Longitudinal Dynamics in High Intensity Single Bunch

Cécile Limborg
SSRL / SLAC

Outline

•Single bunch longitudinal instabilities

Longitudinal Phase Space Parameters

$(\sigma_{\tau,}\sigma_{\delta})$ = (bunch length, energy spread)

✓ Interest for short bunches and small energy spread

✓ Experimental data $(\sigma_{\tau,}\sigma_{\delta})$ vs single bunch current

✓ Simulations

✓ Models

Introduction

•Light sources

✓ Short bunches: sub-ps desired

Time resolved experiments

High Î for SR FEL

Coherent Synchrotron Radiation (1ps = 0.3mm)

✓ Energy spread minimum (high Intensity spectral lines Und.)

•Damping Rings for colliders

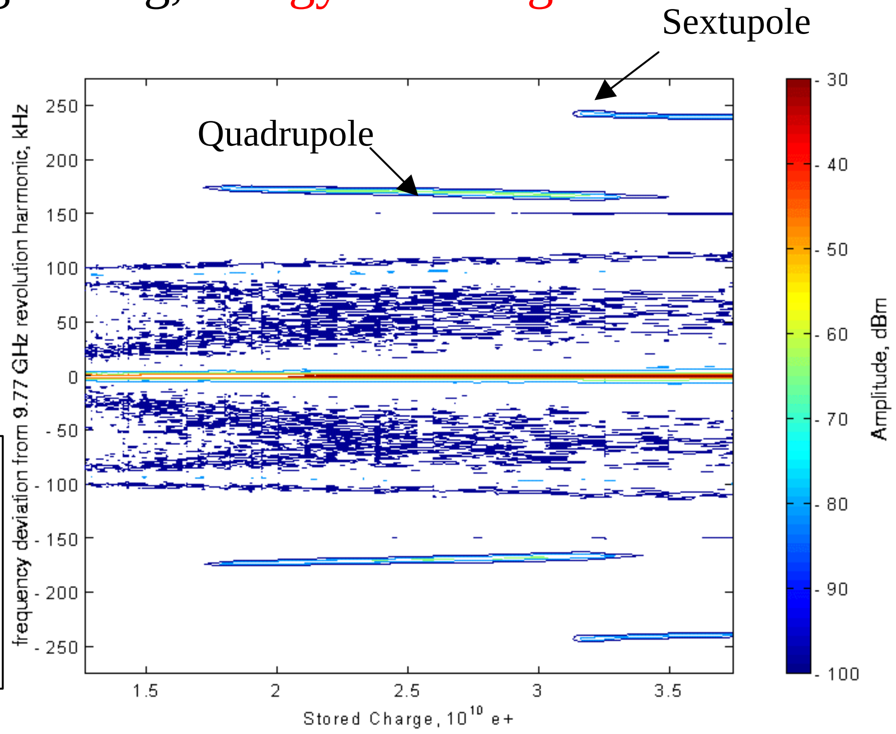
✓ Large Energy oscillations undesirable @ injection in linac

Single Bunch Longi. Instability

- Usually no beam loss, transverse instabilities fix I_{thr}
  "Instability Threshold" = Onset of energy widening

- 2 regimes :
- potential well: lengthening, no energy widening
- microwave instability: lengthening, energy widening

Coherent signals pop up
($+f_s$, $+2\ f_s$, $+3\ f_s$ …)
(saturation or sawtooth)



SLC Damping ring

Coherent sidebands

Courtesy B.Podobedov

Strong Bunch Lengthening

- Natural bunch length $$s_{to} \approx \sqrt{\frac{a\ E^3}{w_{rf} V_{rf}}} \quad @\, I = 0\ mA$$

- Reduction of ε_x (from 2nd to 3rd GLS) ⇒ Intrinsic reduction of α (because of smaller Dispersion in the bending magnets)

- Quasi-isochronous regime tested for both α > 0 and α < 0

- Demonstrated @ (SuperAco, ESRF, ALS, UVSOR…)
@ high current **bunch length independent of α and Energy**

- Slope of asymptotic curve for each ring determined its $|Z/n|_{eff}$

- At high currents, σ_τ nearly follows $$\left(\frac{|Z/n|_{eff}\ I}{w_{rf} V_{rf}} \right)^{1/3}$$

Measurements

• ESRF, Super-Aco, ALS, APS, DaΦne, HER, ATF, Elettra ,NSLS VUV ring… ⇒ **strong lengthening**

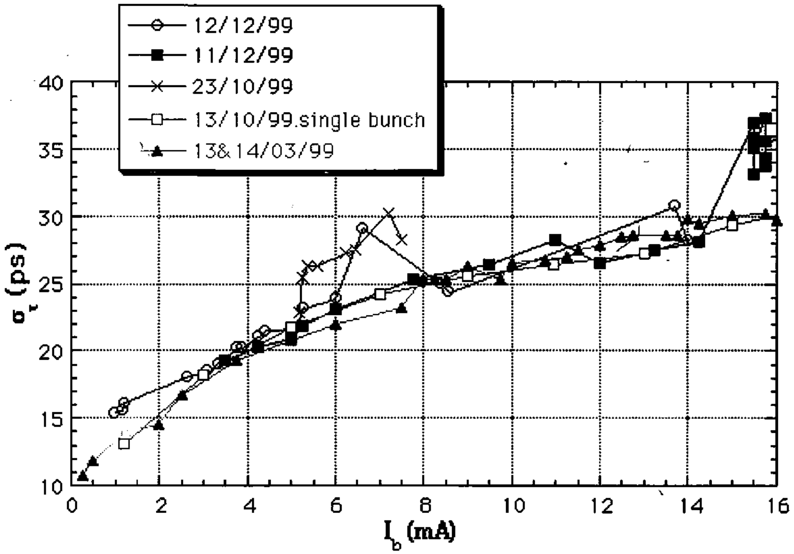
• Some signs of bunch shortening (over very low range of currents)
SPEAR ,CESR , LEP (before SC cavities)

• Threshold of microwave instability
Strong coherent signals on sync. Sidebands for
SLC DR, ALS, SuperAco
Microwave Instability Threshold in number of particles per bunch

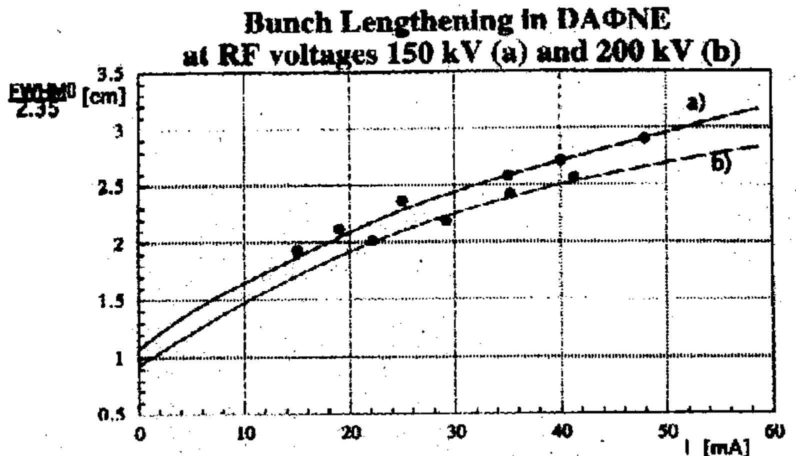
ESRF	APS	Elettra	ALS	Super-Aco	SPEAR
$1.1.10^{11}$	$1.8.10^{11}$	$3.2.10^{10}$	$2.87.10^{10}$	$7.6.10^{10}$	$2.4.10^{10}$

Measurements

Elettra Courtesy of E.Karantzoulis

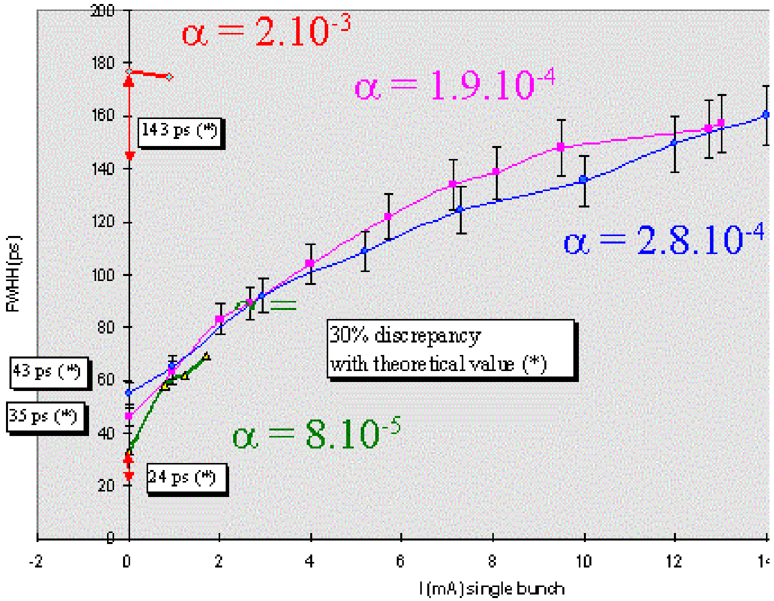


DaΦne Courtesy of A.Ghigo

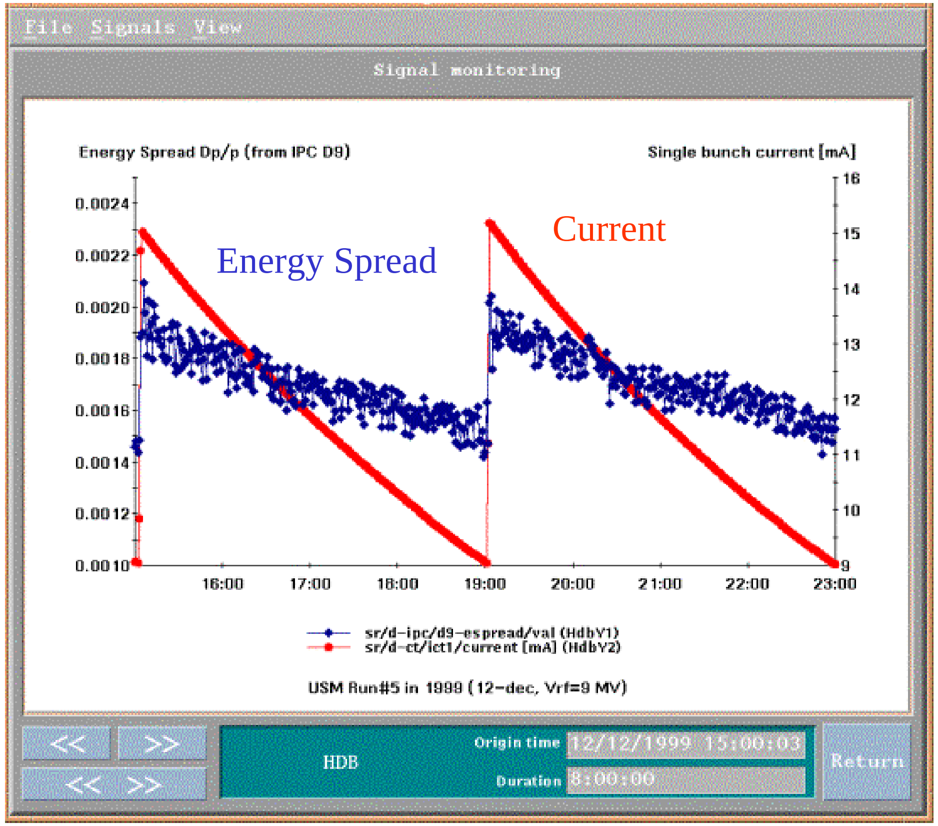


Comparison between the measurement results (dots) and the numerical simulation (line) of the bunch lengthening due to parasitic electromagnetic interaction of a bunch with different elements of the DAΦNE vacuum chamber

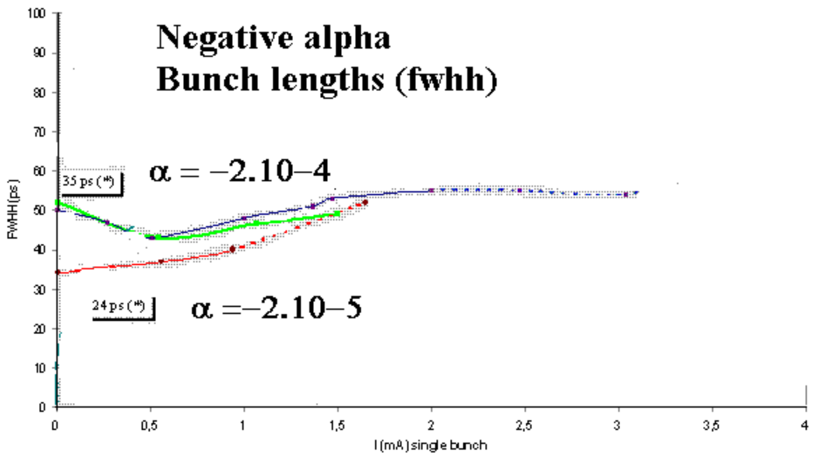
ESRF



α = 2.10-3
α = 1.9.10-4
α = 2.8.10-4
α = 8.10-5
143 ps (*)
43 ps (*)
35 ps (*)
24 ps (*)
30% discrepancy
with theoretical value (*)
FWHH (ps)
I (mA) single bunch



File Signals View
Signal monitoring
Energy Spread Dp/p (from IPC D9)
Single bunch current [mA]
Current
Energy Spread
sr/d-ipc/d9-espread/val (HdbY1)
sr/d-ct/ict1/current [mA] (HdbY2)
USM Run#5 in 1999 (12-dec, Vrf=9 MV)
HDB
Origin time 12/12/1999 15:00:03
Duration 8:00:00
Return



Negative alpha
Bunch lengths (fwhh)
α = –2.10–4
α =–2.10–5
35 ps (*)
24 ps (*)
FWHH (ps)
I (mA) single bunch

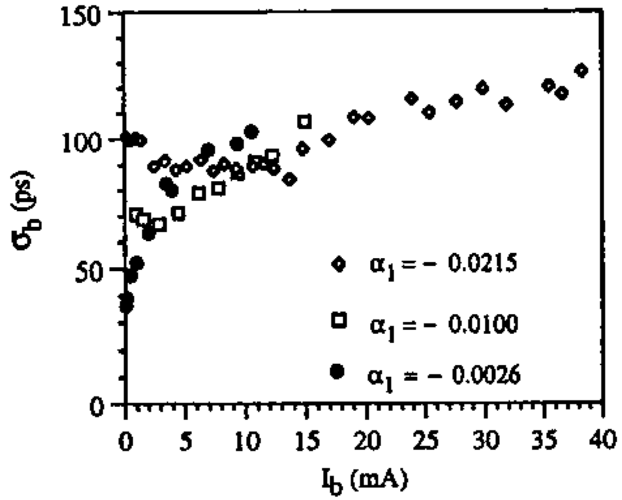


Figure 4. Experimental bunch lengthening with three different negative values of α_1.

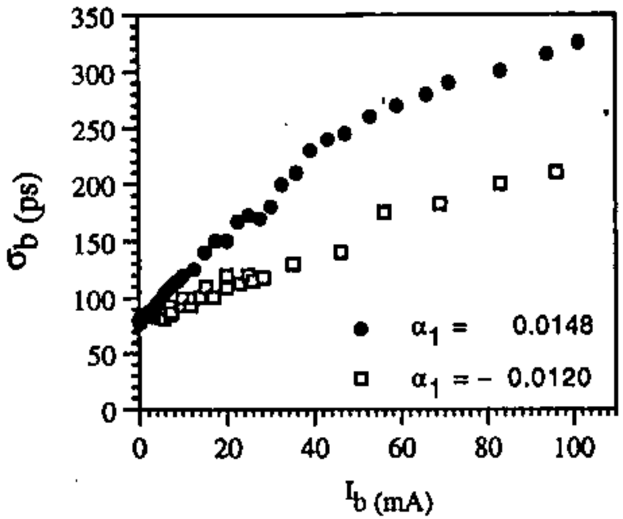


Figure 3. Experimental bunch lengthening with positive and negative α_1.

SuperAco Courtesy of Nadji-Level

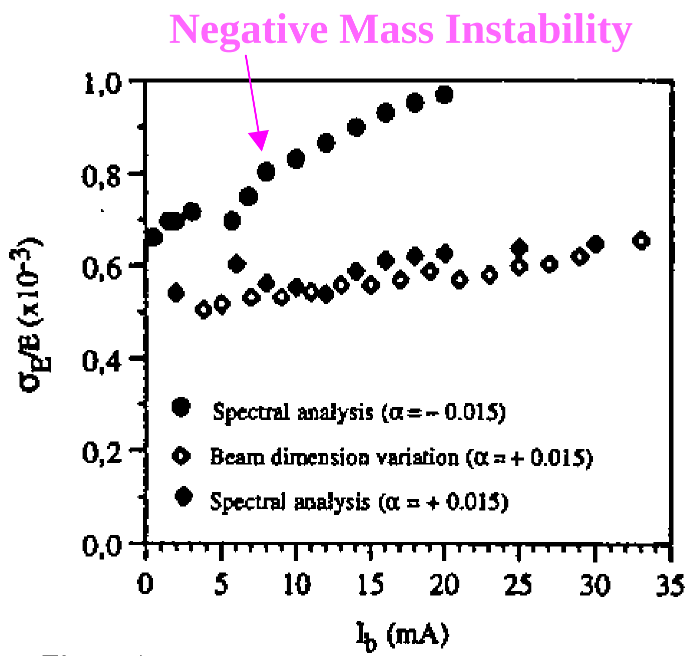
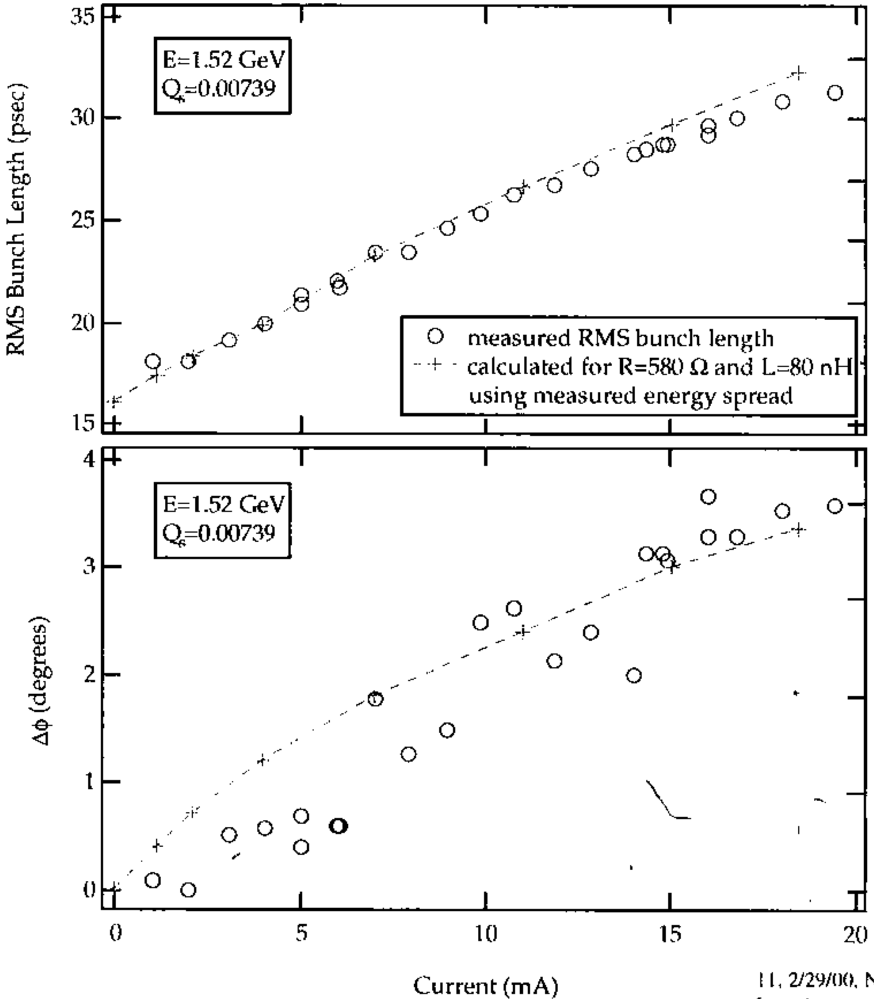


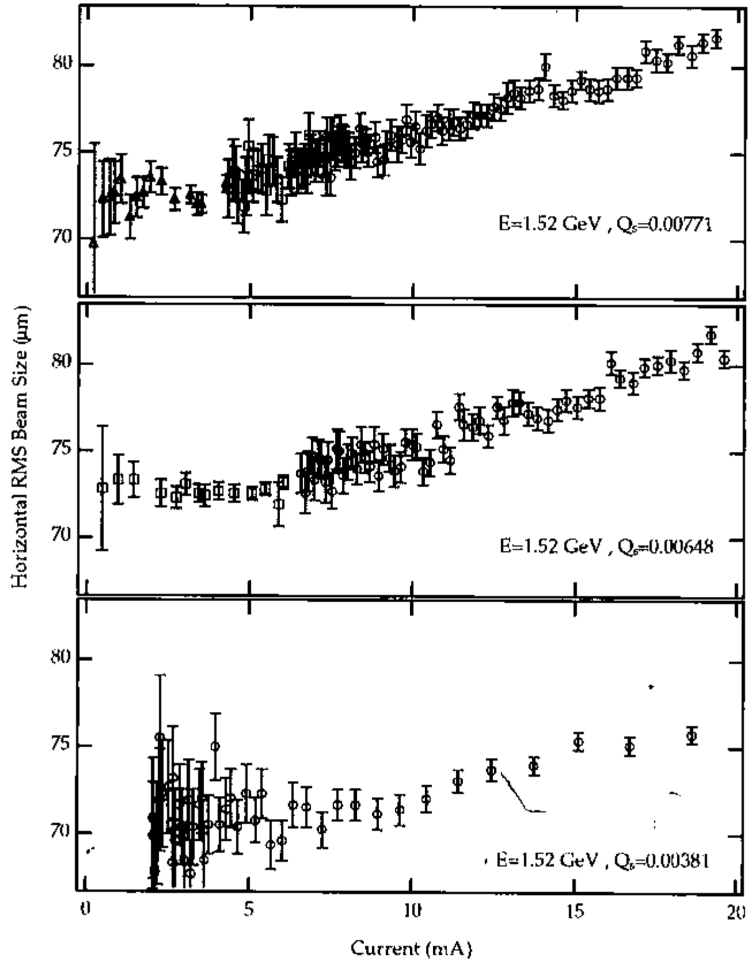
Figure 5. Measured energy spread versus current with positive and negative α.

ALS Courtesy of J.Byrd

Bunch length and synchronous phase shift



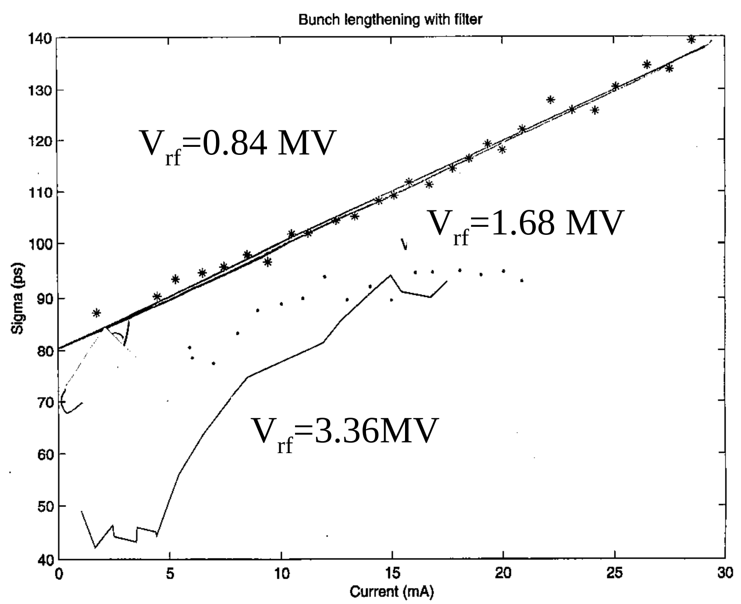
11, 2/29/00, NLC Impedance worksho

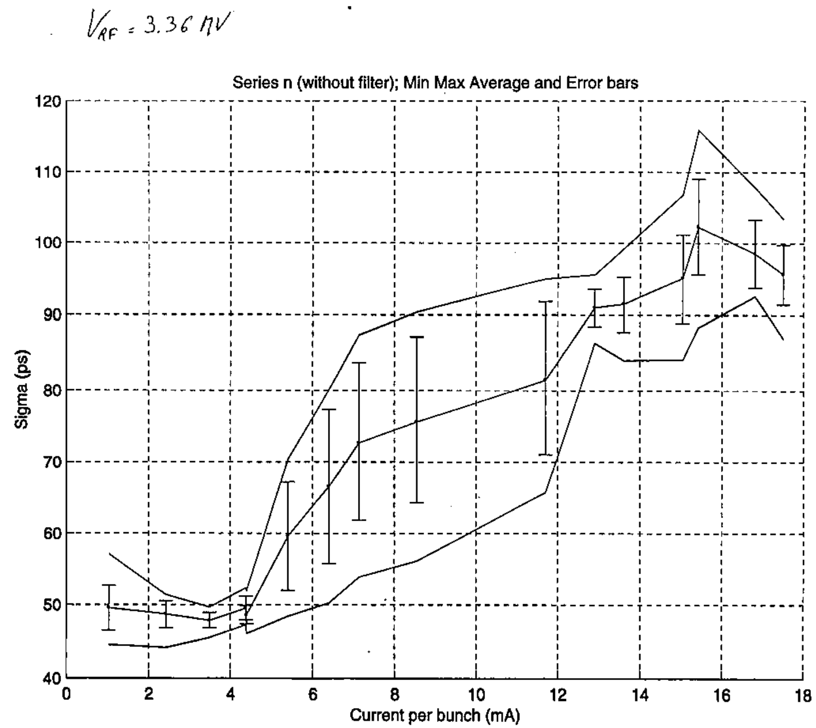


7, 2/29/00, NLC Impedance workshop

Energy Spread

Measurements





SPEAR C.Limborg- J.Sebek 1998

Signs of bunch shortening, but at low currents

Models & Methods

☛ Evolution of distribution of particles in phase space (τ,δ) = (q,p) with increasing current in the presence of short range wakefields

☛ Impedance models
(Zotter review http://www-project.slac.stanford.edu/lc/wkshp/talks)

- Vlasov equation (conservation of charges) + radiation = Fokker-Planck
  - ✓ Stationary solution = Haissinski equation

$$y_o(p,q) = \frac{1}{\sqrt{2p}} \exp(-p^2/2) f_o(q)$$

$$f_o(q) = A \exp\left[-\left(q^2/2 + I \int_q^{\infty} \int_{q'}^{\infty} f_o(q'') W(q'-q'') dq' dq''\right)\right]$$

  - ✓ Linearized form Vlasov ⇒ mode coupling theory
  - ✓ Non-linearized ⇒ numerical solvers (Warnock, Novokhatski)

- Multiparticle Tracking codes

Academic case of $Z_{//}=jL\omega$

- Haissinski equation with purely inductive $Z_{//}$:

$$f_x' = \frac{-x\ f_x}{1+\Delta f_x} \qquad with\ \Delta = \frac{2\pi I L}{V_{rf}\omega_{rf}\left|\cos\varphi_s\right|\left(\frac{\omega_o}{\omega_{so}}\alpha\sigma_\delta\right)^3}$$

✔ There exists a solution $\Leftrightarrow$ $\Delta > 0$

for $\alpha > 0$, Distribution is stable; **NO** σ_δ increase

✔ No solution for $\Delta < -1.55$

for $\alpha < 0$, Negative mass instability; **STRONG** σ_δ increases

- Interest of Purely inductive impedance

Fits bunch lengthening curves
Good benchmark to test numerical noise (tracking code & solvers)

Broadband impedance

- Handy model analytically (R_s, f_r, Q=1)

- <u>Tracking code</u>

RF Voltage -losses — Radiation Damping — Fluctuations

$$d_{n+1}-d_n=\left[\left(\frac{eV_{rf}(j)-U_o}{E_o}\right)-AI\,[W*f_o](t_n)-\frac{T_o}{T_{damp}}d_n+2\sqrt{\frac{T_o}{T_{damp}}}R_n\right]$$

Wakefield

Variation Energy

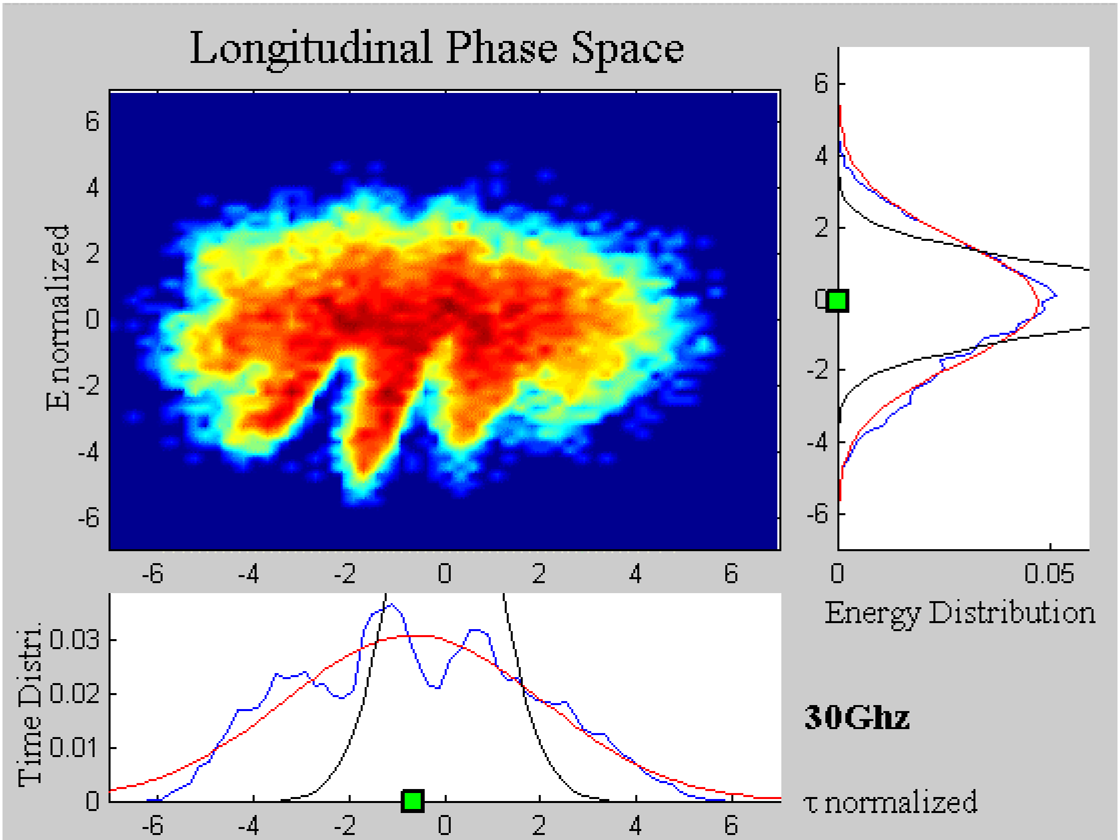
$$t_{n+1}-t_n=a\,T_o\,d_{n+1}$$

Variation Path Length

16 000 particles in 200 cells over ± 7 $\sigma_{\tau o}$
I = 3mA Bunch length ($4\sigma_\tau$) = 150ps
Over 3 Synchrotron Periods
1 image / 5 turns

f_r = 30 GHz, 4 σ_τ = 5 λ_r
f_r = 15 GHz, 4 σ_τ = 2.5 λ_r
f_r = 7 GHz, 4 σ_τ = 0.9 λ_r
f_r = 3.5 GHz, 4 σ_τ = 0.5 λ_r

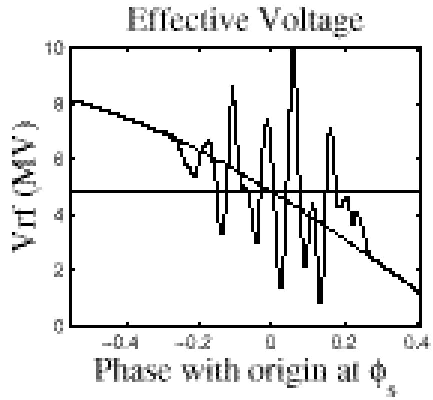
Broadband impedance



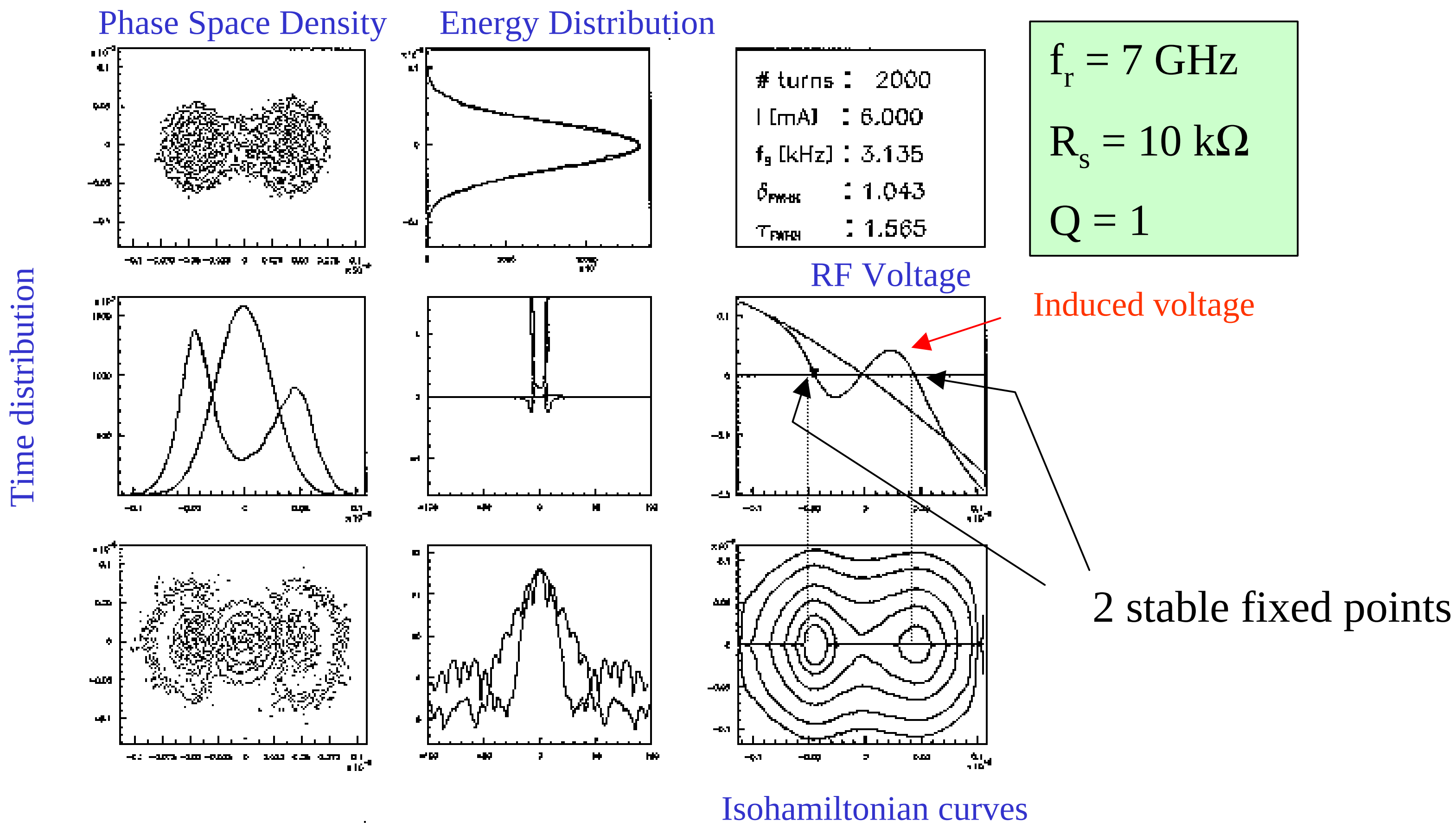
f_r = 30 GHz

R_s = 42 kΩ

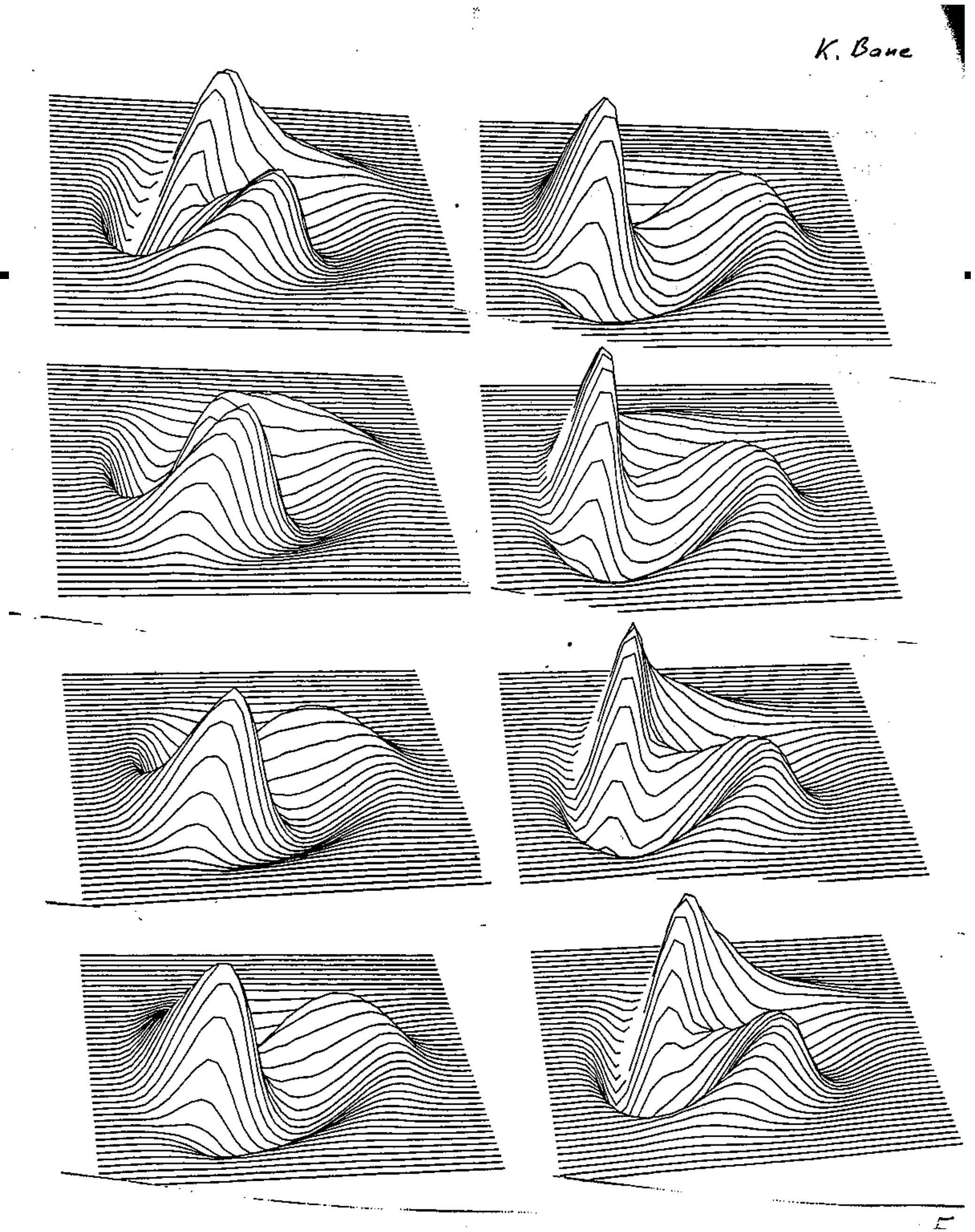
Q = 1



Broadband impedance



From ESRF code Gunzel- Besnier Limborg



- K.Bane simulations of SLC damping ring;
- Uses the numerically computed wakefield
- Exhibit quadrupole form of perturbation (but 3% of total intensity)

Mode Coupling theory

• A.Mosnier thoroughly compared results between tracking and mode coupling theory;

p.w distorsion from Haissinski for stationary distribution

uses Oide-Yokoya radial step function expansion

for determining the stability of modes

compares threshold with tracking code results (good agreement)

$f_r\sigma_\tau>1$, azimuthal mode coupling before radial

$f_r\sigma_\tau<1$, radial mode coupling, sub-bunches

- spread in f_s
- eventual presence of 2 bunchlets

A Few other mechanisms

• Model of sawtooth
Oscillations between 2 "fixed points" as particles diffuse, stability of fixed points is exchanged
Dyachkov-Baartman

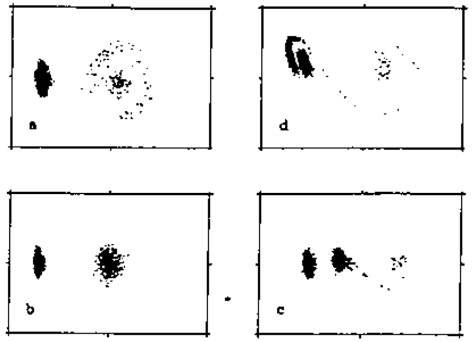
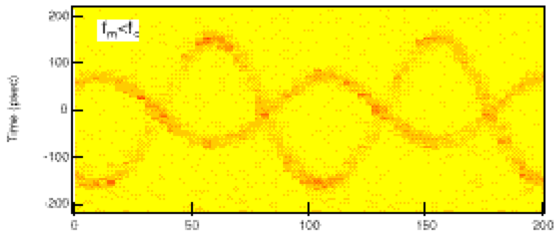
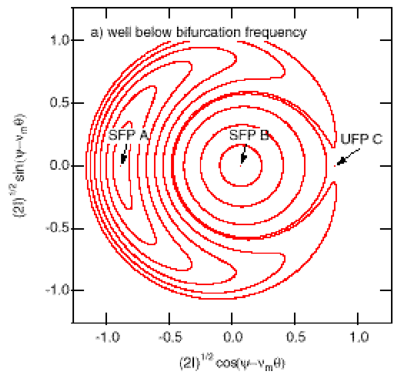


Figure. 4. A complete cycle of the sawtooth instability for the case shown in Fig. 1: $I = 30$ and $\tau_e = 5T_s$. The time sequence is anticlockwise.

•A "controlled instability":

Huang- Li et al PhysRev
Modulation of RF phase
Byrd-Zimmerman experiment-



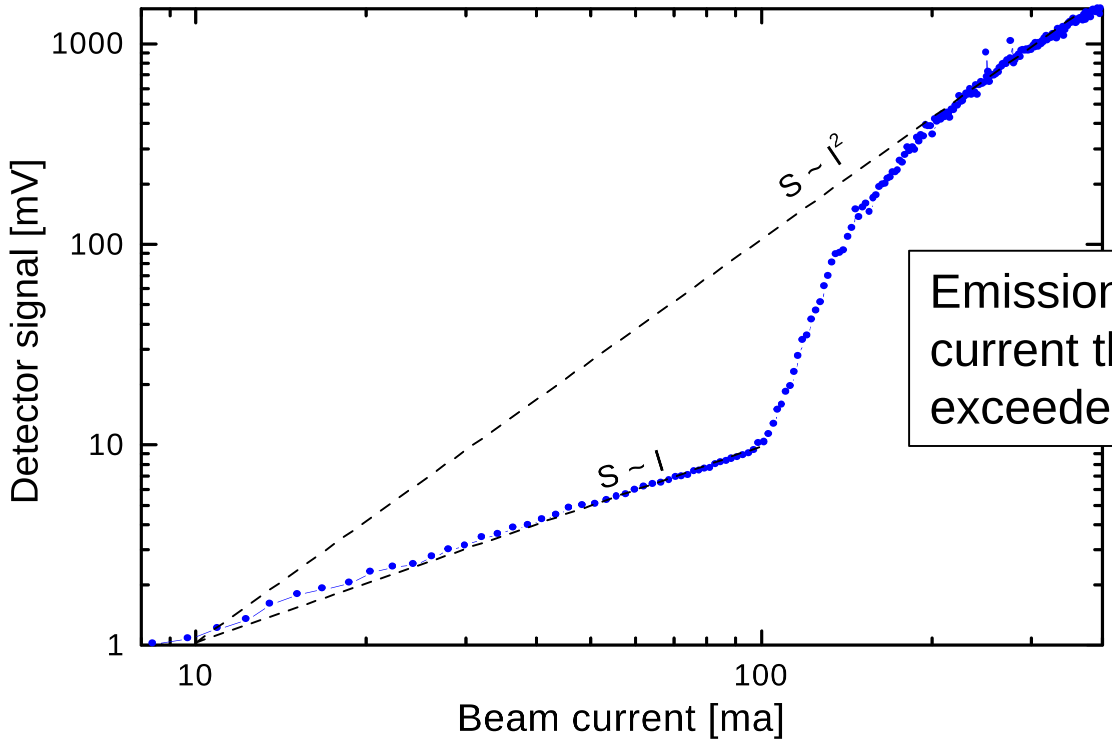


Courtesy J.Byrd, ALS

• **Observe enhanced emission from NSLS VUV ring at 7 mm wavelength -** Courtesy of J.Murphy

Beam current dependence

- I^2 dependence beyond threshold.
- threshold depends on operating parameters (E, bunch length, α).



Emission occurs after a current threshold I_{th} is exceeded, grows as $(I - I_{th})^2$.

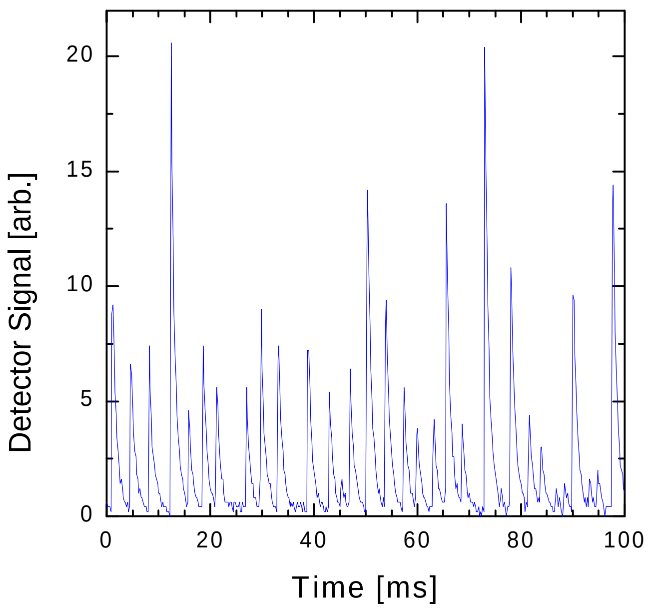
Submitted to PRL (2/2000): G.L. Carr, S.L. Kramer, J.B. Murphy, N*SLS - BNL*
R.P.S.M. Lobo, D.B. Tanner, *Physics Dep't. - Univ. Florida*

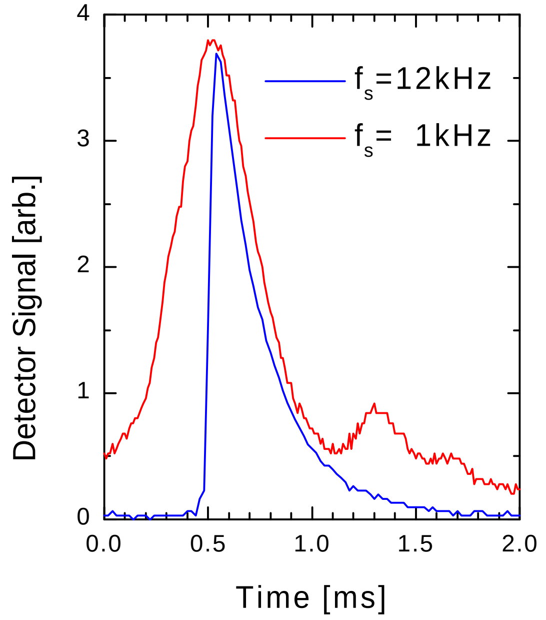
•Emission is not continuous, but occurs in quasi-periodic bursts.
period ~ 1 to 10 ms; rise/fall times faster than synchrotron damping time.

Emission bursts

- *Quasi-periodic bursts*
- *T ~ 1 to 10 ms*
- *detector-limited fall time*

- *Duration < 100 ms for $a = a_o$*
- *increases with decreasing a*





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Conclusions

• Strong bunch lengthening on all rings
Accompanied by strong energy widening above the microwave instability threshold

• Quasi-isochronous tuning (for both positive and negative α) is not the solution for short and intense bunches

• Properties of linear accelerator are more in favor of short bunches (LCLS- TESLA)

• Hope
for coherent IR
much higher Î
pushing up the microwave I_{thr} with harmonic cavities

• Need to put efforts into measuring and computing $Z(\omega)$ at very high ω

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ESRF (Nagaoka- Farvacque- Revol- Ropert- Gunzel- Besnier…)
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Super-Aco (Nadji, Level, Couprie…)
Elettra (Karantzoulis…)
APS (Harkay, Lumpkin, Emery …)
NSLS (Murphy, Podobedov…)
ALS (Byrd…)
SLAC (Heifets, Bane, Krejcik…)
CERN (Hofmann- Zotter…)
SSRL (Sebek)
Daphne (Ghigo)