

A few longitudinal BBU simulations (in the SPL case)

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In2p3

HOM excitation analyses

- **Beam flying ONCE through 1 cavity**
 - Allows to study when a HOM mode hits a beam spectrum resonance line
 - Analytical power analysis is possible (& \pm sufficient)
- **Beam flying ONCE through N cavities**
 - Allows also to study if a Beam Break-Up (BBU) rises « out from the noise »
 - Simulation is required (with very consuming CPU time)
- **(Beam flying N times through 1 cavity)**
 - Non-Applicable to linacs

Input parameters for the SPL case

- **PROTON BEAM**

- 352.2 MHz, 50 Hz, 5% d.c. (1ms pulse)
- 150 MeV input energy
- 400 mA mean pulse current

- **SC LINAC**

- 150 cavities @704.4 MHz
- 20.7MV acc.voltage, -15° synch.phase (-> 3.15 GeV)
- HOM mode considered:
 - 2000 MHz (far from main beam resonances)
 - $Q=1^E8$ (no HOM coupler)
 - R/Q 50 ohms (very high, but will be kept for all simulations)

Errors distribution

- **BEAM ERRORS**

- Bunch-to-bunch CURRENT normal fluctuation w/
 $\sigma = 10\% * I_0$ ($\pm 120\text{mA}@3 \sigma$)
- Bunch-to-bunch input PHASE normal fluctuation w/
 $\sigma = 0.1^\circ$ ($\pm 1.2\text{ps}@3 \sigma$)

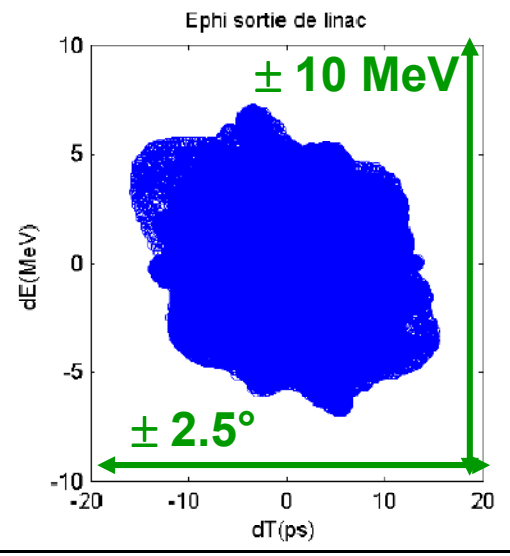
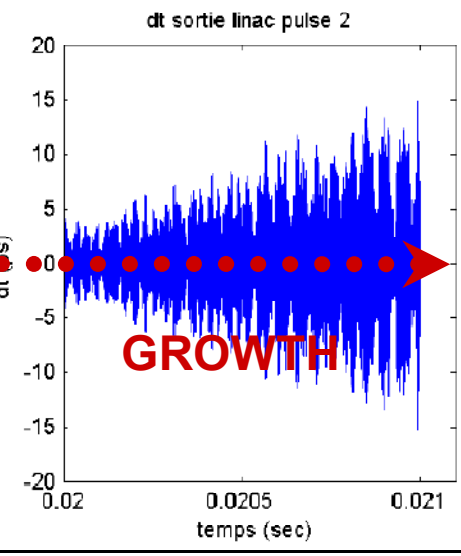
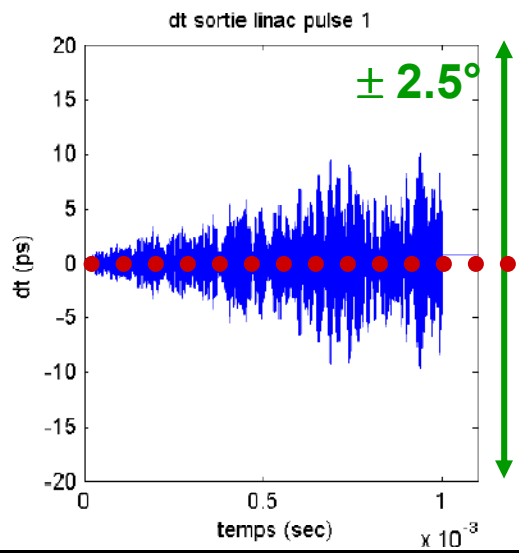
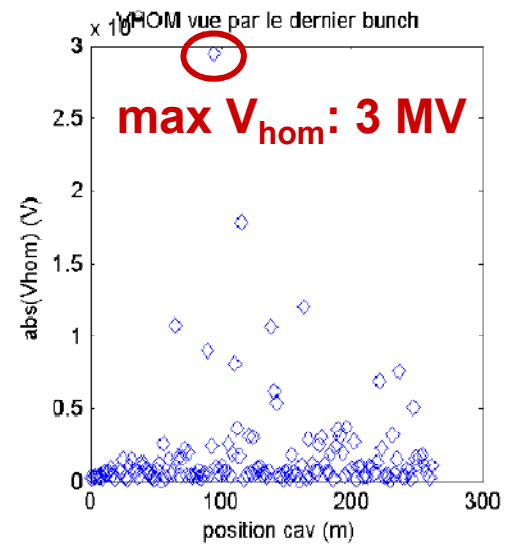
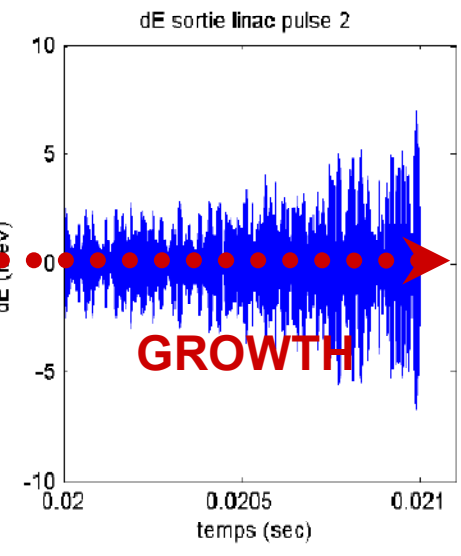
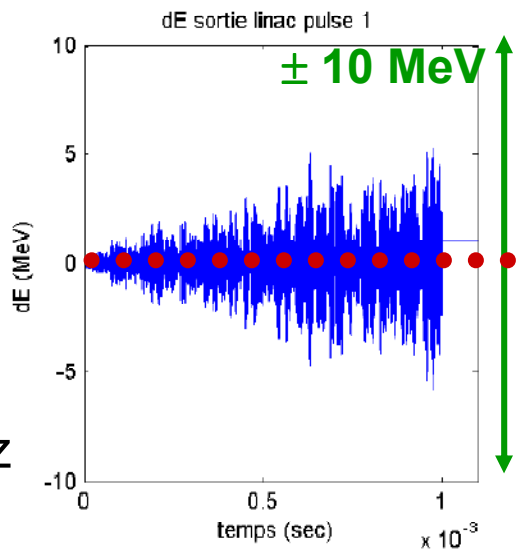
- **LINAC ERRORS**

- Cav-to-cav HOM frequency spread (normal distribution) w/
 $\sigma = 100 \text{ kHz}$ ($\pm 0.3\text{MHz}@3 \sigma$)
- Bunch-to-bunch cavity acc.voltage & phase normal fluctuations w/
 $\sigma_V = 0\% * V$ and $\sigma_\phi = 0^\circ$

Run I (Joachim's more or less)

$I_0=400\text{mA}$
 $\sigma_{I0}=10\%$
 $\sigma_{\phi 0}=0.1^\circ$
 $f_{\text{HOM}}=2\text{GHz}$
 $\sigma_{\text{HOM}}=100\text{kHz}$
 $Q_{\text{HOM}}=1\text{E}8$

$\sigma_{V_{\text{cav}}}=0\%$
 $\sigma_{\phi_{\text{cav}}}=0^\circ$

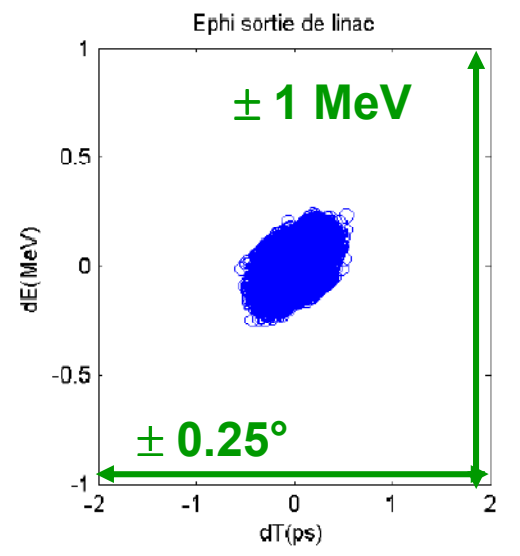
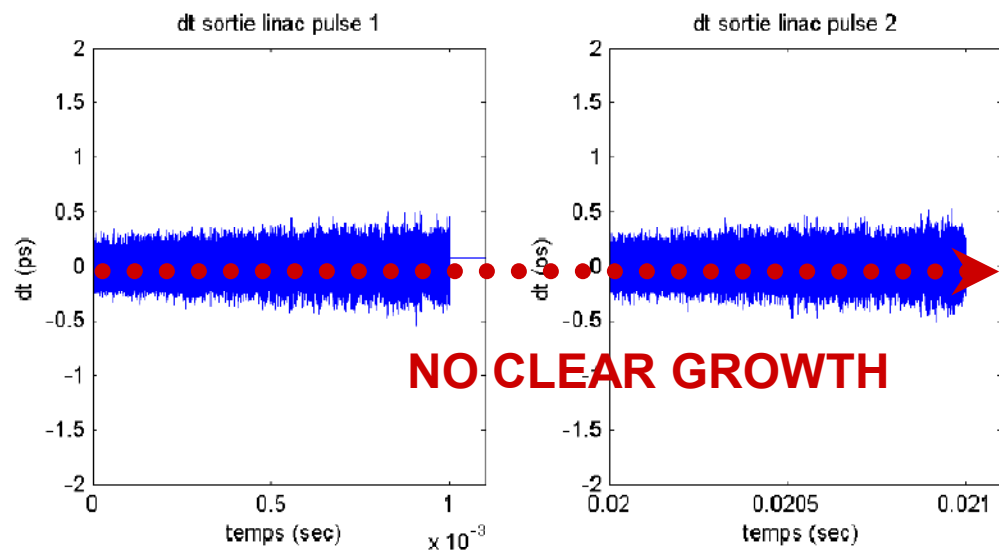
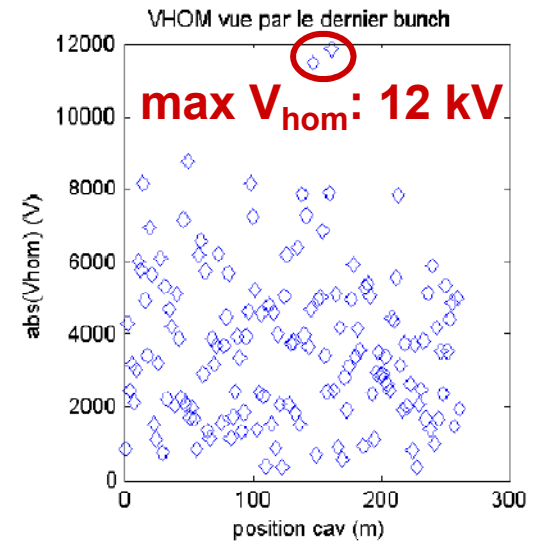
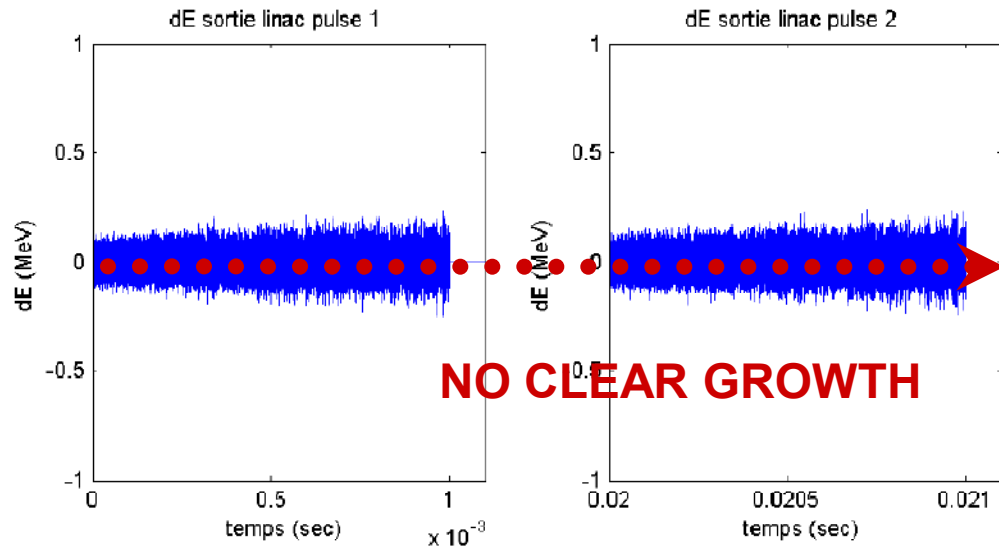


Run II (meeting the real SPL current)

$I_0 = 40 \text{ mA}$
 $\sigma_{I0} = 10\%$
 $\sigma_{\phi 0} = 0.1^\circ$

 $f_{\text{HOM}} = 2 \text{ GHz}$
 $\sigma_{\text{HOM}} = 100 \text{ kHz}$
 $Q_{\text{HOM}} = 1 \text{ E}8$

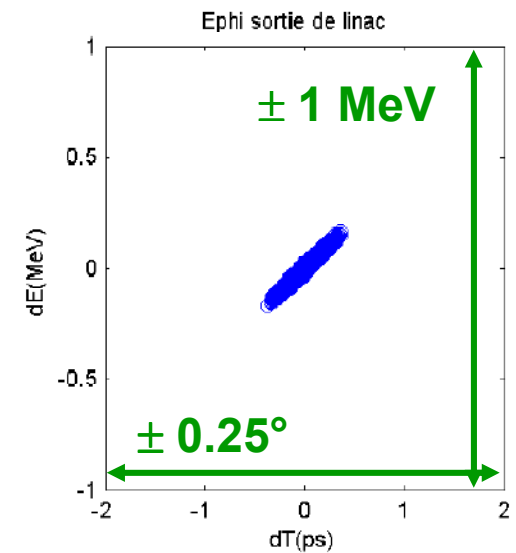
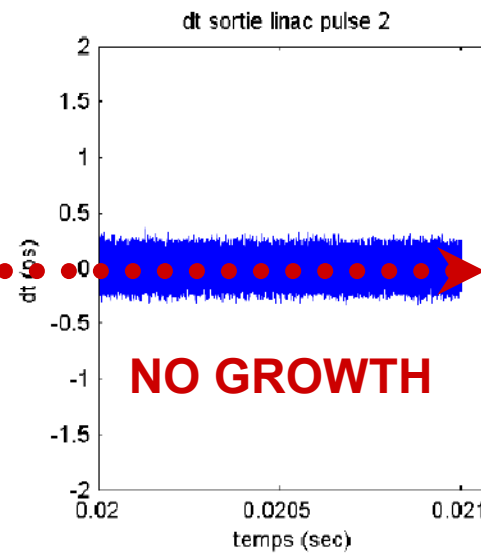
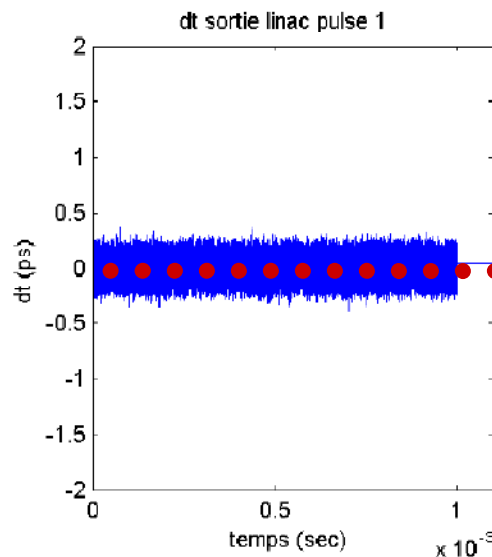
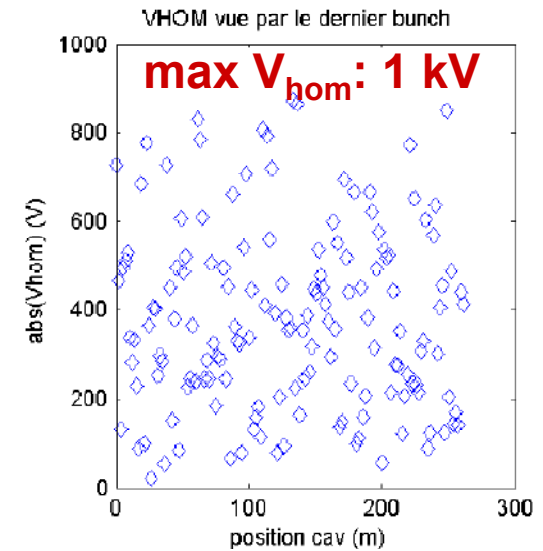
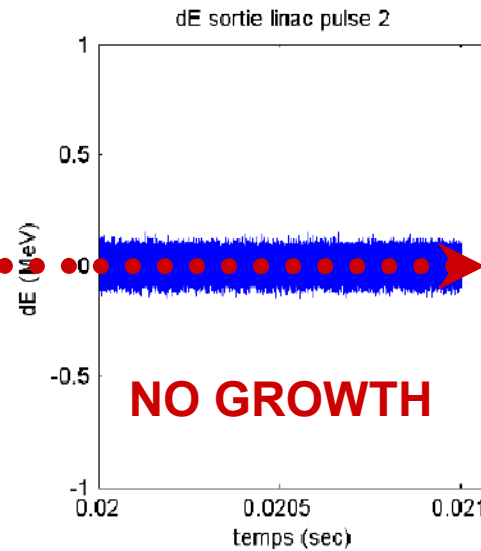
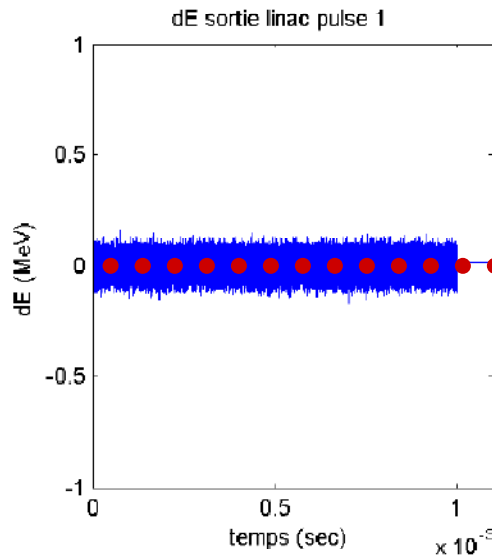
$\sigma_{V_{\text{cav}}} = 0\%$
 $\sigma_{\phi_{\text{cav}}} = 0^\circ$



Run III (with even more realistic inputs)

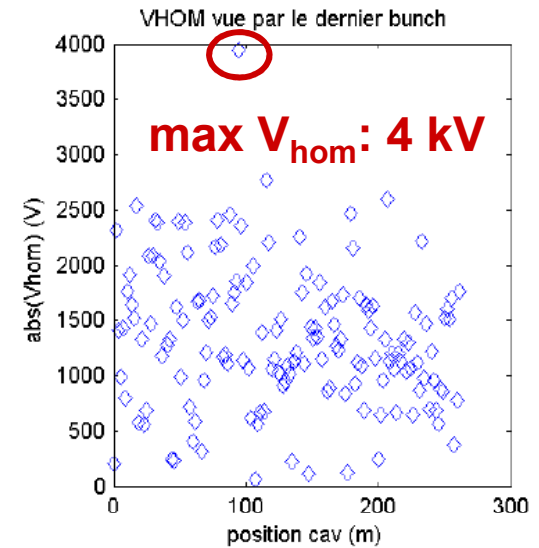
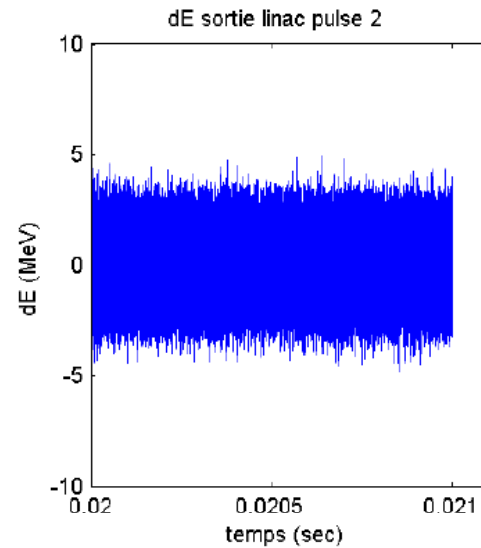
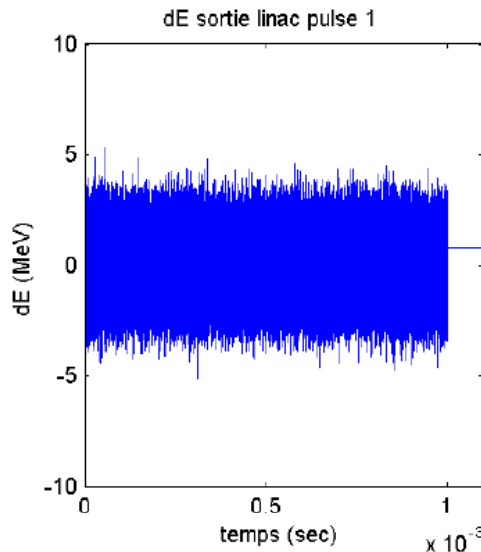
$I_0 = 40 \text{ mA}$
 $\sigma_{I_0} = 1\%$
 $\sigma_{\phi_0} = 0.1^\circ$
 $f_{\text{HOM}} = 2 \text{ GHz}$
 $\sigma_{\text{HOM}} = 1 \text{ MHz}$
 $Q_{\text{HOM}} = 1 \text{ E}8$

$\sigma_{V_{\text{cav}}} = 0\%$
 $\sigma_{\phi_{\text{cav}}} = 0^\circ$



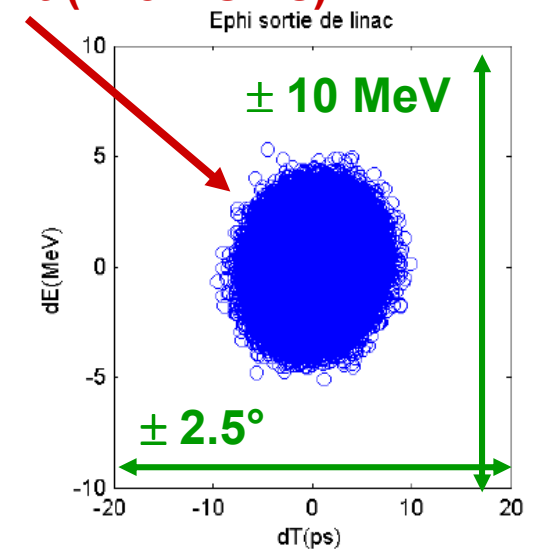
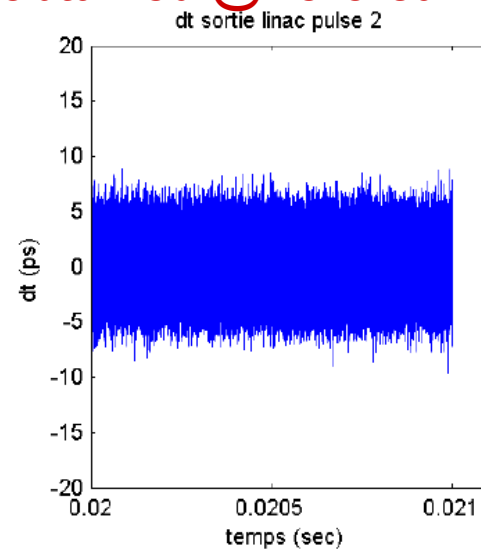
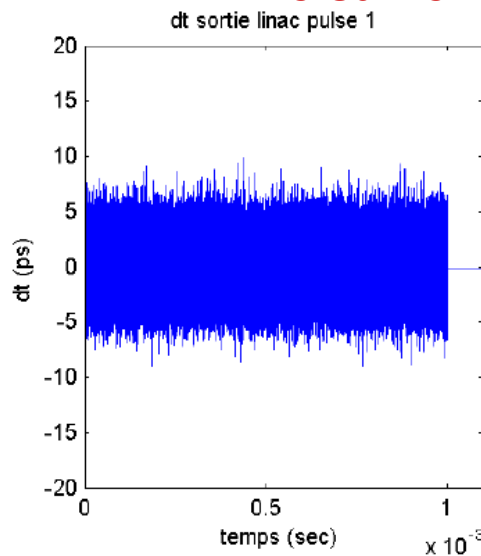
Run IV (the real SPL)

$I_0 = 40 \text{ mA}$
 $\sigma_{I0} = 1\%$
 $\sigma_{\phi 0} = 0.1^\circ$
 $f_{\text{HOM}} = 2 \text{ GHz}$
 $\sigma_{\text{HOM}} = 1 \text{ MHz}$
 $Q_{\text{HOM}} = 1 \text{ E}8$



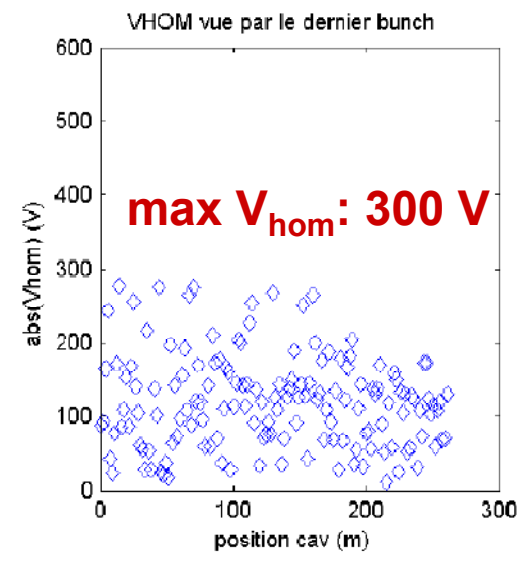
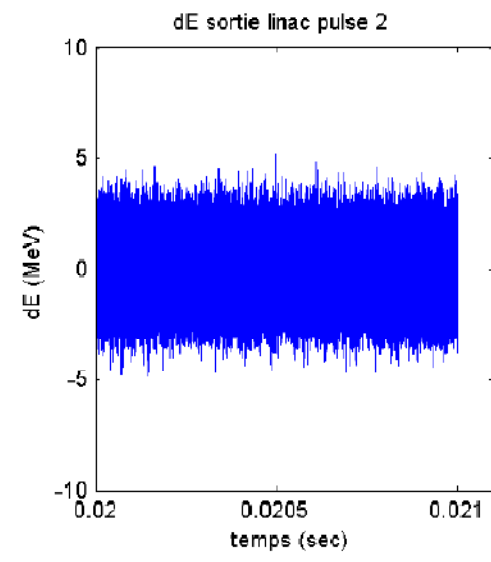
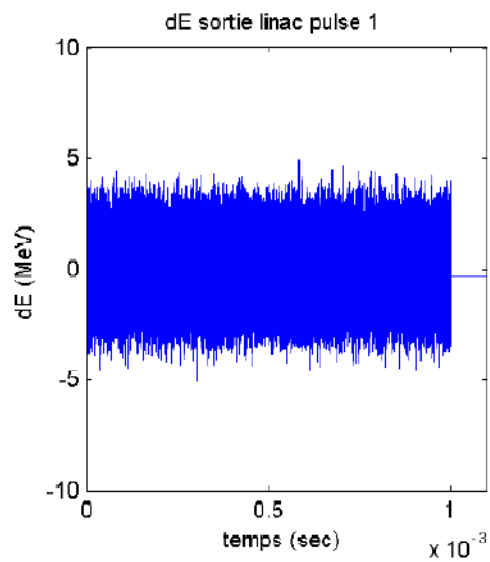
The same is obtained @ zero-current (w/o HOMs)

$\sigma_{V_{\text{cav}}} = 0.3\%$
 $\sigma_{\phi_{\text{cav}}} = 0.3^\circ$



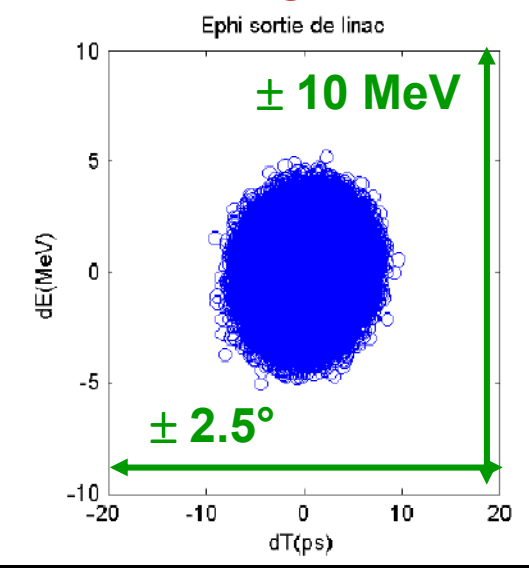
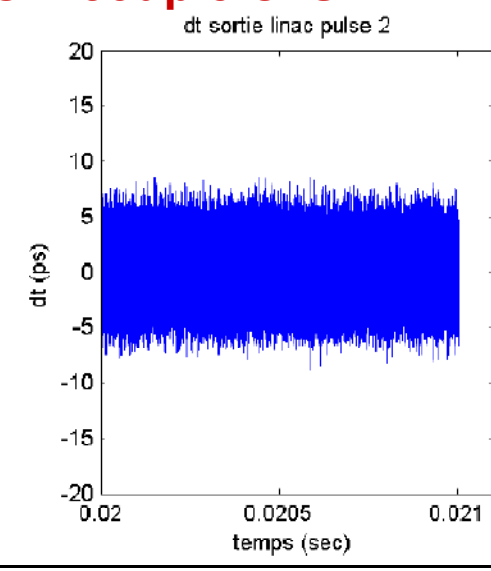
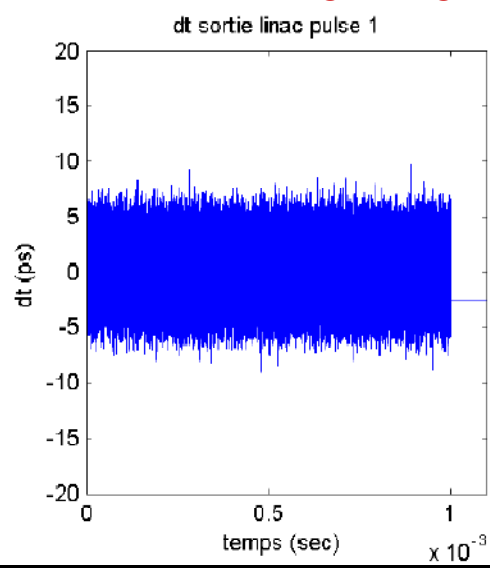
Run V (the real SPL w/ HOM couplers)

$I_0 = 40 \text{ mA}$
 $\sigma_{I0} = 1\%$
 $\sigma_{\phi 0} = 0.1^\circ$
 $f_{\text{HOM}} = 2 \text{ GHz}$
 $\sigma_{\text{HOM}} = 1 \text{ MHz}$
 $Q_{\text{HOM}} = 1 \text{ E}5$



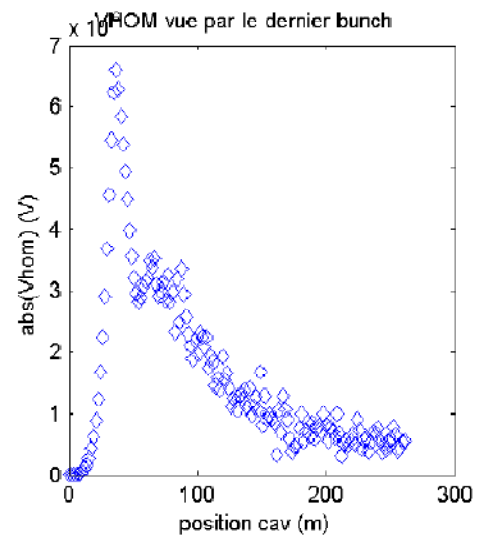
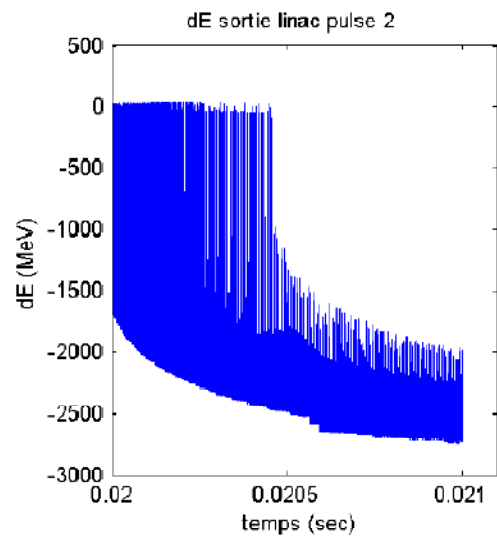
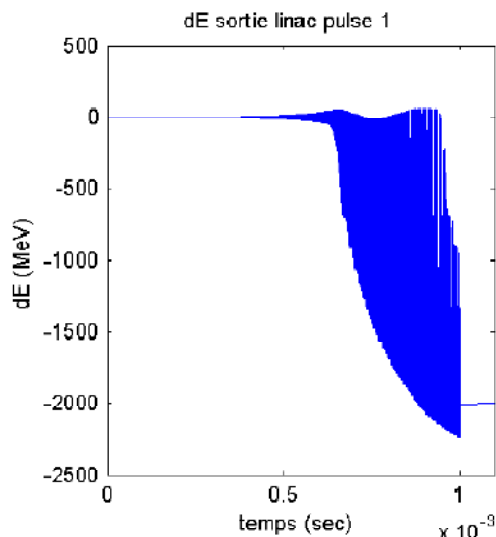
w/ or w/o HOM couplers: SAME BEAM BEHAVIOR

$\sigma_{V_{\text{cav}}} = 0.3\%$
 $\sigma_{\phi_{\text{cav}}} = 0.3^\circ$



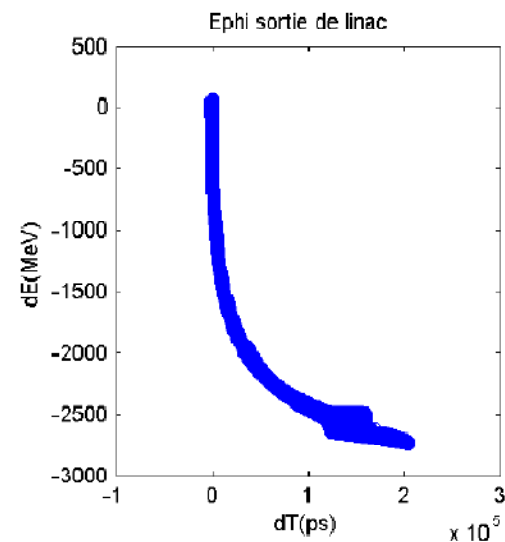
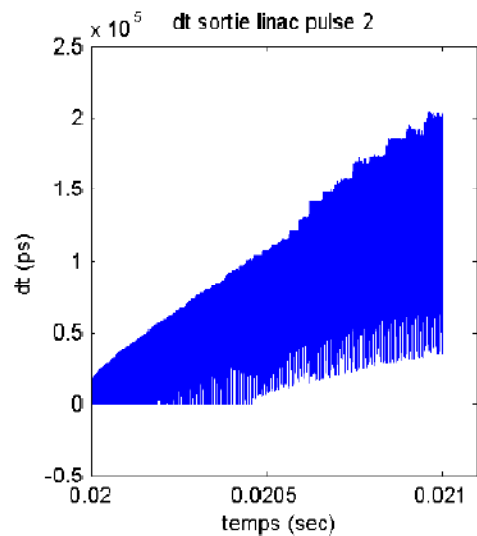
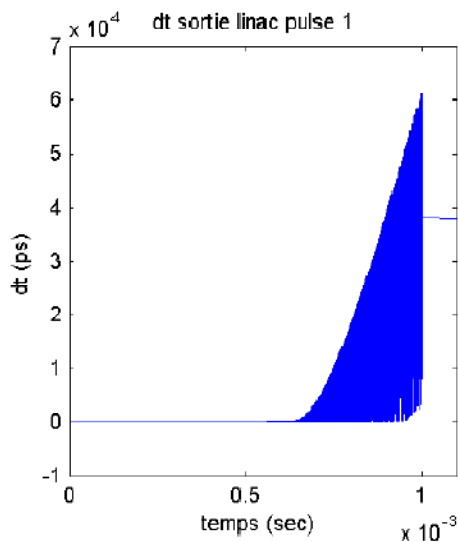
Run VI (synchrotron-like case)

$I_0 = 40 \text{ mA}$
 $\sigma_{I0} = 1\%$
 $\sigma_{\varphi 0} = 0.1^\circ$
 $f_{\text{HOM}} = 2 \text{ GHz}$
 $\sigma_{\text{HOM}} = 0$
 $Q_{\text{HOM}} = 1 \text{ E}8$



Always the same exact HOM freq => BEAM is QUICKLY LOST

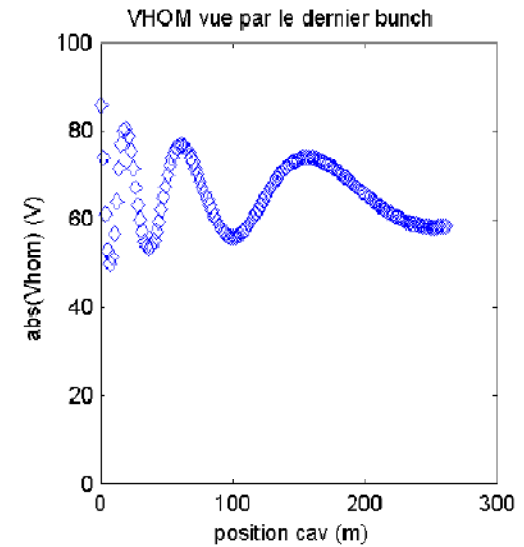
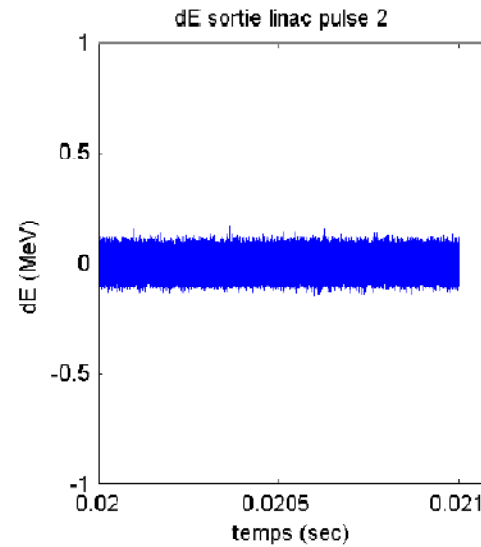
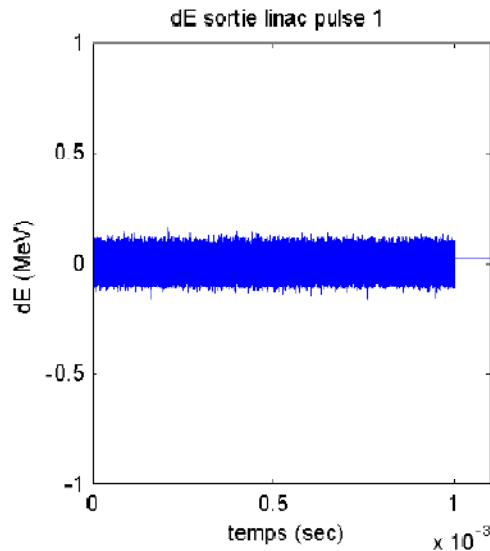
$\sigma_{V_{\text{cav}}} = 0\%$
 $\sigma_{\varphi_{\text{cav}}} = 0^\circ$



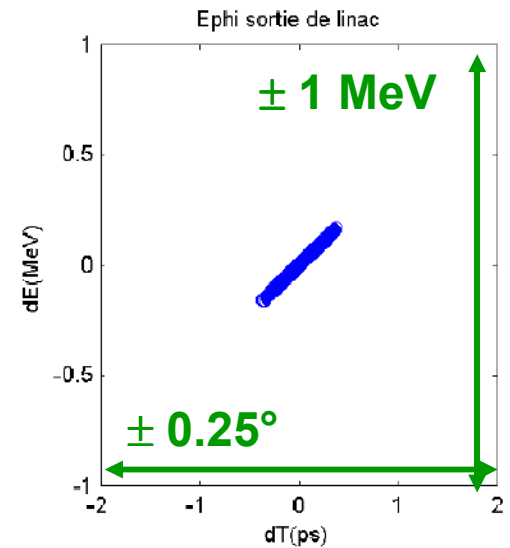
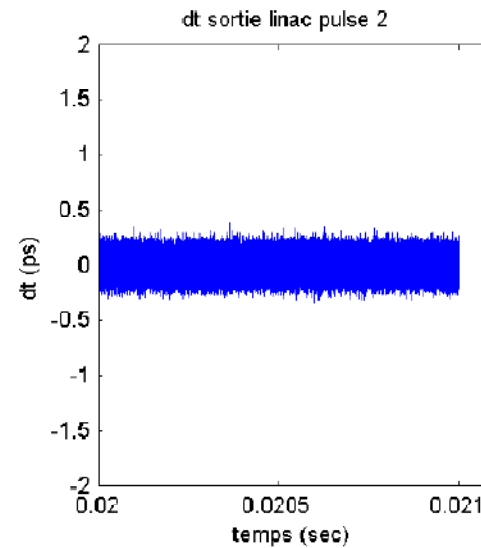
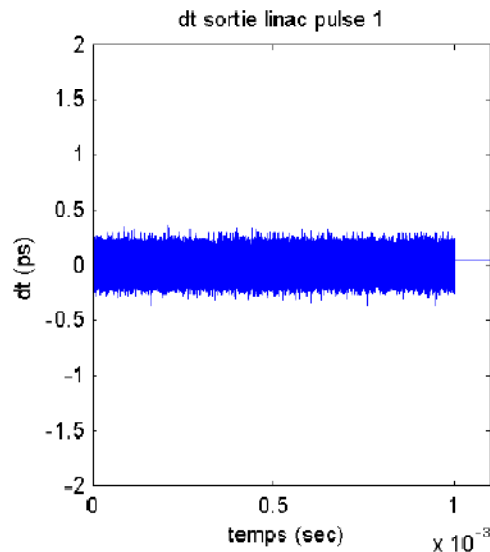
Run VII (synchrotron-like case w/ HOM couplers)

$I_0 = 40 \text{ mA}$
 $\sigma_{I0} = 1\%$
 $\sigma_{\phi 0} = 0.1^\circ$
 $f_{\text{HOM}} = 2 \text{ GHz}$
 $\sigma_{\text{HOM}} = 0$
 $Q_{\text{HOM}} = 1 \text{ E}5$

$\sigma_{V_{\text{cav}}} = 0\%$
 $\sigma_{\phi_{\text{cav}}} = 0^\circ$



If no HOM spread at all => HOM coupler is required & efficient



Run VIII (meeting a beam line, w/ Joachim's inputs)

$$I_0 = 400 \text{ mA}$$

$$\sigma_{I0} = 10\%$$

$$\sigma_{\varphi 0} = 0.1^\circ$$

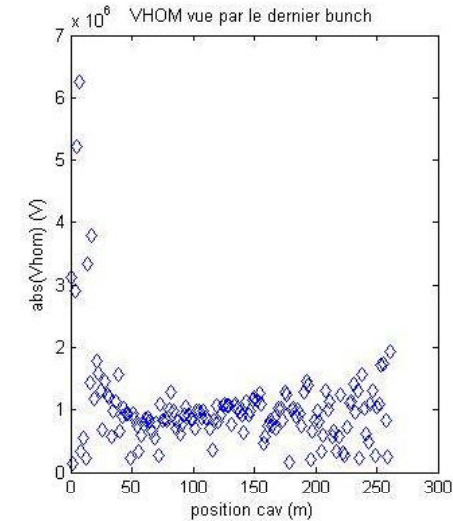
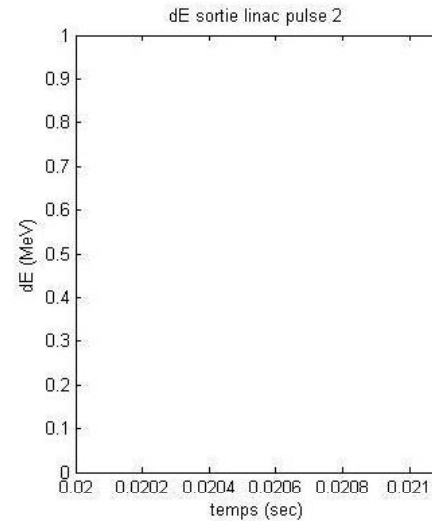
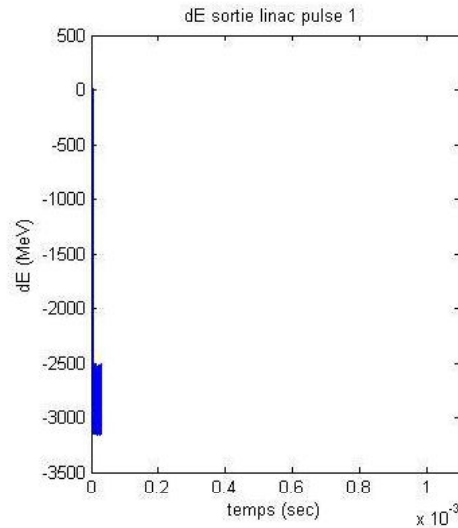
$$f_{\text{HOM}} = 2113.2 \text{ MHz}$$

$$\sigma_{\text{HOM}} = 100 \text{ kHz}$$

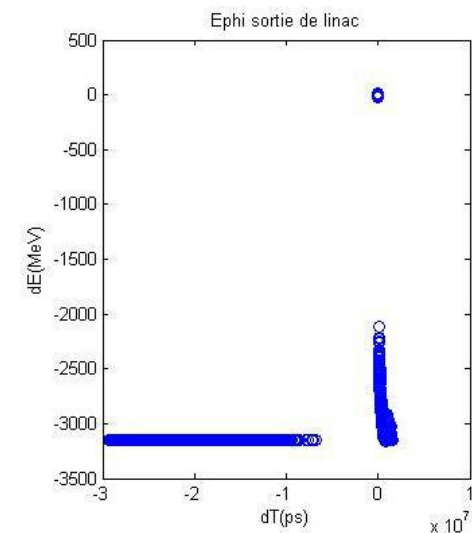
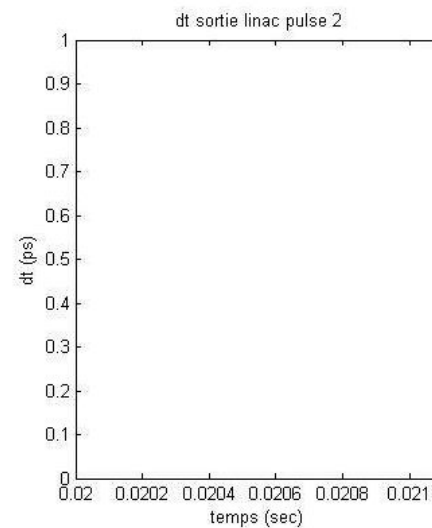
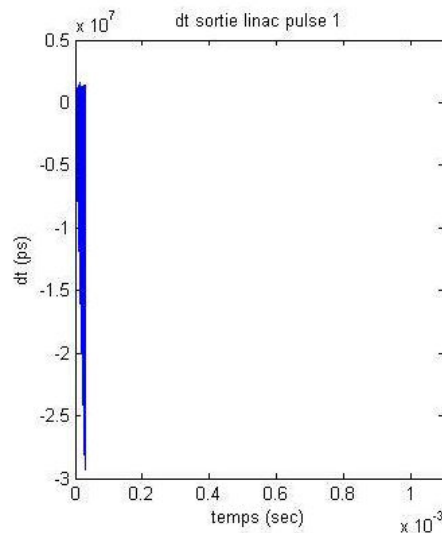
$$Q_{\text{HOM}} = 1 \text{ E} 8$$

$$\sigma_{V_{\text{cav}}} = 0\%$$

$$\sigma_{\varphi_{\text{cav}}} = 0^\circ$$



Complete beam loss after only a few bunch



Run IX (meeting a beam line, more softly)

$$I_0 = 40 \text{ mA}$$

$$\sigma_{I0} = 1\%$$

$$\sigma_{\phi 0} = 0.1^\circ$$

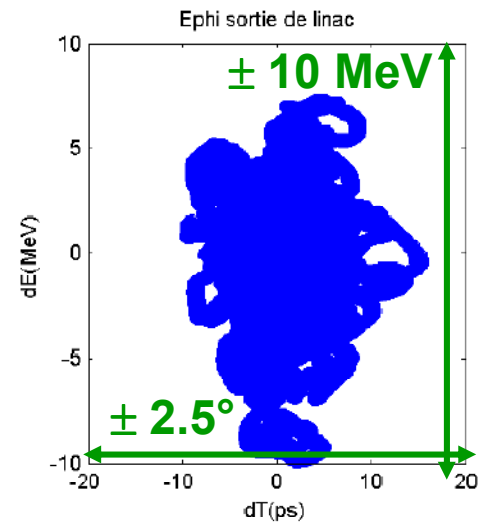
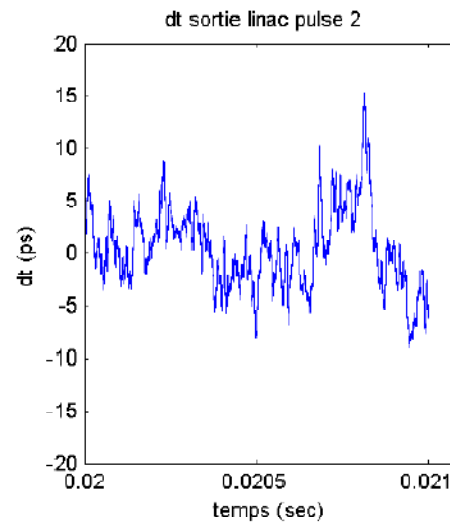
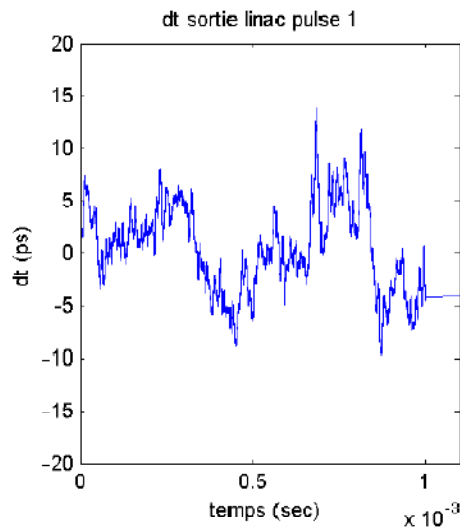
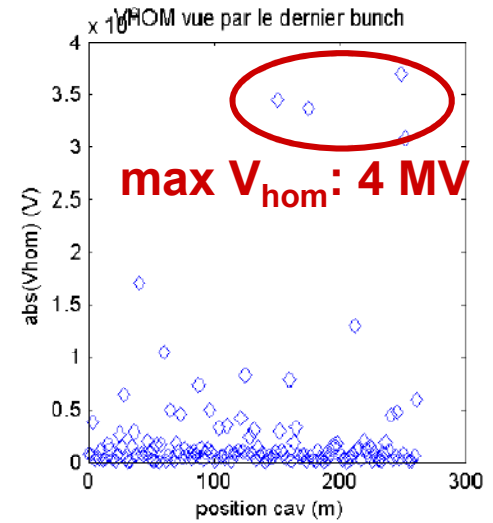
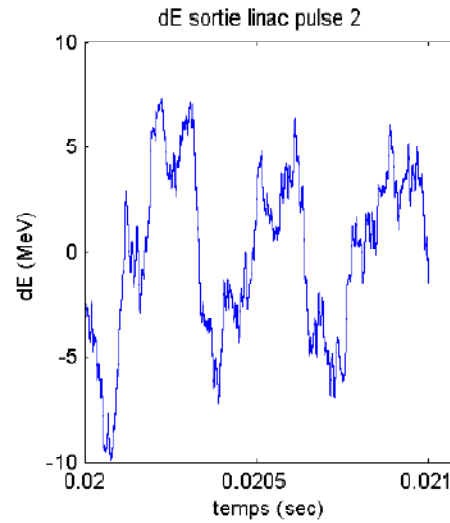
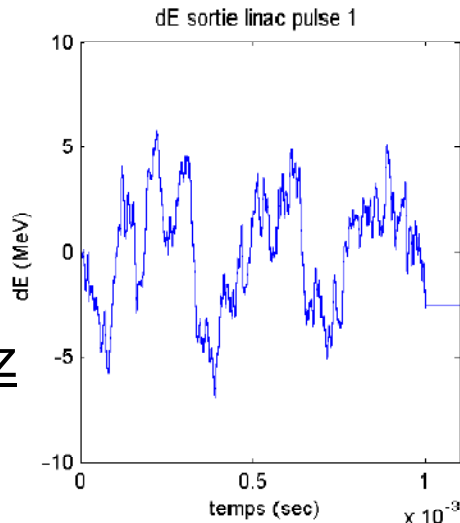
$$f_{\text{HOM}} = 2113.2 \text{ MHz}$$

$$\sigma_{\text{HOM}} = 100 \text{ kHz}$$

$$Q_{\text{HOM}} = 1 \text{ E} 8$$

$$\sigma_{V_{\text{cav}}} = 0\%$$

$$\sigma_{\phi_{\text{cav}}} = 0^\circ$$



Run X (meeting a beam line, even more softly)

$I_0 = 40 \text{ mA}$

$\sigma_{I0} = 1\%$

$\sigma_{\phi 0} = 0.1^\circ$

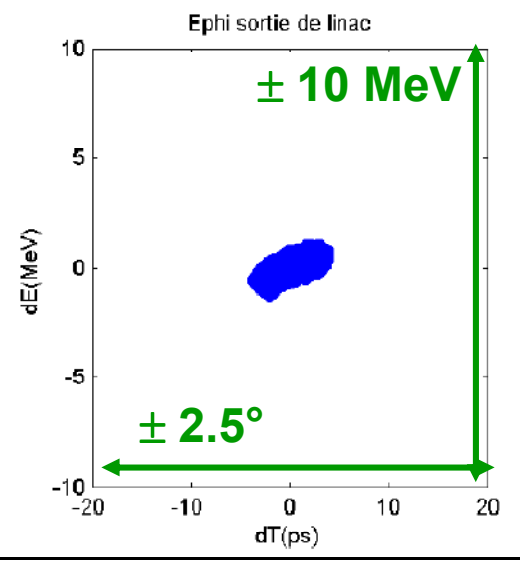
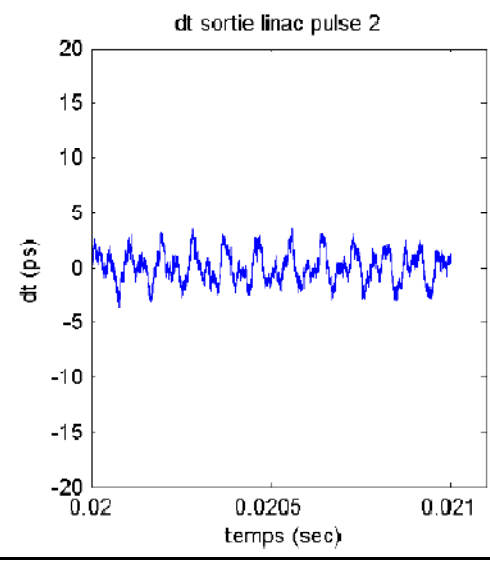
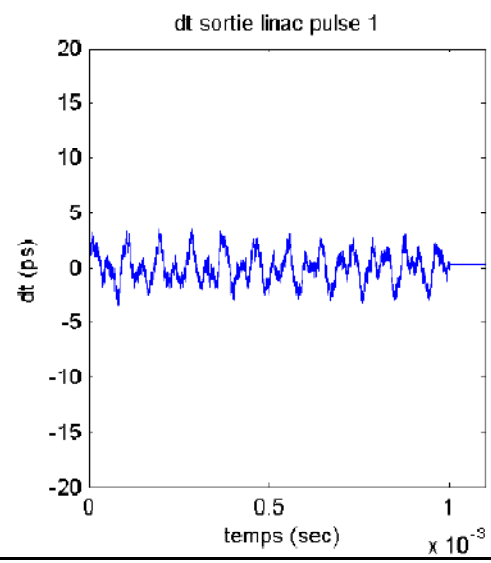
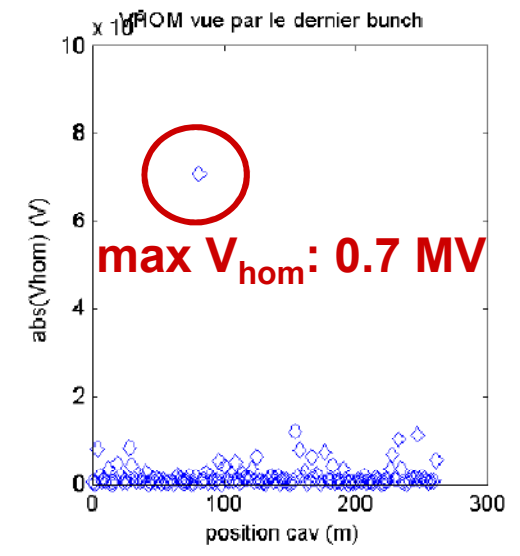
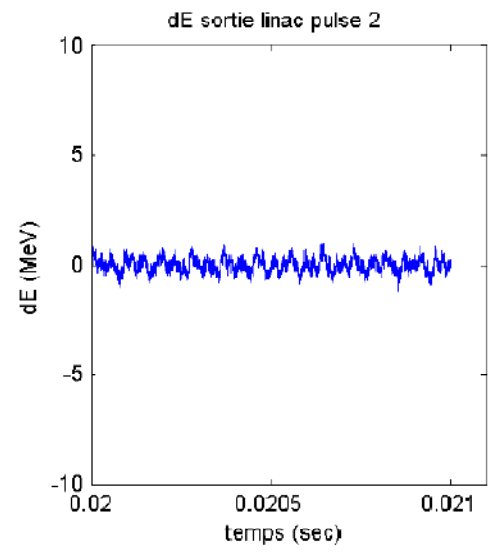
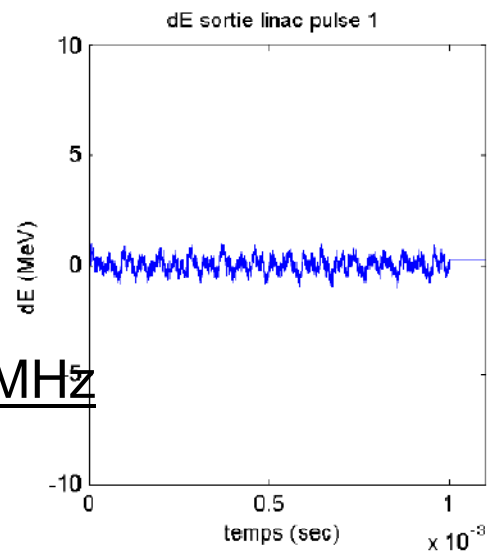
$f_{\text{HOM}} = 2113.2 \text{ MHz}$

$\sigma_{\text{HOM}} = 1 \text{ MHz}$

$Q_{\text{HOM}} = 1 \text{ E}8$

$\sigma_{V_{\text{cav}}} = 0\%$

$\sigma_{\phi_{\text{cav}}} = 0^\circ$



Run XI (meeting a beam line, w/ HOM couplers)

$I_0=40\text{mA}$

$\sigma_{I0}=1\%$

$\sigma_{\phi0}=0.1^\circ$

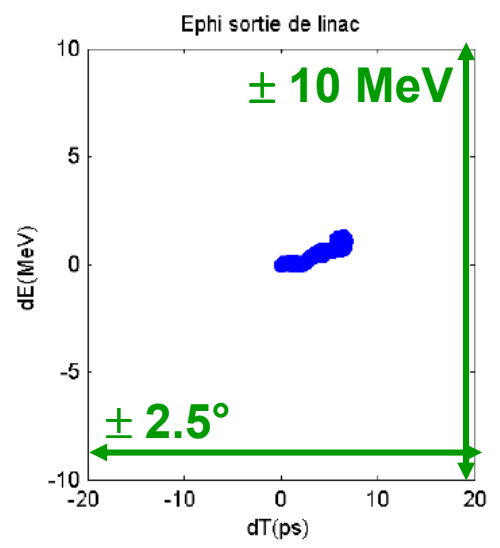
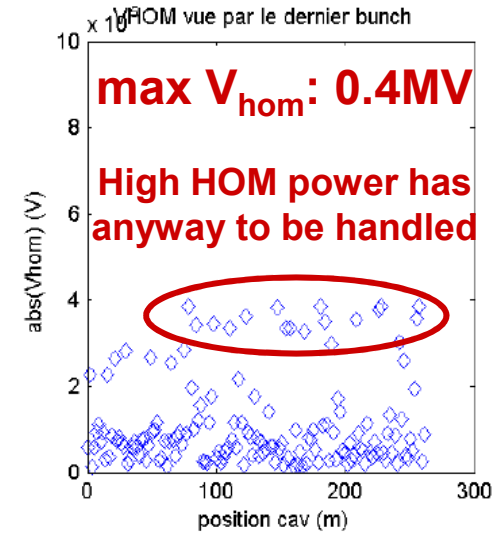
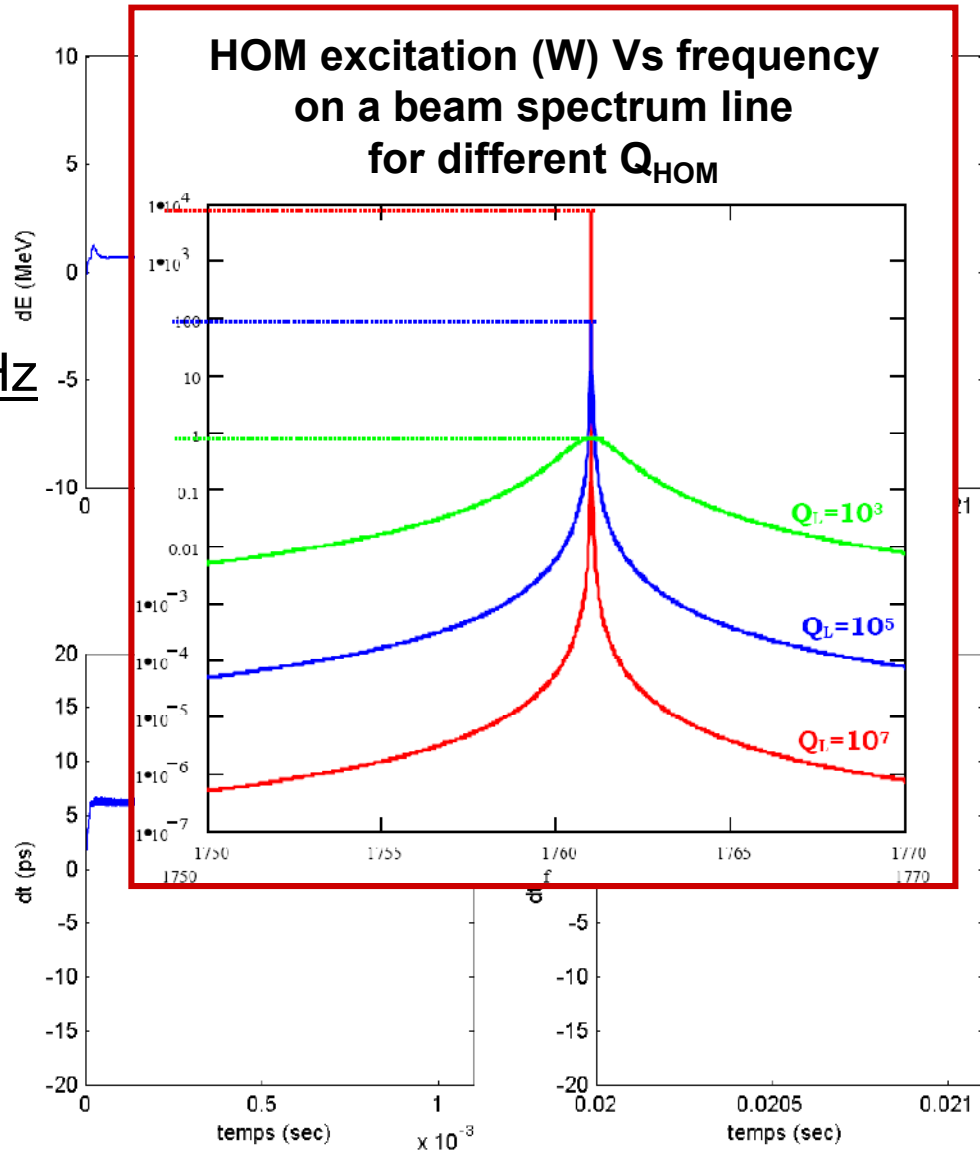
$f_{\text{HOM}}=2113.2\text{MHz}$

$\sigma_{\text{HOM}}=100\text{kHz}$

$Q_{\text{HOM}}=1E5$

$\sigma_{V\text{cav}}=0\%$

$\sigma_{\phi\text{cav}}=0^\circ$



Conclusions (personal draft – for discussion !)

- In SPL-like linacs, BBU « out from the noise » can be damped:
 - **N°1: lowering Q_{HOM}** (e.g. using HOM couplers)
This is the only solution for extreme conditions (100's mA with high fluctuations, low HOM dispersion...) or in circular machines (zero HOM frequency spread)
 - OR
 - **N°2: naturally**
Simply checking that HOM modes are sufficiently distributed from cavity to cavity ($\sigma=100\text{kHz}$ seems even to be enough in the SPL case)
- **Simulating the SPL case without HOM couplers & with realistic input parameters shows apparently no longitudinal Beam Break Up instability rising**
- **Cavities should be designed to avoid having a HOM mode exactly matching a beam resonance line. In the case where this is NOT achieved:**
 - Without HOM couplers (high Q_{HOM}): very low probability to really hit the resonance, but could lead to a cavity quench + beam loss if it happens
-> CURE = simply measure all cavities before installation to check
 - With HOM couplers (low Q_{HOM}): the probability to hit the resonance is far larger but not catastrophic -> HOM couplers have to be designed to evacuate large HOM powers continuously

Limits of these non-definitive conclusions...

- Very poor statistics : more simulations should be performed
- 10^X pulses should be simulated to confirm the behavior with a « quasi-infinite » pulse train, and to check if any instability linked with the pulse structure is rising (even if for SPL, it is a priori non-relevant for such low pulsing frequencies)
- The real SPL linac layout should be taken as input, including, for each cavity family, all HOM properties (f , Q , $r/Q(\beta)$)...
- More realistic (non-white) noises should be considered
- Being aware that all this would imply enormous CPU time...