Longitudinal Beam Dynamics with Harmonic RF Systems

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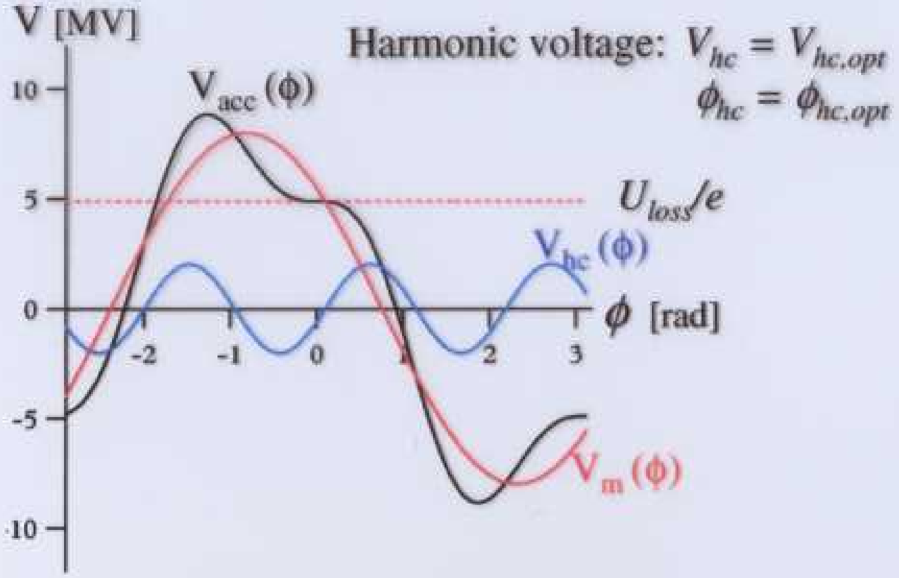
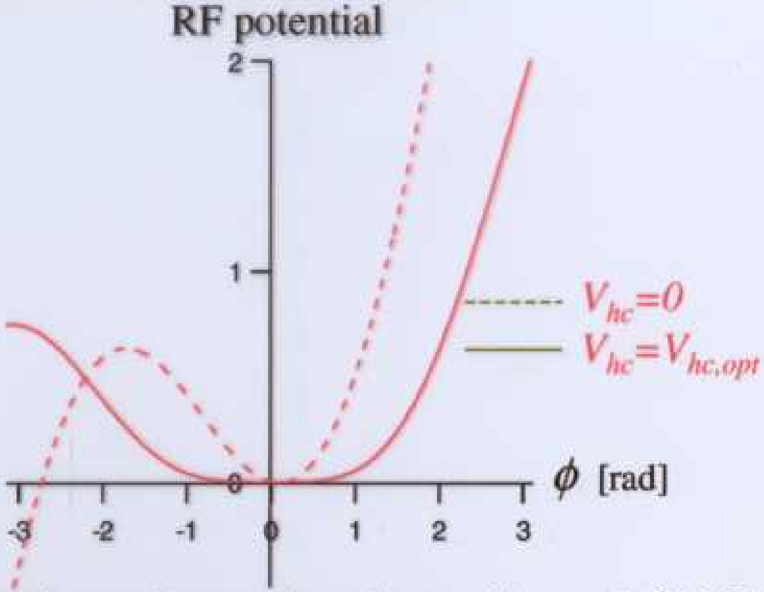
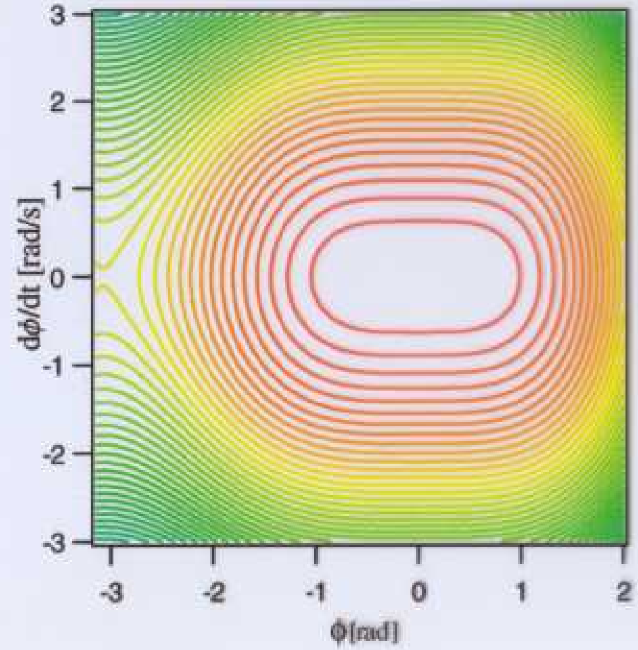
6th ESLS RF meeting, PSI, November 28 - 29, 2002

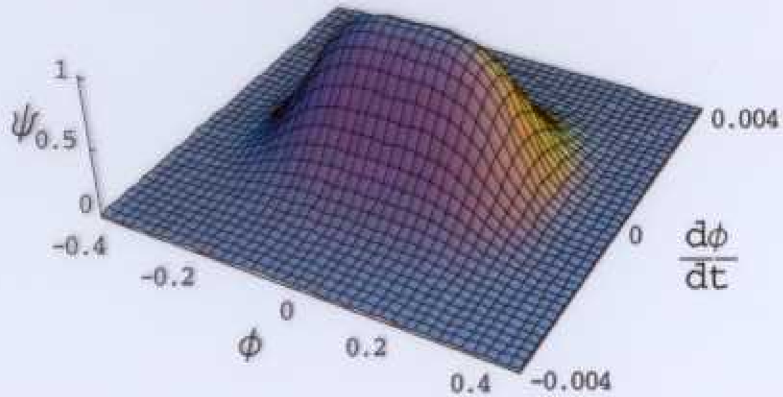
Double RF system - Optimum bunch lengthening case





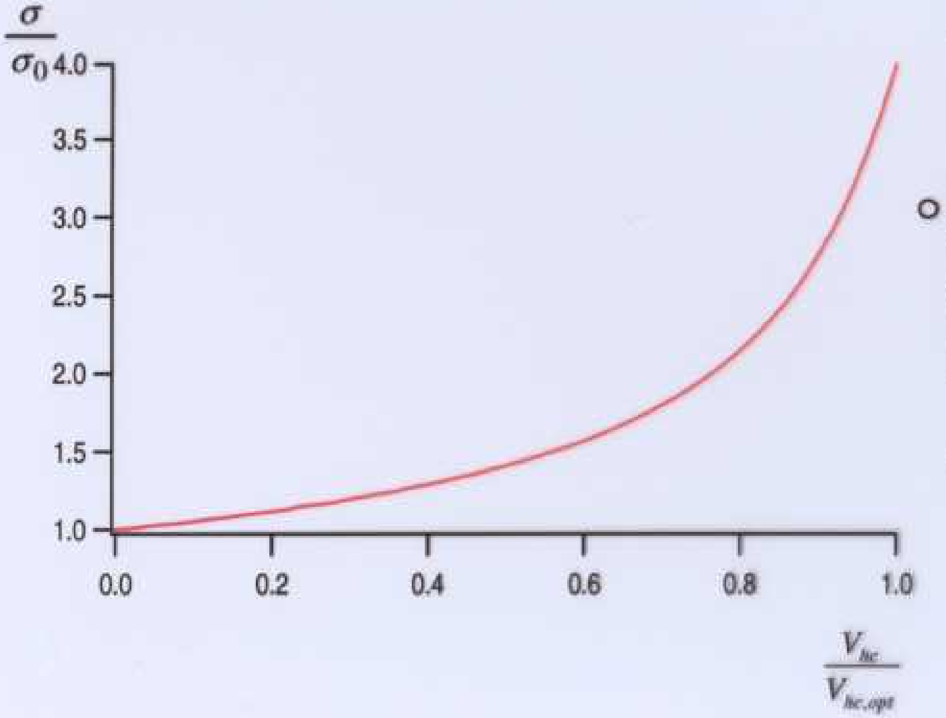
- optimum harmonic voltage : $V_{hc,opt}=2.03$ MV
- RF potential: ϕ^4
- Non Gaussian longitudinal distribution



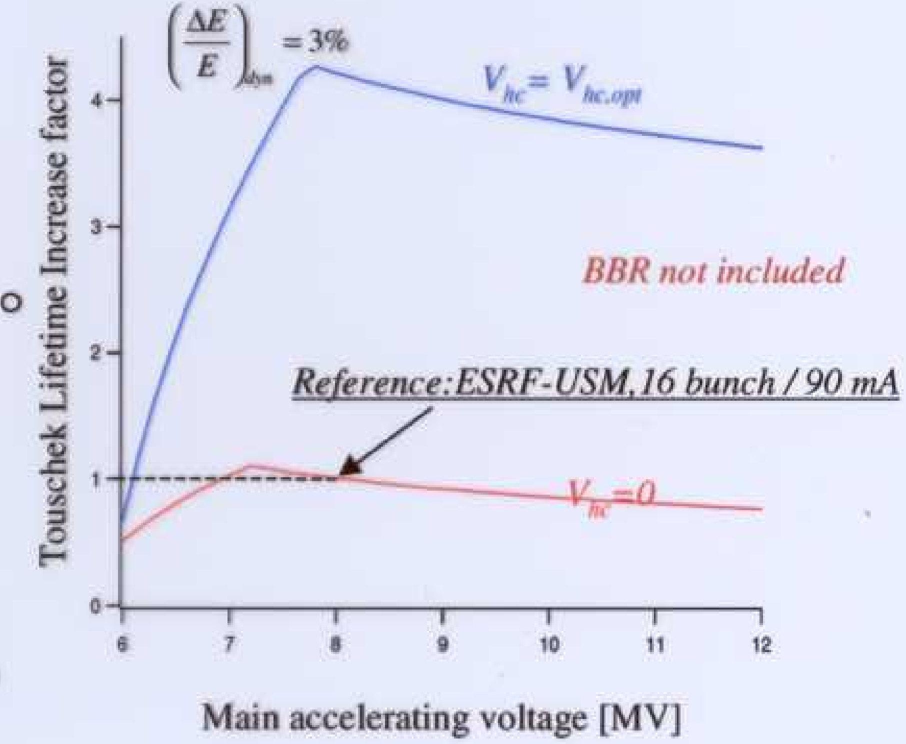


Bunch lengthening and Touschek lifetime improvement

ESRF paremeters, $V_{acc,main}$= *8 MV*, main RF only :σ_0=*16 ps*



σ : rms "zero current" bunch length



Longitudinal Beam Dynamics

Synchrotron equation:

$$\ddot{\phi}+\frac{2\pi\alpha\, hf_o^2}{E_b}\left(e.V_{acc}(\phi)-U_o\right)=0$$

with: $V_{acc}(\phi)=V_m\sin(\phi_s+\phi)+V_h\sin(n(\phi_h+\phi))$

Beam motion:

Main RF system only: $\phi=\hat{\phi}\cos(2\pi f_{s0}t+\varphi)$

Double RF system: $\phi=\hat{\phi}\; cn(\Omega(\hat{\phi})t,m)$

Optimum bunch lengthening:

$$\begin{cases} m=0.5 \\ \Omega(\hat{\phi})=\dfrac{\pi^2}{K(0.5)}\sqrt{\dfrac{n^2-1}{12}}\,f_{so}\hat{\phi} \end{cases}$$

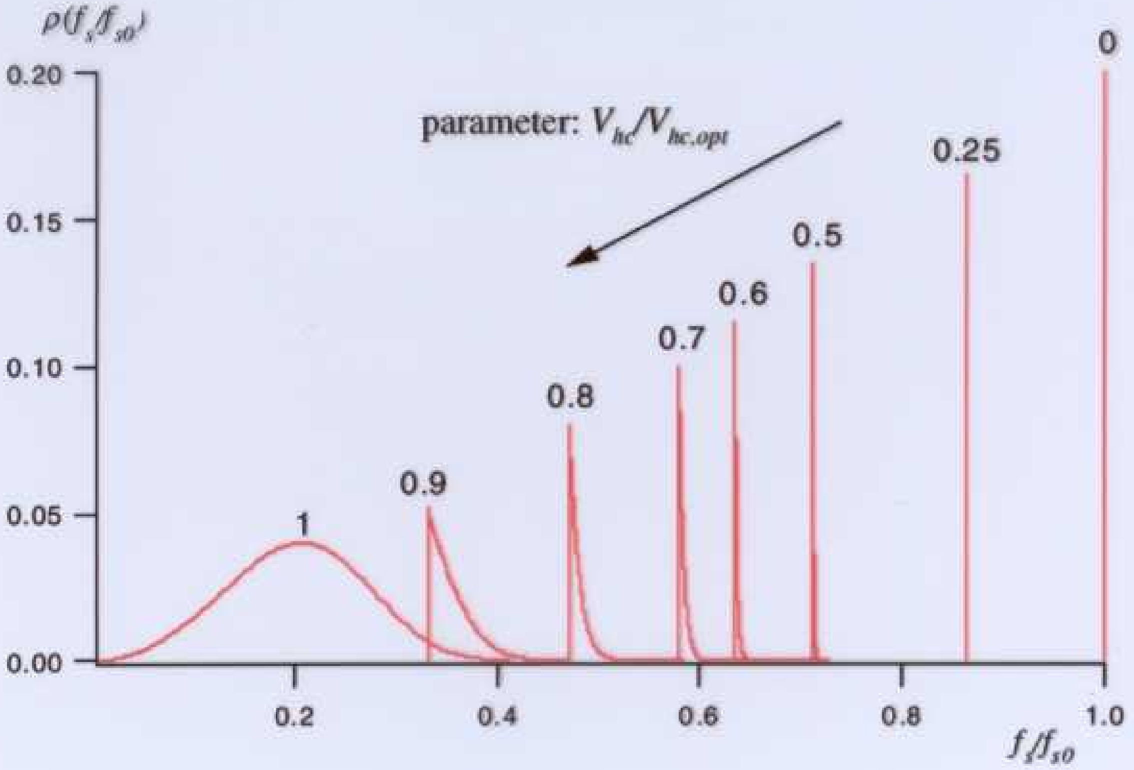
The synchrotron frequency Ω depends on the amplitude

↓

Non linear beam motion

Synchrotron frequency distribution within bunches

The non linearity of the accelerating voltage induces a spread of the synchrotron frequencies within the bunches



ESRF parameters, third harmonic RF system

Touschek Lifetime Improvement at ESRF ?

Beam lifetime at the ESRF:	– Uniform filling:	$\xi_v=0.4$ *to* 0.5	200 mA	$\tau =$ 60 h
	– 16 bunch filling:	$\xi_v=0.6$	90 mA	$\tau =$ 10 h
	– Single bunch:	$\xi_v=0.9$	20 mA	$\tau =$ 4 h

Motivation for a harmonic cavity at the ESRF:

Improve the beam lifetime for the single and 16 bunch operation modes

An accurate evaluation of a harmonic RF system should take into account:

- The non-linearity of the beam motion
- All longitudinal instability mechanisms

Longitudinal Instability Mechanisms

Robinson Instabilities:

Interaction of the beam and the fundamental impedance of the RF systems

DC : limitation for smaller machines but not for ESRF
AC: concerns both single and 16-bunch fill patterns

→ Determines the mimimum number of harmonic cavities for stable operation

Potential Well & Microwave Instability:

Interaction of the beam and the longitudinal broad band impedance of the storage ring

→ Increase of the bunch length and energy spread with the beam intensity
Concerns both single and 16-bunch fill pattern

Longitudinal Coupled Bunch Instability:

Interaction of the beam and the Higher Order Modes of the RF systems

Concerns only the 16-bunch fill pattern for the ESRF

Extended Tracking Code

- Single bunch multiparticle model:
  –BESAC, Potential Well and Microwave Instability
  [G.Besnier, C.Limborg, T.Günzel]
  ESRF

- Multibunch single particle model:
  –Transient beam loading effects with harmonic RF system
  [J.Byrd, S.De Santis, J.Jacob, V,Serriere]
  ALS, ESRF

- Multibunch multiparticle model
  [J,Jacob, V.Serriere]

Only way to take into account intrabunch nonlinear effects on multibunch oscillations

– Allows computing the longitudinal beam motion taking into account simultaneously:

– Impedance of the RF systems $\Longrightarrow$ Robinson instabilities
– BBR $\Longrightarrow$ Potential well distortion & Microwave instability
– Higher Order Modes $\Longrightarrow$ Longitudinal Coupled Bunch Instabilities

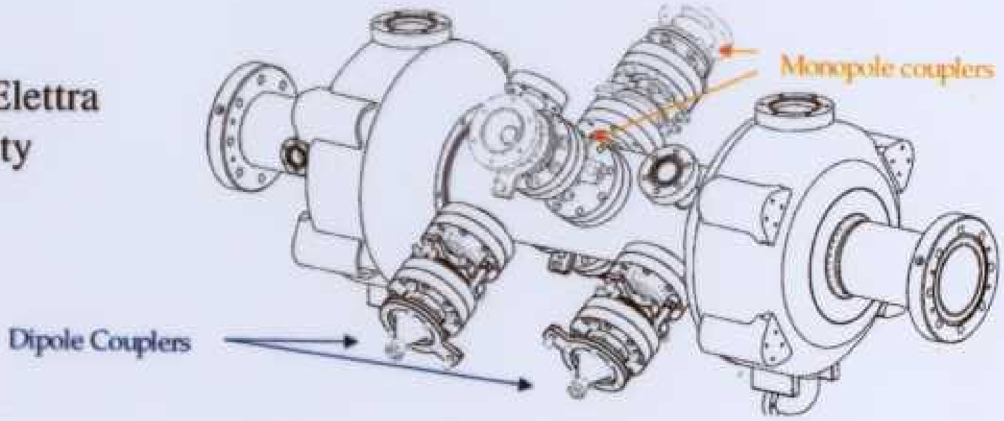
Harmonic Cavities for the ESRF ?

Only superconducting technology allows to provide the necessary optimum harmonic voltage within a reasonable space

Super-3HC cavity:

- 3rd harmonic cavity for: SLS & Elettra
- Scaling of the SC SOLEIL Cavity
- Construction: CEA & CERN

- $R_s/Q= 90\ \Omega$
- Quality factor: $Q_0= 2.10^8$
- $f_{res,hc} = 1.5\ GHz$



Superconducting Module with a pair of cavities

ESRF : Scaling of Super-3HC to $f_{res,hc} = 1056.6\ MHz$

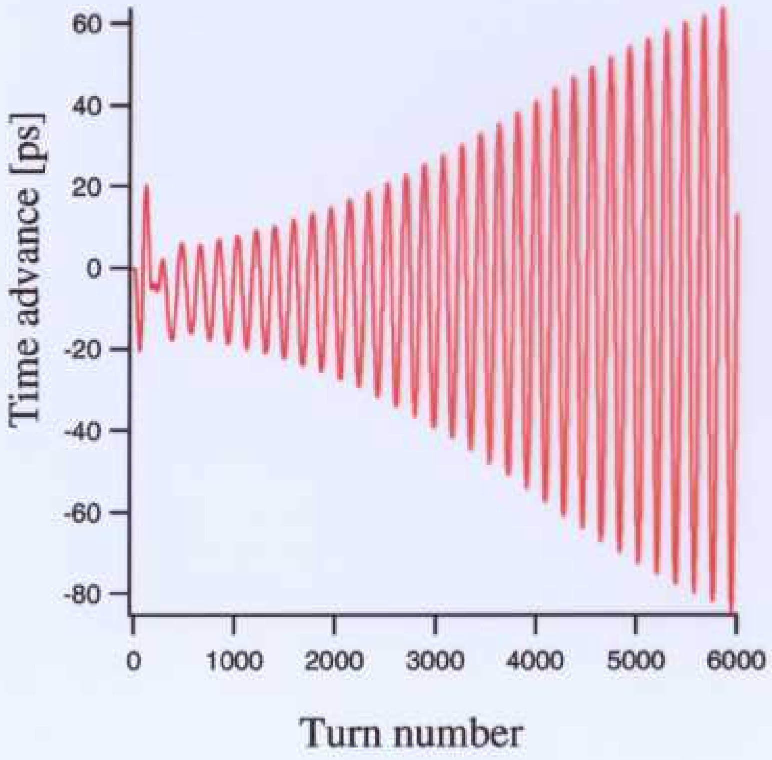
Passive harmonic RF system: the beam drives the harmonic voltage

Active harmonic RF system: the harmonic RF system is fed by an external generator

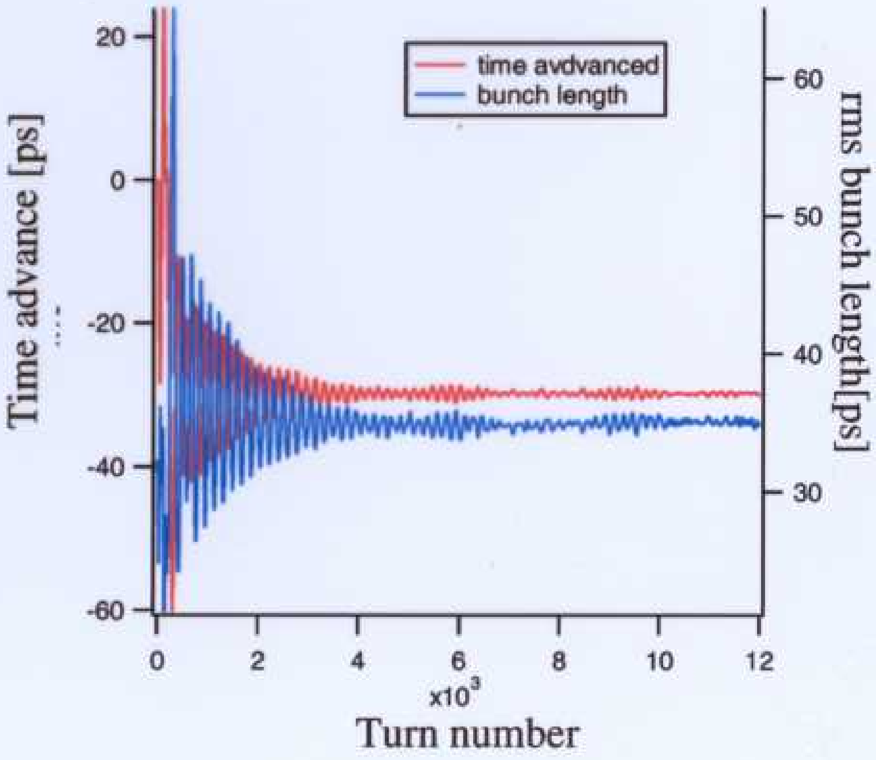
AC Robinson Instability for passive cavities @ ESRF

- I_{beam} = *10 mA* (single bunch)
- $V_{hc,set}$ = *1.5 MV*

2 modules/ 4 cells



4 modules/ 8 cells



Passive or Active Harmonic RF system for ESRF ?

Passive harmonic RF system:

- **4 modules** / 8 cells **necessary** for stable operation in single and 16-bunch operation modes.
- Even with a compact design a full ESRF straight section would be required.

Active harmonic RF system:

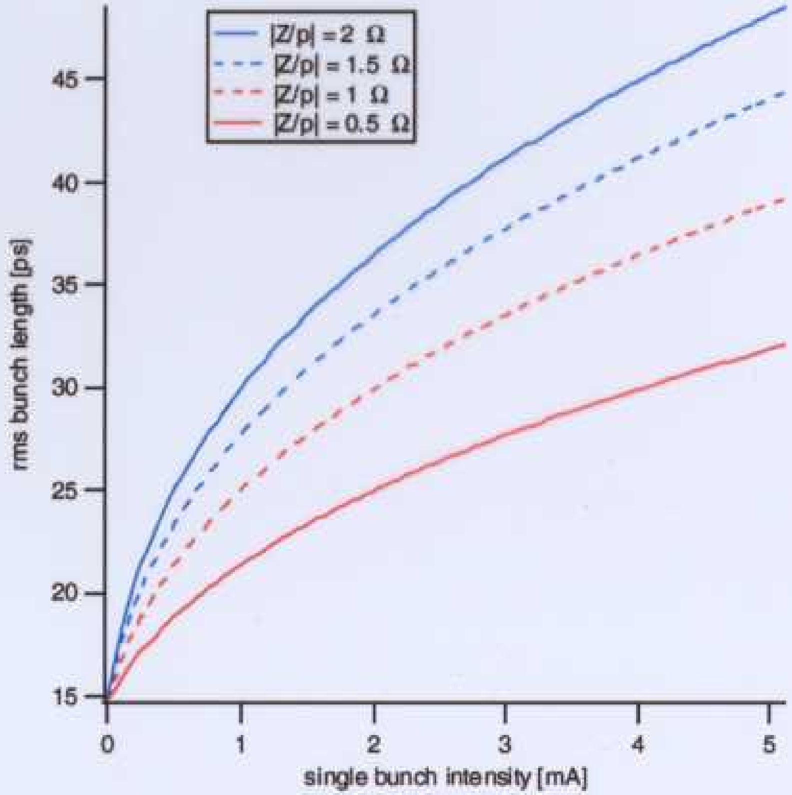
- **1 module** / 2 cells **sufficient.**
- Maximum generator power below 60 kW

Potential well

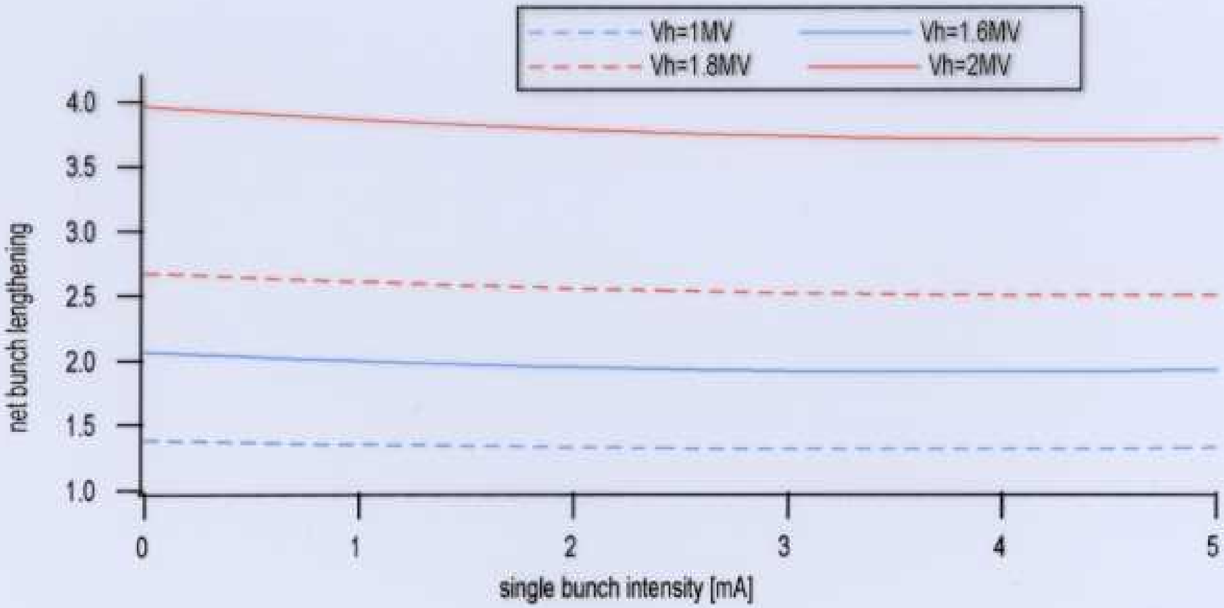
In the potential well regime, the longitudinal distribution is given by the Haissinski equation:

$$\Psi(\phi,\Delta E) = K_1 \Psi_0(\phi,\Delta E)\exp\left(-\frac{1}{2}\left(\frac{Q_s}{\alpha h \sigma_E/E}\right)^2 \times h\left|\frac{Z_L\omega_0}{\omega}\right|(I(\phi)-I(0))\right)$$

Without harmonic RF system:



Potential well with harmonic RF system



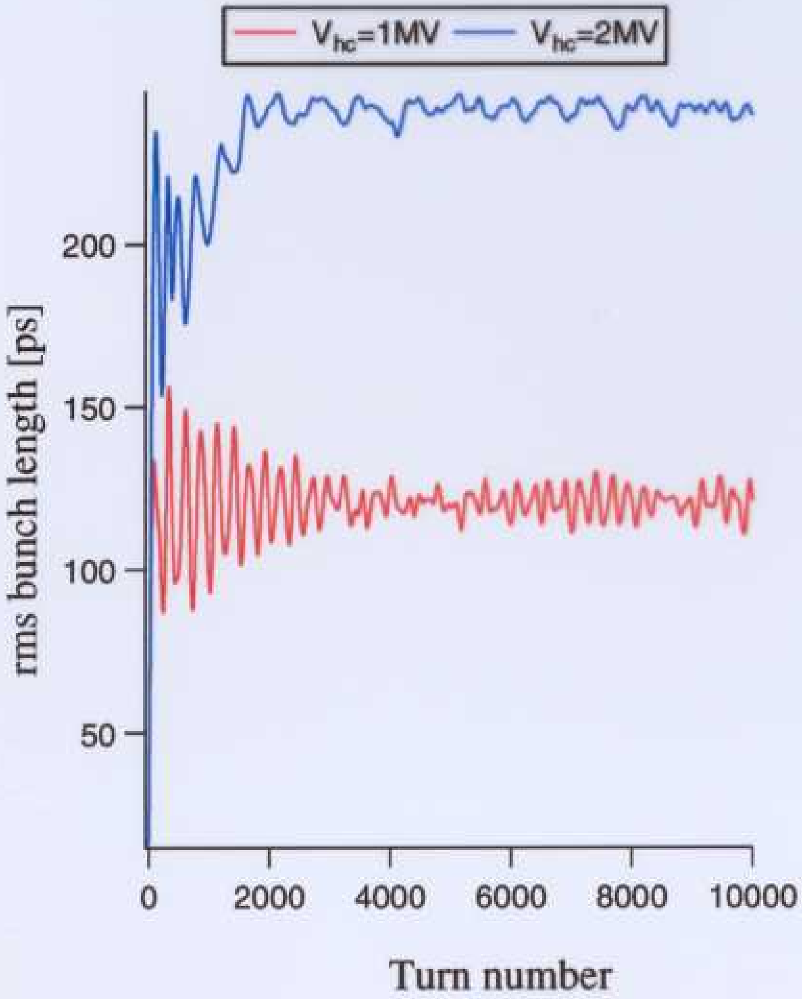
Tracking code & numerical resolution of the Haissinski equation:

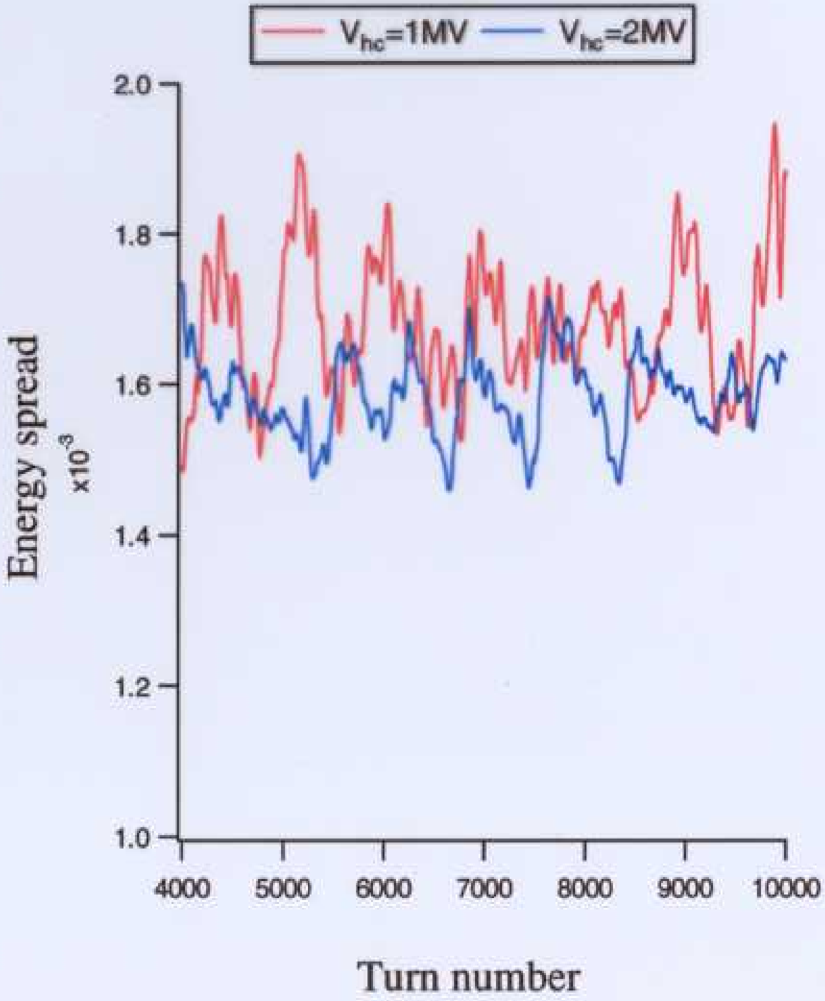
the total bunch length increase is obtained by multiplying
the elongations from the harmonic voltage and from the potential well effect

Microwave Instability - Numerical Example for ESRF -

Standard ESRF BBR model: $f_{res} = 30\ GHz,\ R = 42\ k\Omega,\ Q = 1$

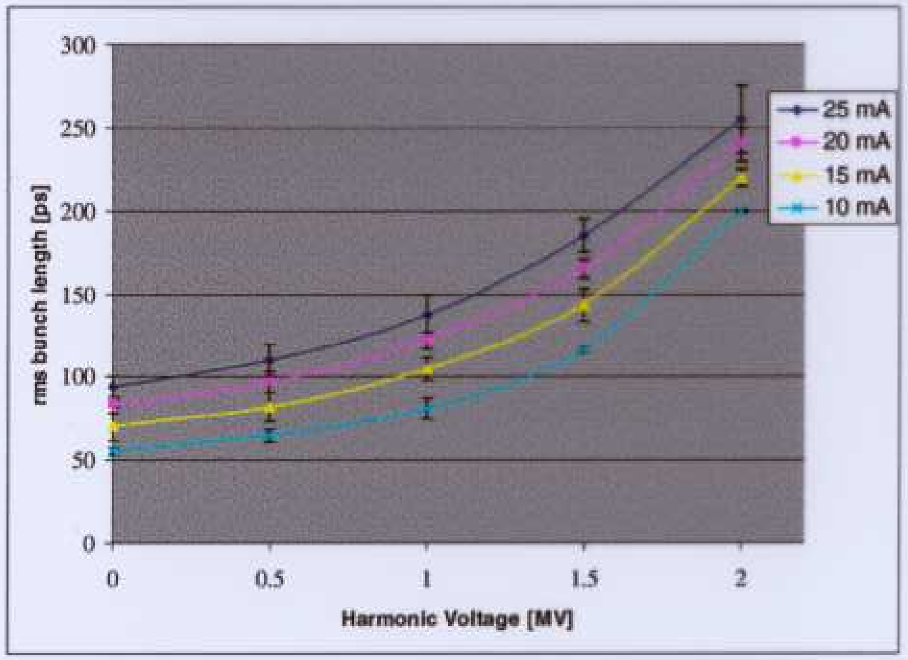
Single bunch - 20 mA

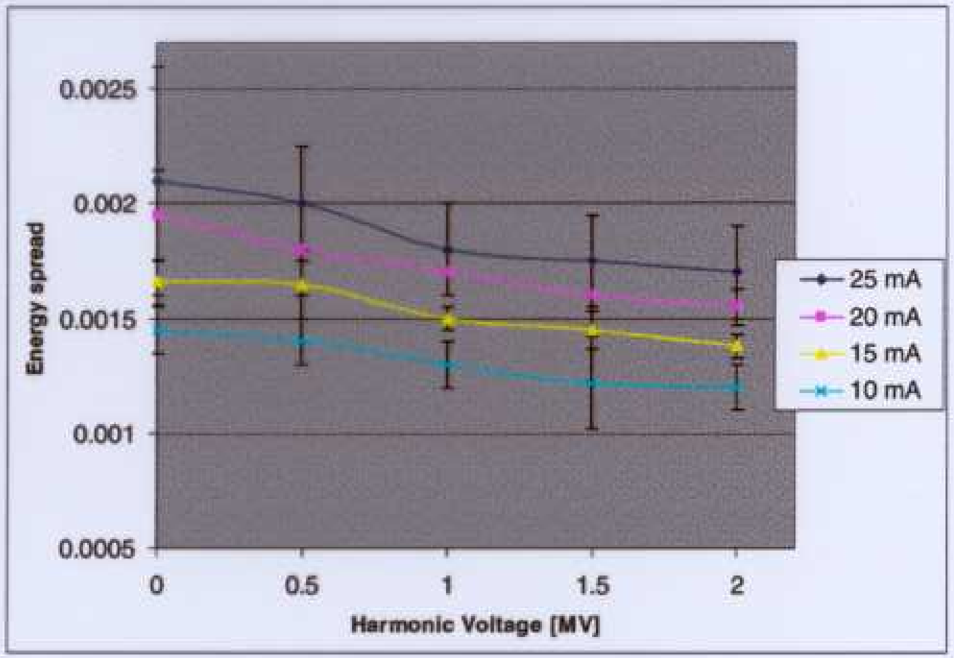




Microwave Instability
bunch lengthening and energy spread @ ESRF

Single bunch operation





At 25 mA, a bunch length increase factor up to 2.7 can still be reached

A harmonic RF system reduces the increase in energy spread

Longitudinal Coupled Bunch Instability - typical ESRF case

NB: 4 bunches were sufficient to simulate LCBI for any symmetric fill pattern as uniform and 16 bunch operation mode

Main RF system only
$I_b = 90\ mA$

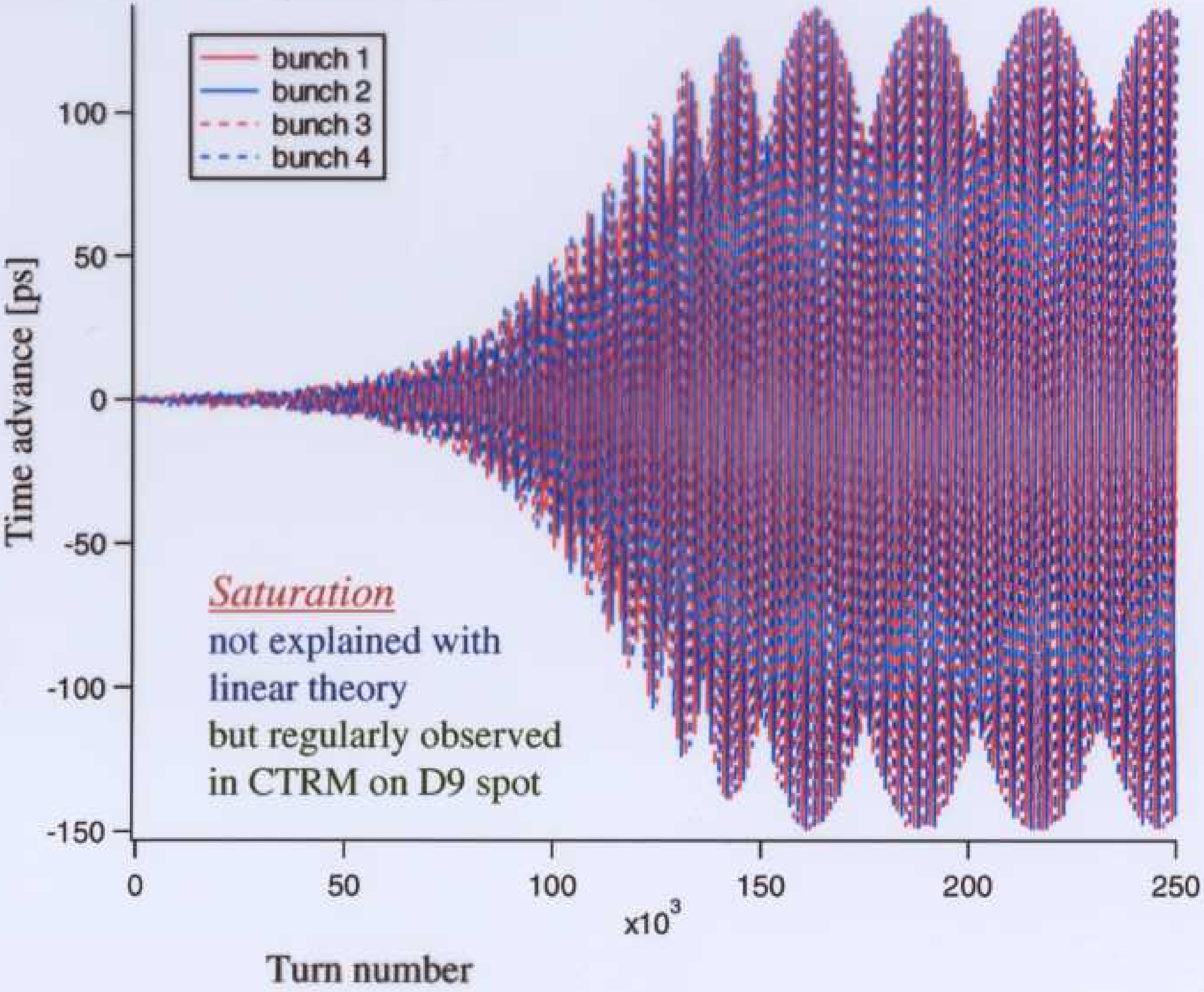
$f_{res,HOM} = f_{RF} + 417 * f_0 + f_{s0}$
$R_s = 2.2 M\Omega\ \&\ Q = 30000$

Theoretical threshold:

$$I_{th} = \frac{2\delta_n f_{so} T_o E / e}{\alpha f_{HOM} R_{s,HOM}} = 91 mA$$

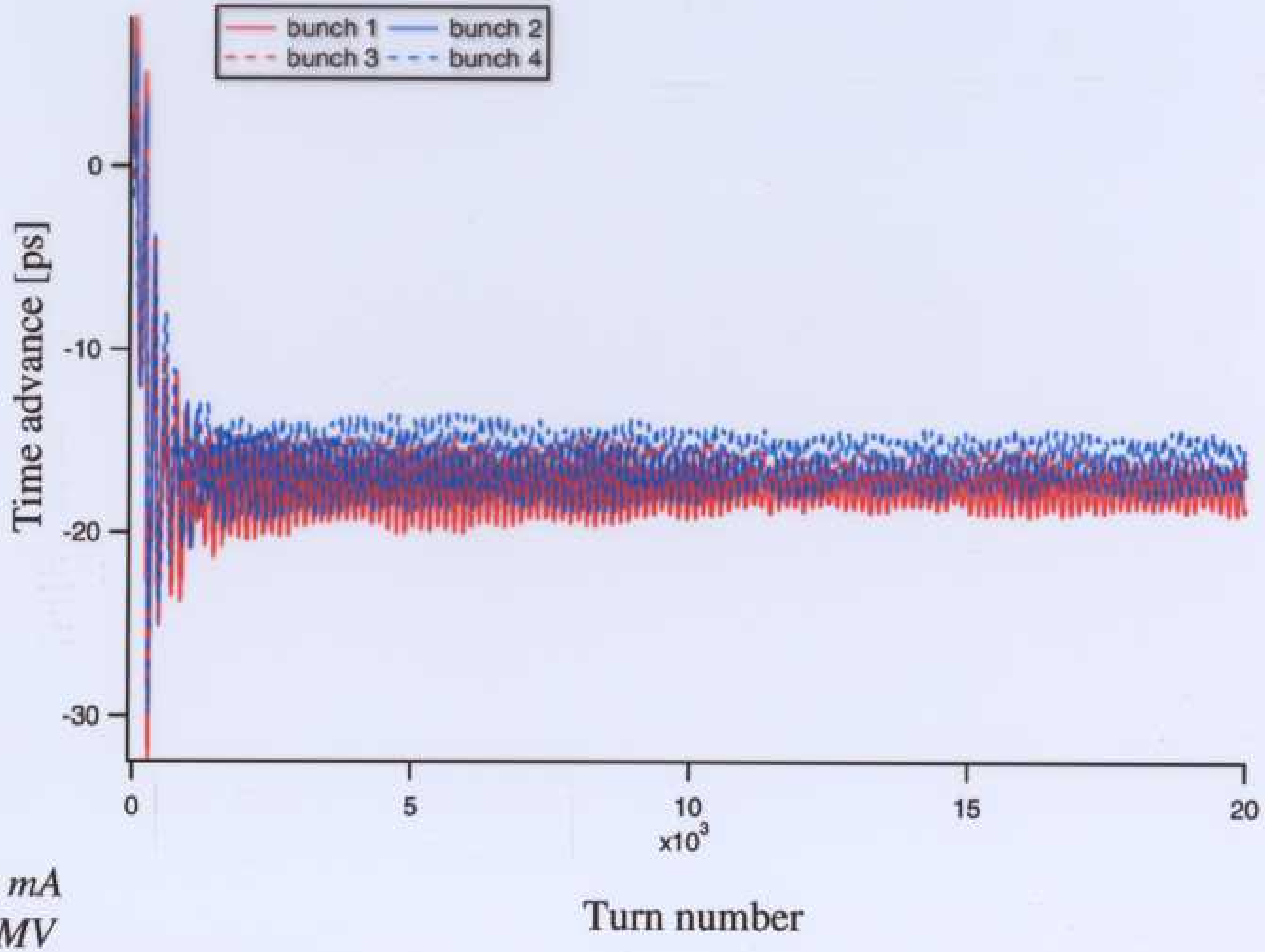
The tracking code shows a modulation of the bunch length and the energy spread at $2 f_s$

$$\langle \sigma_E / E \rangle \approx 5 \times (\sigma_E / E)_0$$



Saturation
not explained with linear theory but regularly observed in CTRM on D9 spot

Longitudinal Coupled Bunch Instability and Landau Damping with Harmonic RF system @ ESRF



$I_{beam}=95\ mA$

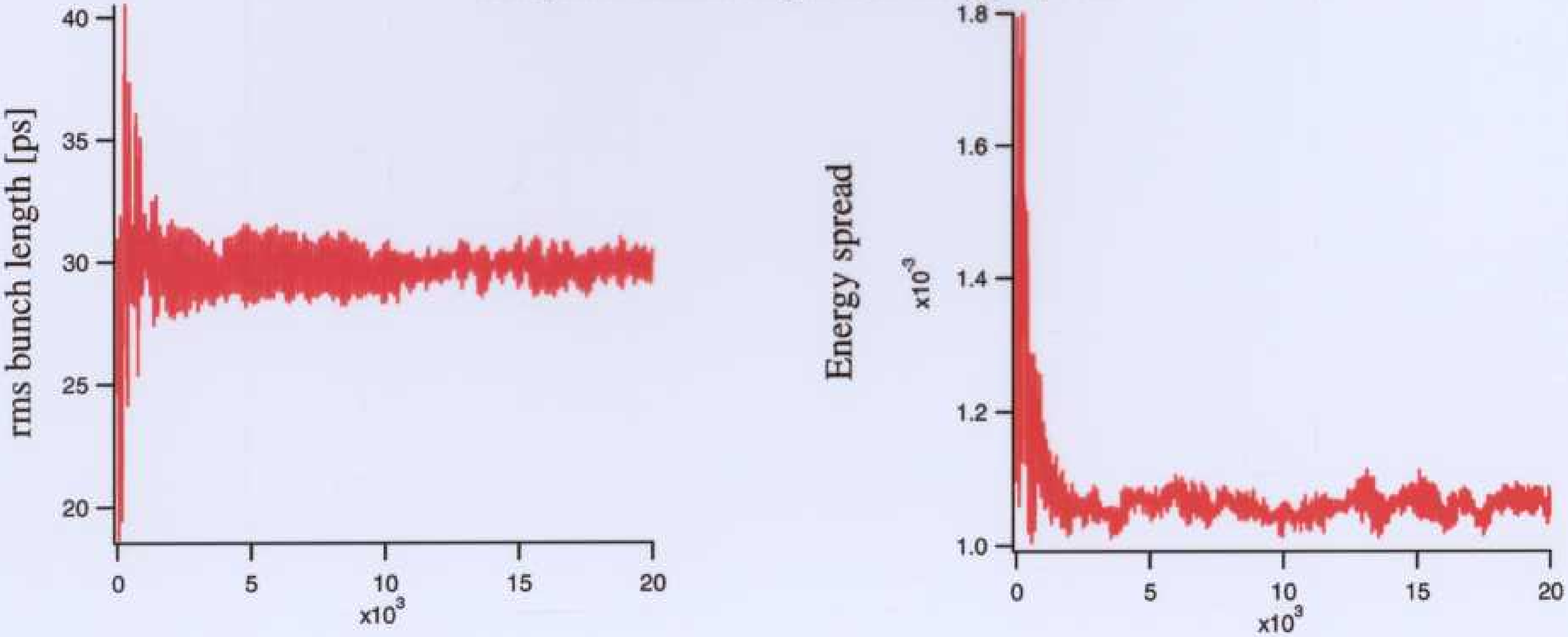
$V_{hc}=1.6\ MV$

$f_{res,HOM}=f_{rf}+417*f_0+<\rho(f_s,V_{hc})>$

Longitudinal Coupled Bunch Instability and Landau Damping with Harmonic RF system @ ESRF

$I_{beam}=95\ mA$
$V_{hc}=1.6\ MV$
$f_{res,HOM}=f_{rf}+417*f_0+<\rho(f_s,V_{hc})>$

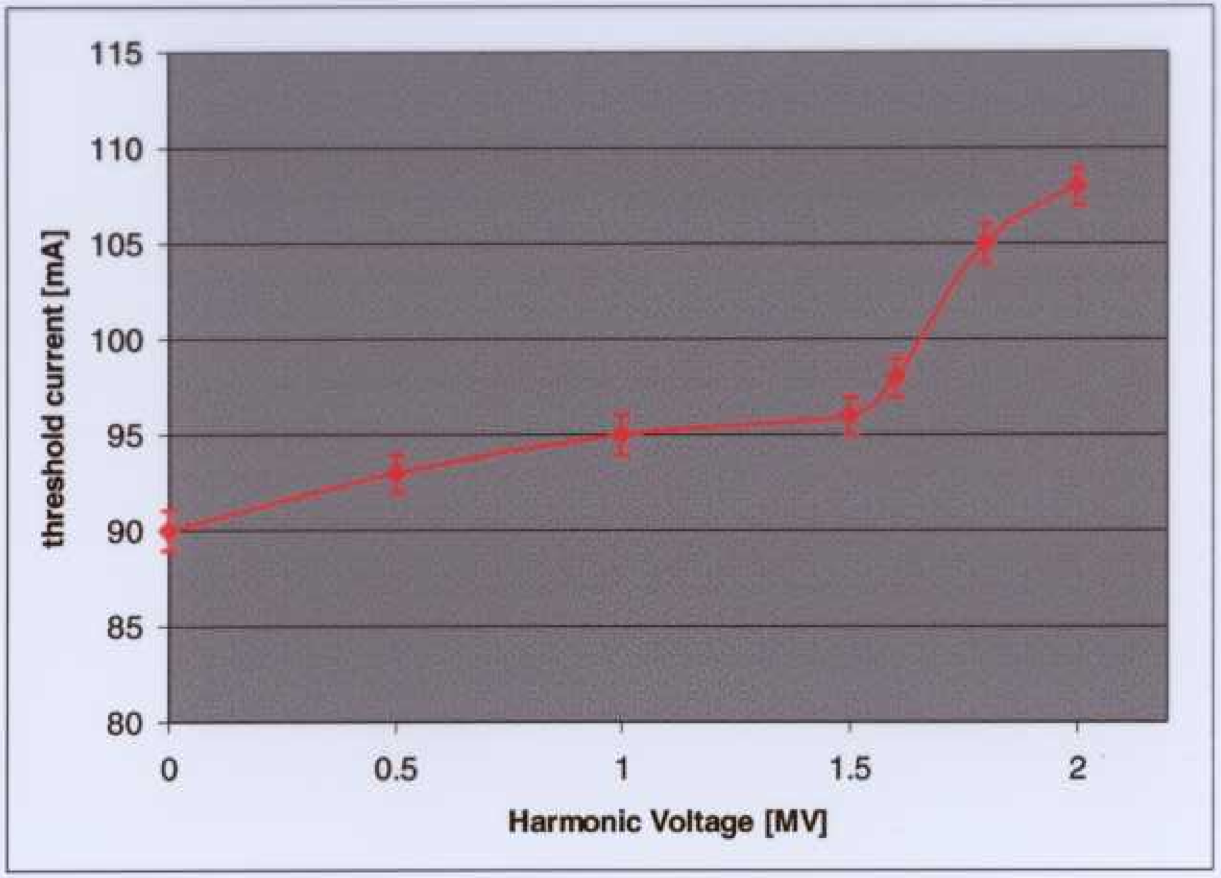
Computed bunch length and energy spread



$\sigma_\tau = 30\,ps$

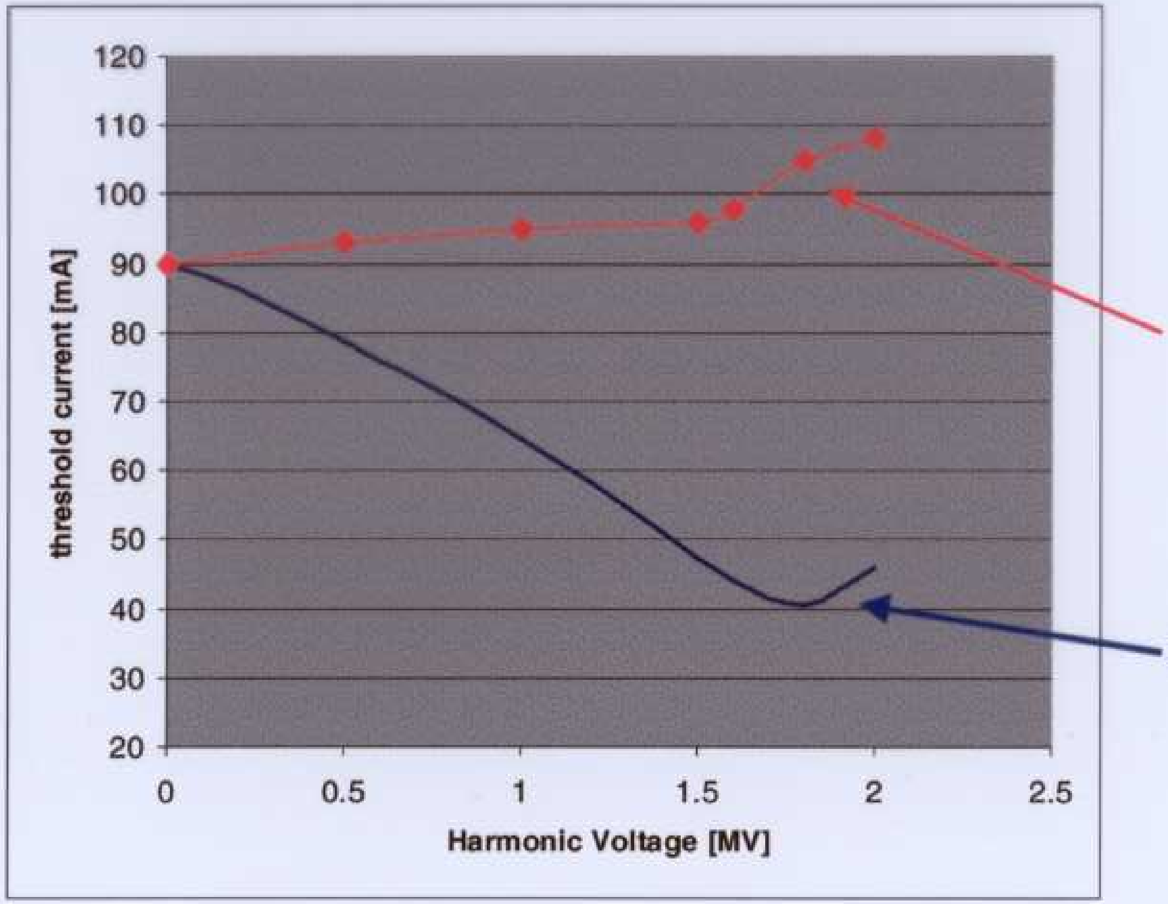
$\sigma_E / E = (\sigma_E / E)_0$

Longitudinal Coupled Bunch Instability Thresholds with a Harmonic RF system @ ESRF



Inside the marker the energy spread is increased by a factor up to 3

Longitudinal Coupled Bunch Instability Thresholds with a Harmonic RF system @ ESRF

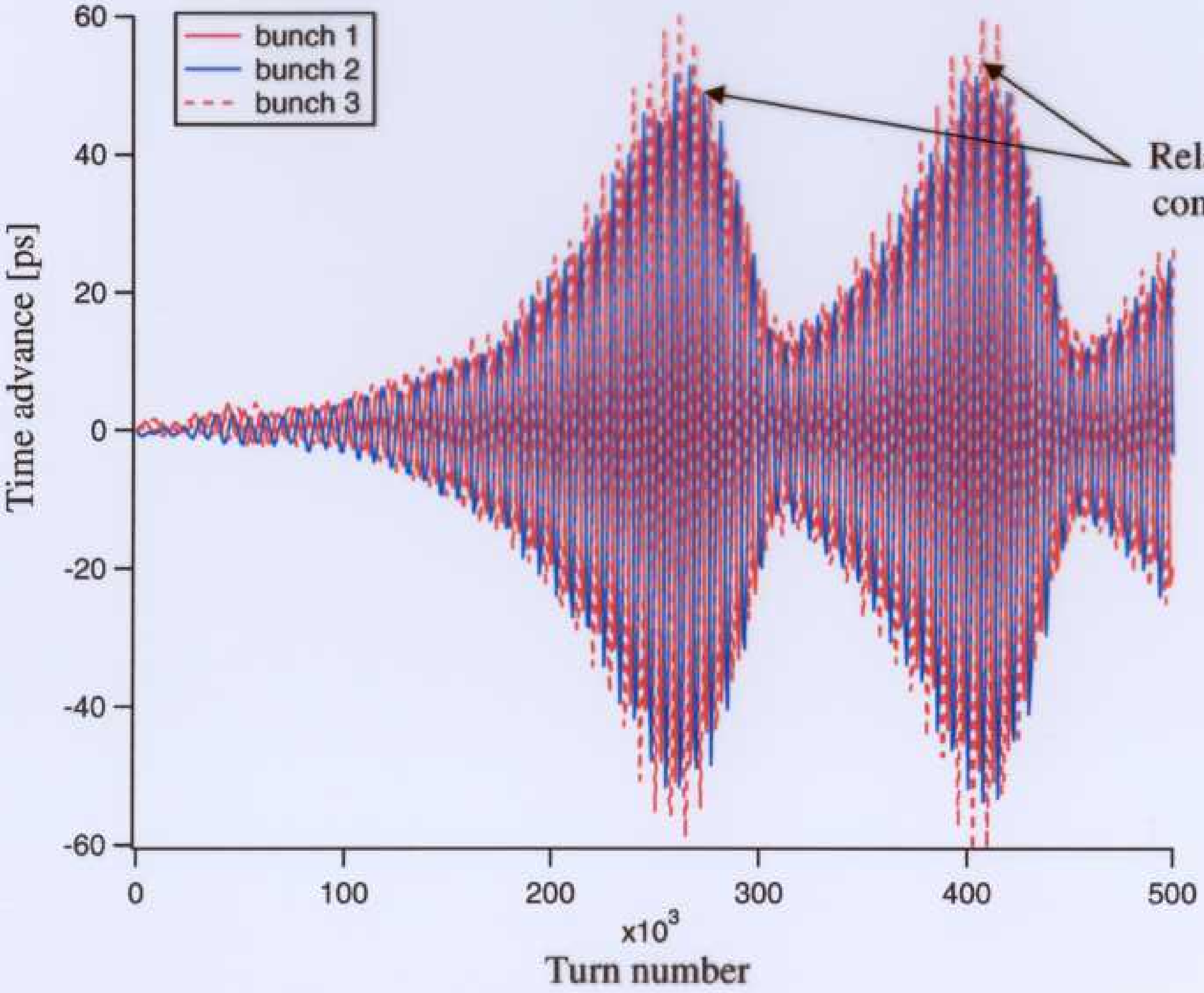


New tracking code

Linear model

Longitudinal Coupled Bunch Instability - Example of MAX-II

MAXII parameters
3 bunches and an arbitrary HOM



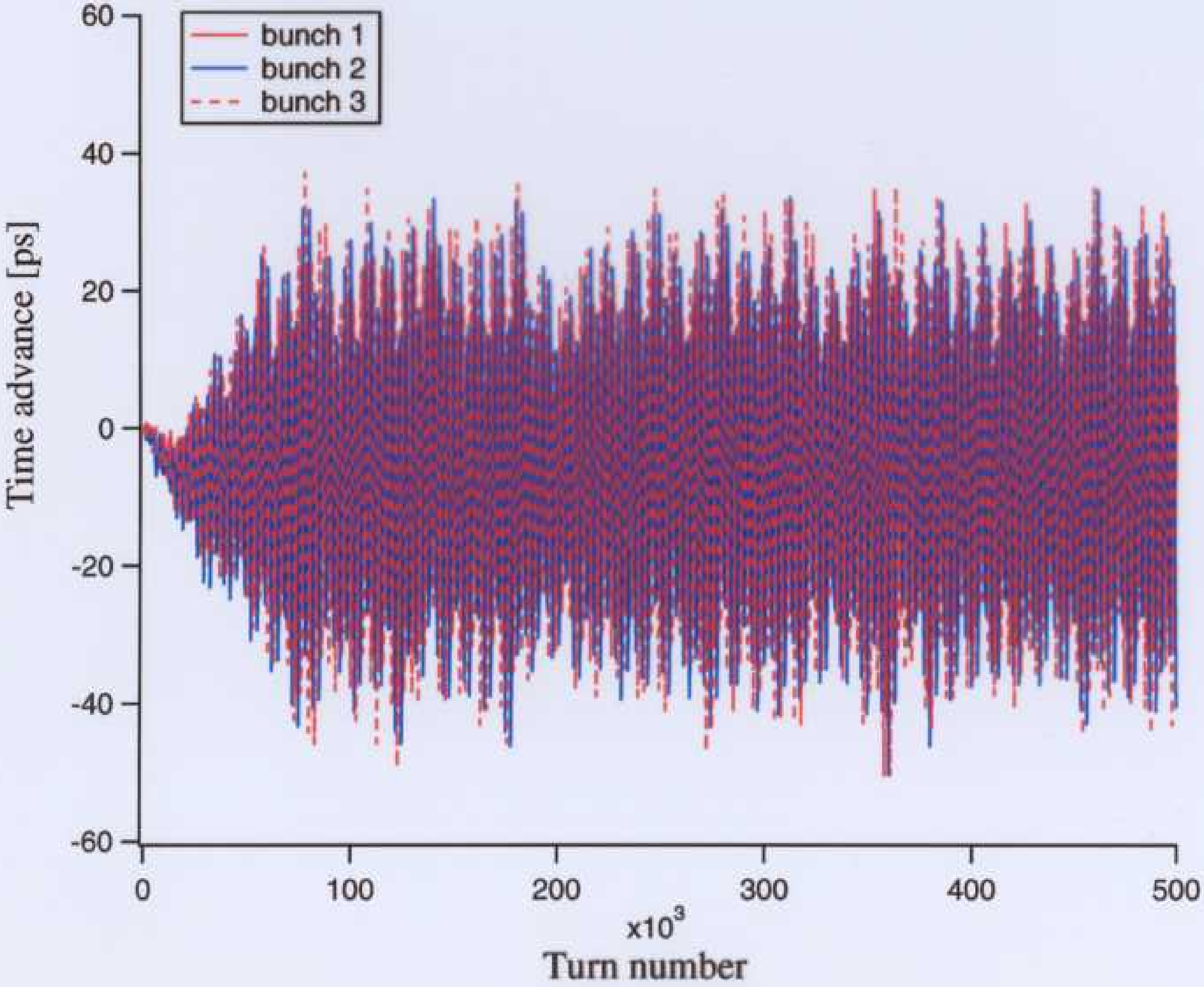
Relaxation also observed and
computed by C.Limborg and
J.Sebek / SPEAR

$$V_{hc} = 0$$

$$\downarrow$$

$$\frac{\sigma_E}{E} \approx 1.1-2.3\times10^{-3}$$

LCBI - Example of MAX-II

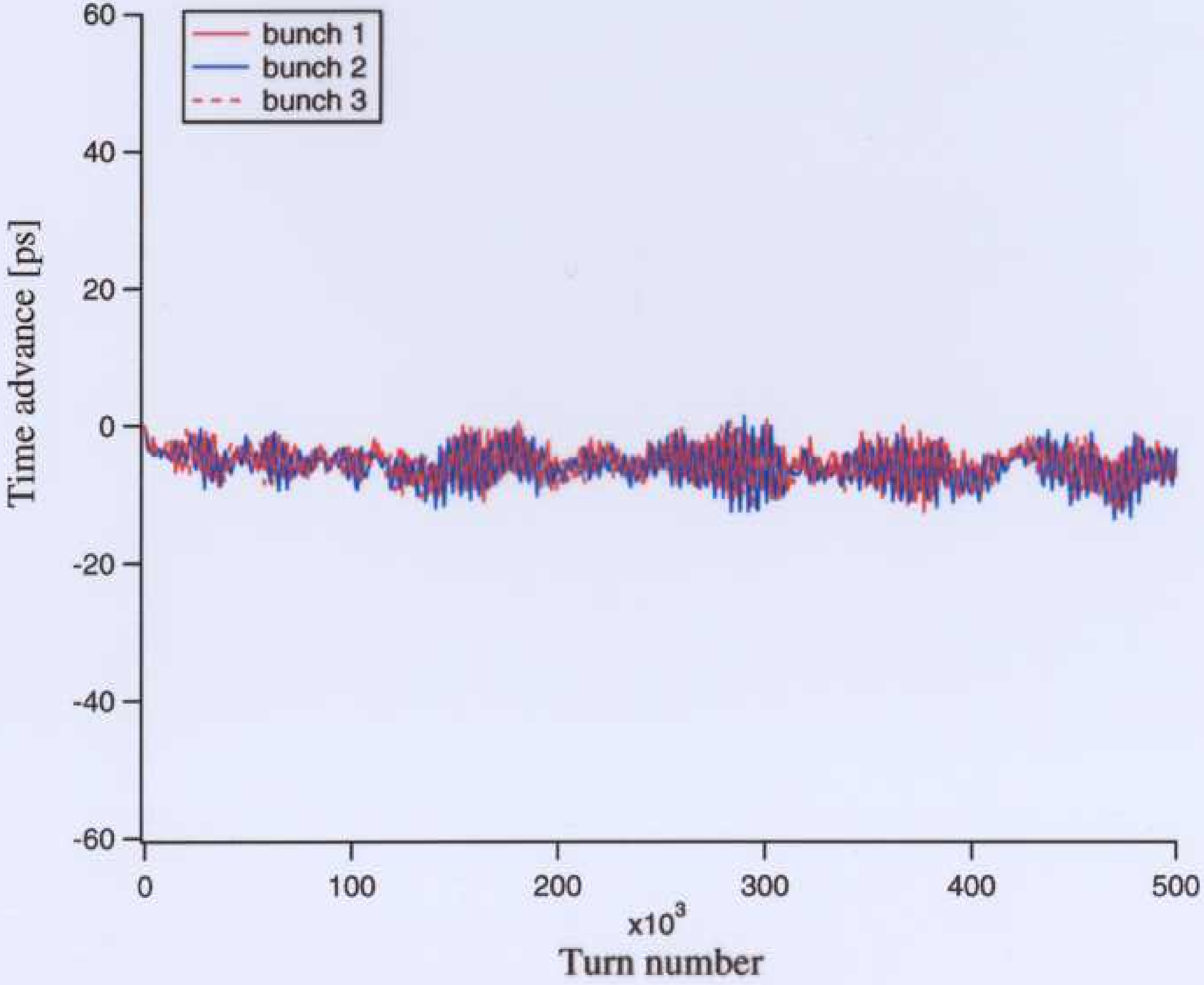


$V_{hc} = 40\ kV$

↓

$\frac{\sigma_E}{E} \approx 1-1.6\times10^{-3}$

LCBI - Example of MAX-II



$V_{hc} = 80\ kV$

$\downarrow$

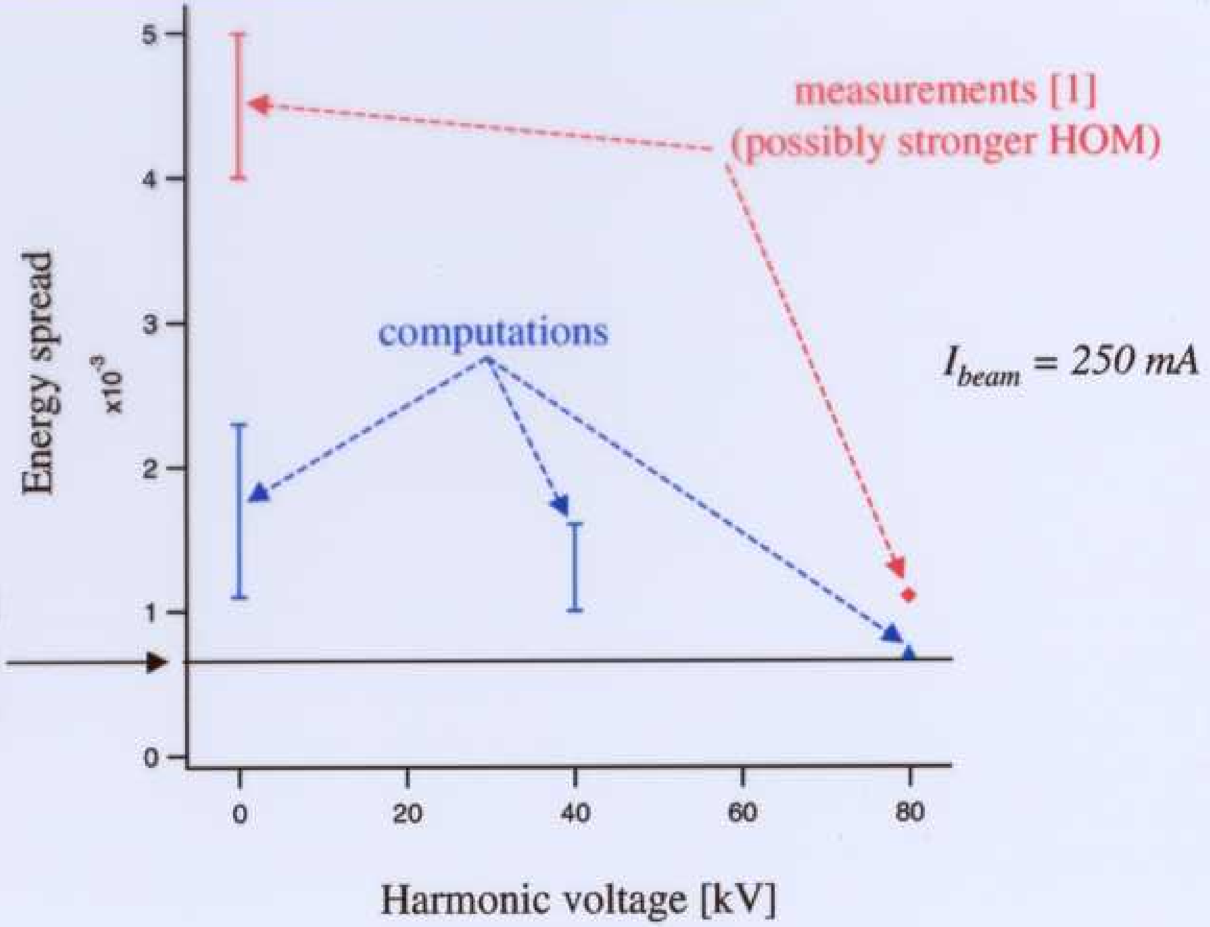
$\frac{\sigma_E}{E} \approx 7\times10^{-4}$

(natural energy spread)

Longitudinal Coupled Bunch Instability
Example of MAX-II

Arbitrarily assumed HOM:

$f_{res,HOM} = f_{RF} + 20*f_0 + f_{s0}$
$R_s=4.2M\Omega$ & $Q=30000$
$I_{th}=10\ mA$



measurements [1]
(possibly stronger HOM)

computations

$I_{beam} = 250\ mA$

natural
energy
spread

The new mutibunch multiparticle tracking code confirms qualitatively
the observations made at MAX-II

[1] Å. Anderson & al.