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Saw-Tooth Instability Studies in the Stanford Linear Collider Damping Rings

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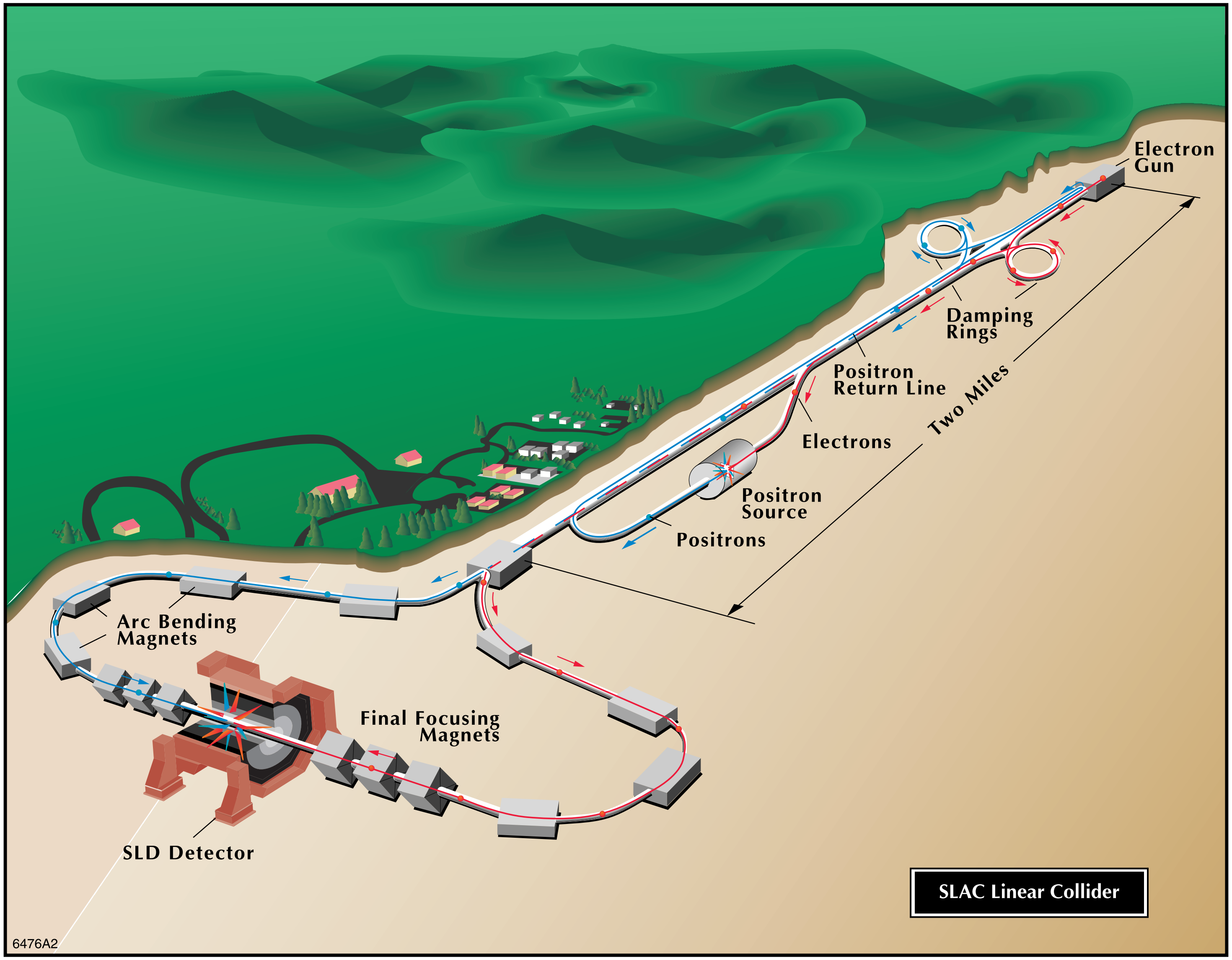
Outline

- Introduction
  SLC, Damping Rings, BPM signals, Instability history
- Hardware
  BPM signal processing, Streak camera
- Experimental results
  Instability phase space structure, Linac correlation studies, Stored beam studies
- Theoretical understanding
- Conclusions and outlook

Stanford Linear Collider



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
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
Momentum Compaction	α	0.015
Energy Damping Time (NDR, SDR)	τ_d, γ_d^{-1}	1.91 ms, 1.78 ms

High Peak Current => Longitudinal Single Bunch Effects?

Instability History

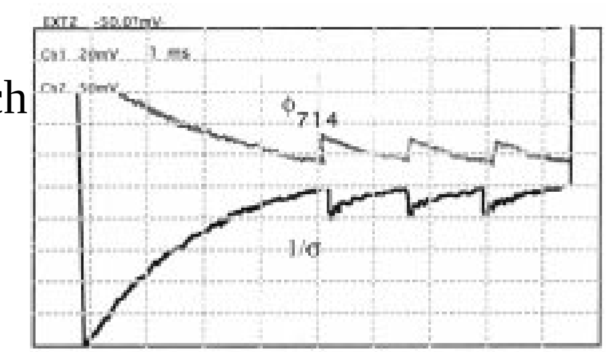
- 1992

  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

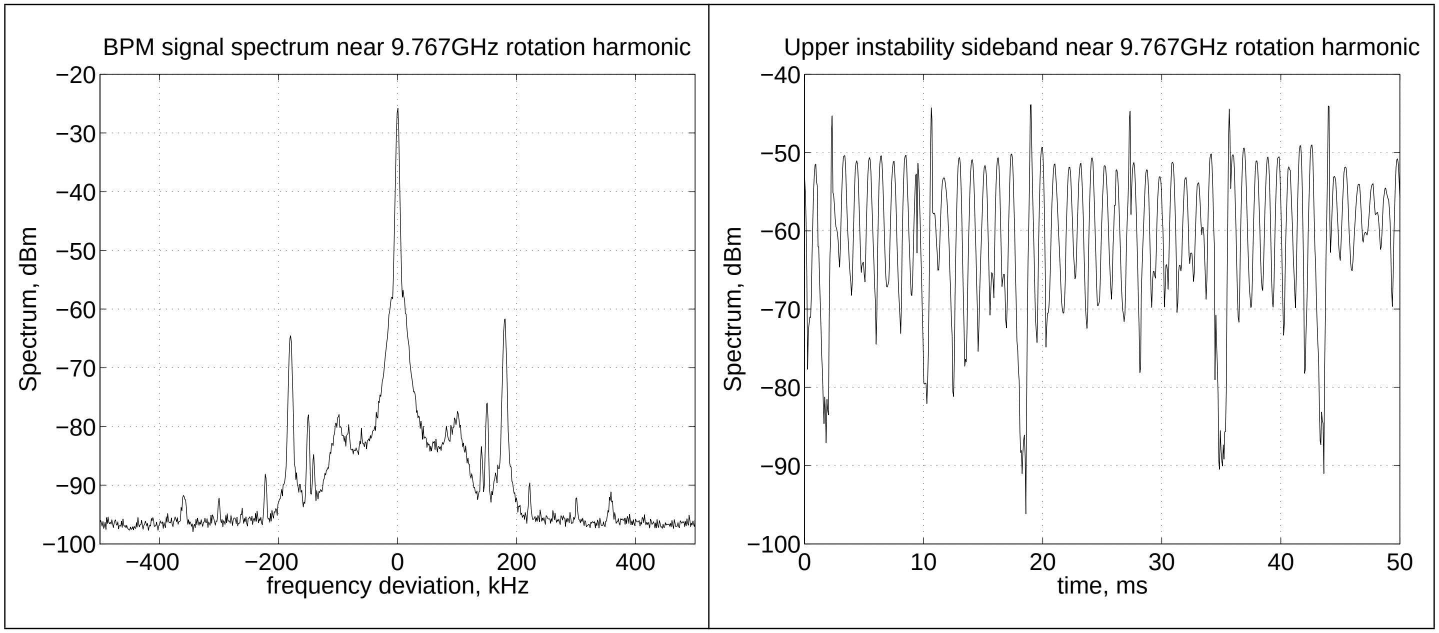
- 1994-1998

  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

How to interpret BPM spectra?

Motivation

for our studies was to find out the following

- Effect of the instability on the beam
- Effect (if any) on the SLC performance
- Some clues into the instability mechanism

Problems with Old Diagnostics

- Most instruments (wire scanner, streak camera) average over many injection cycles

- Spectrum analyzer shows instability presence within one injection cycle but the data cannot be directly connected to the quantities of interest (i.e. phase-space snap-shots)

- Studies of a single bunch instability require BPM signal from a single bunch

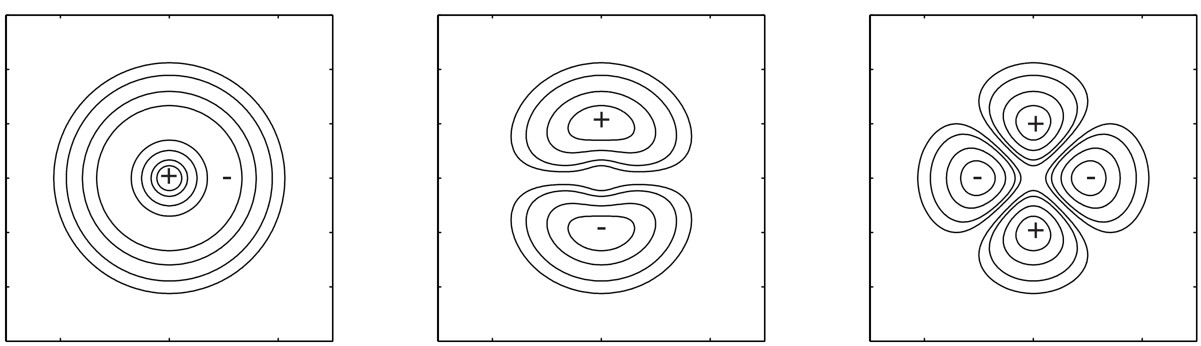
- Linac correlation studies require differentiation between bunches and stores

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 $J \to \frac{p^2}{2} + \frac{x^2}{2}\ ,\ \ \varphi \to \operatorname{asin}\left(\frac{p}{x}\right)$
- Beam phase space density is Fourier transformed into sum over azimuthal modes

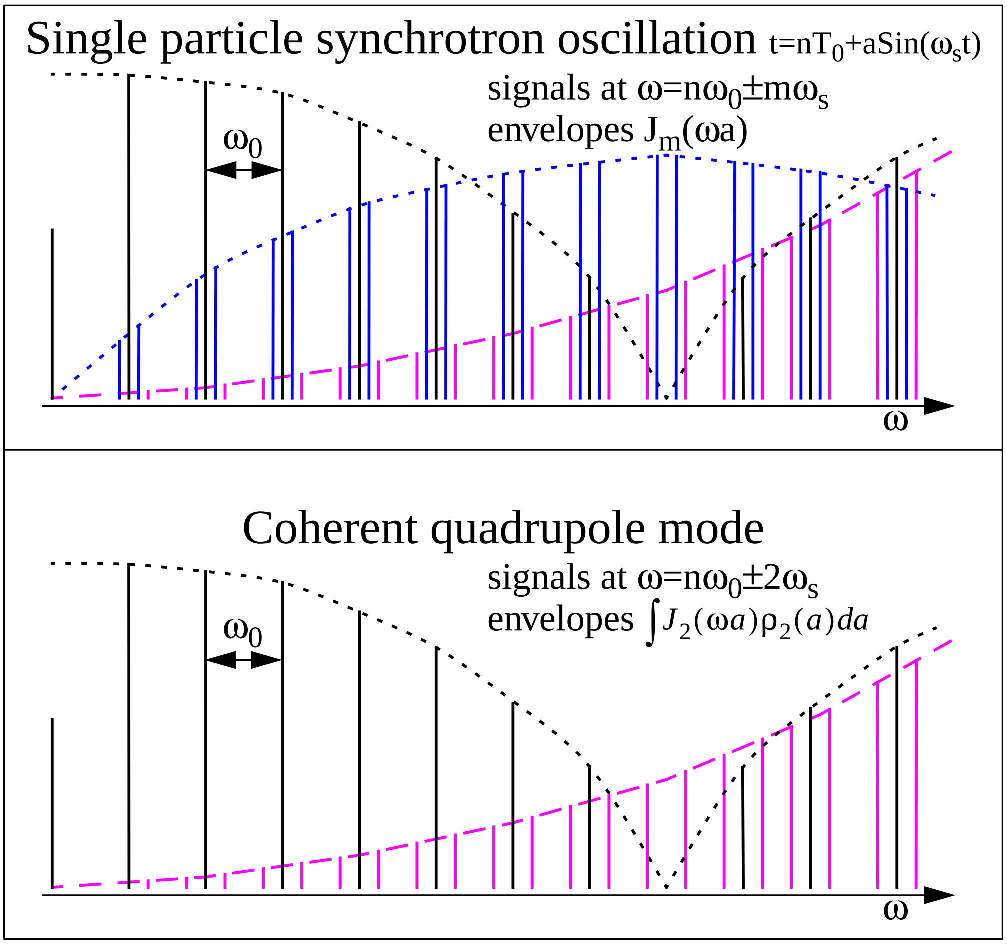
$$\rho(J, \varphi, \tau) \ = \ \sum_m \rho_m(J) e^{i\Omega\tau - im\varphi}$$

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 $\omega \sim m/\sigma$
- Spectrum completely describes beam phase space
- Radial structure is in the envelope
- Azimuthal orientation is in phase of any sideband

Ideas for New Apparatus

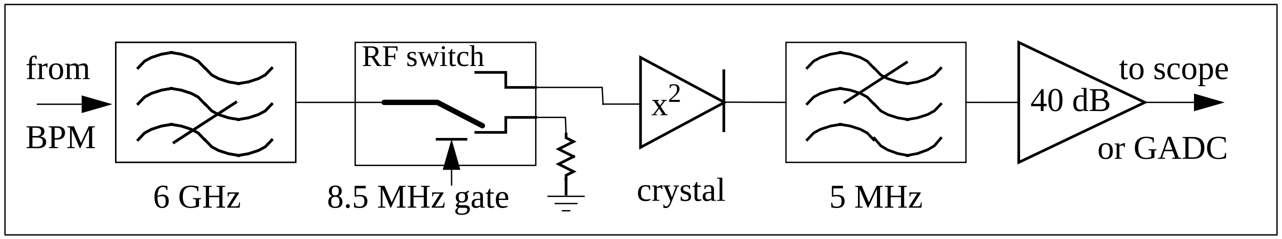
- Instability information resides in sidebands to high frequency revolution harmonics. It should be possible to extract instability information from can be demodulated from those sidebands

- Low frequency (less than a few GHz) BPM signal is not useful and too high in amplitude. It should be filtered out

- Separate signals from two bunches by a fast RF switch

Detecting Instability Signal I

Detector Schematics



Cuts RF power | Separates two bunches | Detects instability signal | Removes higher frequency products

RF Switch and Crystal Specifications

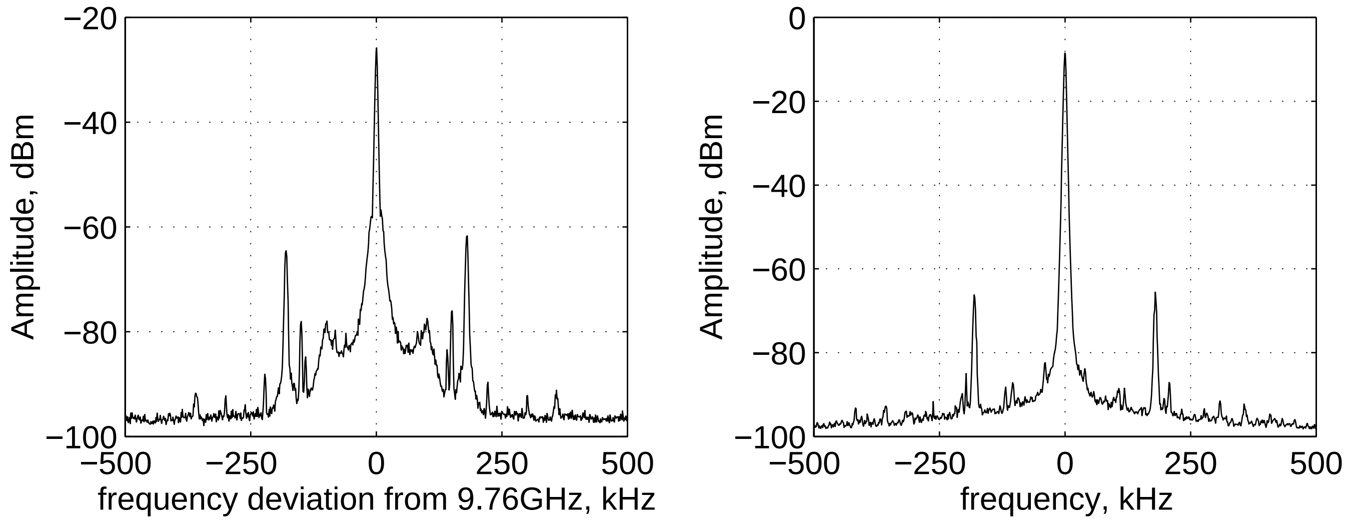
	WJ-MSE203	MITEQ-S138B	ACTP-1506N
Type	SPDT Reflective	SPST Absorptive	Square Law Detector
Bandwidth	2-18 GHz	2-18 GHz	8-18 GHz
Switching time	25 ns	20 ns	N/A
Isolation	~60 dB	80 dB	N/A
Video Bandwidth	N/A	N/A	2 MHz

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



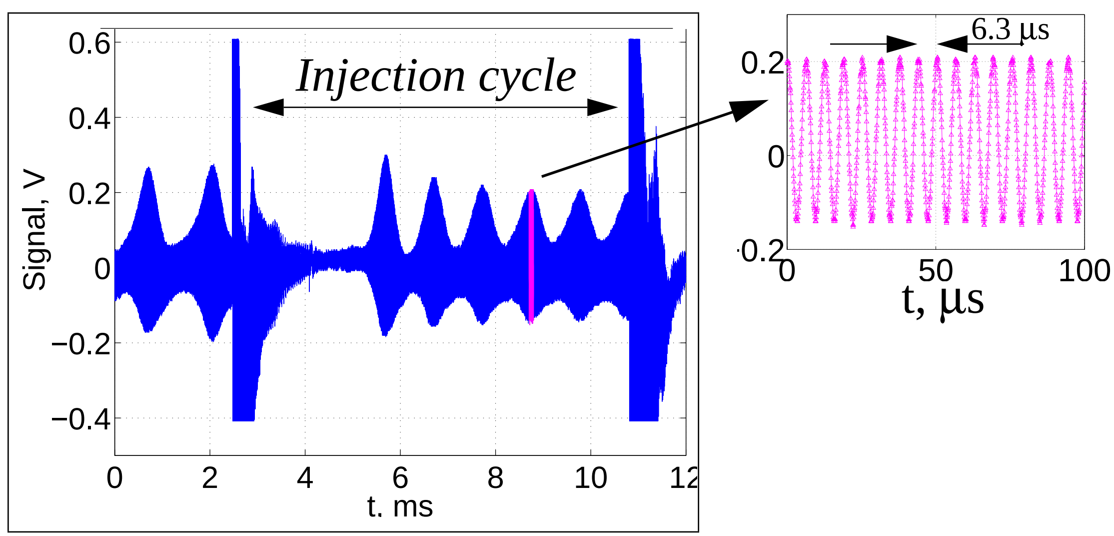
Signal after the Detecting Circuit

Instability frequency

160 kHz <~ 2 f_s

Envelope frequency

1 kHz ~ γ_d

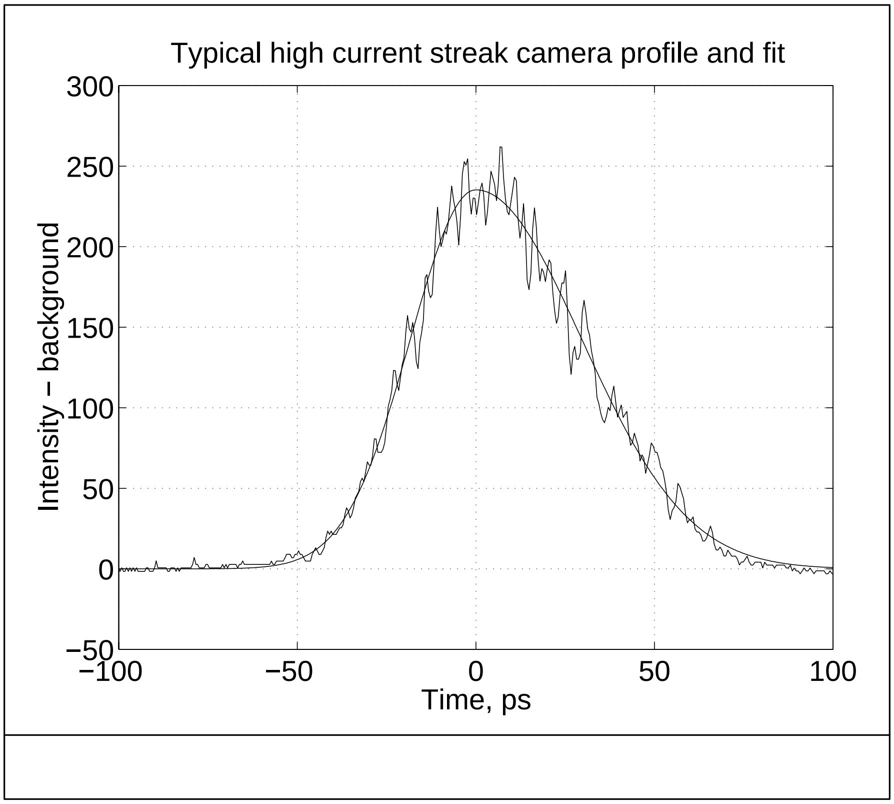


Streak Camera

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

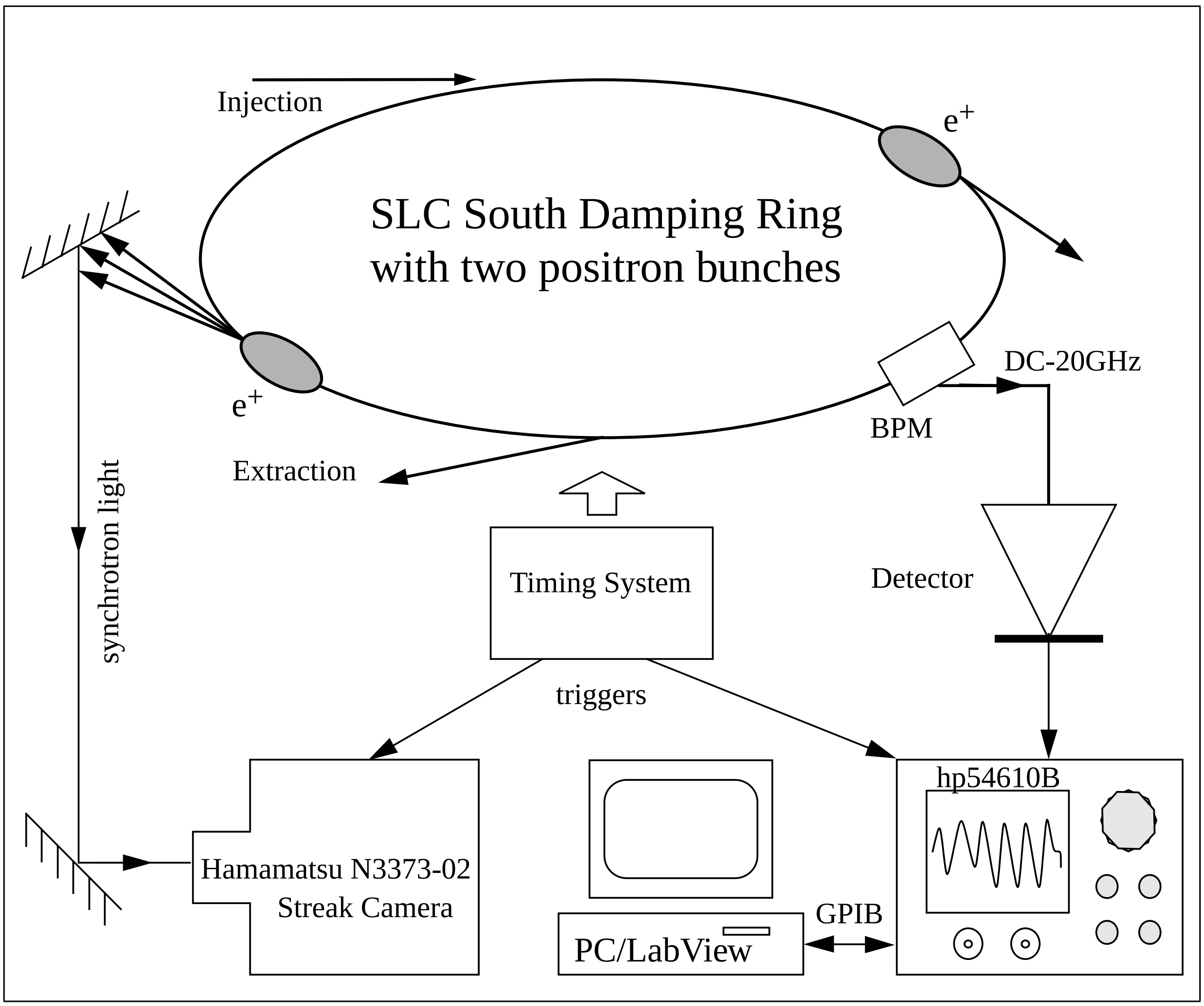
- Advantages: extremely high resolution
- Problems for instability studies: noise, slow data acquisition, trigger jitter, stand-alone instrument...

Typical Streak Camera Data



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

Streak Camera Instability Study: Setup

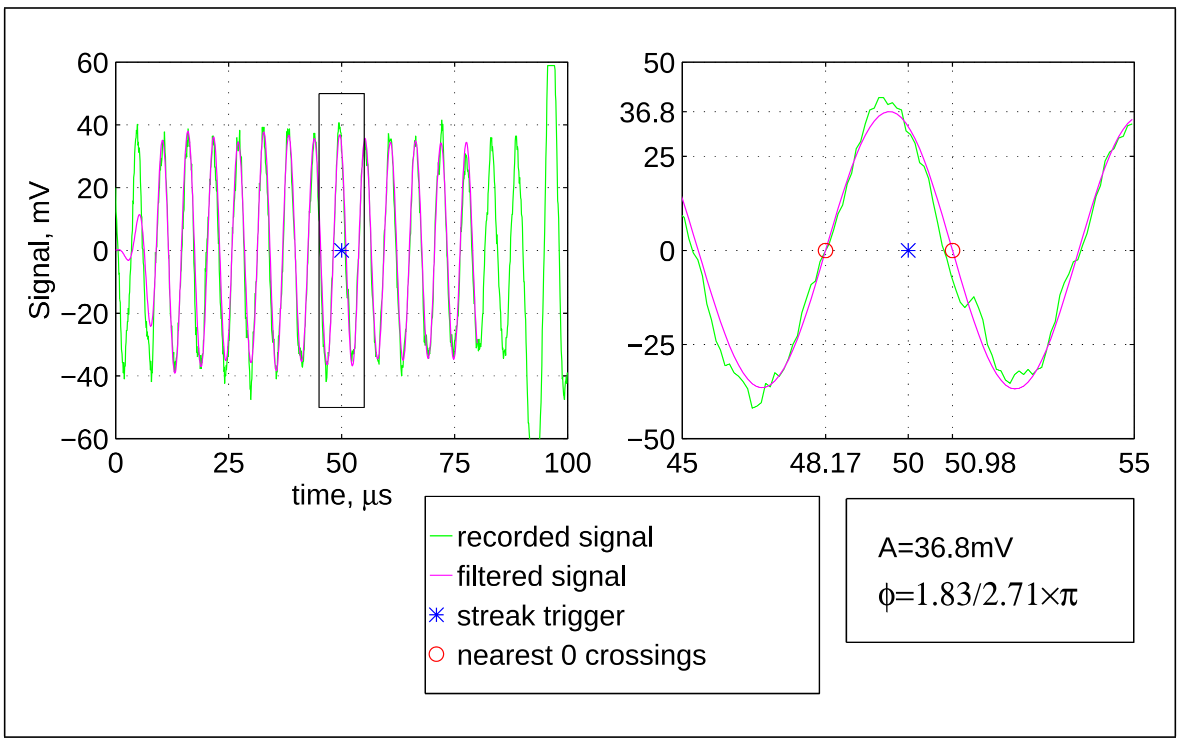


Streak Camera Instability Study: Data Analysis

Scope traces

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

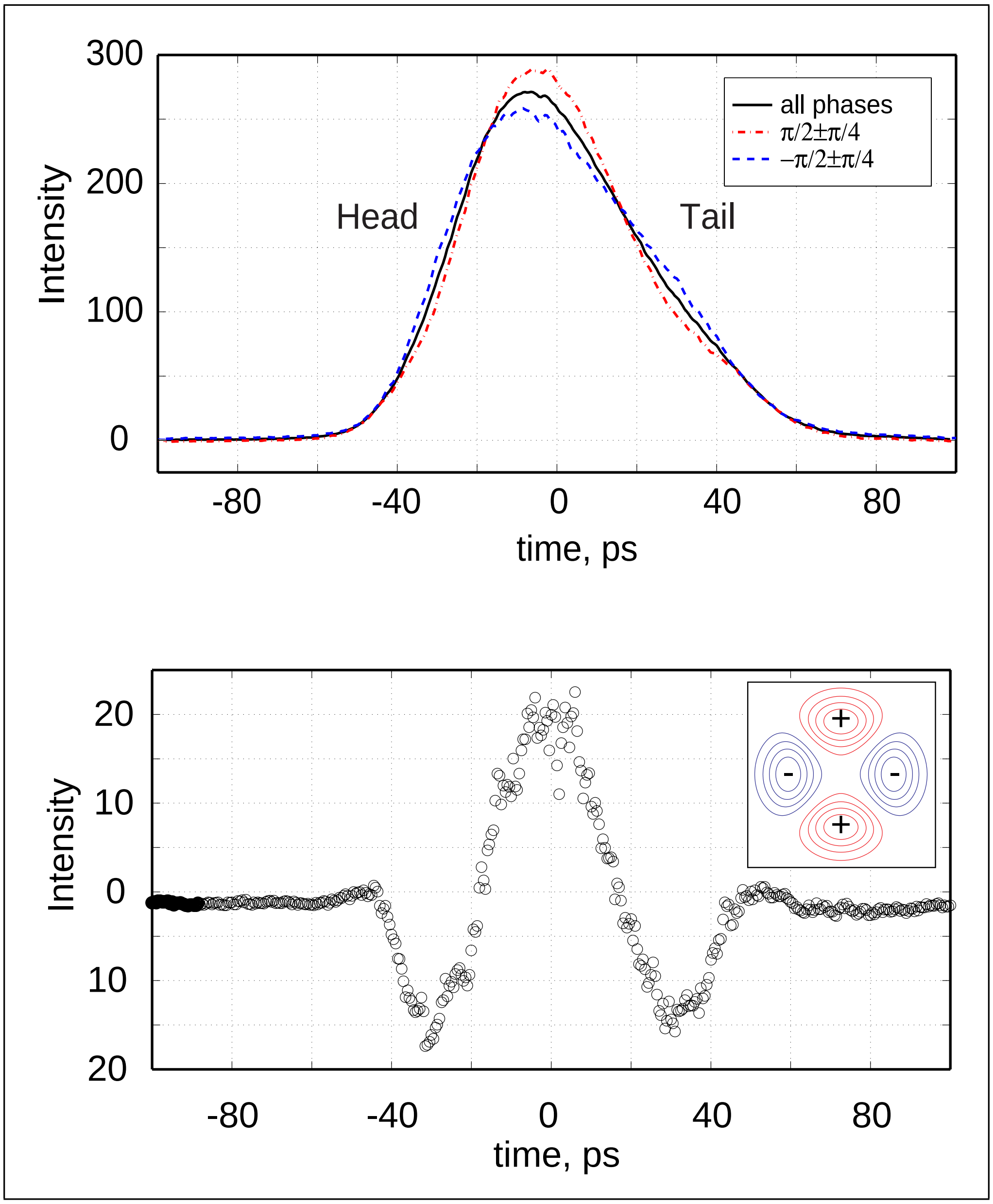
Extracting “Instability Phase” from Scope Traces



Streak profiles

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

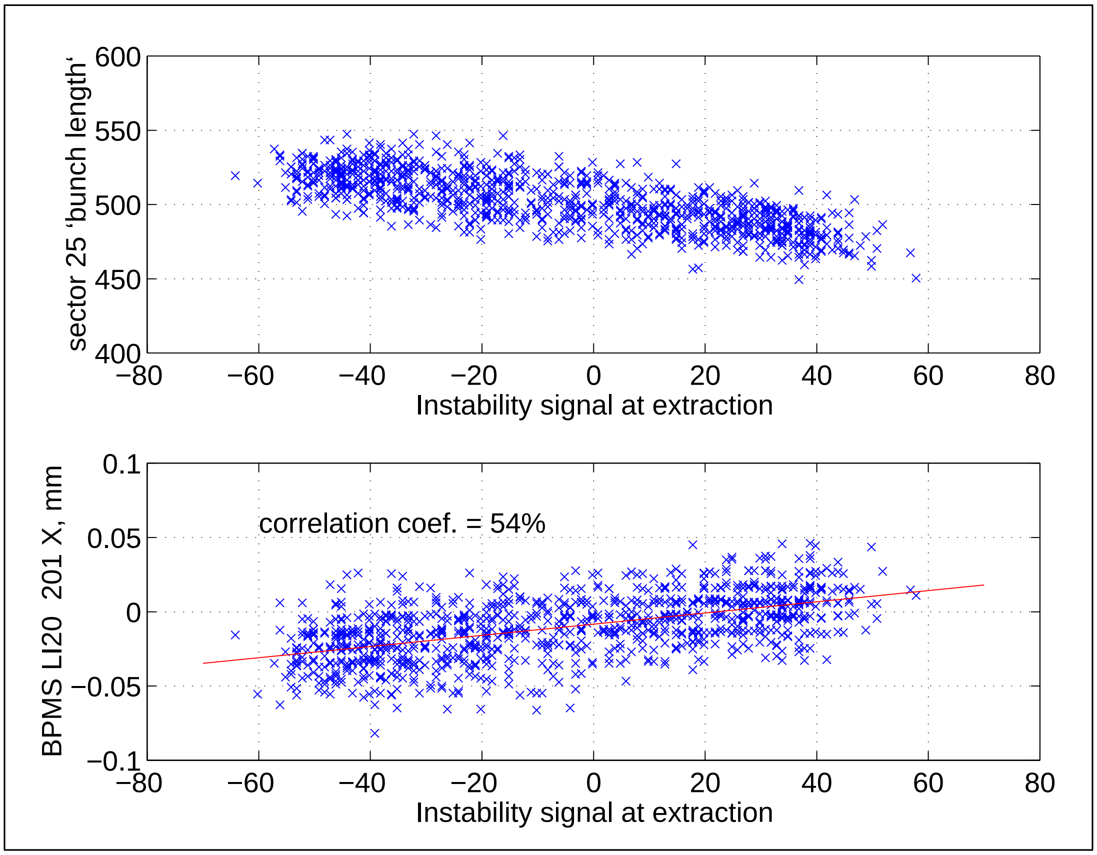
Streak Camera Instability Study: Results



- Complete phase-space picture
- Unstable mode contains ~3% of beam

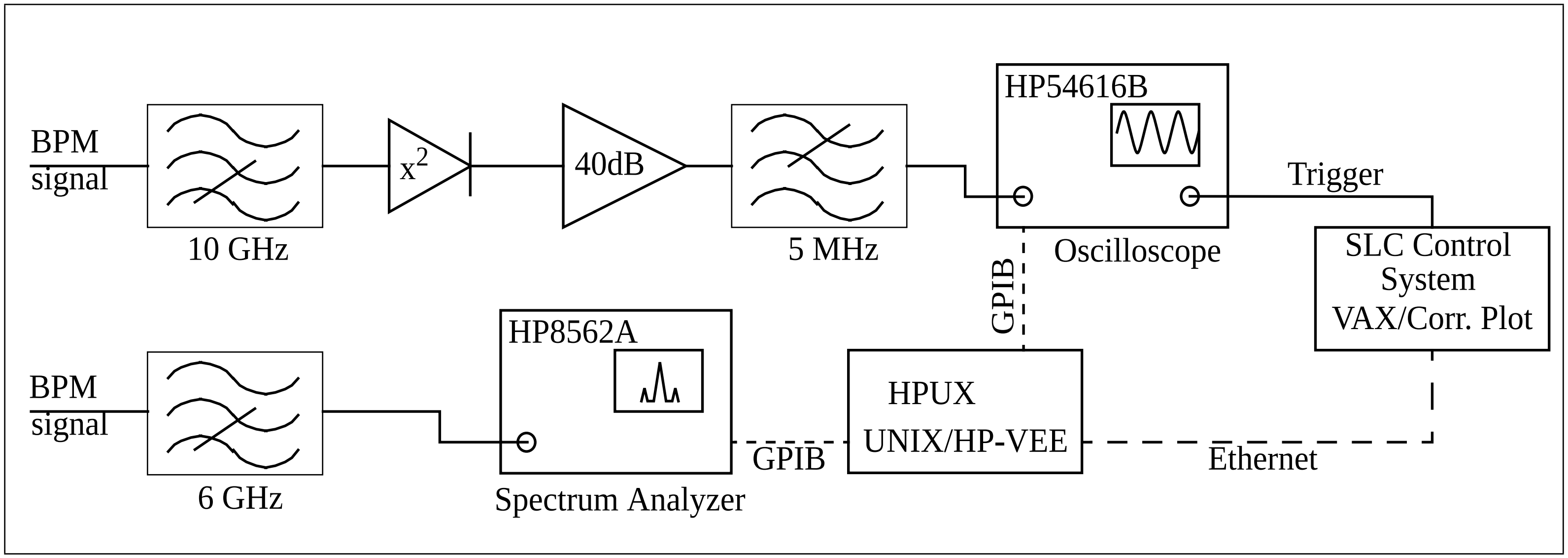
Linac Correlation Experiment

Correlating Instability Signal at Extraction with Linac Bunch Length and Trajectory



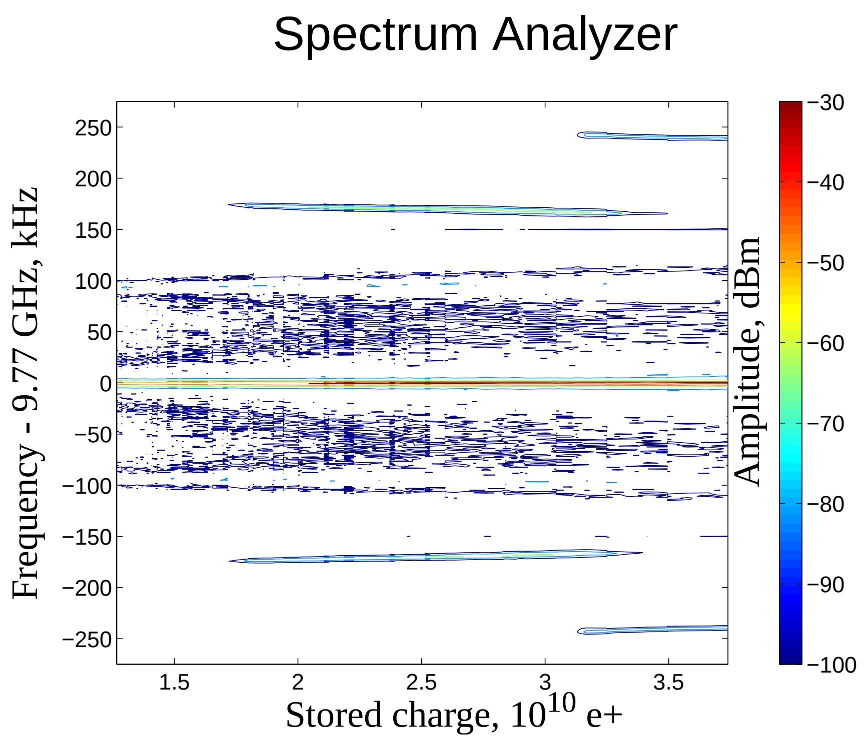
- Instability contributes to the transverse jitter in the linac
- Estimated 40% of the jitter power is due to the instability
- Could this be a problem for the NLC?

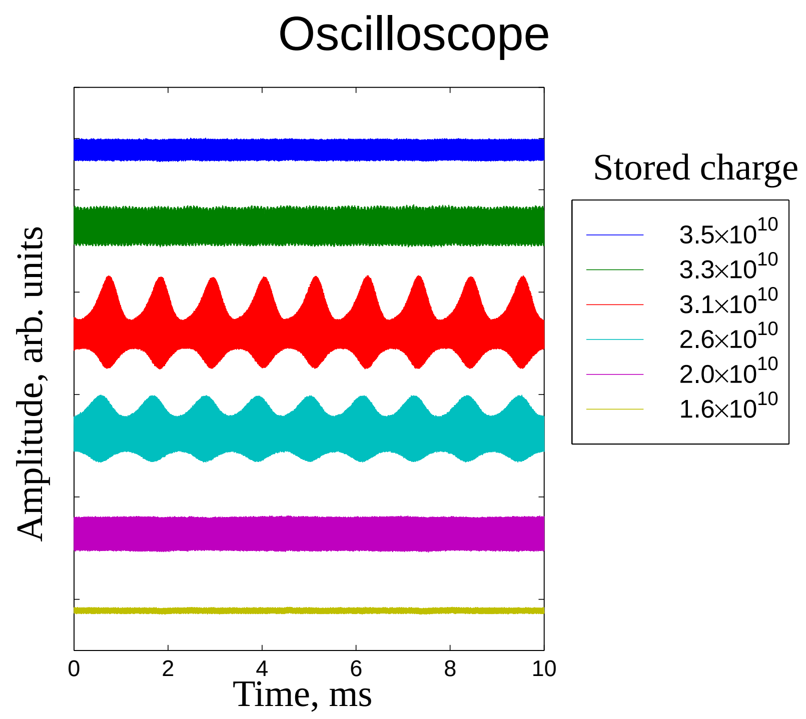
Stored Beam Experiment: Setup



- Positron ring, Single bunch stores ~10 minutes
- Charge decays down from $\sim 3.5 \times 10^{10}$
- 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 and Results





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

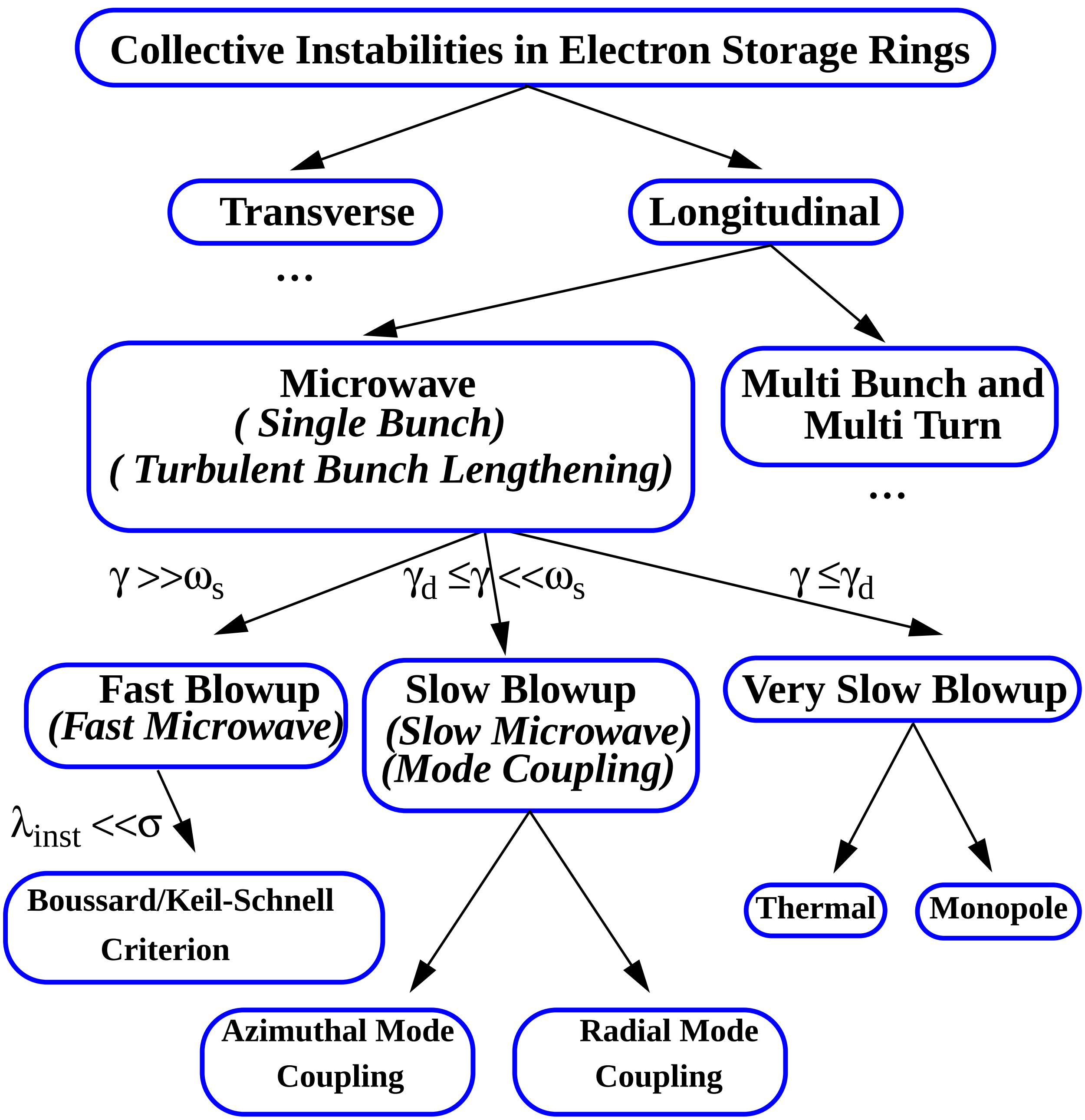
Theory and Simulations I

The problem is difficult

- Most interesting features (saturation, bursting, mode switching) are clearly nonlinear
- Instability growth rate and envelope time scale are comparable to the radiation damping time. To account for the radiation effects a more complex Fokker-Planck equation replaces a better treatable Vlasov equation.
- Instability period is much shorter than the growth rate which complicates numerical tracking

yet there is some hope

- The problem is interesting enough to attract theorists' attention
- The problem is 1D
- The amount of charge involved is small (3%)
- Frequency shifts are small (one azimuthal mode only?)
- Confidence in the wake model


Collective Instabilities in Electron Storage Rings
Transverse
...
Longitudinal
Microwave
(Single Bunch)
(Turbulent Bunch Lengthening)
Multi Bunch and
Multi Turn
...
γ >>ω_s
γ_d ≤γ <<ω_s
γ ≤γ_d
Fast Blowup
(Fast Microwave)
Slow Blowup
(Slow Microwave)
(Mode Coupling)
Very Slow Blowup
λ_inst <<σ
Boussard/Keil-Schnell
Criterion
Thermal
Monopole
Azimuthal Mode
Coupling
Radial Mode
Coupling

Theory and Simulations II[1]

Linear Theory

- Effect is different (and more subtle) than ones due to Boussard/Keil-Schnell or original Sacherer formalism
- Including PWD into radial mode coupling allows for a simple analytic formula for the threshold which agrees with experiment

Nonlinear Theory and Models

- Numerous models proposed
- Possibility of bursting and saturation due to few coupled radial modes

Simulations

- Vlasov-based techniques: they work for linear theory
- Particle tracking: when is done without short-cuts gives correct threshold, mode structure
- Direct Fokker-Planck integration: the most complete comparison (and good agreement) with experiment to date

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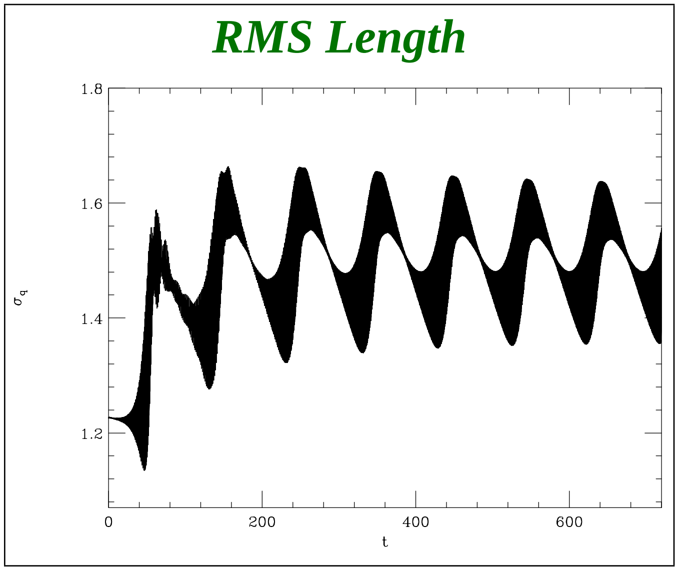
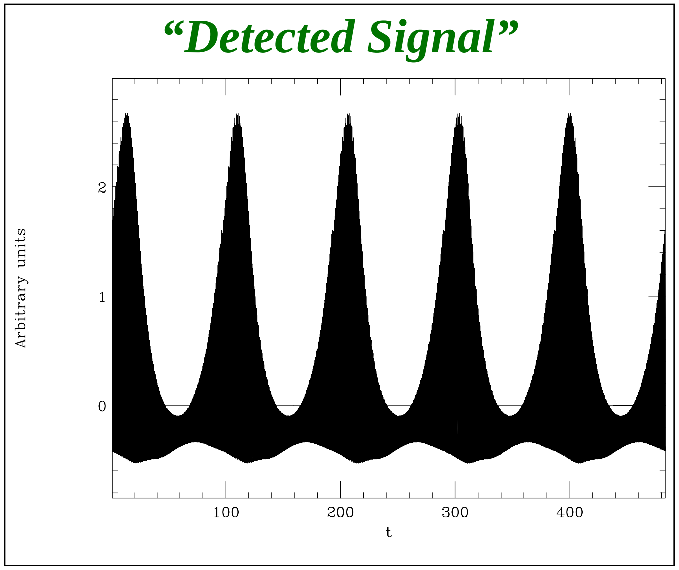
1. *references don't fit - see the thesis*

Direct Fokker-Planck Integration for SLC DR beams

From R.L. Warnock and J.A. Ellison, SLAC-PUB-8404 (2000)





- $N=3\times10^{10}$ runs shown
- Agrees in threshold and mode frequency with experiment
- Bursting behavior with correct envelope shape

Conclusions and Outlook

- New hardware for instability diagnostics
- Measured properties of instability
  - Phase space structure
  - Effect on the linac
  - Driven and self-excited beam response
- Theoretical understanding
- Beyond the SLC

Final Thoughts

We know how to predict/avoid the instability

We know how to calculate and measure most of its properties

Can we get the instability to work for us?