Do we need HOM dampers on superconducting cavities in p linacs?

“Yes, we ~~can~~ do”: a personal view(*)

J. Tückmantel
11-12 Dec 08

(*) where I disagree with many people but agree in essence with retired ‘heavy-weights’ Ernst Haebel and Ron Sundelin
… however, this presentation is my <u>personal justification</u> for it …

‘Prelude’

”The question is already settled, have a look at ..”

… a thesis work (author unfortunately not present, but he knows)

It examines only the **power** coupled out from the beam.

NO DIRECT BEAM STABILITY CONSIDERATIONS !!!

Conclusion: HOM coupler are not necessary for …. (p-linac)

The treatment of the power-aspect is all OK but there is a

Logical Problem:

One cannot ignore the **main benefit** of an object – **impedance reduction** – and conclude from the study of secondary effects – power outflow – that one does not need this object !

(Maybe one really doesn’t need it, but everything has to be included in a valid analysis !)

—> work does NOT answer the question

Sneak in the power study as beam instability study:

"To drive the beam unstable, one needs sufficiently high fields." (**agreed**)

"The latter can only be produced when there is an HOM sitting on a machine line (.., what else G. Clooney ?)"

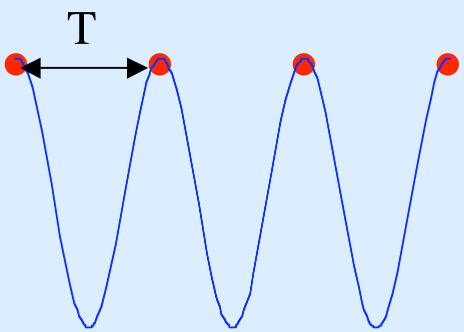
NO, we shall see why!

("The probability for a high-Q_{ext} mode hitting such a machine line (within a BW...) is very, very low, hence ....").

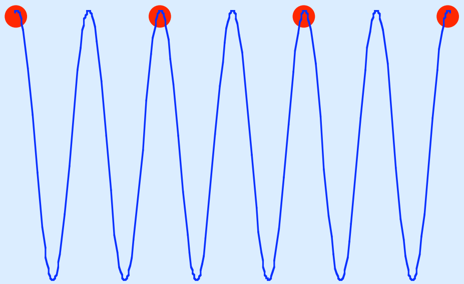
("In SNS no power output seen" Bad argument: **damping was good enough to keep it so low !!**

(Agreed fact: the more one damps the less comes out!)

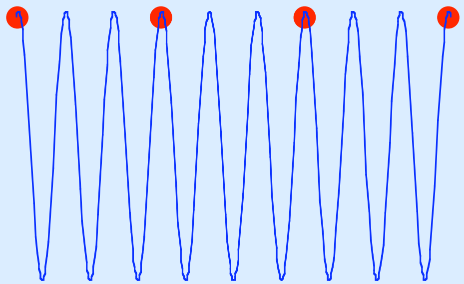
A **continuous** sine-wave has **only one** resonant frequency: its own.
But bunches arrive stroboscopically: 1 bunch each time T that 'tick' the observing oscillator: spectrum analyzer, cavity mode, …



1st machine line: 1 oscillation between 2 consecutive bunches
Resonant on $f_{ML} = 1/T$



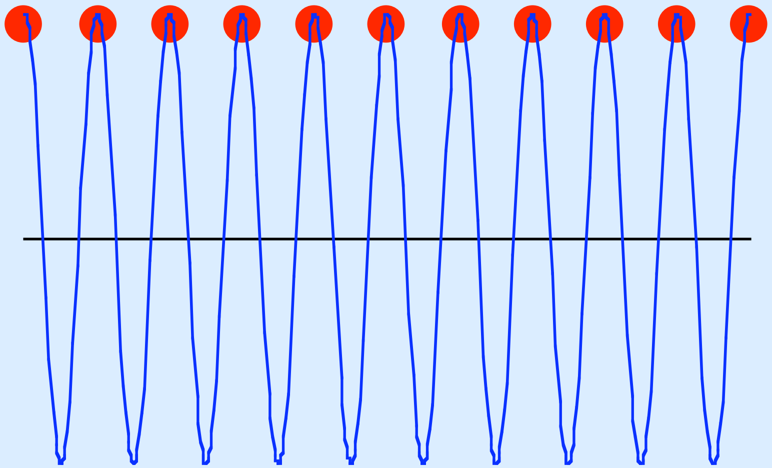
2nd machine line: 2 oscillation between 2 consecutive bunches
Resonant on $f_{ML} = 2/T$



3rd machine line: 3 oscillation between 2 consecutive bunches
Resonant on $f_{ML} = 3/T$

Bunches have transverse displacement: Express any pattern by Fourier components: harmonic position modulation

- Example 1: Constant (transverse) displacement



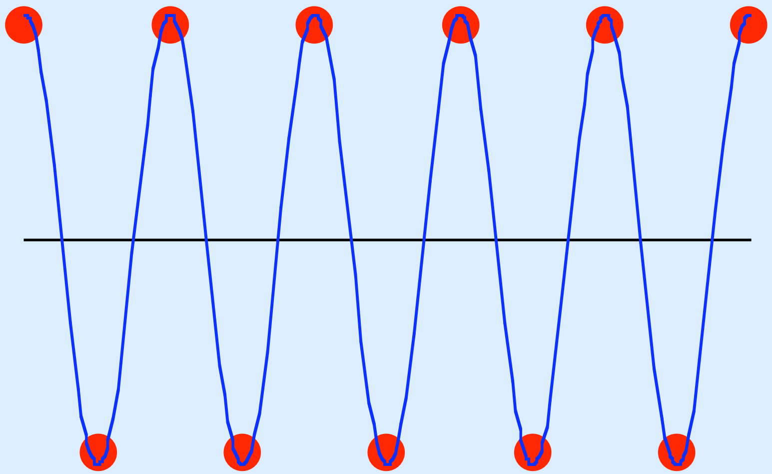
Bunch n: $t_n = n \cdot T$

Displacement $x_n = 1 = \cos(0 * 2\pi n)$

Resonant oscillation: $\cos(\omega_0 \cdot t)$

$f = f_0 = 1/T$; $\omega_0 = 2\pi \cdot f_0$

• Example 2: Up-down (right-left) modulation (‘ξ =1/2’)



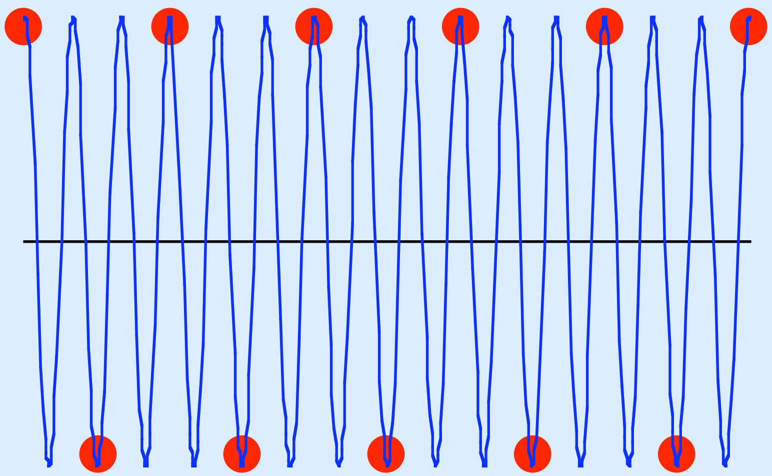
Bunch n: $t_n = n \cdot T$

Displacement $\cos(0.5 * 2\pi \cdot n)$

Res. Osc. $\cos((1-0.5) \cdot \omega_0 \cdot t)$

$f = f_0 \cdot (1-0.5) = 0.5 \cdot f_0$

Lower sideband: Not on ML



Bunch n: $t_n = n \cdot T$

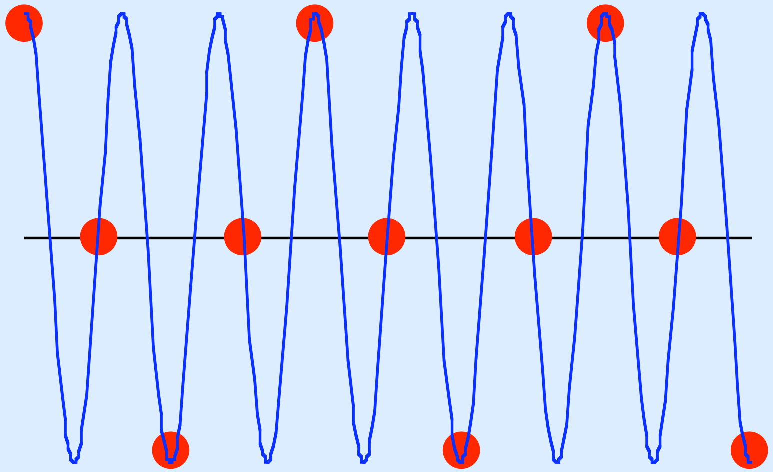
Displacement $\cos(0.5 * 2\pi \cdot n)$

Res. Osc. $\cos((1+0.5)\ ) \cdot \omega_0 \cdot t)$

$f = f_0 \cdot (1+0.5)\ ) = 1.5 \cdot f_0$

Upper sideband: Not on ML

- Example 3: Up-zero-down-zero modulation (‘ξ =1/4’)



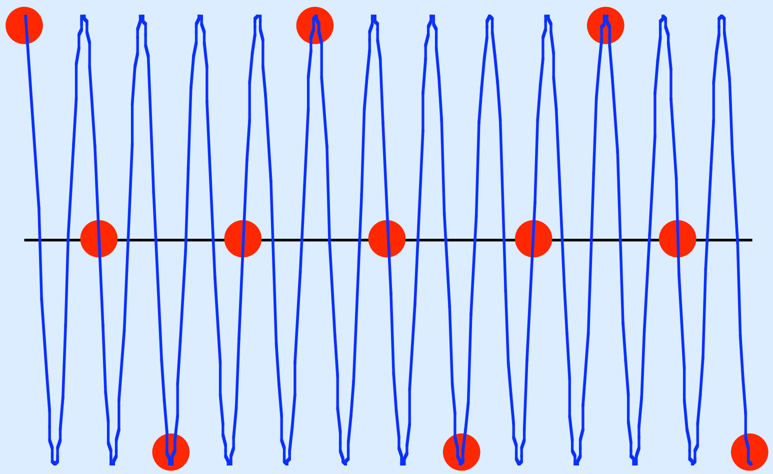
Bunch n: $t_n = n \cdot T$

Displacement $\cos(0.25 \cdot 2\pi \cdot n)$

Res. Osc. $\cos((1-0.25) \cdot \omega_0 \cdot t)$

$f = f_0 \cdot (1-0.25)) = 0.75 \cdot f_0$

Lower sideband : Not on ML



Bunch n: $t_n = n \cdot T$

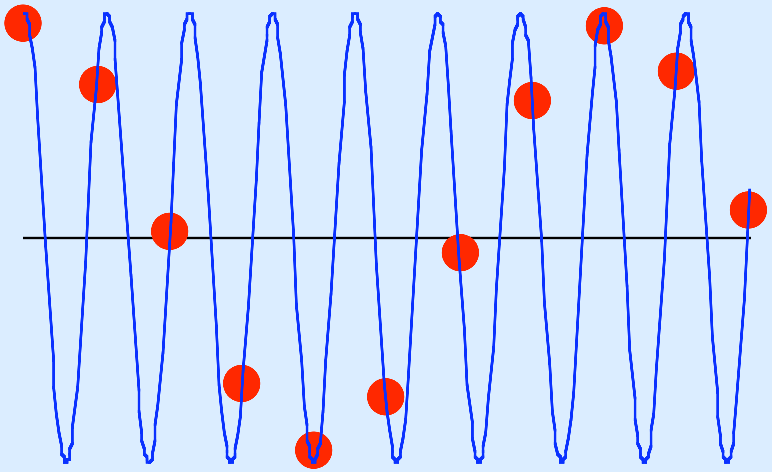
Displacement $\cos(0.25 \cdot 2\pi \cdot n)$

Res. Osc. $\cos((1+0.25)) \cdot \omega_0 \cdot t)$

$f = f_0 \cdot (1+0.25)) = 1.25 \cdot f_0$

Upper sideband : Not on ML

• Example 4: **Anything** (even irrational number) ('ξ =0.123')



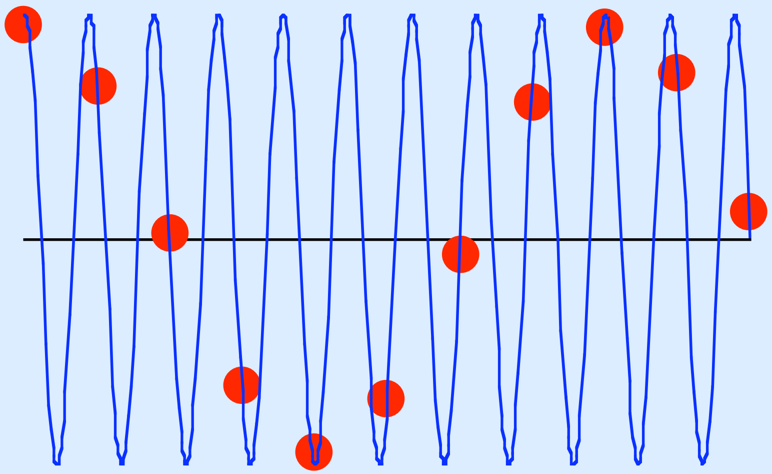
Bunch n: t_n=n·T

Displacement cos(0.123 · 2π · n)

Res. Osc. **cos((1-0.123)·ω_0·t)**

f=f_0·(1-0.123))=0.877· f_0

Lower sideband : Not on ML



Bunch n: t_n=n·T

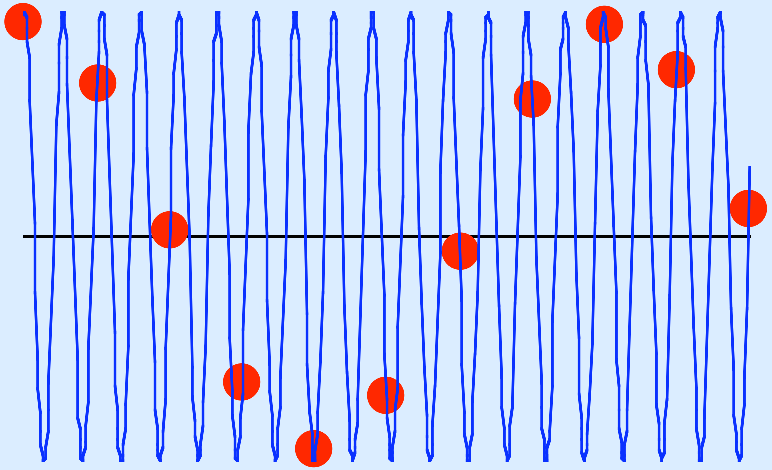
Displacement cos(0.123 · 2π · n)

Res. Osc. **cos((1+0.123)·ω_0·t)**

f=f_0·(1+0.123))=1.123· f_0

Upper sideband : Not on ML

• Example 5: An additional integer number of oscillations (between other machine lines)



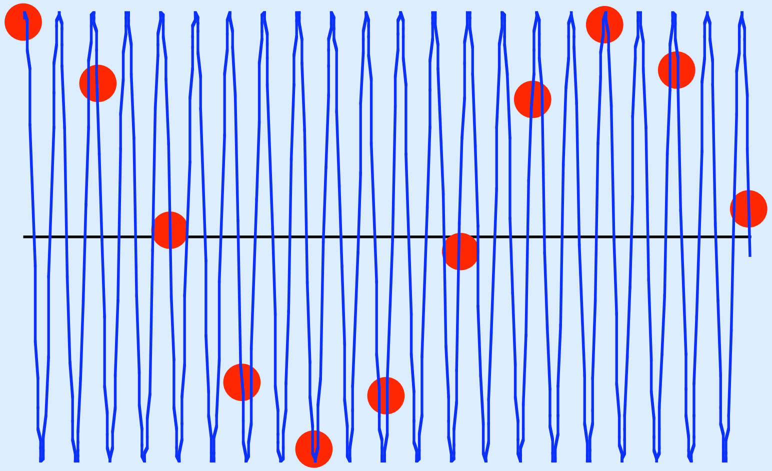
Bunch n: $t_n = n \cdot T$

Displacement $\cos(0.123 \cdot 2\pi \cdot n)$

Res. Osc. $\cos((2-0.123) \cdot \omega_0 \cdot t)$

$f = f_0 \cdot (2-0.123)\ ) = 1.877 \cdot f_0$

Lower sideband : Not on ML



Bunch n: $t_n = n \cdot T$

Displacement $\cos(0.123 \cdot 2\pi \cdot n)$

Res. Osc. $\cos((2+0.123) \cdot \omega_0 \cdot t)$

$f = f_0 \cdot (2+0.123)\ ) = 2.123 \cdot f_0$

Upper sideband : Not on ML

Numerical example:

Given: Bunch repetition rate 350 MHz, T=1/350MHz
Assume f_{HOM} = 1234.567890 MHz (<u>any number</u>)

1234.567.. / 350 = 3.527… = 3+0.527 (= 4 - 0.473)

f_{HOM} above 3rd, below 4th machine line (ML)

1234.567… - 3*350 = 184.567… [MHz] above 3rd ML
(1234.567... - 4*350 = -165.433… [MHz] below 4th ML)

Bunch pattern has ξ=0.527 oscillations per T (527 on 1000)

For ANY mode frequency exists matching pattern !!!

Possible excitation of an Instability (circular machines):

• Any HOM-f has a matching pattern: hence any HOM-f can be resonantly excited **provided this pattern is present** (*)

• If an HOM is excited, it 'momentum modulates' (kicks) the passing beam, **exciting this matching pattern**

• 'Momentum modulation' transforms (over 'drift', focussing) into 'position modulation'

• In **circular machines** the 'position modulated' beam passes the cavity(s) again (and again), possibly increasing the HOM field.

• An increased HOM field may increase 'momentum modulation'

—> causes **well known** **C**oupled **B**unch **I**nstability
(even normal conducting cavities – low Q – do the job !!)
—> HOM damping (sc. cav) in circular machines **accepted fact**

(*) neglect shift by betatron frequency, not an essential point for the present discussion

Claim: It is improbable that HOM-f and a given pattern match

Wrong argument:

- A once existing HOM excites THE matching pattern
- This pattern excites HOM on the initially exciting frequency

—> not ‘independent events’, **probability is not applicable**

In circ. machine HOM amplitude A increases by factor g per turn:

$$A_n = A_o \cdot g^n \qquad \text{… and pattern amplitude with it}$$

Where is first A_0 coming from ? **Noise on the (injected bunches) !**

HOM filters its own frequency out of the noise: initial step A_0

Example: Beam of 2.5 mA at T=1/350 MHz : **10^8 protons per bunch**

Average position of 10^8 particles has relative scatter of 10^{-4}:

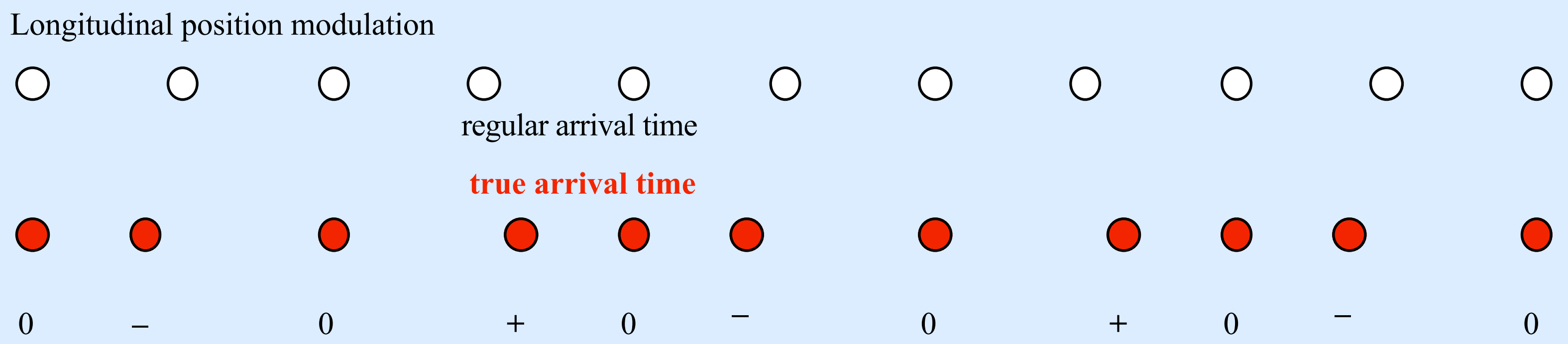
Bunch centre position jitters by 10^{-4} bunch-lengths

(cum grano salis)

There is much more … RF noise on main field, injector jitter, …

no hope for $A_0 \equiv 0$

CBI exists also in longitudinal plane (easier to draw transverse):
Position modulation by time advance/delay of bunch arrival:



$t_n = T \cdot (n + a \cdot \cos(2\pi \cdot n \cdot \xi))$ arrival time modulation

at kth machine line (assume a<<1)

$f_{ML} = k \cdot f_0$ amplitude 1

$f_{SB} = (k \pm \xi) \cdot f_0$ amplitude $a/(2\pi)$

Is a similar mechanism possible in a linac ?

Seems not: each bunch encounters each cavity only once, but

- HOM gets excited by the (tiny) noise on the arriving bunches (the complex voltage vector 'random walks' in the complex pane, the 'noise power' drives <V^2> lineraly up in time till compensated by *damping*: not reached for high Q_{ext} modes)
- Excited cavities 'kick' later bunches imposing the matching 'momentum pattern' sent to more downstream cavities
- Over drift/focussing transforms into 'displacement pattern'
- More downstream cavities are coherently excited (Coherent: time of flight from cavity M to cavity N constant)
- even more downstream cavities get even more excited ….

Much simplified model to understand principle:

• Each cavity is driven only by the beam deviation due to nearest upstream cavity with very **weak** coupling factor κ

(neglect more upstream, transported through focusing system (*))

• HOM field changes by complex factor d during T, $|d| \approx 1$

d complex: HOM not on ML!!

(Consider noise only on first cavity; study first 3 cavities: U, V, W)

$U^{(n+1)} = d\cdot (U^{(n)} + \delta U^{(n)})$; $\delta U^{(n)}$ = random noise signal

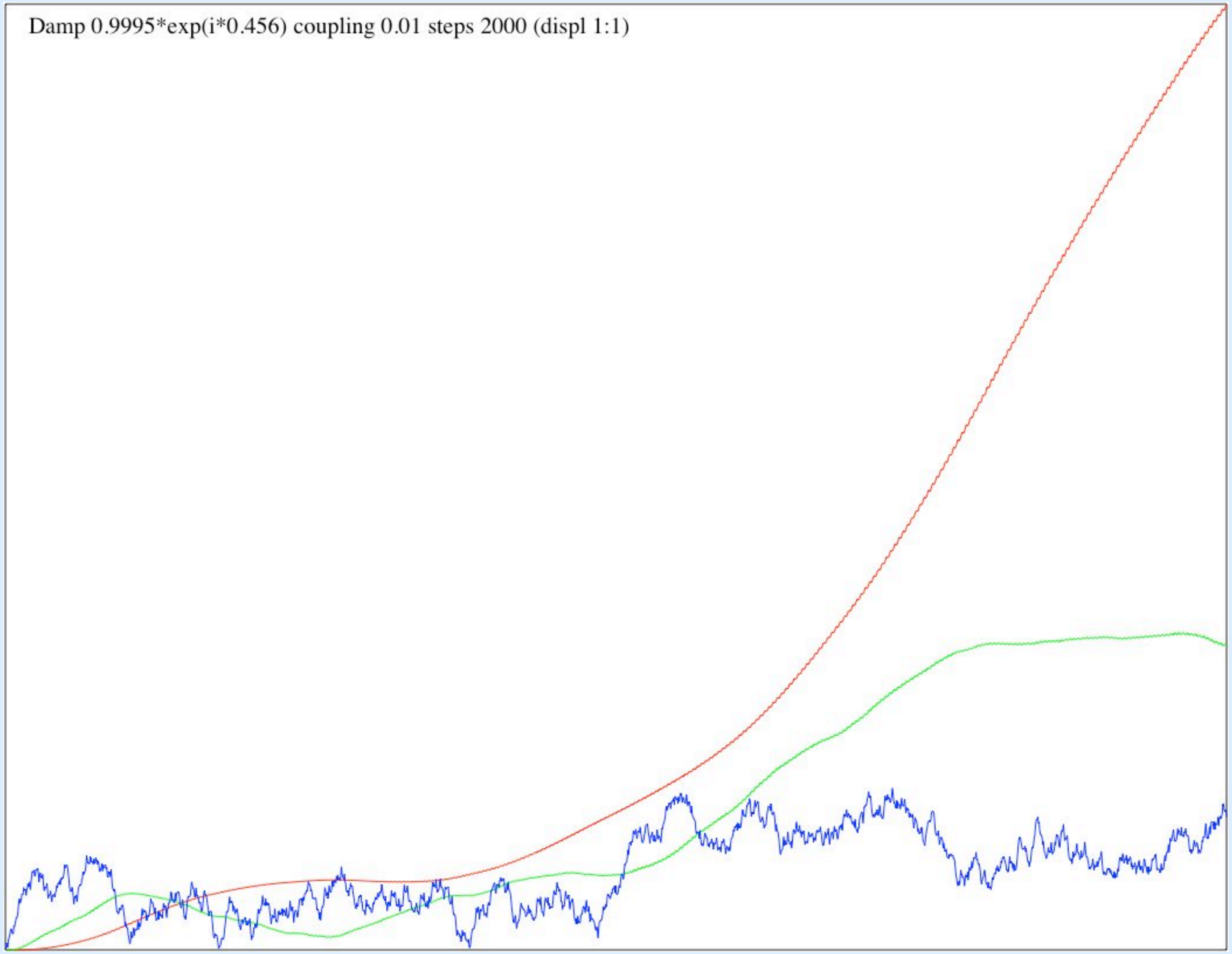
$V^{(n+2)} = d\cdot(V^{(n+1)} + \kappa *Re(U^{(n+1)}))$;

$W^{(n+3)} = d\cdot (W^{(n+2)} + \kappa *Re(V^{(n+2)}))$; can be analyzed mathemat.

(1 ms beam pulse at 352 MHz: 350,000 bunches)

(*) All deviations coming from more upstream are mutually coherent: All particles have 1) fixed time of flight 2) see same focusing system

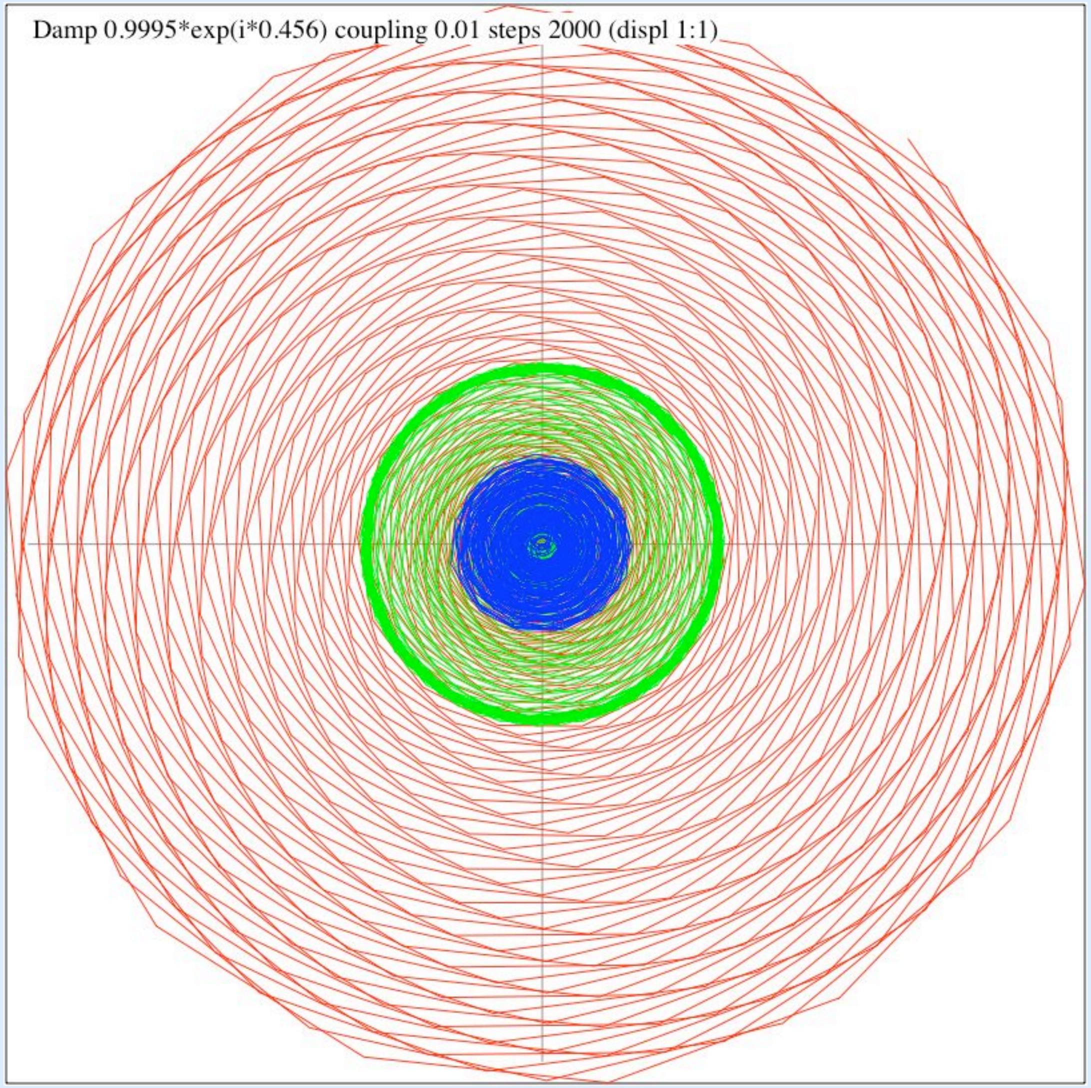
|V| as function of time/bunch number, 2000 bunches



U:Cavity 1 **V:Cavity 2** **W:Cavity 3**

Time-wise ‘increase’ and also increase cavity-to-cavity

Polar display of complex cavity voltage: reference main Main Line

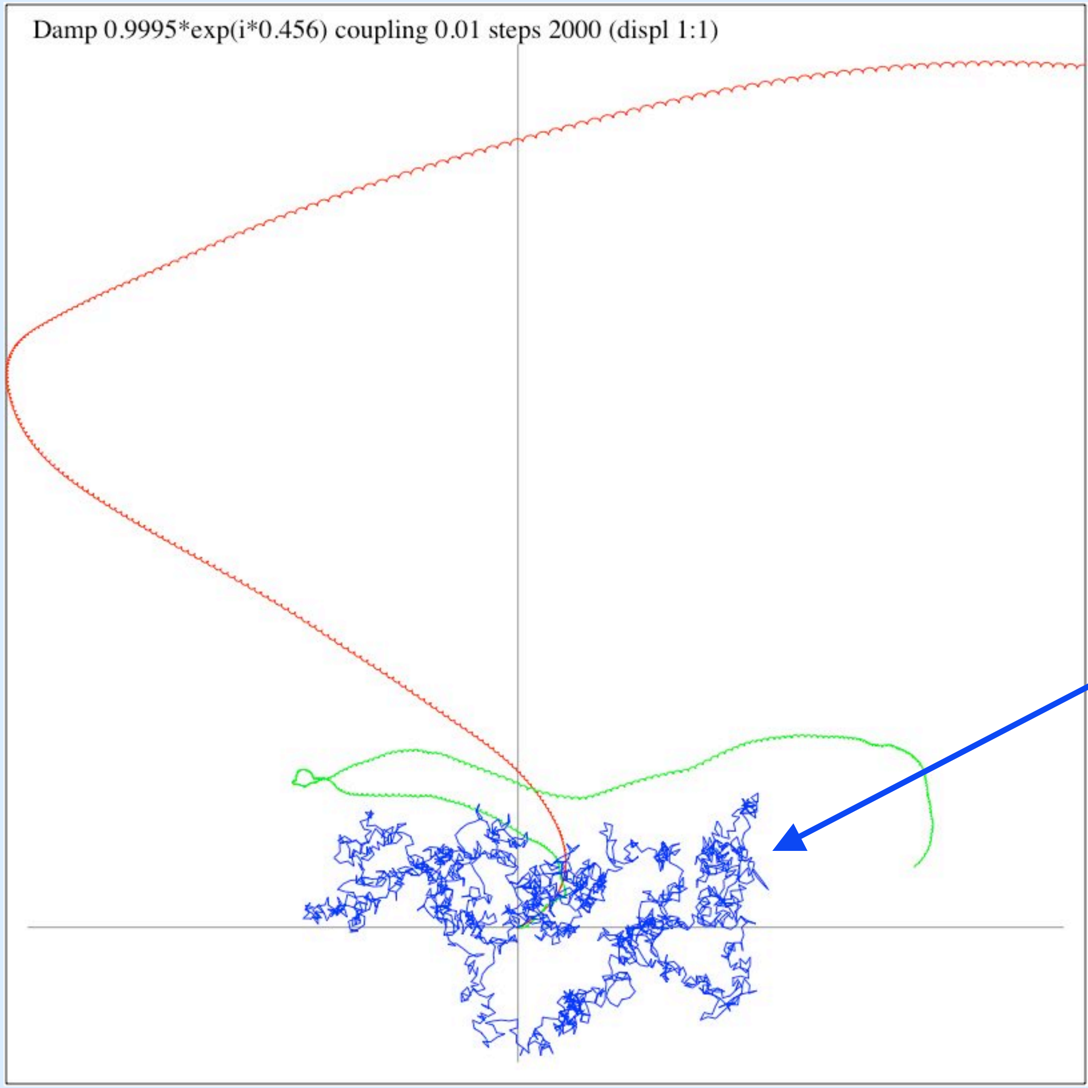


Each vector is turned by a further complex d per step

2000 steps

U:Cavity 1 **V:Cavity 2** **W:Cavity 3**

Polar display of complex cavity voltage: reference HOM

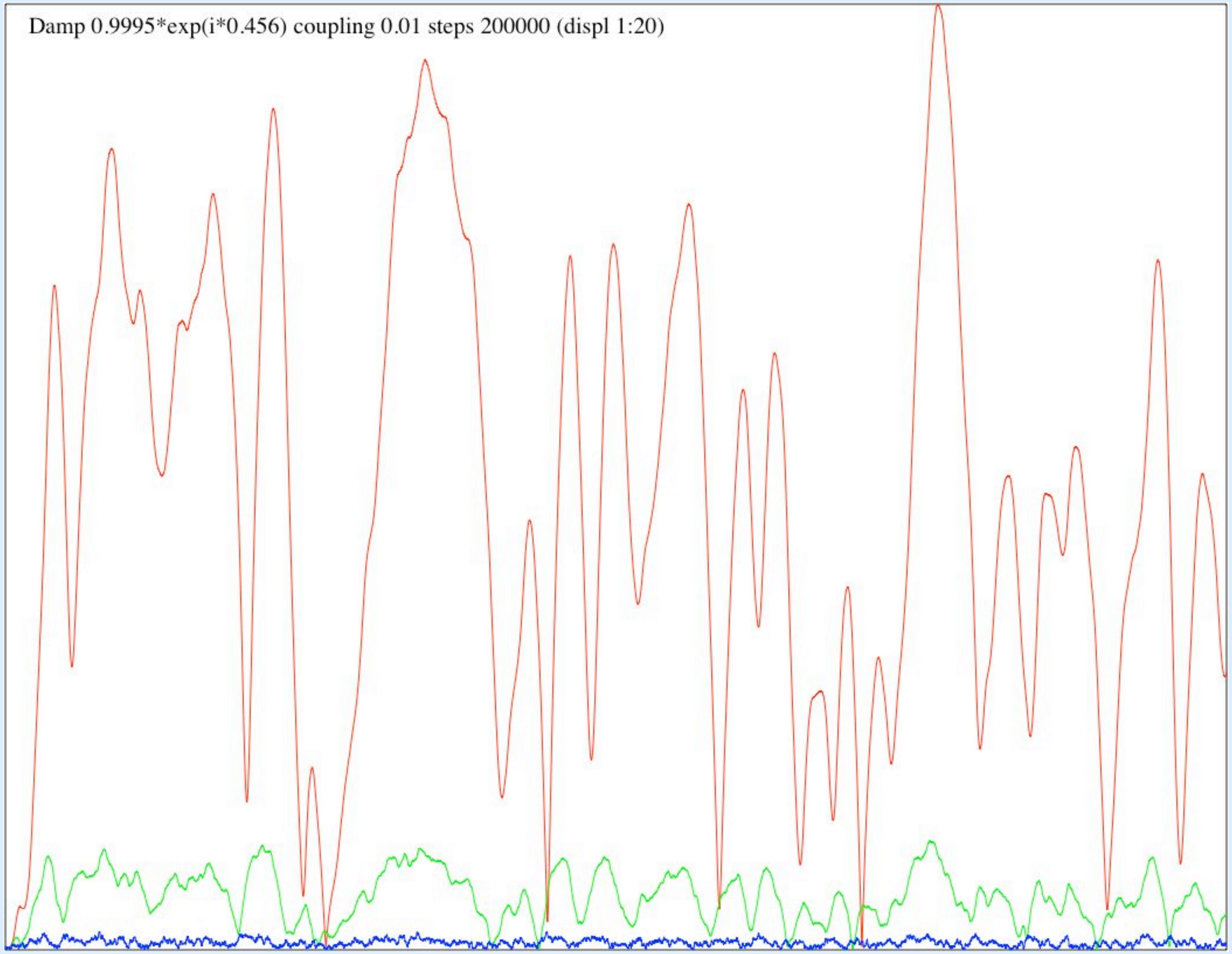


2000 steps

Random walk of noise driven voltage in cavity 1

U:Cavity 1 **V:Cavity 2** **W:Cavity 3**

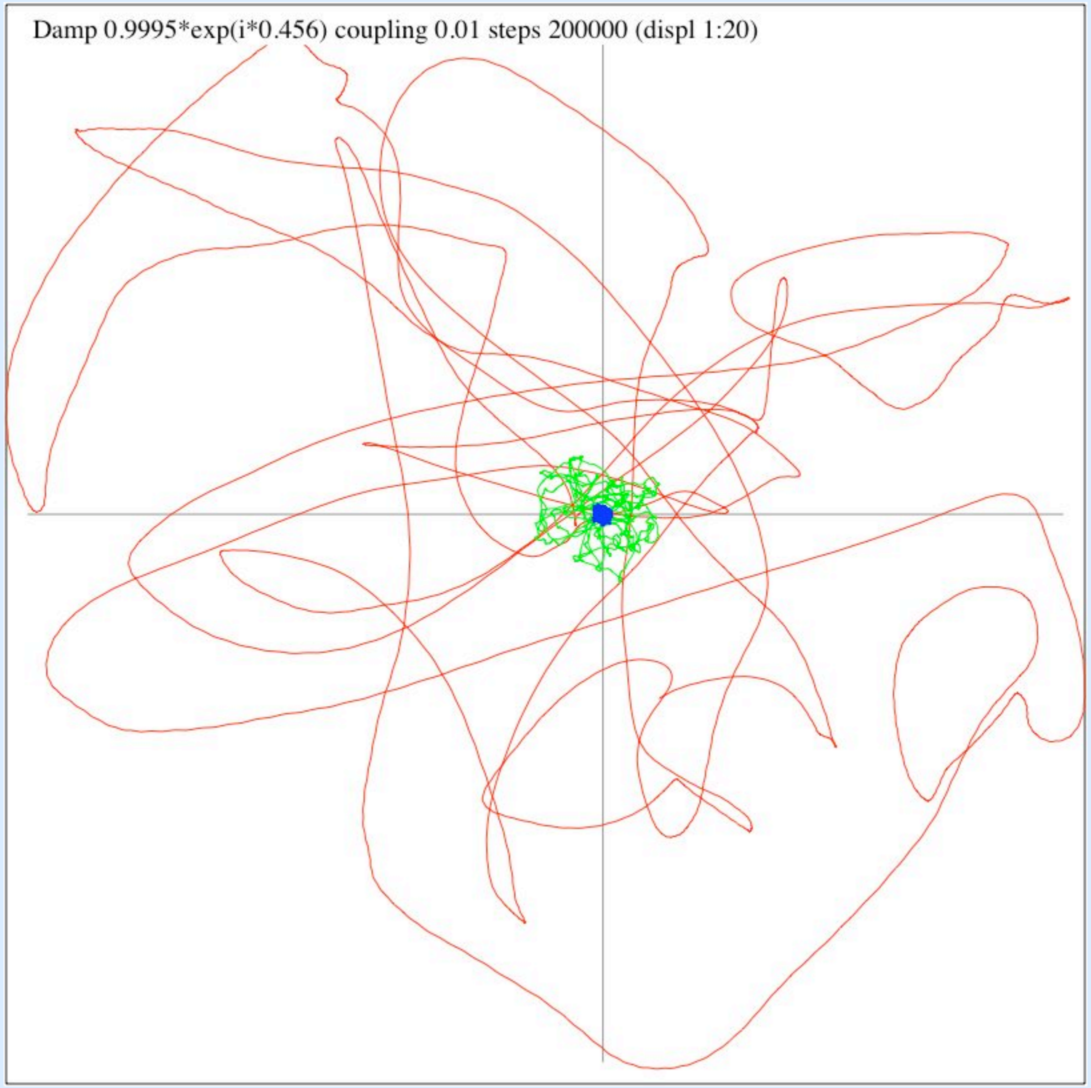
|V| as function of time/bunch number, 200,000 bunches (≈1/2 ms)



U:Cavity 1 **V:Cavity 2** **W:Cavity 3**: in saturation (depends Q_{ext})

Time-wise 'constant' but increase cavity-to-cavity

Polar display of complex cavity voltage: reference HOM



200,000 steps

U:Cavity 1 **V:Cavity 2** **W:Cavity 3**

In a linac noise driven beam blow-up
might be possible, to be checked !!!
Detailed analysis with true machine conditions

First simulations with true physics (for a generic p-linac similar SNS and SPL) for **only one** HOM (at a **random frequency**) indicate that

Beam-loss due to such effects

cannot be excluded

(beam driven out of acceptance for some pulses)

Best means to fight it:

HOM frequency scatter from cavity to cavity

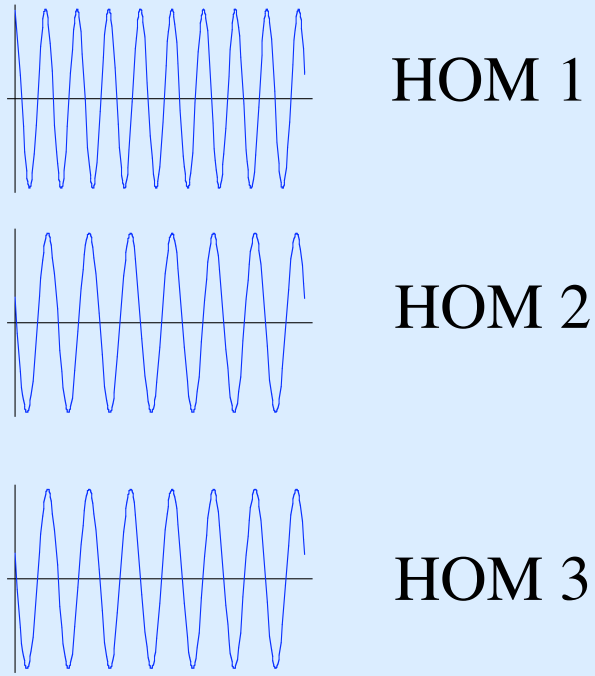
Comparison circular-linear:

• In a circular machine bunch pattern passes again and again, in a linac only once:
less efficient excitation mechanism

• In a circular machine with N bunches in the turn, there are (periodicity condition) only the 'rational' pattern with $\xi = k/N$ oscillations per T possible (k integer $0 \leq k < N$,)
Hence HOM-f can be matched only 'about', i.e. not necessarily exactly on the HOM peak while in a linac (no periodicity condition) any mode can be **perfectly matched** with a bunch displacement pattern: each mode participates 'at best of its possibilities'

• In a circular machine generally the ‘worst’ mode makes the race, others have no time to show before beam is lost

• In Linac all modes, excited on HOM peak, may collaborate to kick out the beam:



Sum of action of **incoherent** HOM 1, 2 and 3