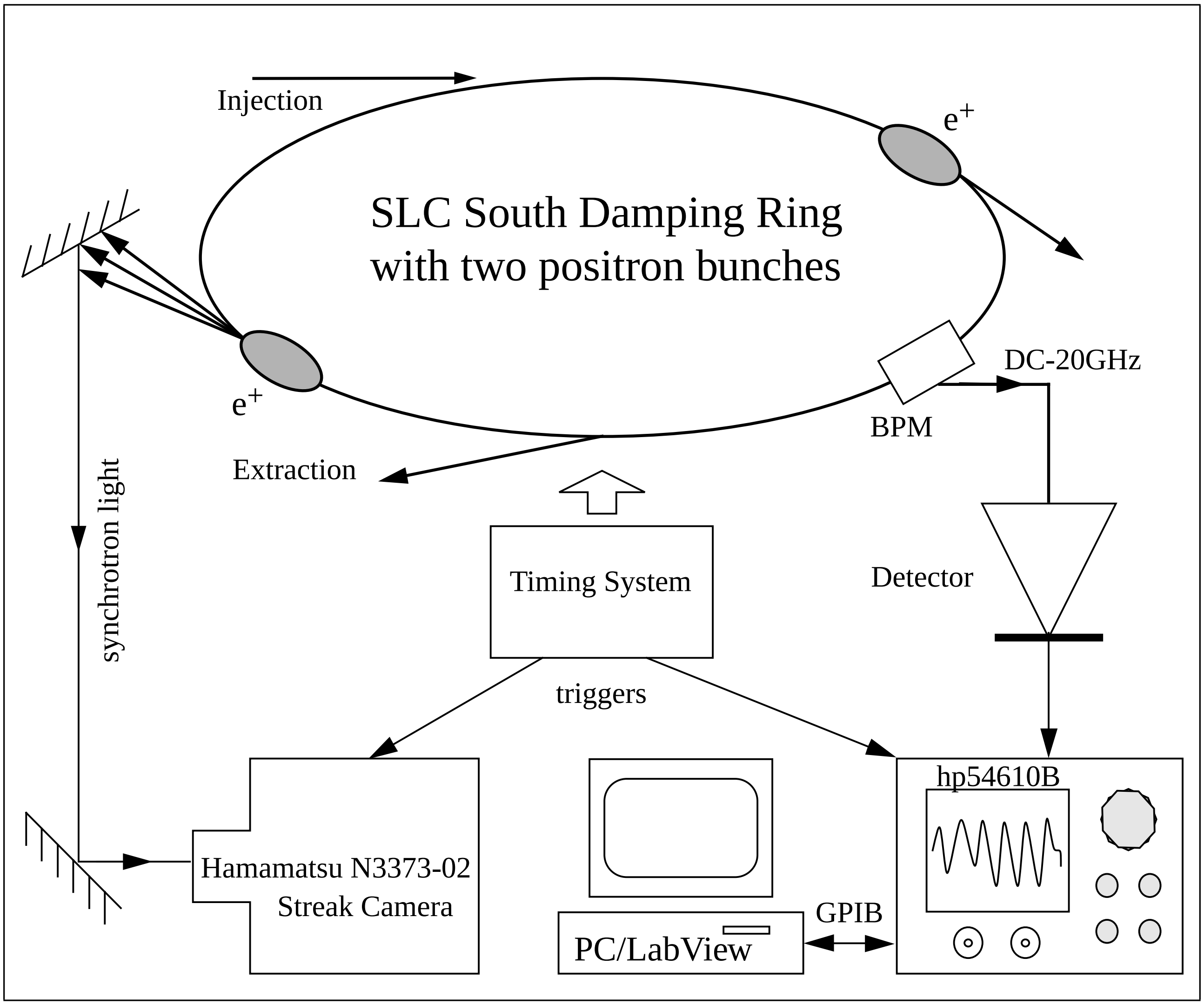
- Advantages: extremely high resolution
- Problems for instability studies: noise, slow data acquisition, trigger jitter, stand-alone instrument...

Streak Camera Data



- Clear potential well distortion
- Significant amount of noise
- No obvious signs of instability

Streak Camera Instability Study: Setup

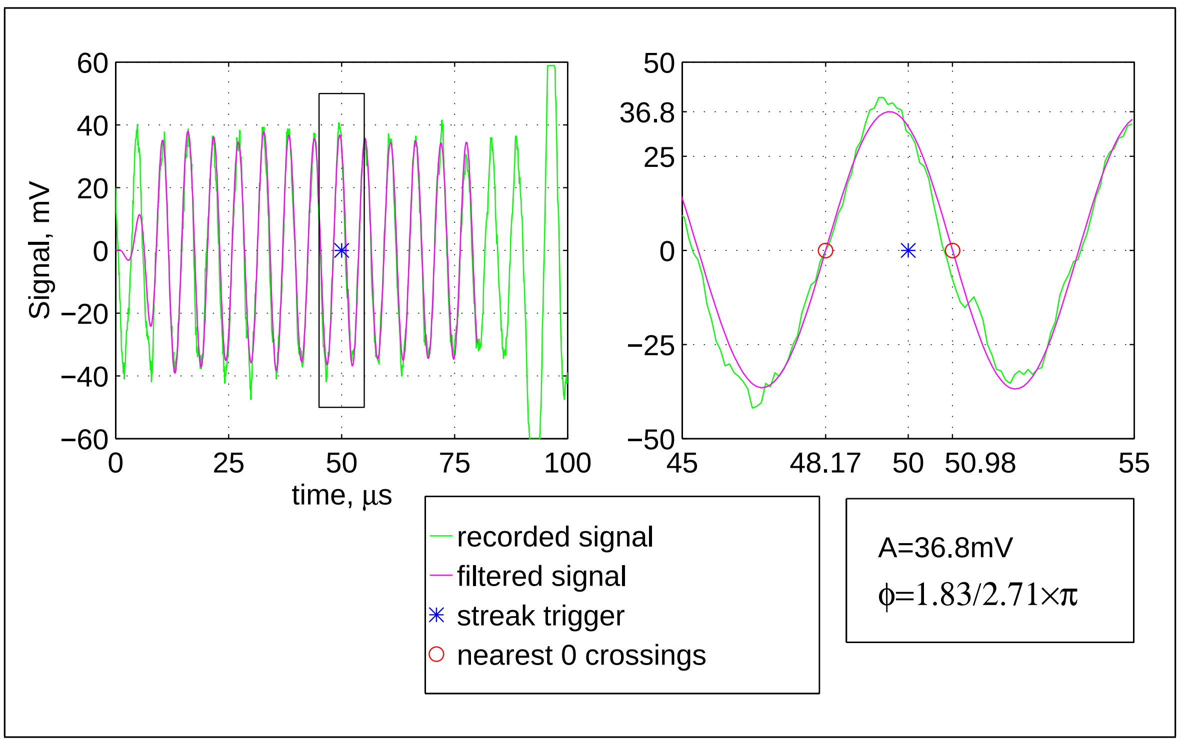


Streak Camera Instability Study: Data Analysis

Scope traces:

- Digitally filtered to reduce noise
- Used to extract instability amplitude and phase

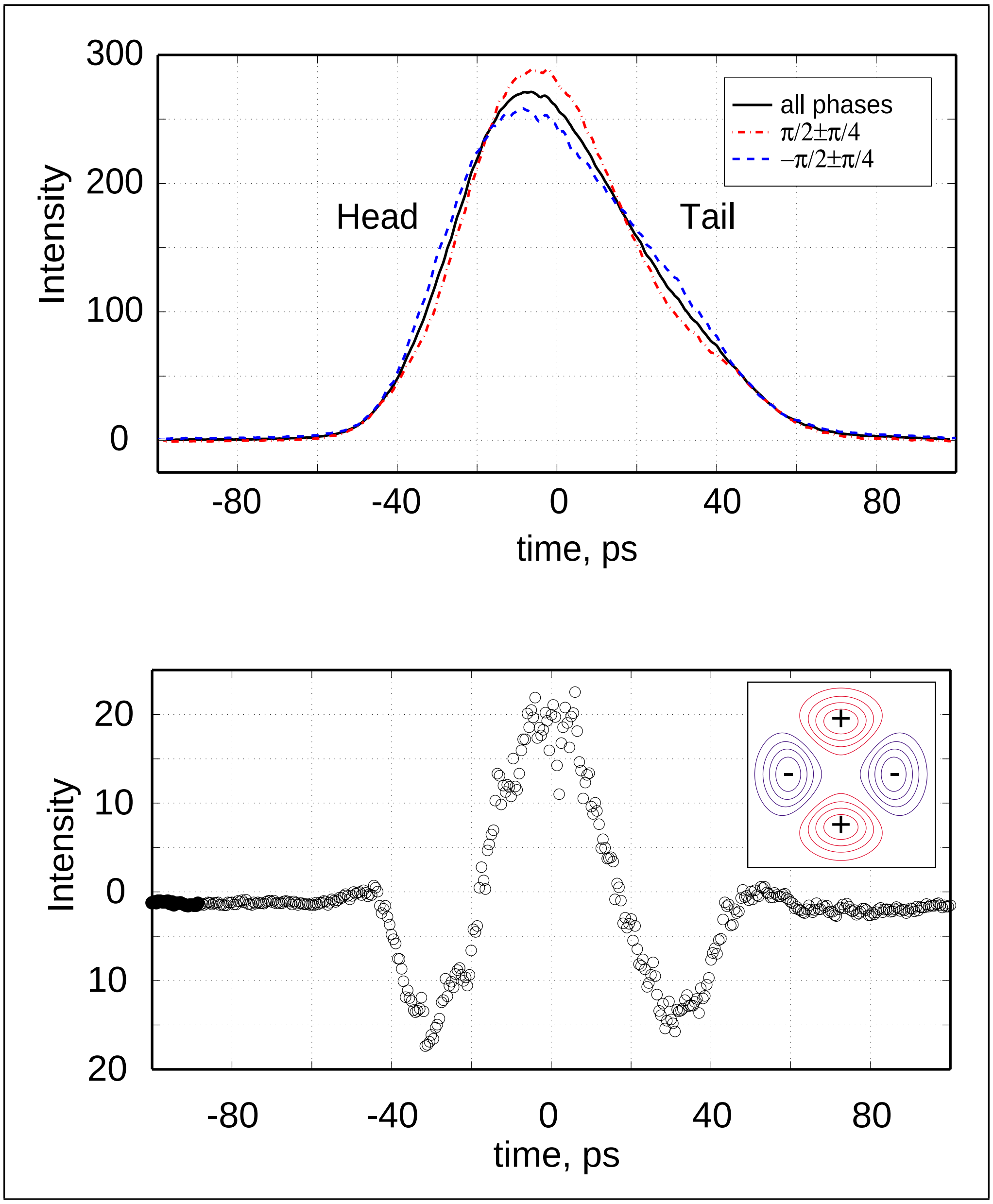
Extracting “Instability Phase” from Scope Traces



Streak profiles:

- Calibrated for sweep nonlinearity
- Binned in instability amplitude and phase

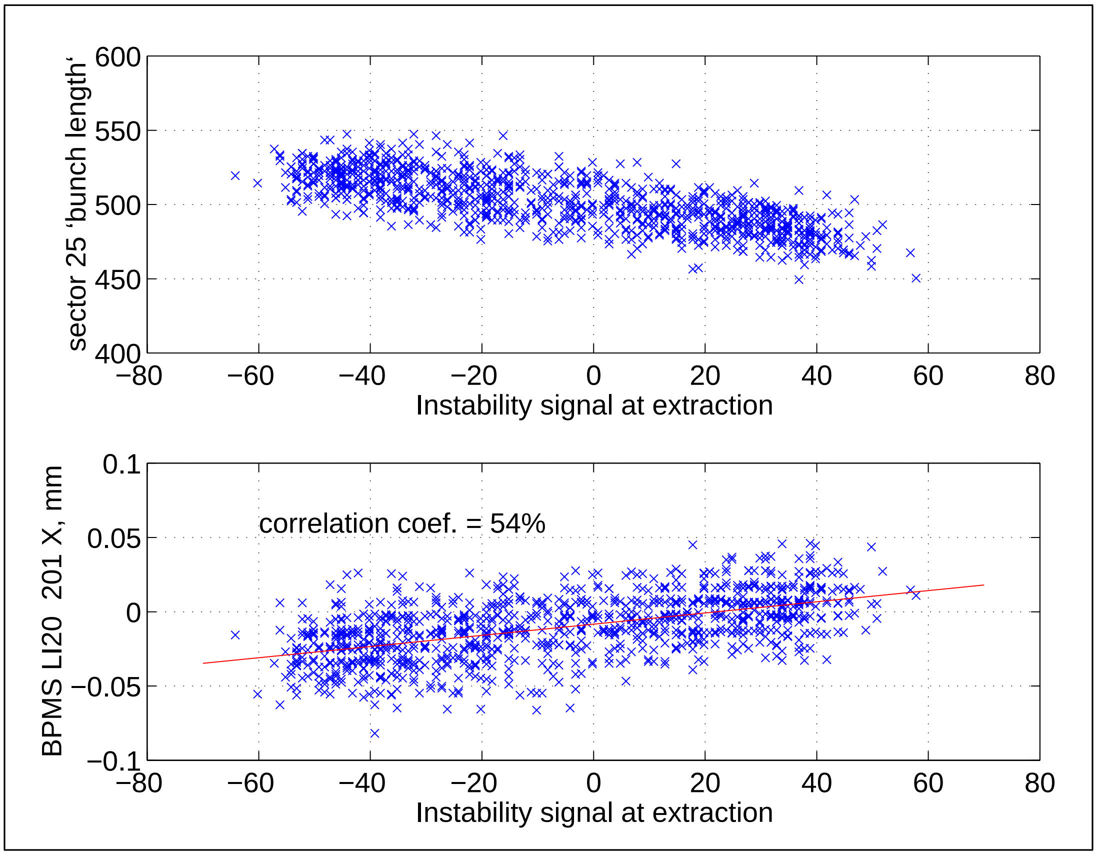
Streak Camera Instability Study: Results



Unstable mode contains ~3% of beam

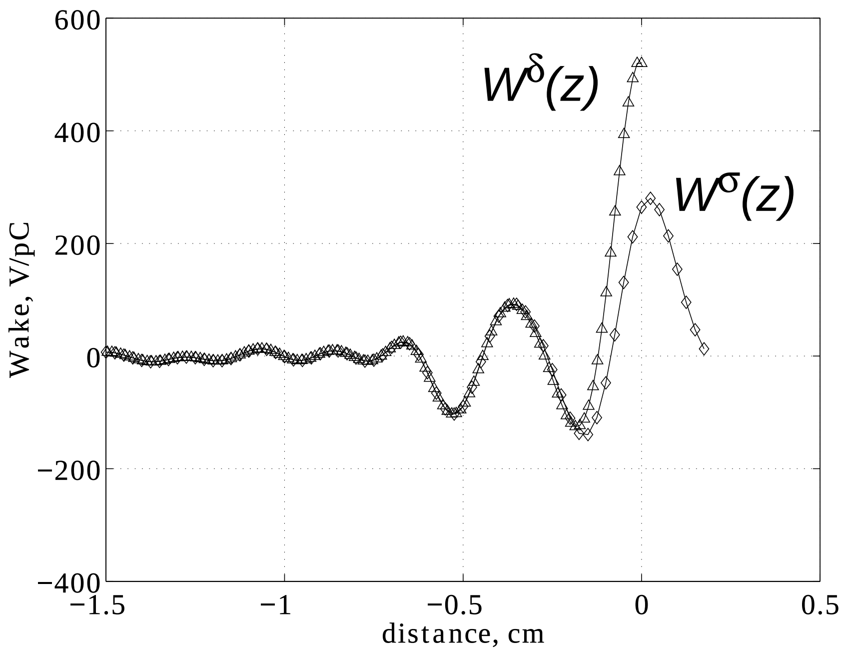
Linac Correlation Experiment

Correlating Instability Signal at Extraction with Linac Bunch Length and Trajectory



- Instability contributes to the transverse jitter in the linac
- We estimate that about 40% of the jitter power is caused by the instability
- This effect could be a problem for NLC

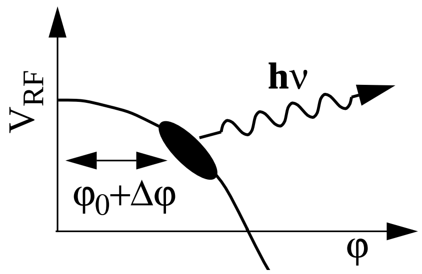
Bane-Ng Wake Function Model for the SLC Damping Rings



- Calculated using time-domain parts of MAFIA programs
- Used σ=0.1 mm driving bunch
- Accounted for all the metallic structures in the chamber
- Hard to model 3D structures were treated approximately

Synchronous Phase Measurement I

Physics: Losses = Radiation + Wake-Related



φ_0 *synch. phase at N->0*
σ_0 *bunch length at N->0*
U_0 *energy loss/turn due to Synch. Rad.*
$\tilde{\rho}(\omega)$ *Fourier transform of* $\rho(z)$

- $eV_{RF}\cos(\varphi_0+\Delta\varphi) = U_0 + ke^2N$ Energy balance
- $k = -\frac{\Delta\varphi}{eN}V_{RF}\sin\varphi_0$ Loss factor
- $k = \frac{1}{2\pi}\int Re(Z(\omega))|\tilde{\rho}(\omega)|^2 d\omega$ Relation to impedance
- $R = \frac{2\sqrt{\pi}\sigma_0 k}{c}$ Effective resistance

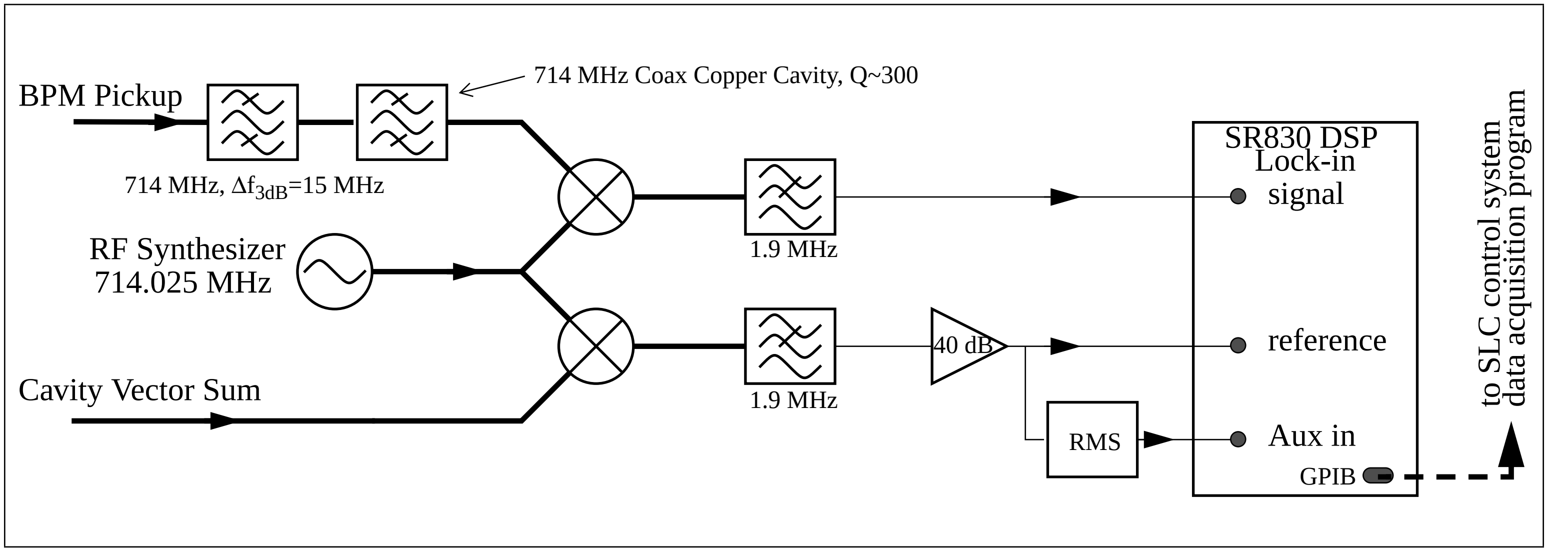
Predictions for SLC Damping Rings based on Bane-Ng model:

- $k \sim 15$ V/pC $R \sim 950\ \Omega$ Calculated values
- $\frac{\Delta\varphi}{\Delta N} \sim 1.7°$ per 10^{10} particle loss

Small value, hard to measure

Synchronous Phase Measurement II

New Apparatus



SR830 Specifications

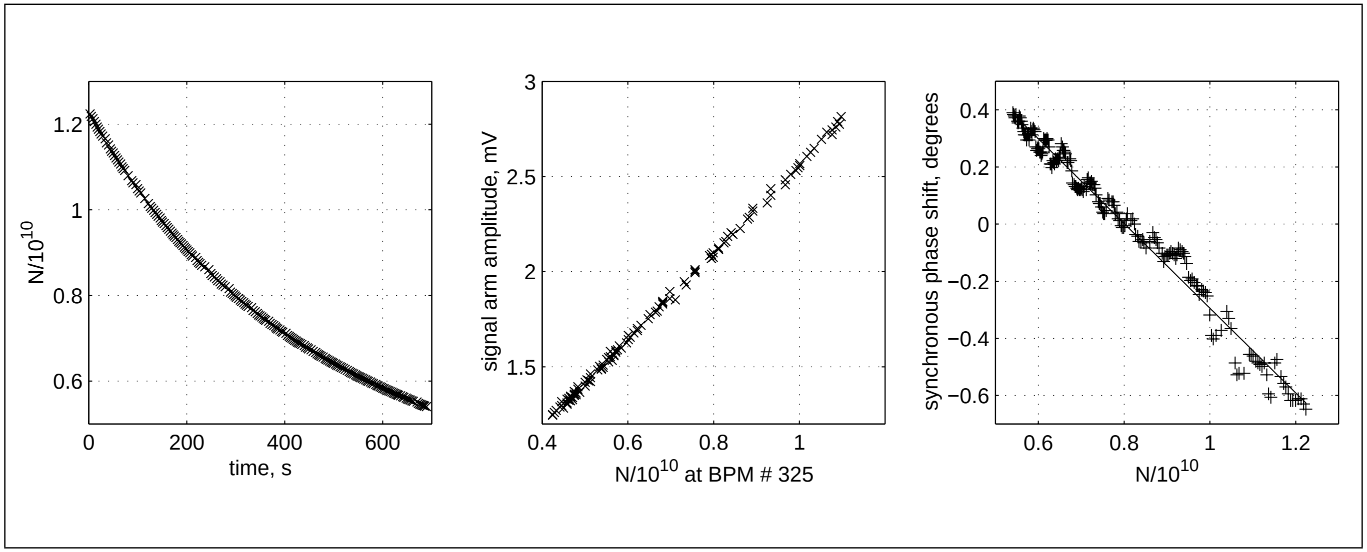
Frequency Range	1 mHz to 102 kHz
Rel. Phase Error	< 0.01°
Phase Drift	< 0.1°/°C
Time Constants	10 µs to 30 s
Dynamic Reserve	> 100 dB

Advantages of the apparatus over standard vector voltmeters

- Precision
- Flexibility
- Low cost

Synchronous Phase Measurement III

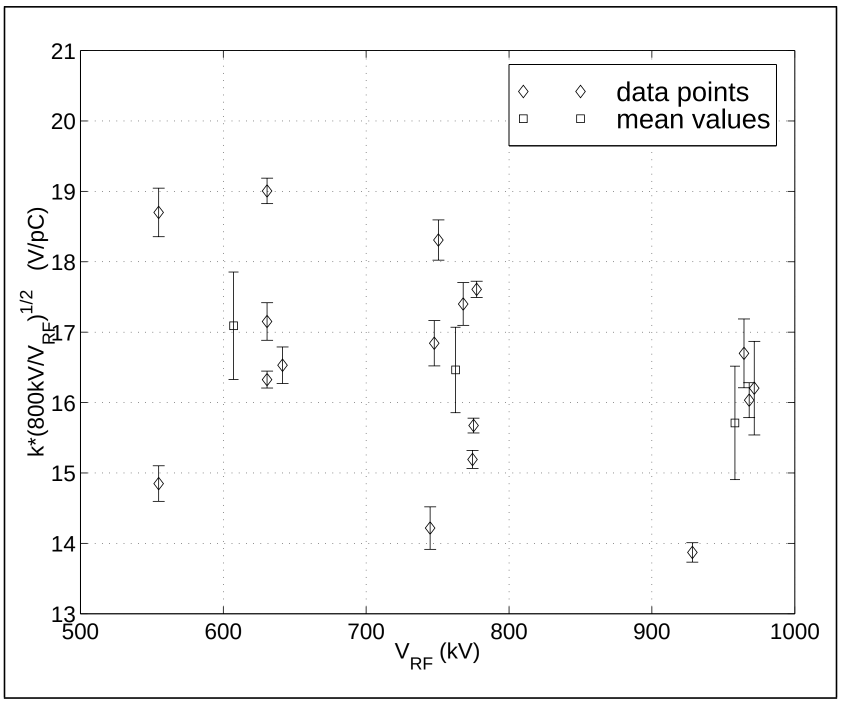
Raw Data for a Typical Store



- Signal is clearly beam induced
- Phase changes linearly with current
- Reproducible from store to store

Synchronous Phase Measurement IV

Results

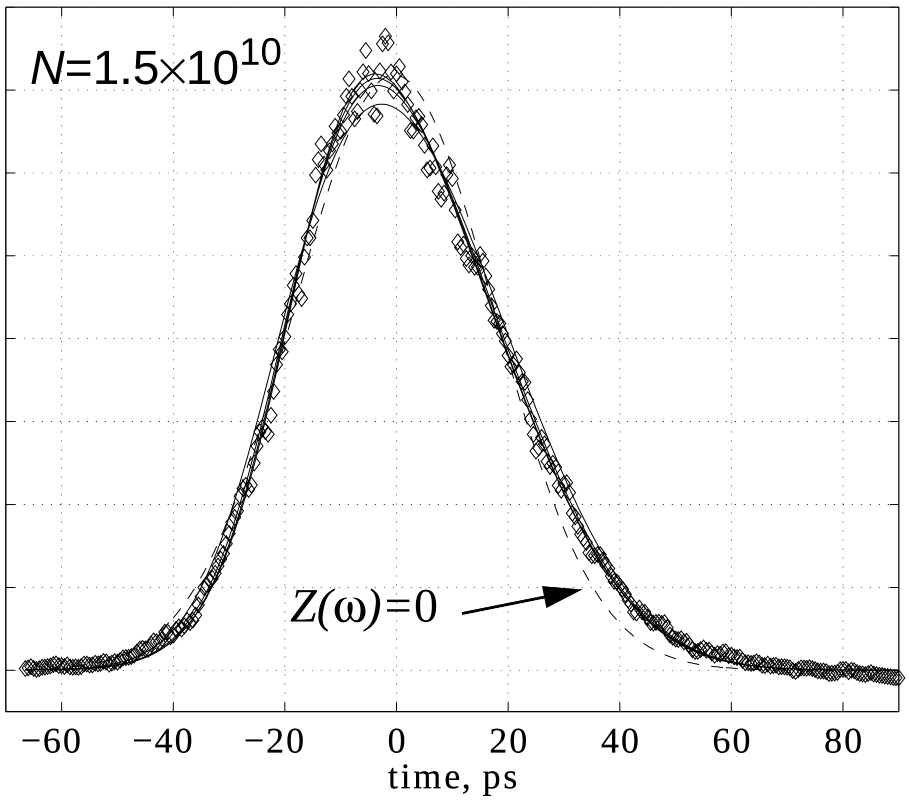


$$k = 16.5\ V/pC \pm 15\%$$

$$(R \sim 1\ k\Omega)$$

- Consistent values
- Error mainly due to uncertainty in V_{RF} , N
- Good agreement with calculations and streak camera bunch shape measurements at low current.

Impedance Estimate from Low Current Bunch Shape



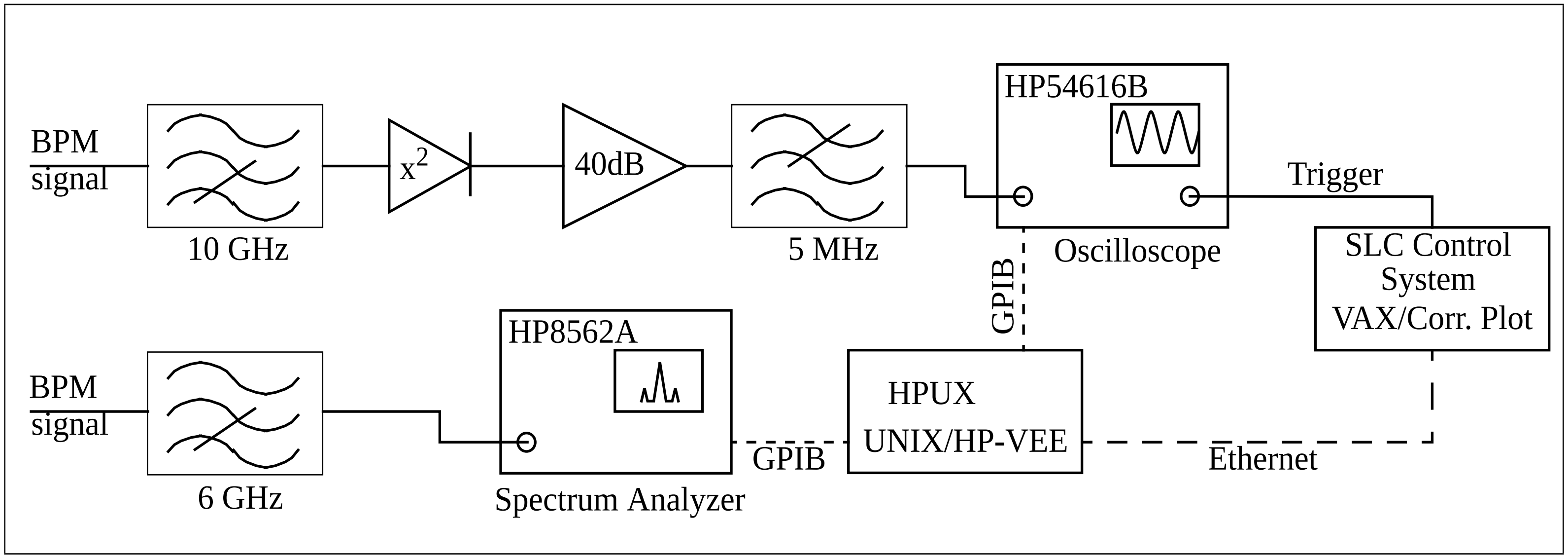
- Recorded beam profiles at $N=9\times10^{10}$-1.5×10^{10}
- Fitted them with Haissinski solution for $Z(\omega)=0$, $Z(\omega)=R$, $Z(\omega)=R-i\omega L$, and Bane-Ng wake model
- Results: $R=1$ kΩ± 130 Ω, L~few nH (fits poorly)
- Agrees well with Bane-Ng model
- Problems: indirect method, not enough sensitivity

Summary of Impedance Measurements

- Used three different methods
- Consistent results
- Agreement with Bane-Ng model
- Cannot measure more than 2-3 parameters

Question: How many impedance parameters do we need to explain high current phenomena?

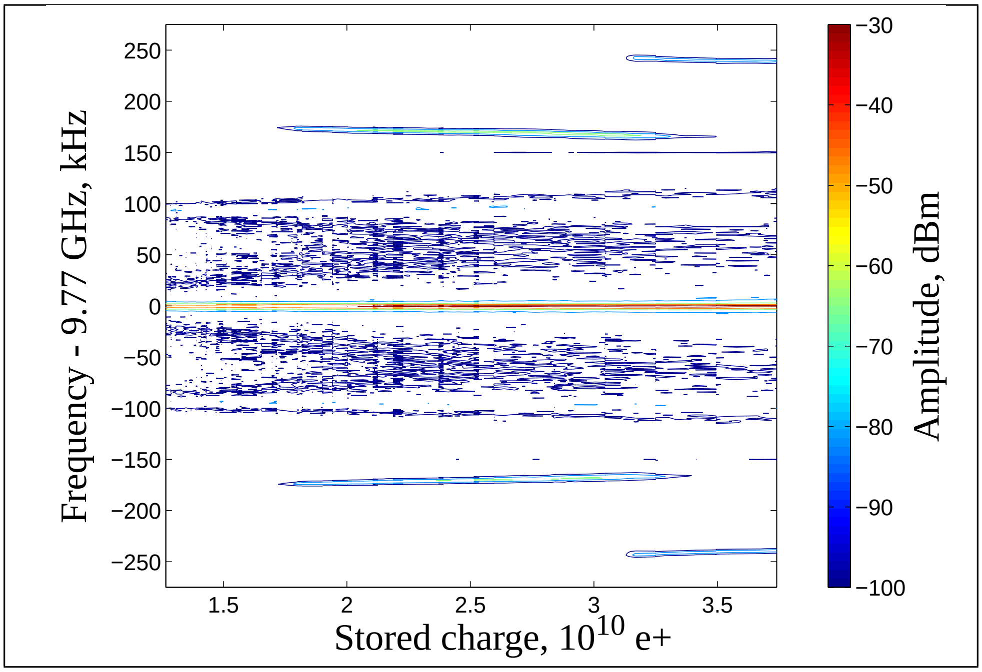
Stored Beam Experiment: Setup



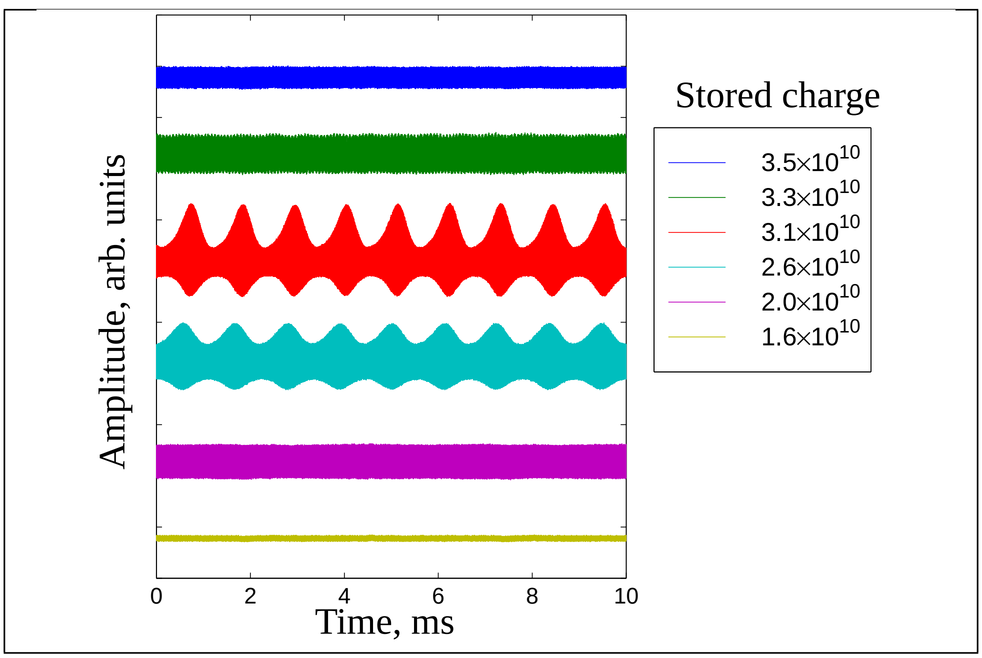
- Positron ring, Single bunch stores ~10 minutes
- Charge decays down from ~3.5×10^{10}
- Different RF voltages 600 kV<V_{RF}<1 MV
- High frequency BPM signal is measured directly with a spectrum analyzer
- Similar signal from other BPM is demodulated in the detector circuit and measured with an oscilloscope

Stored Beam Experiment: Data

Spectrum Analyzer Data

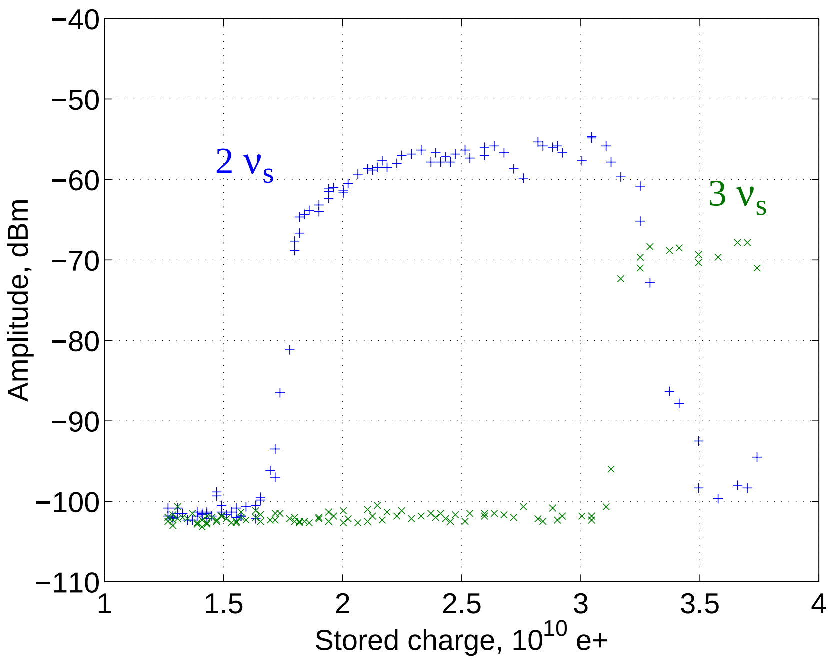


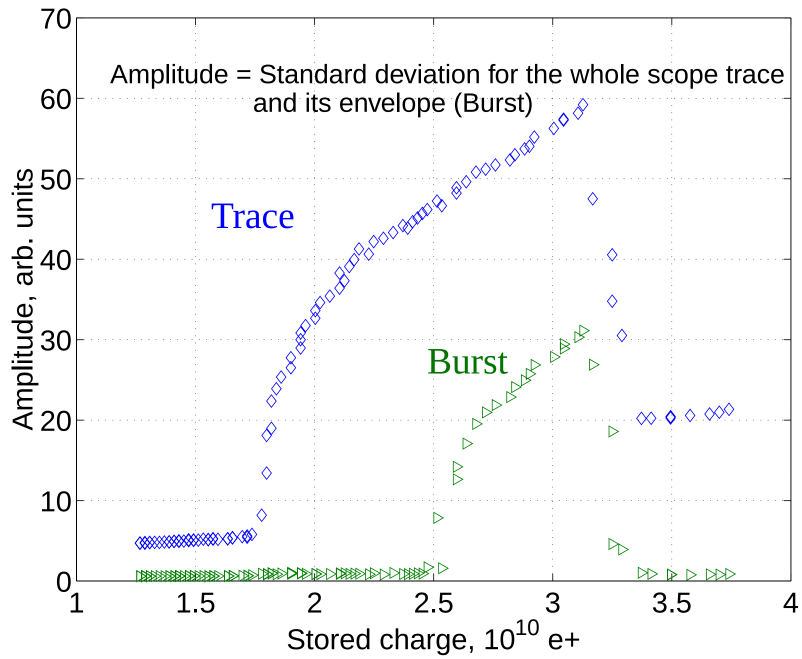
Scope Traces for Different Stored Charge



Stored Beam Experiment: Results

Instability Amplitudes from Spectrum Analyzer (left) and Scope Data





- Measurement agreement between two instruments
- Clear thresholds for quadrupole and sextupole modes
- Region of bursting behavior for quadrupole mode
- Quadrupole mode disappears at $N>3.3\times10^{10}$
- Cannot be explained by azimuthal mode coupling

Conclusion

- New hardware for instability diagnostics ✔
- Measured properties of instability ✔
    - Phase space structure
    - Effect on the linac
    - Driven and self-excited beam response
- Impedance-related measurements ✔
    - Agreement between different experiments
    - Agreement with calculated model
- Theoretical explanation ✔?