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

do

“Yes, we ~~can~~ !!”

Often feeling as

Don Quixote de la Mancha

tilting at windmills

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(HOM damper WS 25 June 2009)

Some history of the last decade (1999 –> today):

1) French sc p-linac project:
   Examined HOM power coupled from beam
   phD: technically very well done but beam stability not considered
   Conclusion based on the power analysis:
   HOM dampers not necessary: **Conclusion not justified**

2) Eminent colleague(*): “You cannot excite these modes, (away from machine lines) it is simply not possible … you are too afraid (to hit such a machine line)”
   It is possible : Real beams are not stiff nor regular

Tried my best to ‘lead back to the right path’ : no success !
Occupied by other things (LEP/LHC) till …….

(*) … there were/are others …

3) SNS intends removal of HOM couplers (techn. problems)(*)
"If your car has problems with the brakes, remove them!
This will solve all your problems" (maybe forever provided you drive fast enough)

4) … and whispers at CERN: (behind my back, … ask Roland for confirmation)
"If SNS … do we (SPL) really need …."

5) Forced me to 'move'

Prevent an SPL 'flop' :

paycheck is signed by CERN !

(*) For those (SPL, project X, …) who have not yet decided on their HOM couplers (if):
The SNS HOM coupler has the capacitor of its fundamental mode notch filter up in the 'hat': the main field has to pass along the whole length of the coupler, hence is present in the whole coupler, possibly driving MP, heating, arcing …
The 'hook-coupler' (LEP2, LHC) has its fundamental mode notch filter concentrated at the 'entry' of the coupler: there is no main field elsewhere in the coupler, only coupled HOM fields. The 'hook-coupler' is dismountable: it can be replaced.
Attention: No warranty, the 'hook coupler' was only really tested in LEP2 to relatively low field, there may be other hidden snags.
—> Start R&D soon, cutting metal (not Si for CPUs but steel, Cu, Nb, …!!!) and cook some He

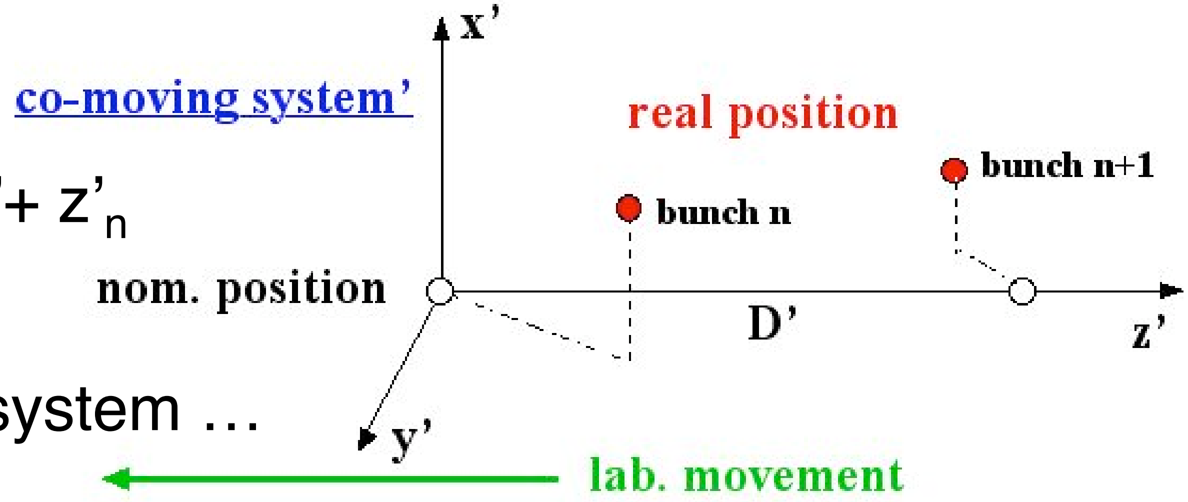
–> in medias res:

No bunch exactly on its nominal position (circular machines and linacs)

In **beam based (co-moving) system**:

all 3 directions equivalent (convention: z=beam-direction ('longitudinal'))

$z'_{(\text{bunch } n)} = -n \cdot D' + z'_n$



Transform to Lab system …

Transverse x=x' and y=y' invariant

Longitudinal $z_{(\text{bunch } n)} = v_b \cdot t - n \cdot D + z_n$

More convenient: D/v → T (with regular inter-bunch time T); $z_n/v \rightarrow dt_n$

$$t_{arr,n} = n \cdot T + dt_n$$

Is assumption of regular time-of-arrival $t_{arr,n} = n \cdot T$ valid ?

Transverse movement:
Assumption $t_{arr,n} = n \cdot T$ (about) OK (multipole modes have $V_{||}$ for displaced beam !!)
(x, p_x) and (y, p_y) can. conj. variables for transverse movements

Longitudinal movement:

Assumption $t_{arr,n} = n \cdot T$ is not valid

(dt_n, dE_n) **the** can. conjugate variables for longit. movement

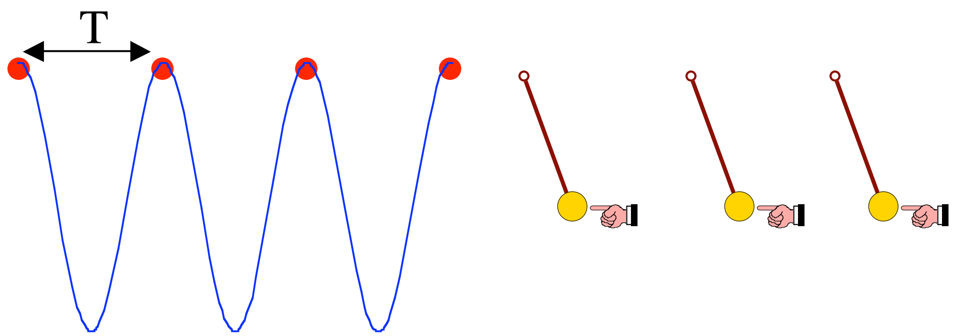
need: $t_{arr,n} = n \cdot T + dt_n$

Imposed regularity = longitudinal oscillations can not exist;
in circ. machines: no longitudinal CBI is possible
in **contradiction to all observations**

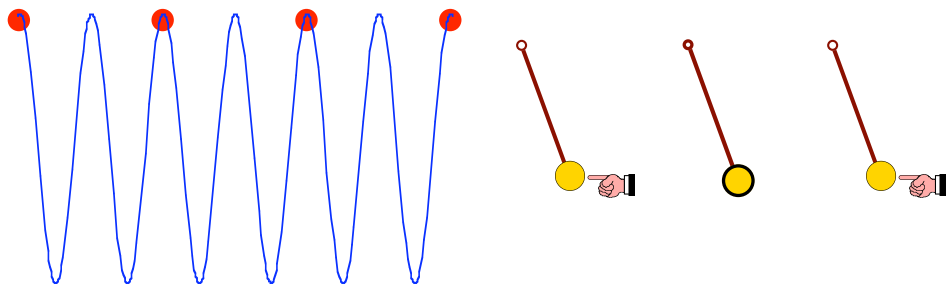
Sketch transverse : easier to draw and see

Bunches arrive stroboscopically: irrelevant how the (RF) wave wiggles between two bunches provided 'it is back in time' when the next bunch arrives

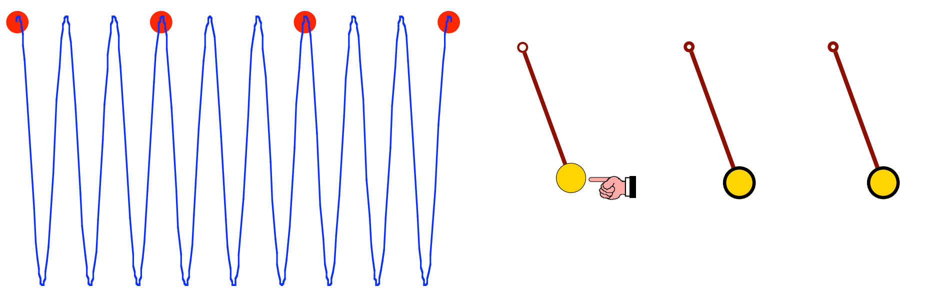
☞ 'tip' the observing oscillator: spect. analyzer, cavity mode ..



K=1st machine line: 1 oscillation between 2 consecutive bunches
Resonant on $f_{ML} = 1/T = f_0$



K=2nd machine line: 2 oscillation between 2 consecutive bunches
Resonant on $f_{ML} = 2/T = 2\ f_0$



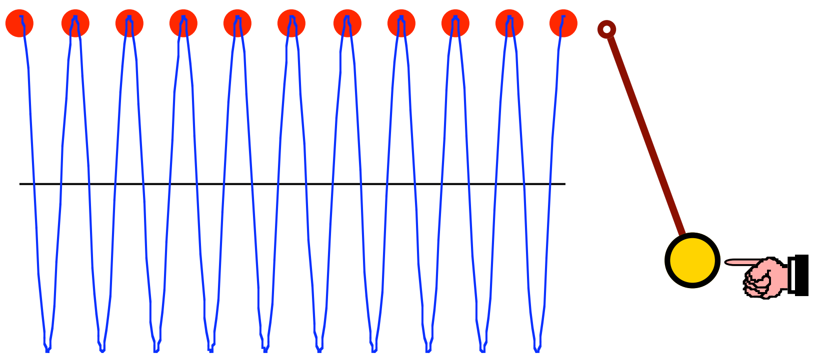
K=3rd machine line: 3 oscillation between 2 consecutive bunches
Resonant on $f_{ML} = 3/T = 3\ f_0$

displaced bunches: harmonic position modulation

(express arbitrary displacement-pattern by spatial Fourier components)

• Example 1: Constant (transverse) 'up' (right) displacement

For transverse examples: bunch n: $t_n = n \cdot T$



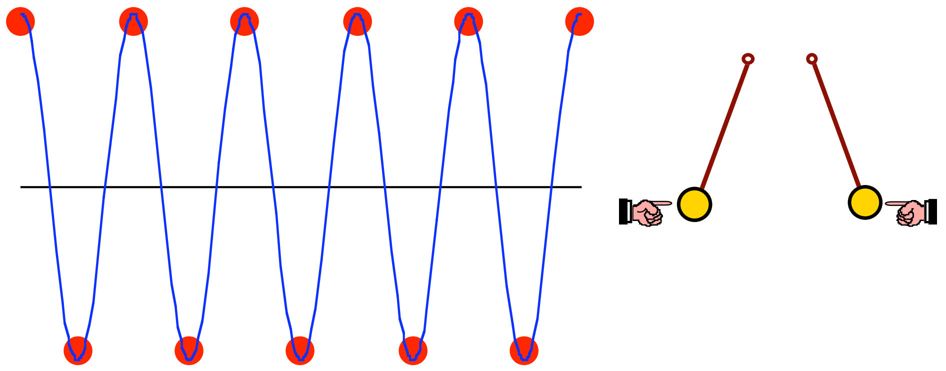
resonant oscillation: $\cos(2\pi f_0 \cdot t)$

$f = f_0 = 1/T;$

When bunches arrive, they are always there where also the wave is …   **resonant interaction**

• Example 2: Up-down (right-left) pattern ('μ =1/2'); Bunch n: $t_n = n \cdot T$

μ: bunch-to-bunch phase shift parameter

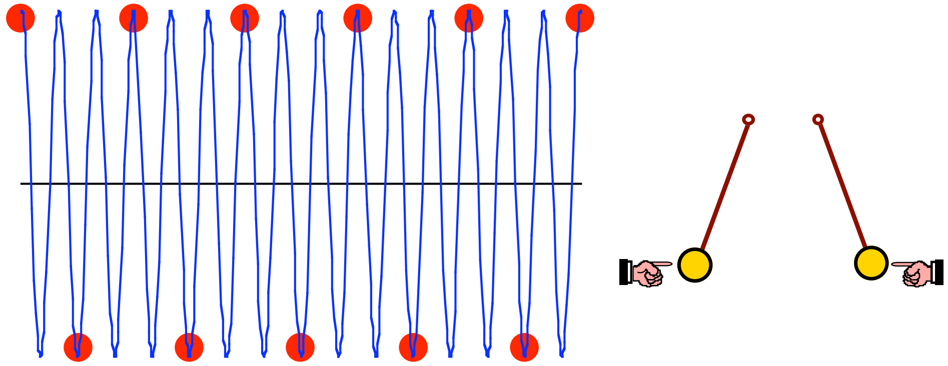


Displ. $\cos(1/2 * 2\pi\, n)$ = ±1

$f = f_0 \cdot (1-1/2) = 0.5 \cdot f_0 = 0.5/T$

Lower sideband: Not on ML

Same pattern !!!!!!

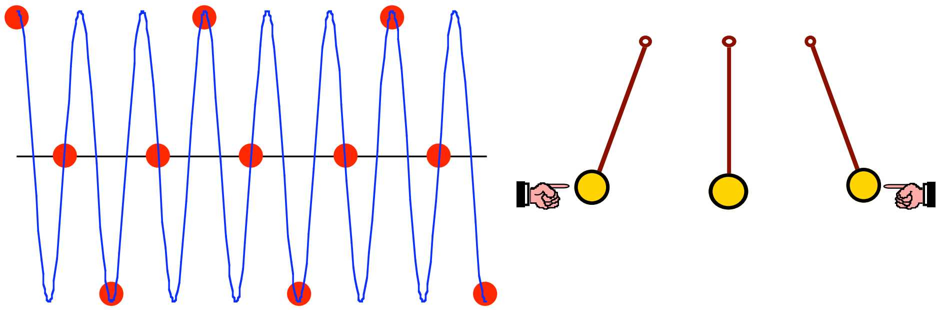


$f = f_0 \cdot (1+1/2) = 1.5 \cdot f_0$

Upper sideband: Not on ML

Bunches are always there (up .. down) where the wave is …

- Example 3: Up-zero-down-zero pattern ('μ =1/4'); $t_n = n \cdot T$

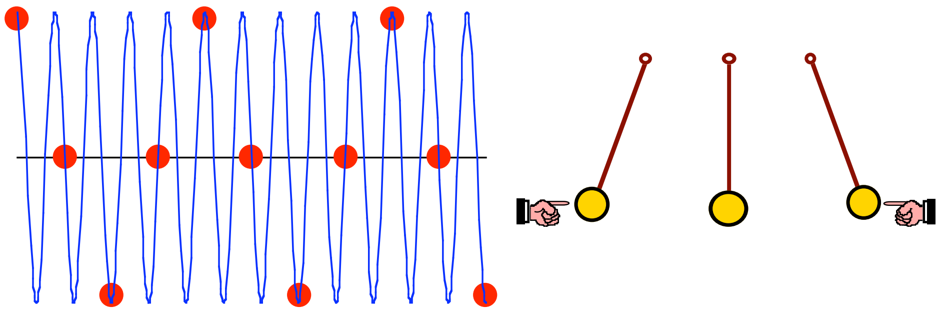


displacement $\cos(1/4 \cdot 2\pi\, n)$

$f = f_0 \cdot (1-1/4) = 0.75 \cdot f_0$

Lower sideband : <u>Not on ML</u>

Same pattern !!!!!!

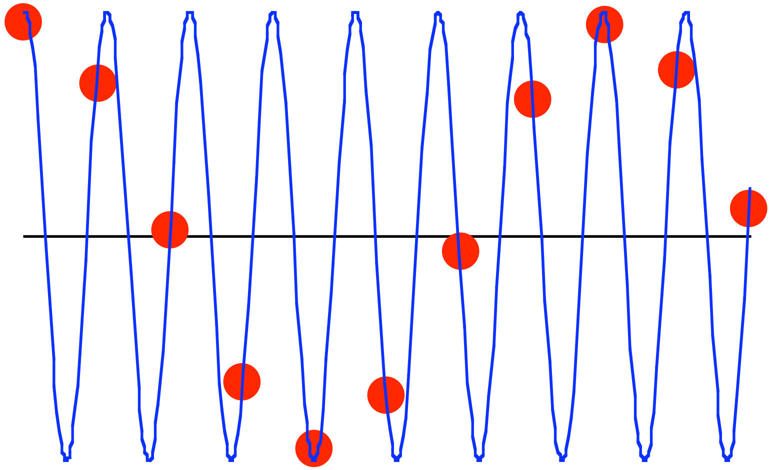


$f = f_0 \cdot (1+1/4) = 1.25 \cdot f_0$

Upper sideband : <u>Not on ML</u>

Bunches are always there (up, down, zero) where the wave is …

- Example 4: **anything** (even irrational number) ('μ =0.123')

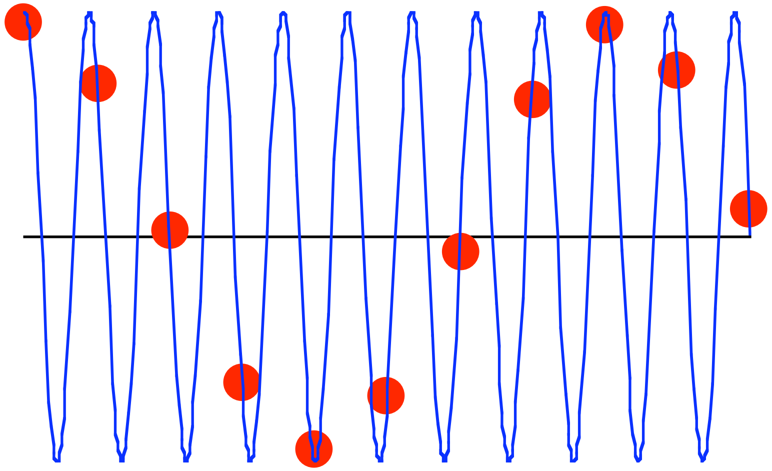


Displacement **$\cos(0.123 \cdot 2\pi\, n)$**

$f=f_0\cdot(1-0.123)\ )=0.877\cdot f_0$

Lower sideband : Not on ML

Same pattern !!!!!!

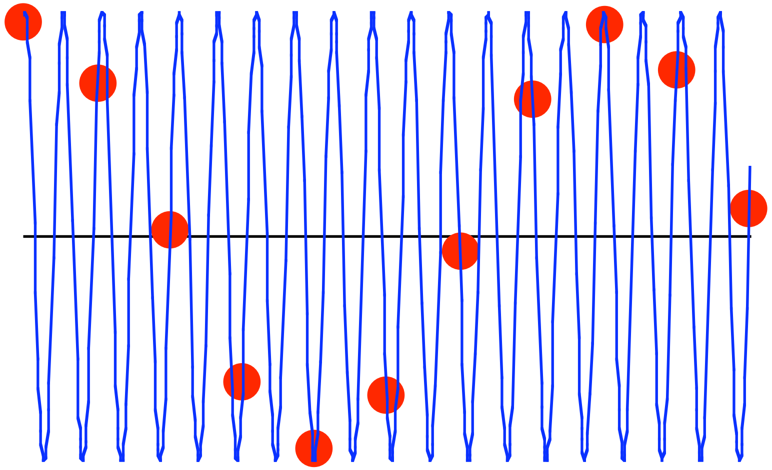


$f=f_0\cdot(1+0.123)\ )=1.123\cdot f_0$

Upper sideband : Not on ML

Bunches are always there where the wave is …

- Example 5: An additional integer number of oscillations (K=2) (between other machine lines)

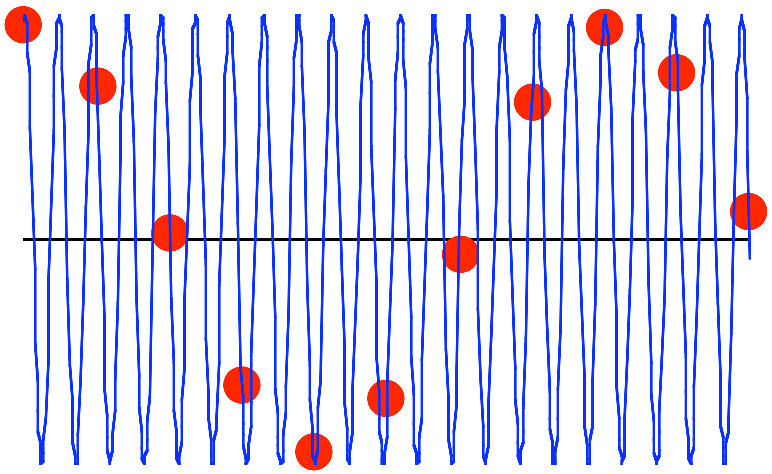


Displacement $\cos(0.123 \cdot 2\pi\, n)$

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

Lower sideband : Not on ML

Same pattern !!!!!!



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

Upper sideband : Not on ML

Bunches are always there where the wave is …

Numerical example (the other way round):

Not pattern is given but the

f_{HOM} = 1234.567890 MHz (may be anywhere)

Bunch repetition rate 350 MHz, T=1/350MHz

1234.567890 / 350 = 3.527… = 3 **+ 0.527** (= 4 **- 0.473**)

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

Bunch pattern: μ_1=0.527xxx phase advance per bunch

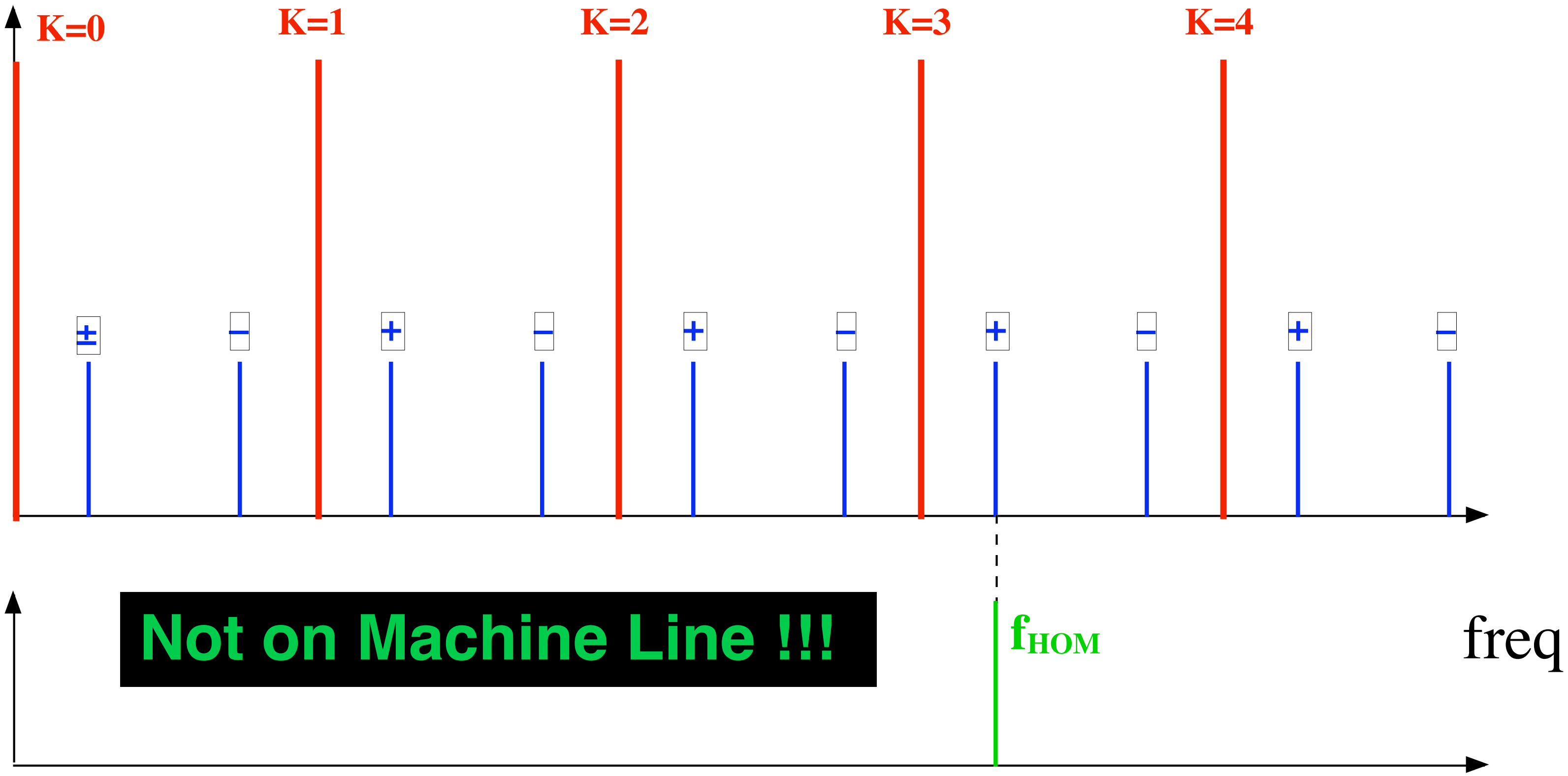
(or μ_2=0.473xxx … details see note)

ANY f_{HOM} has a matching pattern: one SB of this pattern matching the f_{HOM}

Summary: The spectrum of a beam with (harmonic) pattern

Machine lines: f_{ML}=K/T

Side bands: f_{SB}=(K±μ)/T



HOM (essentially) interacting with <u>only one</u> of the SBs

In circ. mach. pattern are not static but oscillate in time with betatron/synchrotron frequency:

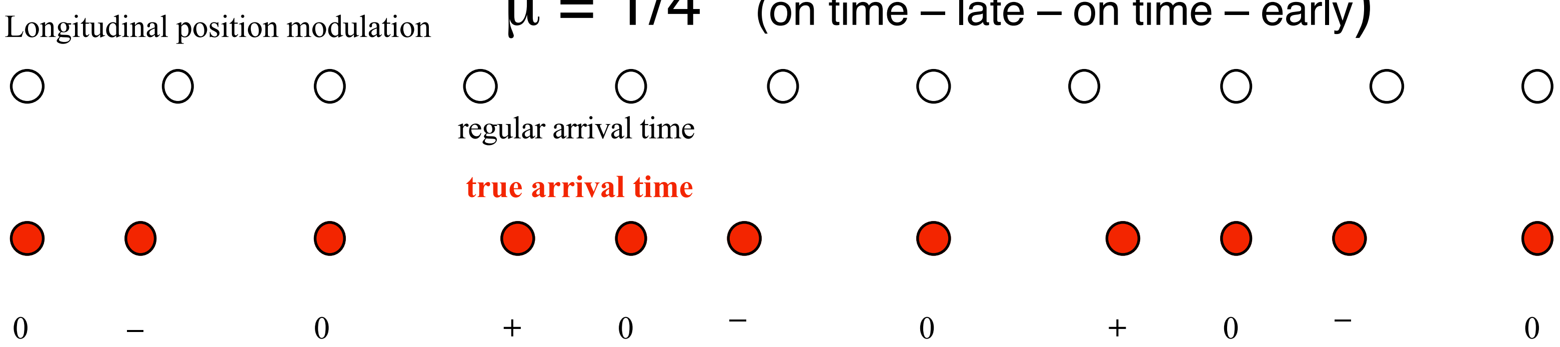
Observed SBs shifted by these frequencies wrsp. μ

longitudinal

<u>(more difficult to sketch and to imagine)</u>

Position modulation: time advance/delay of bunch arrival:

$\mu = 1/4$ (on time – late – on time – early)



For harmonic pattern with (any) phase-shift parameter μ

$t_{arr,n} = T \cdot (n + \delta \cdot \cos(2\pi \cdot n \cdot \mu))$ arrival time modulation

Arrival time bunch n $t_{arr} = n \cdot T + \delta \cdot T \cdot \cos(2\pi \cdot n \cdot \mu)$

Sorry : (no good idea for a sketch): need some mathematics / RF theory

For **wave**: replace integer n by continuous $n \to t/T$

For wave ‘around’ Kth ML $\omega_{K,ML} = 2\pi \cdot K/T;$

$A = \cos\left(\omega_{k,ML} \cdot (t + \delta \cdot T \cdot \cos(\Omega \cdot t))\right) \; ; \quad \Omega = 2\pi / T \cdot \mu$

Express as sum of (for δ T << 1 only carrier (ML) and 1st order SBs important)

0th order: Carrier = machine line $A_{ML} = \cos\left(\omega_{k,ML} \cdot t\right)$

1st order: sideband(s) $A_{SB} = \delta \cdot T \cdot \omega_{k,ML} \cdot \sin\left(\omega_{k,ML} \cdot t\right) \cos(\Omega \cdot t)$

lower SB upper SB

$$A_{SB} = \delta \cdot T \cdot \omega_{k,ML} / 2 \cdot \left(\sin\left((\omega_{k,ML} - \Omega) \cdot t\right) + \sin\left((\omega_{k,ML} + \Omega) \cdot t\right) \right)$$

plus mth order SBs at $\omega_{SB,m} = \omega_{ML,K} \pm m \cdot \Omega$ (only significant for ‘large’ δ)

See ‘sketches’ again but replace “transverse” =>” longitudinal”

“up-down” (“right-left”) => “early - late”

No principal difference (only more difficult to draw/imagine/…)

Intermediate recapitulation:

- **Hypothetical** beam with arbitrary constraint

dt=0: only perfect bunches {similar transverse x=0 and/or y=0}

Beam <–> HOM interaction only if $\mathbf{f_{HOM}}$ **close to machine line**

- **True** beam : no such arbitrary constraints

'free variable': dt≠0 (<—> t_{arr} = n T + dt) { similar transverse x≠0 and/or y≠0}

Allows pattern in

dt (longitudinal) {similar x y (transverse)}

with ANY (spatial) period:

Beam <–> HOM interaction possible for $\mathbf{f_{HOM}}$ **ANYWHERE**
with respect to machine lines

Short Intermezzo:

Coupled Bunch (Mode) Instabilities

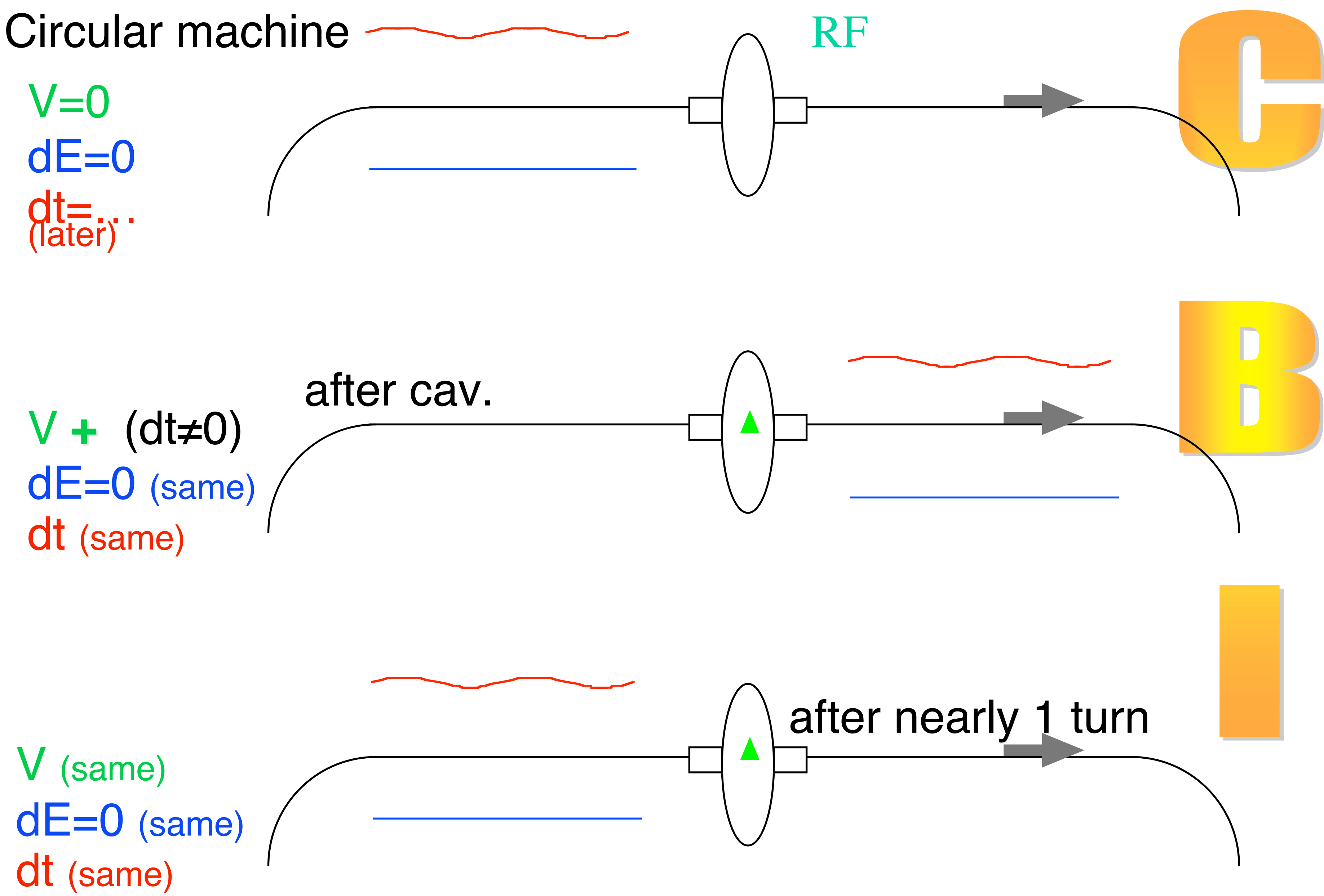
Accepted fact plague circular machines: need HOM dampers !!!!

First explained by

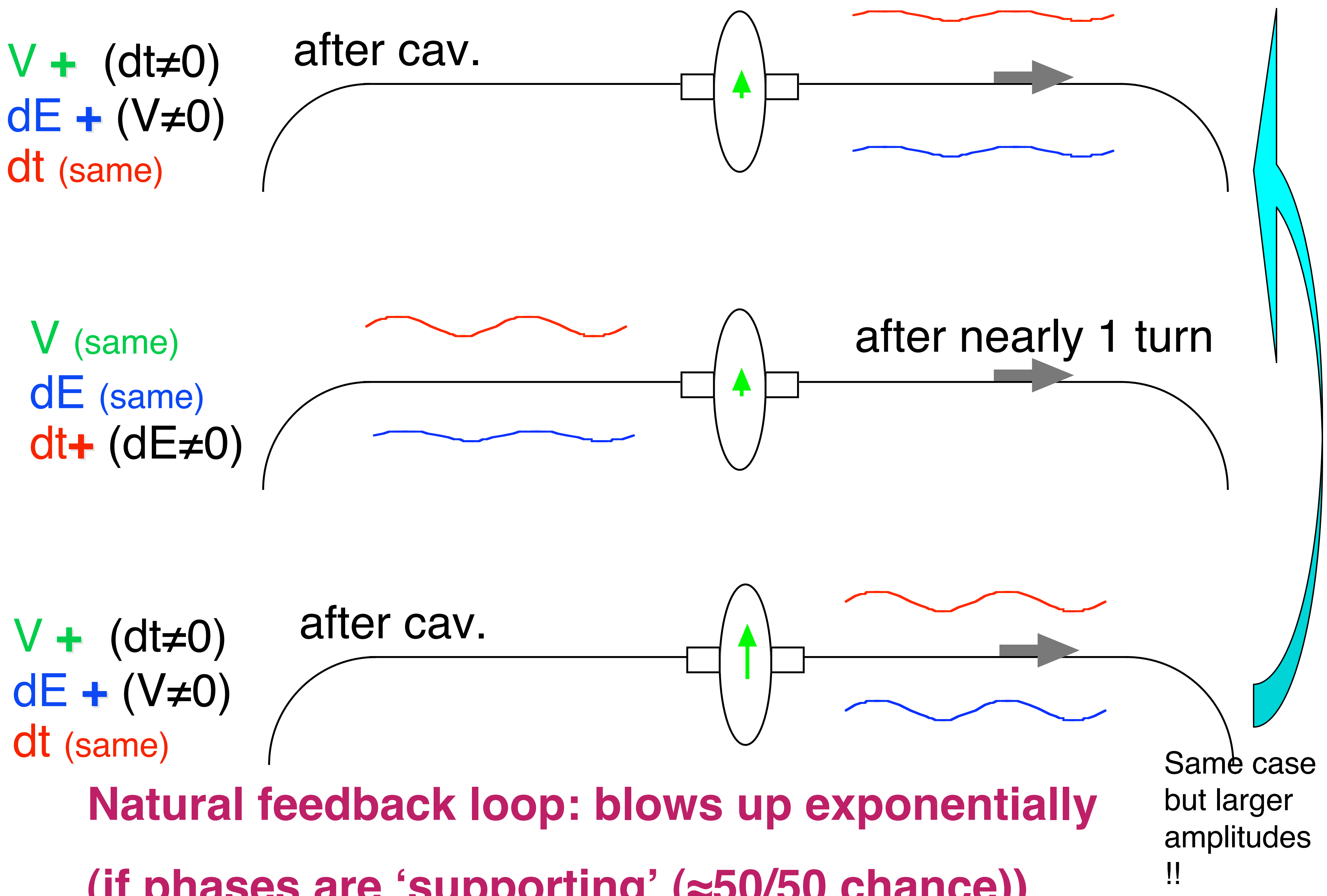
Frank Sacherer:

Genius of beam dynamics
(died untimely 1978
in a mountain accident)

Theory ‘universal’, but loaded with ‘some mathematics’.
For point-bunches one can ‘sketch’ the physics …



Circular machine
RF
C
V=0
dE=0
dt=...
(later)
after cav.
B
V + (dt≠0)
dE=0 (same)
dt (same)
I
after nearly 1 turn
V (same)
dE=0 (same)
dt (same)



Natural feedback loop: blows up exponentially

(if phases are ‘supporting’ (≈50/50 chance))

HOM voltage V changes by factor g per turn:

$V_n = V_o \cdot g^n$ (in parallel $(dt,dE) = (dt_0,dE_0) \cdot g^n$)

Where is first V_0 , dt_0, dE_0 coming from ? (need at least one of them)

Noise ... on the injected bunches (or other effects…)

– Blowing (=noise) an organ pipe or over an empty Coke bottle
excites fundamental resonance and all HOMs !!!

– Scratching with the bow (=noise) a violin string
excites fundamental resonance and all HOMs!!!

Very efficient processes

… and never refuses to work !!!

HOM filters <u>its own</u> frequency out of the noise

initial step V_0

(lousy example) **10^8 protons per bunch** e.g. beam of 2.5 mA at T=1/350 MHz

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

charge centre have a bunch-to-bunch jitter of 10^{-4} bunch-lengths **(Schottky like noise)**

There is much more noise in the <u>real</u> world:

… RF noise on main voltage, ……. injector jitter, … bunch charge jitter

No hope for $V_0 \equiv 0$: if $|g|>1$, CBI takes off

All imperfections (as noise) are important ingredients !!!

Not to be excluded from a realistic simulation !!!

The

1 Million

for Europeans

Question

for US citizens:
in Gold we trust

Is a similar mechanism possible in a linac ?

(for transverse: seems agreement) **only longitudinal here**

- beam-cavity interaction identical (in linac or circular machine)
- Bunch sequence:

- circular machine: bunches 'come back' with their pattern:
  memory in HOM and bunches, bunch noise only at injection
- linac: always new bunches: memory in HOM only;
  but new noise contributions -> 'random walk up' for V_H

- the process "dE produces dt over drift" works in
  - circular machine: over one turn (RF concentrated) $dt/dE \neq 0$
  - linac: from cavity to cavity (drift distance L)

  for time-of-flight t_f

  (for more details ask Albert)

$$\boxed{\frac{dt_f}{dE} = -\frac{L}{c \cdot m_0 c^2 \cdot (\gamma^2 - 1)^{3/2}}}$$

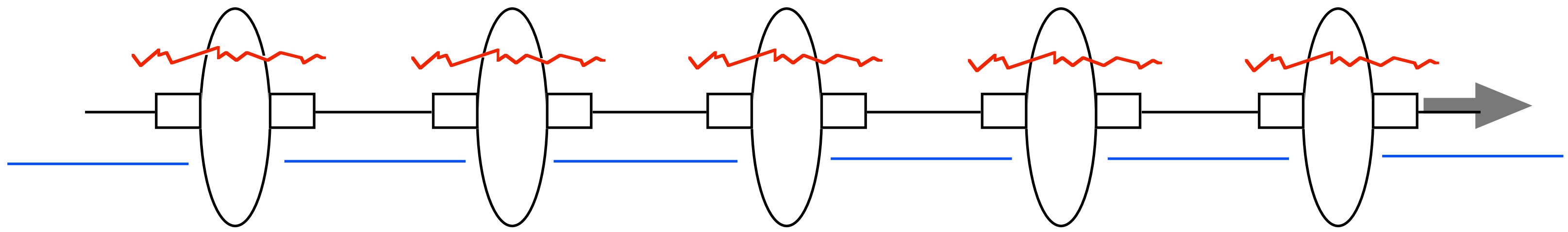
– electrons $\gamma >> 1$: $dt/dE \approx 0$: even $dE \neq 0$ -> $dt \approx 0$: 'no' problem

– heavy protons: $dt/dE \neq 0$: there might be a problem !!

How self-excitation might work in a linac ....

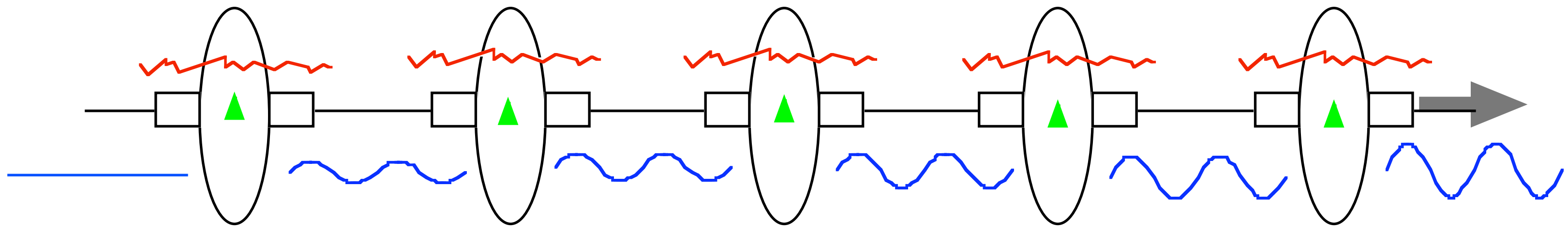
Heuristic 3-cavity model with simplified beam dynamics: was • mathematically analyzed and • numericaly iterated (agreement). Shows that under certain conditions beam may 'blow up longitudinally' ; gives some (coarse) parameter dependencies (too lengthy now, see note).

Start: random dt-noise passes the whole linac, dE=0, V=0



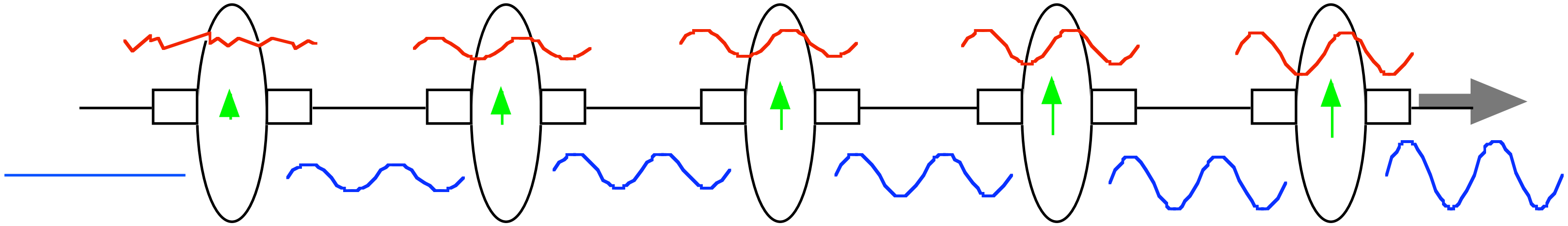
dt-noise excites V (.. coke bottle ..); V excites dE

(dE larger the more downstream: more V 'seen')

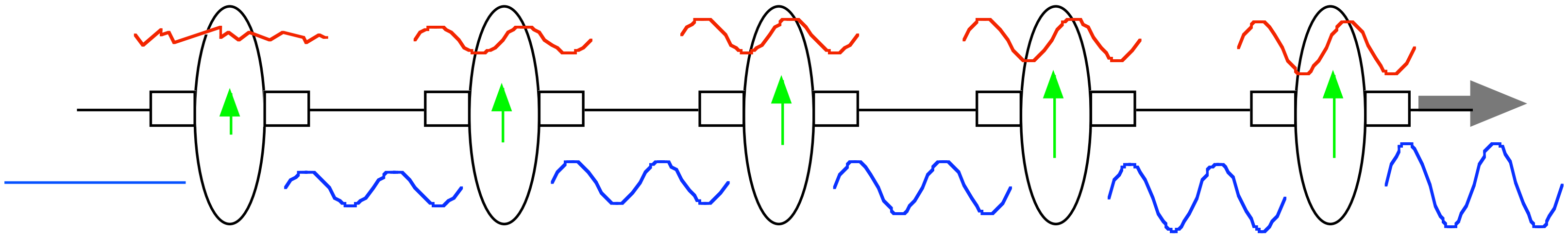


dE (by drift) drives coherent dt (superimposed to new noise)

(dt larger the more downstream: larger dE there)



larger (coherent) dt excites larger V; larger V excites larger dE; larger dE excites larger dt (and so on)



It might be possible !!

Does it really take place ? Ask nature ->

D o s i m u l a t i o n s

How the Simulation is done

– Give nature a chance: <u>no ‘prejudice’ incorporated in model:</u>
dE and dt <u>both free</u> variables as all HOM voltages $V_{H,m}$

– No theoretical assumptions whatsoever (except fundamental physics laws):
simply inject bunch after bunch into the ‘number-cruncher’
(if specified : every one with its proper injection jitter)

– Nature decides on dt, dE, $V_{H,m}$ tracking bunches along the linac
(= its substitute: the ‘number-cruncher’)

If nature always replies (except for f_{HOM} very close to MLs) :

dt ≈0; dE≈0; $V_{H,m}$≈0 : HOM dampers not <u>absolutely</u> necessary

If nature replies (even for f_{HOM} far away from MLs) (…. accidental direct hit onto ML ….)

$V_{H,m}$ >> 0, dt >> 0, dE >> 0 : one should consider HOM dampers
(and above …. limits)

5 lines C++ code = the essential physics !!! for (dt,dE) → (dt’,dE’)

(Nothing to hide (§): have a try with these lines ….)

Va, c0Fac: complex variables, all others real (double)

```
dE = dE + VRF[i]*cos(dt*omMainRF + phiS0) - dECav[i];  // main RF
psi = dt*omMode[i];                   // dt equivalent HOM phase angle
dE = dE + real(Va[i])*cos(psi) - imag(Va[i])*sin(psi) - selfV; // HOM
Va[i] = (Va[i] - complex(dVInd*cos(psi),-dVInd*sin(psi)))*c0Fac[i];
dt = dt + dtdE[i]*dE;                 // time slip till next cavity
```

```
pre-definitions:
dVInd=qb*RQ*<omMode>;           // defined > 0 here !!
selfV=dVInd/2;
dECav[i] = VRF[i]*cos(phiS0);  // nominal E-gain at cavity i
dtdE[i]                         // relativistic dt-slip(E)
c0Fac[i]                        // complex damping/phase factor over T
```

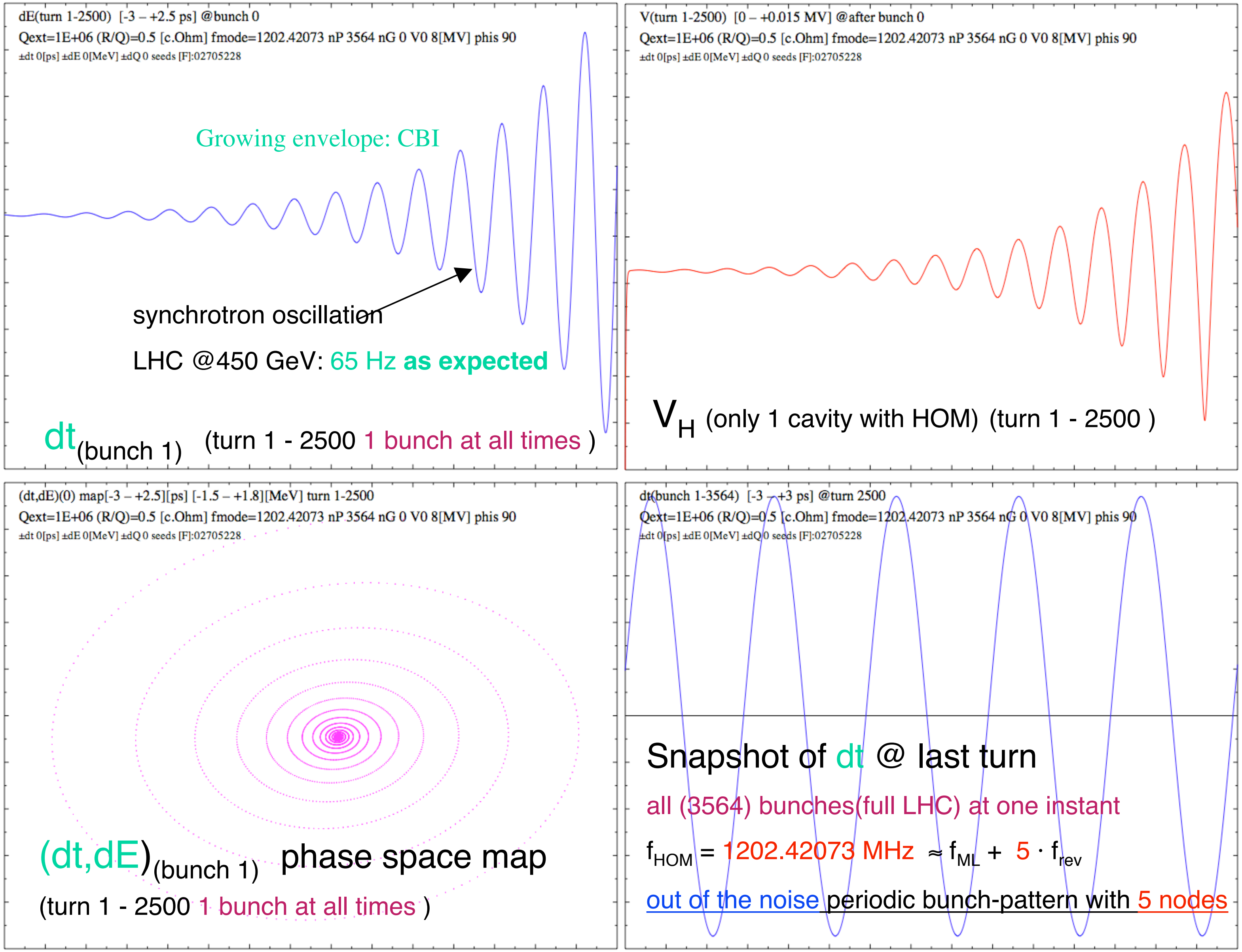
(§) to be completely honest: a) dE = dE + … for non C-programmers here (in code dE += …)

b)Code with indexed variables (as Va[i]=) is easier to read for humans. The running code is an absolutely equivalent version (checked) replacing indices by C-pointers (as *VaPtr++=); it should run faster. But the code optimizer (Xcode IDE, Apple Inc.) is so clever that there is an only insignificant CPU-time difference. Still the C-pointer code was kept ...

c) The apparent double calculation of sin(psi) and cos(psi) is ‘caught’ by the optimizer

Study: What these 5 lines do in a **synchrotron** (program slightly modified(*)):

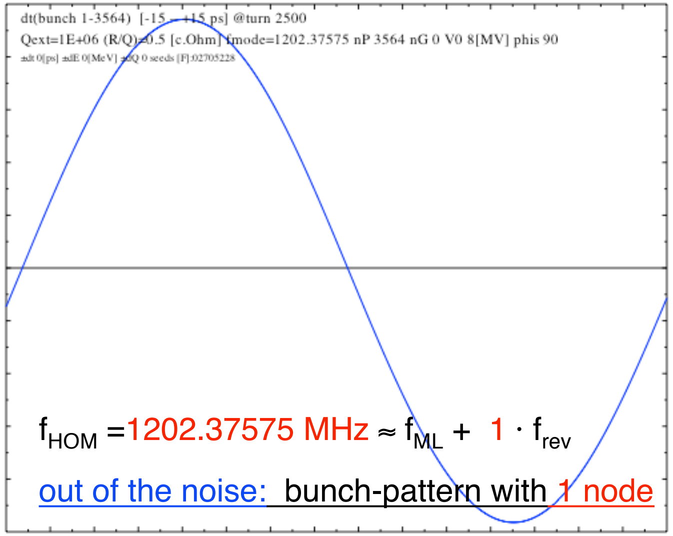
LHC with 3564 bunches (&). The **expected CBI** images ? **Yes, here they are !**

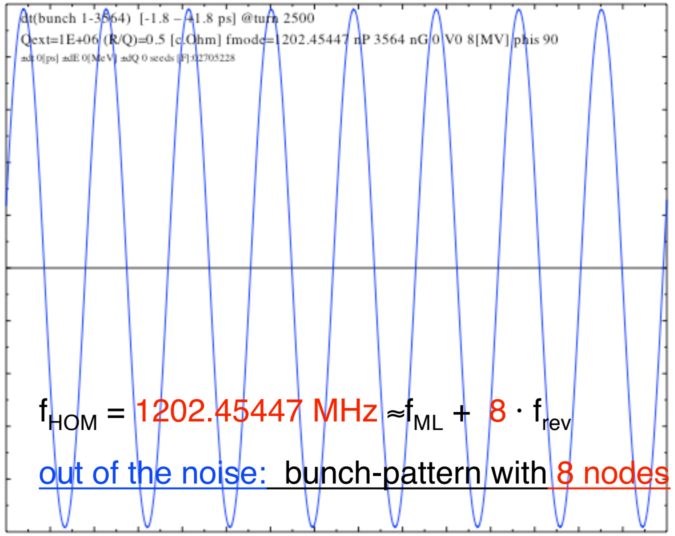


(*) periodic bunch repetition, single cavity; (&) p·c=450GeV inj. coast, no beam gap, dt/dE for LHC γ_t=53.7, V_{RF}=8MV @ 400MHz

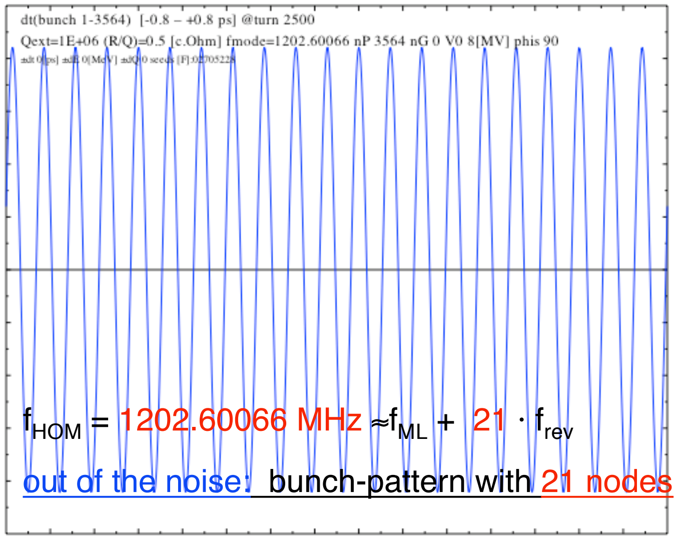
Matching pattern $\longleftrightarrow$ $f_{HOM} \approx f_{ML} + \mathbf{m} \cdot f_{rev}$ $(0 \leq m < 3564)$

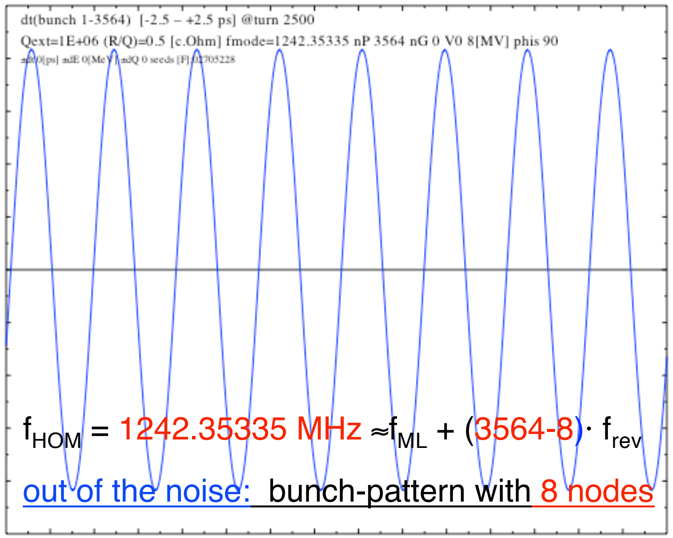
Nothing assumed or imposed: pattern is ‘born out of the noise’:





upper SB





lower SB

Linac simulations (generic p-linac similar SNS/SPL)

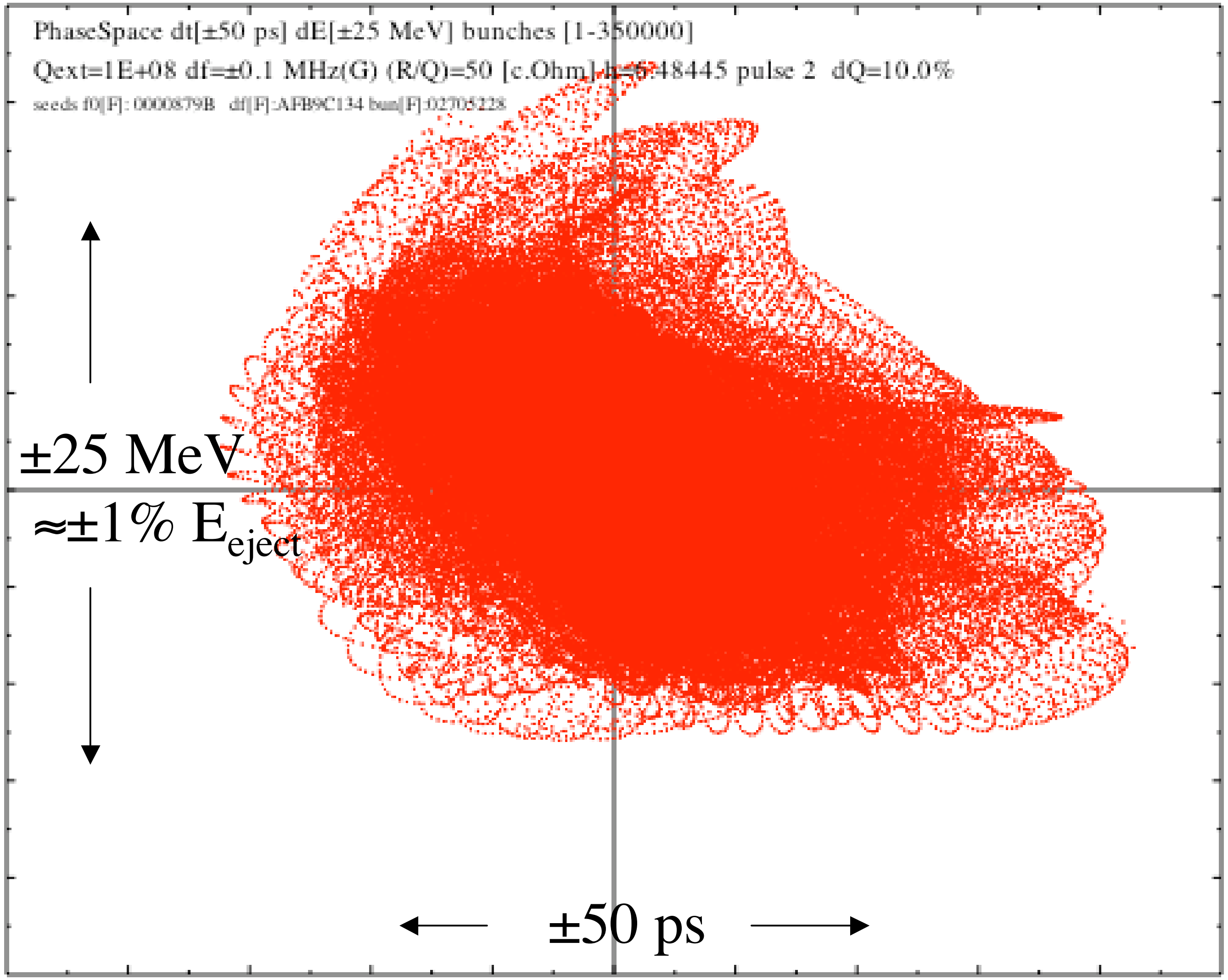
- acceleration 150 –> 3150 MeV; 150 cavities ; V_{RF}=20.7 MV
- **only one** HOM considered; | $V_{RF} \cdot \cos(\varphi_{s0})$ = 20 MV
- centre <f_H> at any **random frequency (no relation to MLs)**

  (between K=6 and K=7; Δf-range = 352 MHz, 3–3.5 f_{fund} below cut-off)
- individual f_H scatters with **$\sigma_{\Delta f}$=100 kHz** (or more) around <f_H>
- $I_{b,DC}$ = 400 mA (**10x** design **as by SNS simul**. : safety factor)
- (R/Q) = 50 circuit Ω = 100 linac Ω (or less)
- $Q_{ext} = 10^8$ (or less …. 10^5)
- pulse(s) of 350,000 bunches (1 ms) + 19 ms pause (50 Hz rep rate)

  possibly consecut. pulses: keep V_H over beam pulse pause
- **q_b-jitter 10%** (or dt jitter 1ps @ inj.; or no scatter but <f_H> close ML)

(and many others conditions, see note)

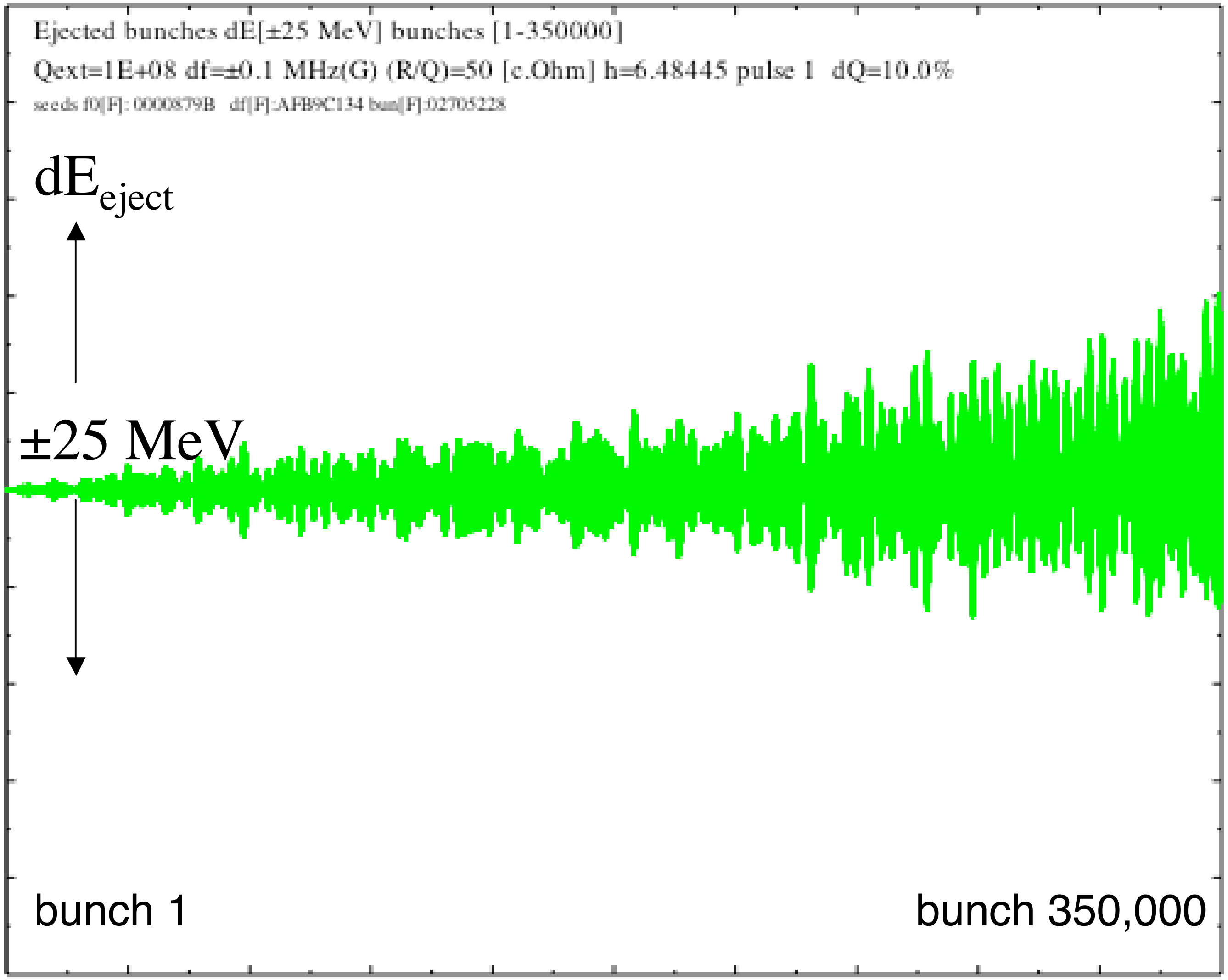
Bunch phase-space dot-map at ejection: 350,000 bunches



Simulation with (R/Q)=50Ω; I_b=400mA; $Q_{ext}=10^8$;

$\sigma_{\Delta F}$=100 kHz; bunch charge scatter Gaussian 10%

dE at ejection: 350,000 bunches (0 - 1 ms)



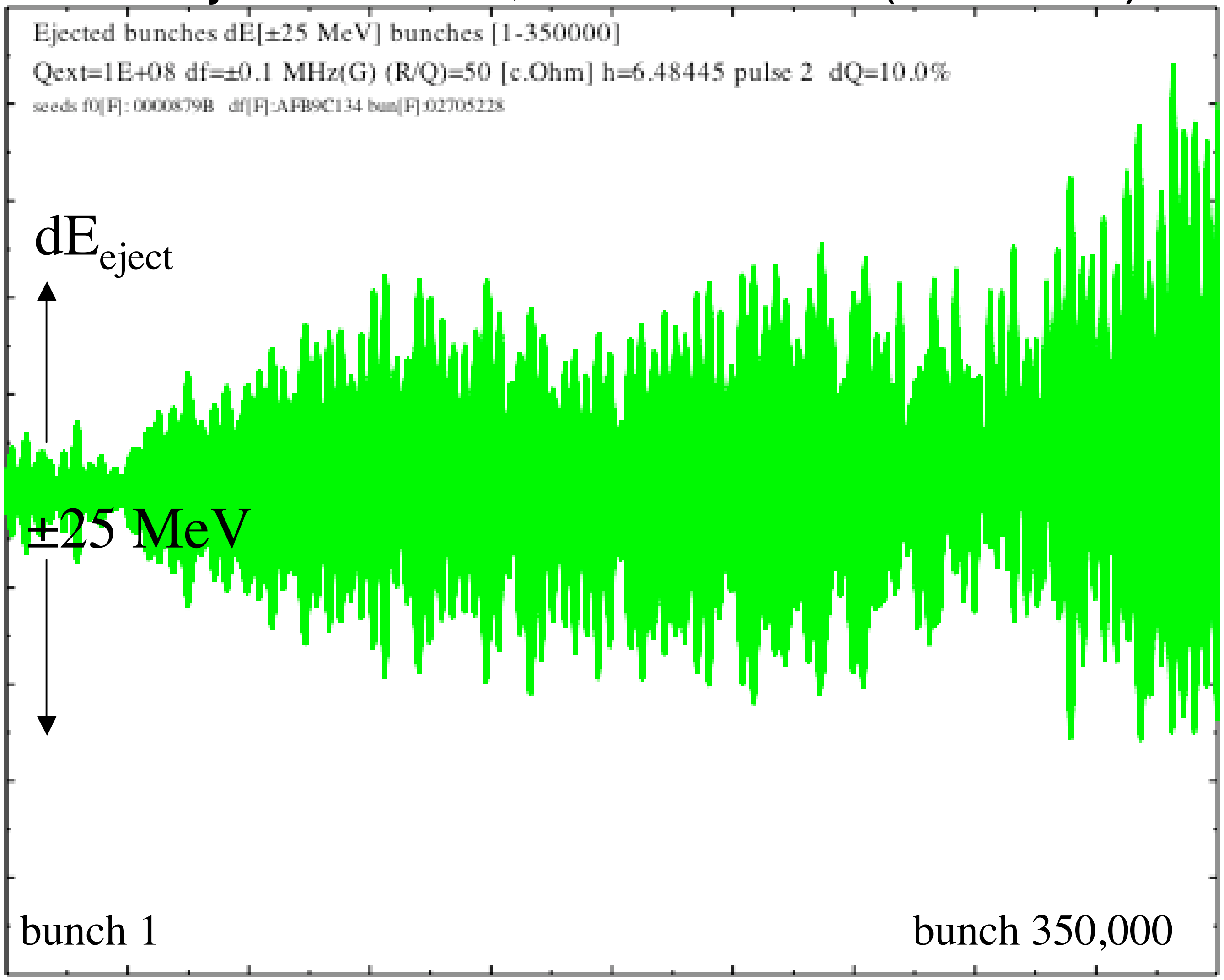
Followed by 19 ms beam pulse pause

Conditions as before

dE versus bunch-number (time): first pulse: dE starts at zero

dE at ejection: 350,000 bunches (0 - 1 ms)

After 1st beam
pulse pause

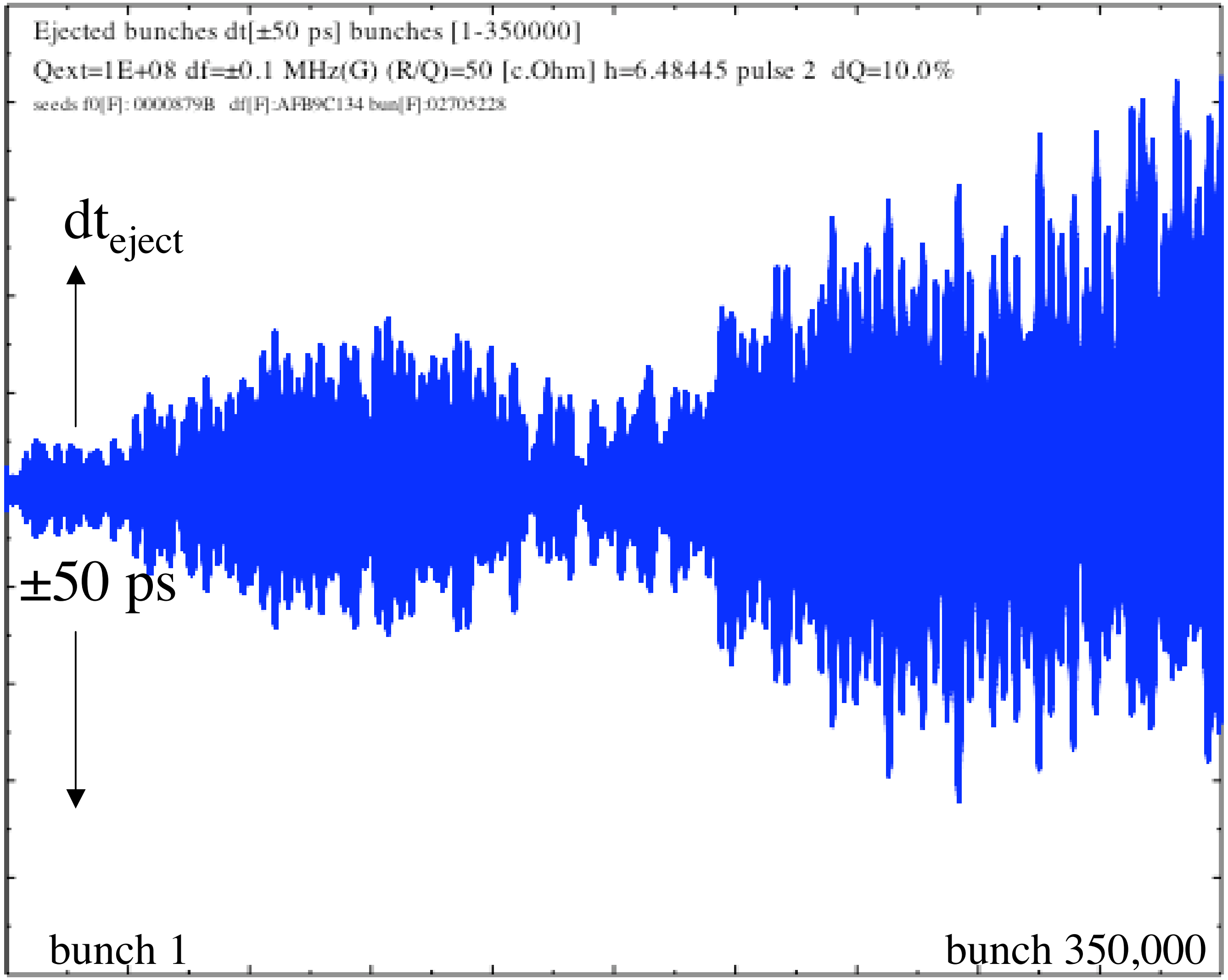


Conditions as before

2nd pulse: does not start at zero

residual V_H from previous pulse at $Q_{ext}=10^8$

dt at ejection: 350,000 bunches (0 - 1 ms)

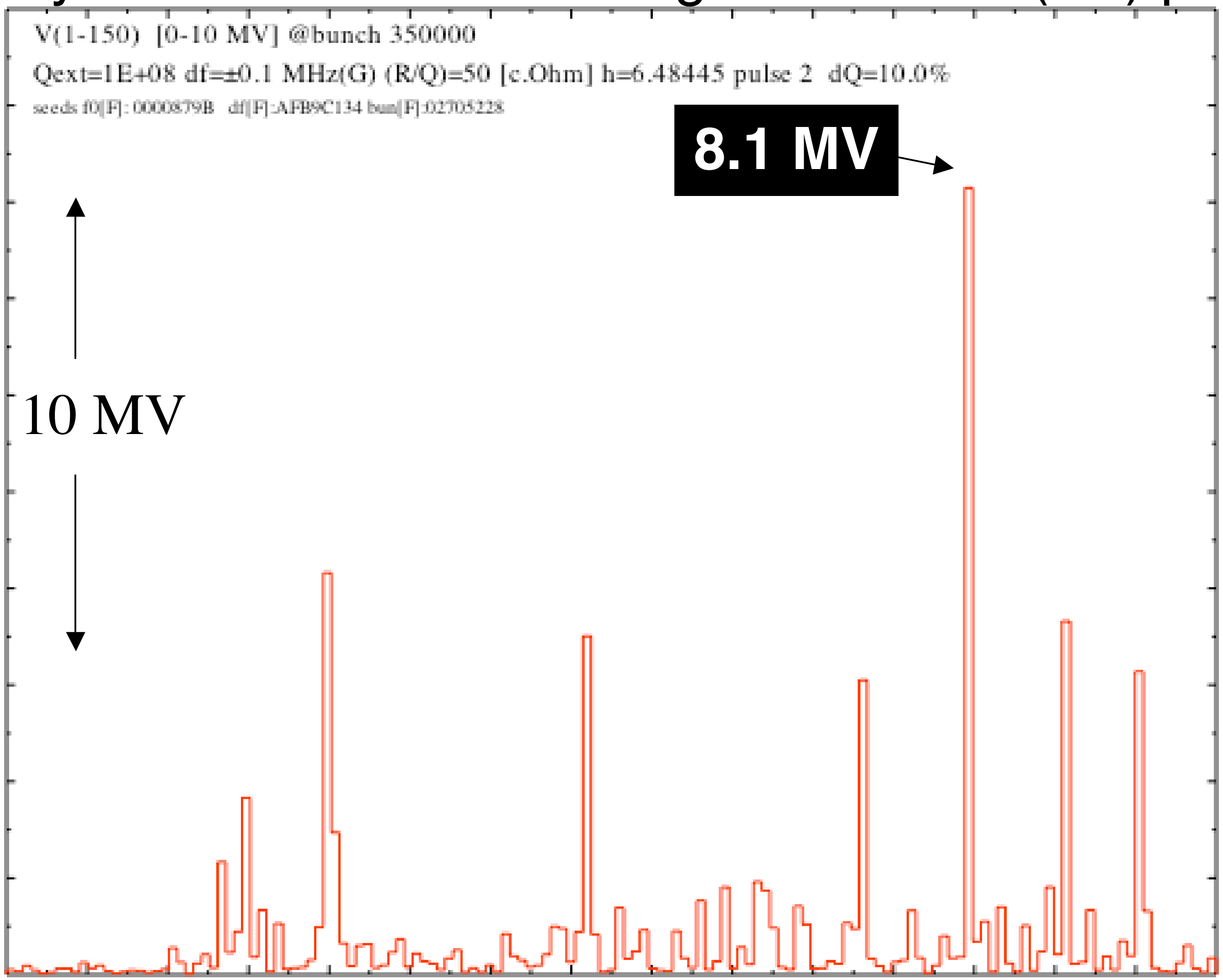


Conditions as before

2nd pulse: does not start at zero

residual V_H from previous pulse at $Q_{ext}=10^8$

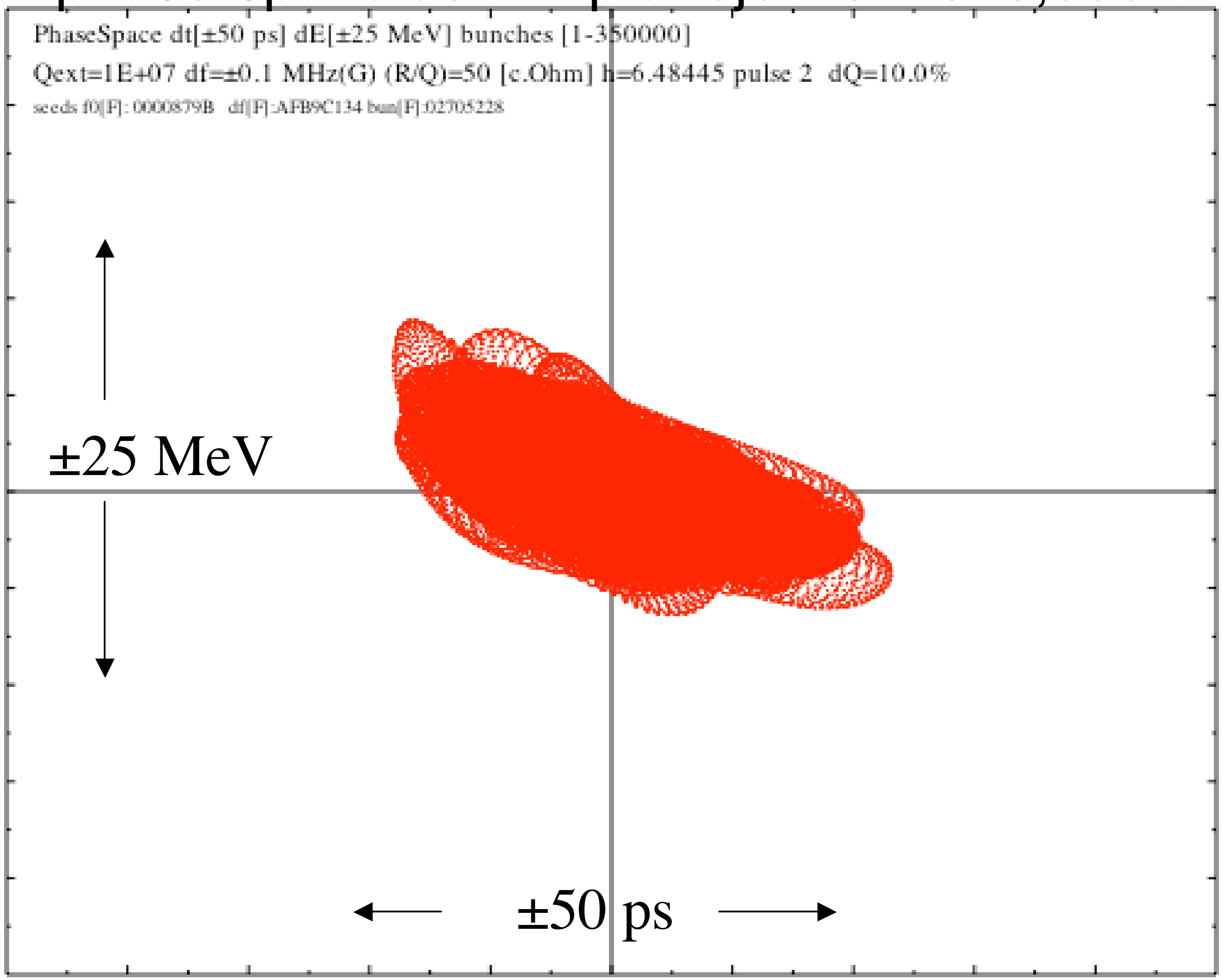
Cavity 1 … 150: excited voltages at end of (2^{nd}) pulse



Conditions as before; voltage scatter due to f_{HOM} scatter of individual cavities

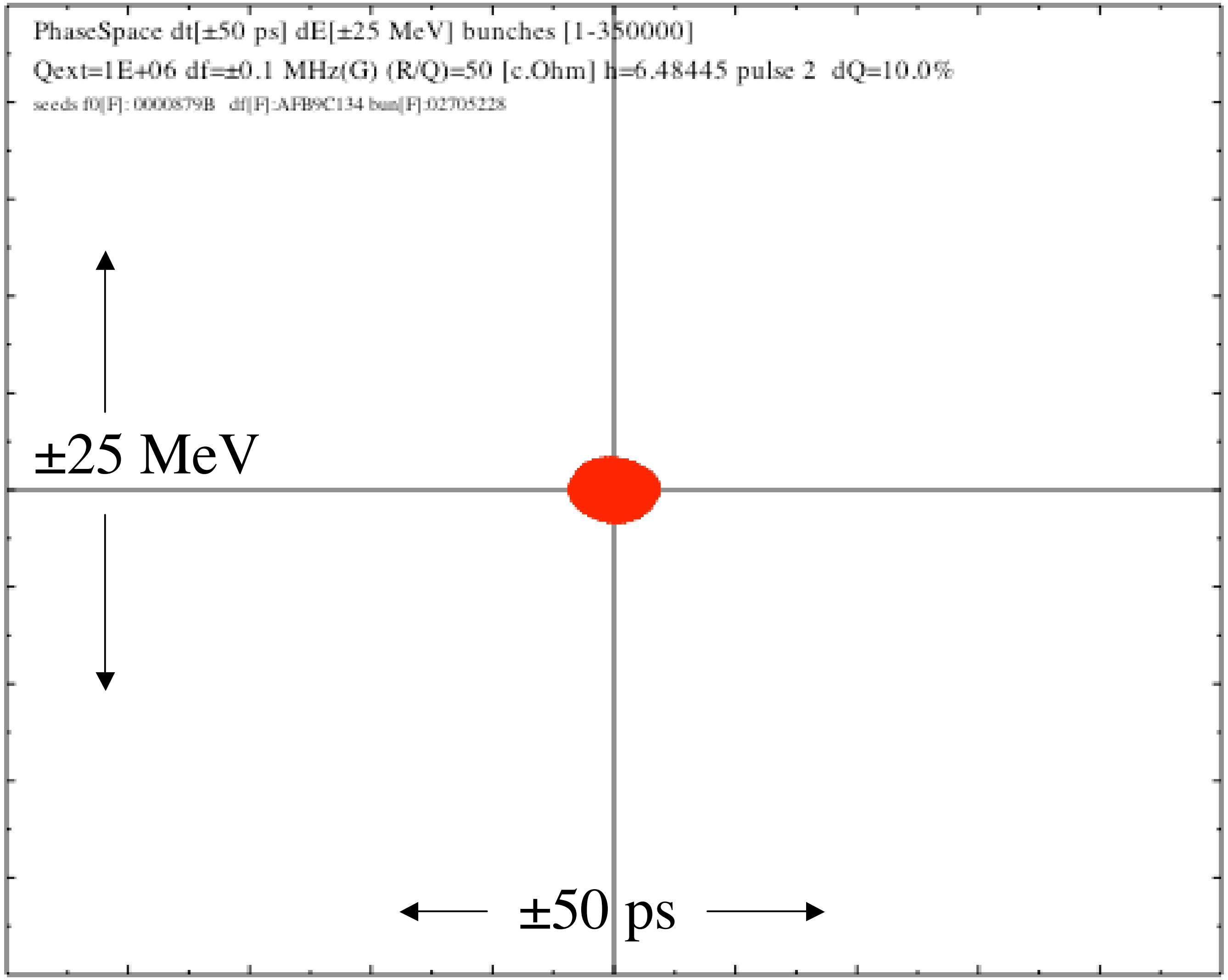
(so far for: "… you can not excite these modes…it is **simply not possible**….")
$P_{ext} = 1/2\, V^2/((R/Q)\, Q_{ext})$ = 6.4 kW (at last instant of beam pulse)

Bunch phase-space dot-map at ejection: 350,000 bunches



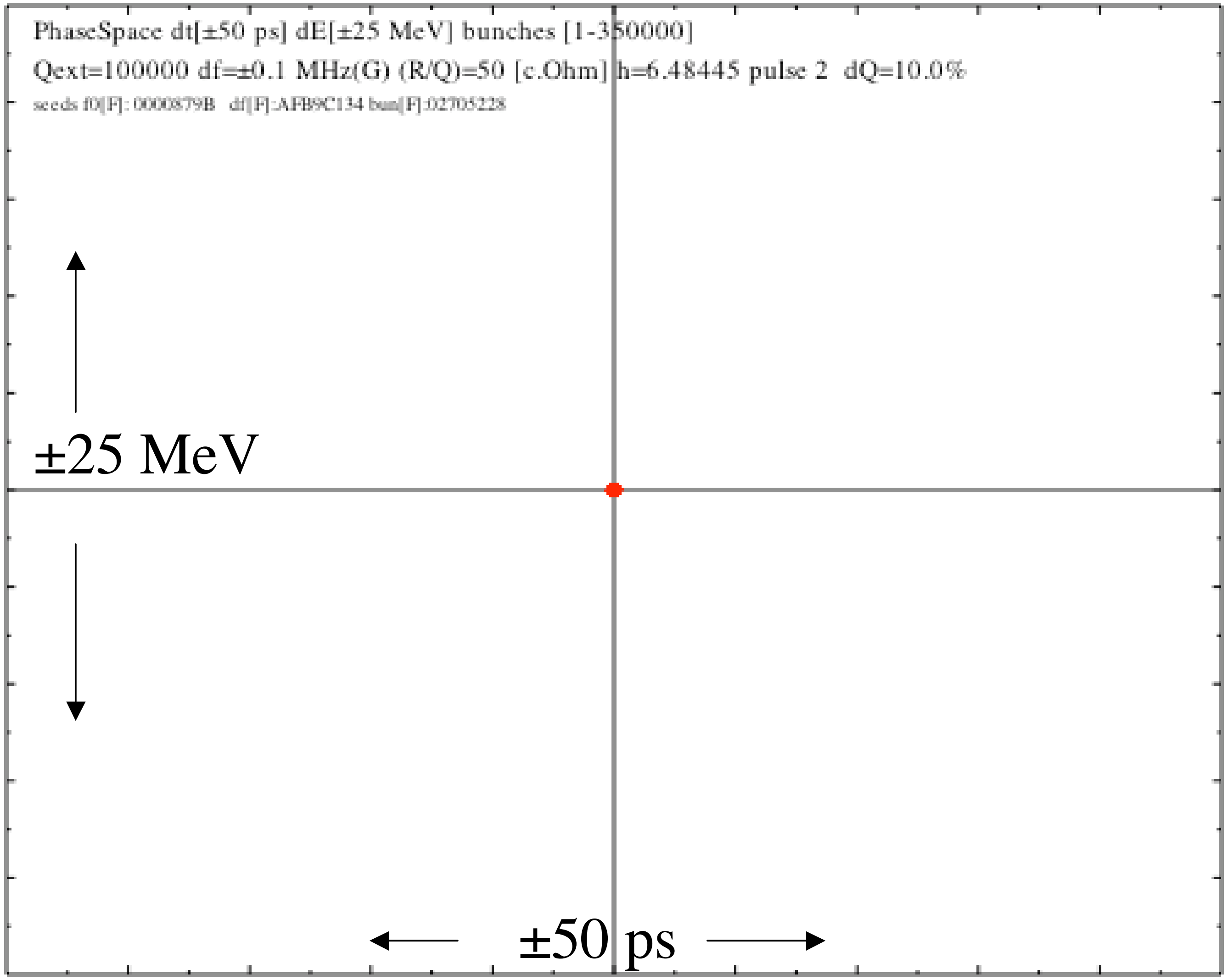
Conditions and scaling as before (including same random #) but $Q_{ext}=10^7$

Bunch phase-space dot-map at ejection: 350,000 bunches



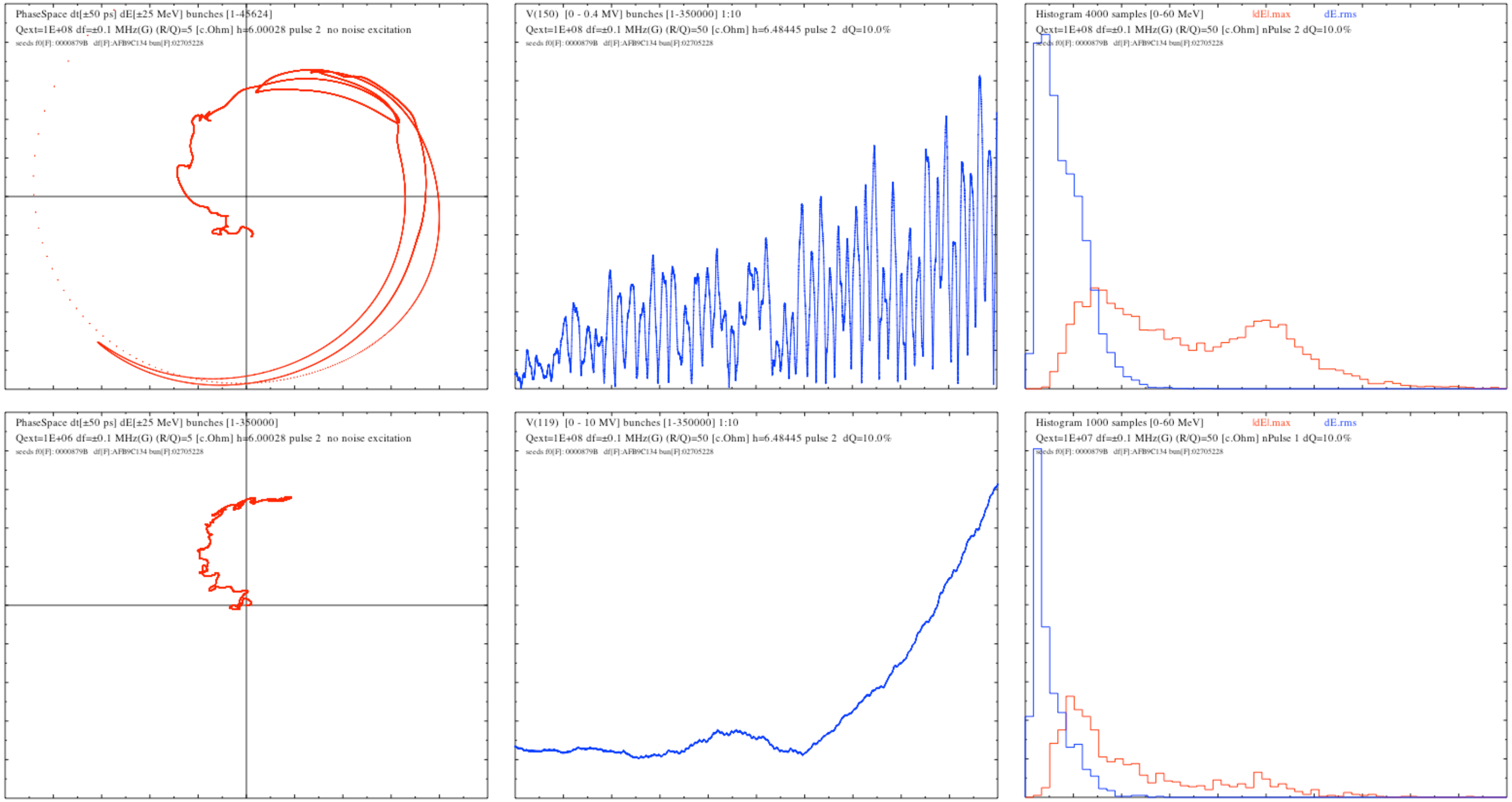
Conditions and scaling as before (including same random #) but $Q_{ext}=10^6$

Bunch phase-space dot-map at ejection: 350,000 bunches



Conditions and scaling as before (including same random #) but $Q_{ext}=10^5$

Appetizer: … have a look into the note



Phase space dot map

(at ejection)

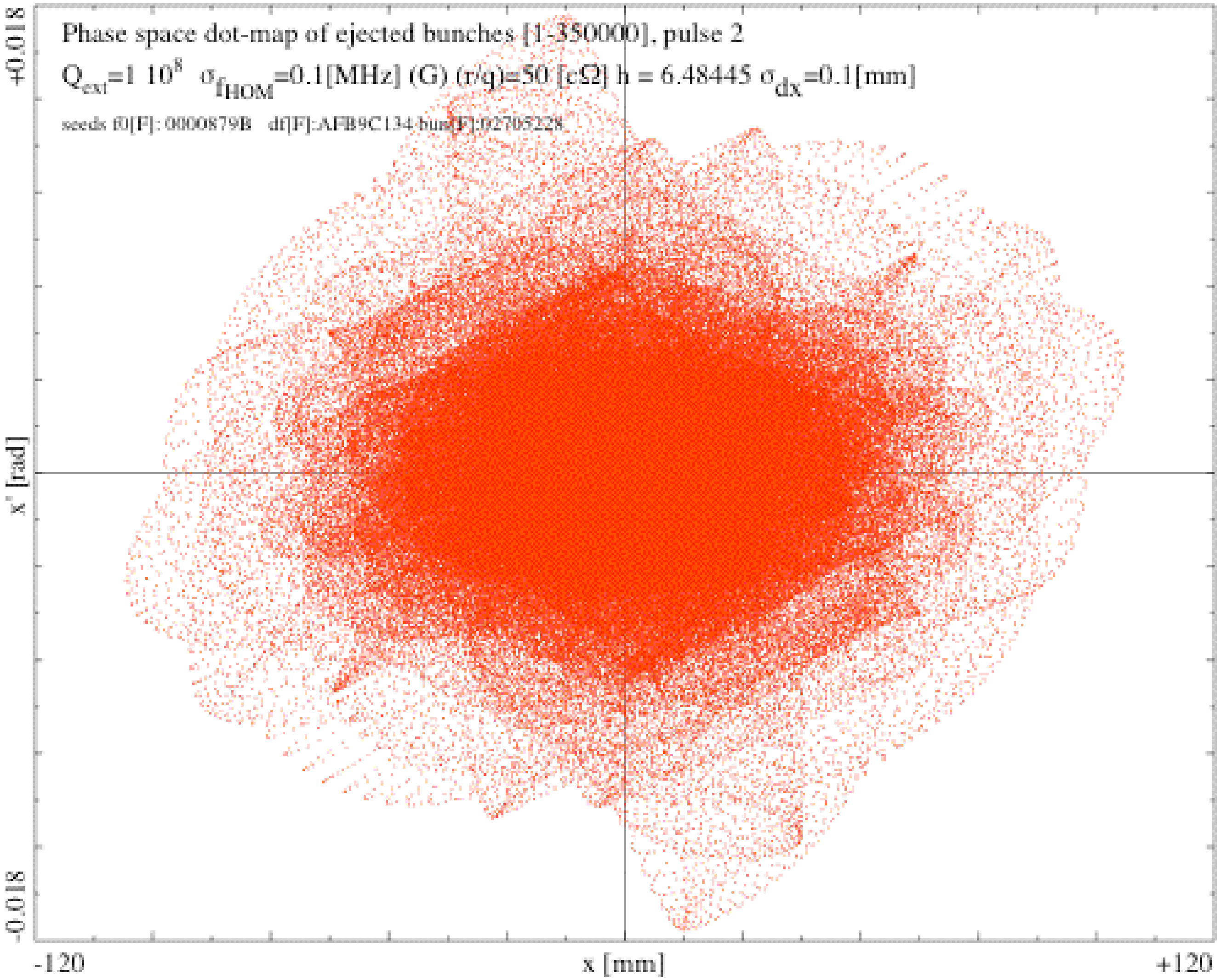
mode close ML

$V_H(t)$ 0-1 ms

dE_{max}-histo [0-60 MeV]

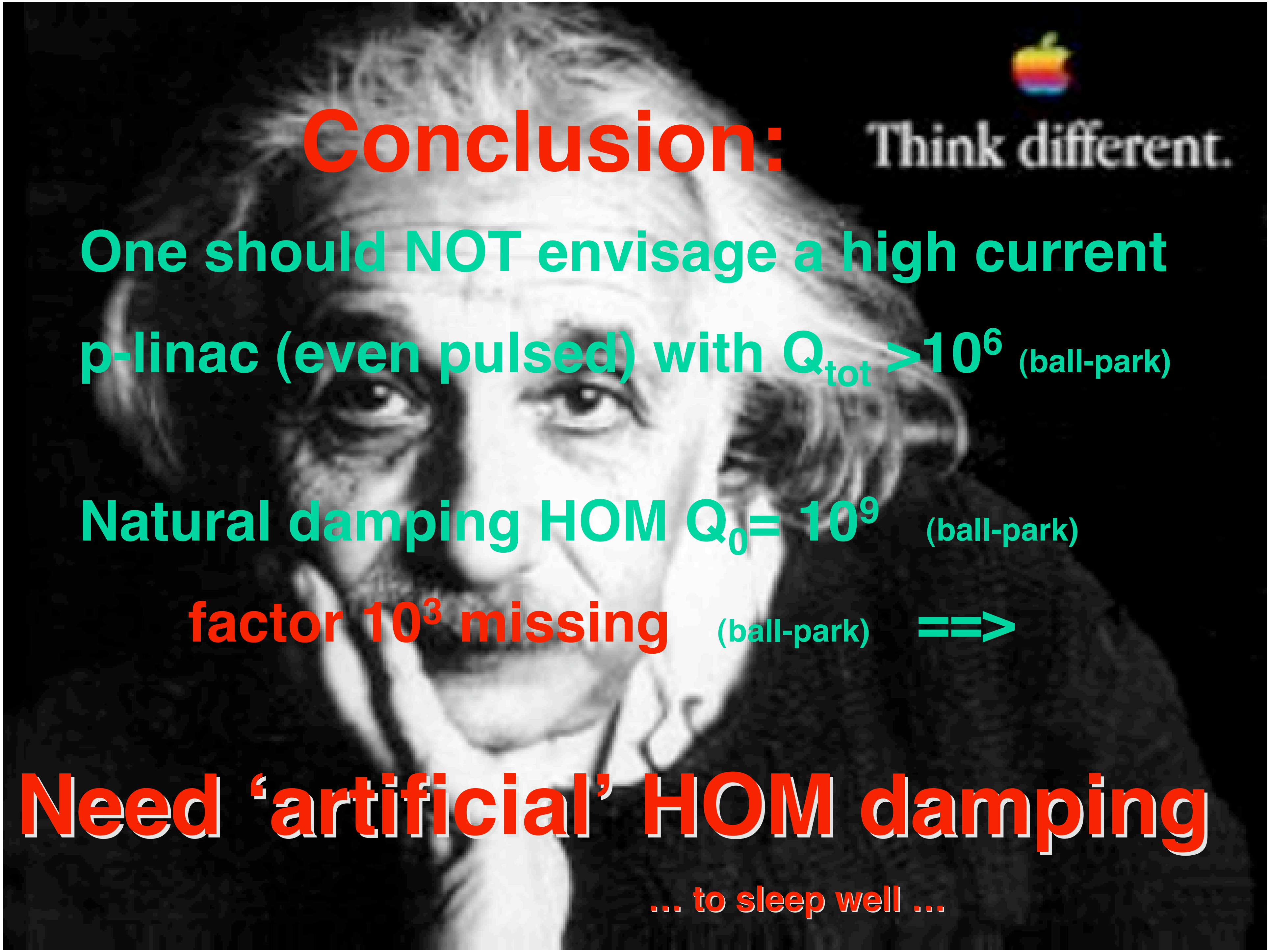
(4000 linacs)

and much more



Transverse: 0.1 mm transverse injection scatter: ±100 mm

(‘standard case’ with Qext=10^8 and $(R/Q)_\perp$=50Ω)



Conclusion:

One should NOT envisage a high current p-linac (even pulsed) with $Q_{tot} > 10^6$ (ball-park)

Natural damping HOM $Q_0 = 10^9$ (ball-park)

factor 10^3 missing (ball-park) ==>

Need ‘artificial’ HOM damping

… to sleep well …