Probing the 16L2 instability by an equivalent resonator model

D.Amorim, S.Antipov, N.Biancacci, L.Carver,
E.Métral, X.Buffat, B.Salvant

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The observed tune shift can be created by ~ $1\text{x}10^{13}$ m^{-3} of electron cloud

- Assuming uniform distribution (field-free)

$$n_e \sim \frac{4\varepsilon_0 \gamma \Delta Q_y Q_y}{r_p R_0{}^2} \sim 10^{13}\,\mathrm{m}^{-3}$$

- If only due to multipacting, the saturation density would be just a bit higher:

$$n_{e,sat} \sim \frac{N_b}{\pi r_{cham}{}^2 s_b} \sim 1.5\times10^{13}\,\mathrm{m}^{-3}$$ for $s_b = c$ x 25 ns bunch spacing

- We suppose this high density is due to the electrons coming from the ion gas ionization.

For reference please refer to:
F. Zimmermann, “Review of single bunch instabilities driven by an electron cloud”, *PRST-AB* **7**, 124801 (2004)

Resulting beam break-up instability can be fast

- High frequency of **~ 2.6 GHz** – consistent with the head-tail monitor

$$\omega_e = c\sqrt{\frac{N_b r_e}{\sigma_\perp^2 \sqrt{2\pi}\sigma_z}} \sim 2\pi \times 2.6\,\mathrm{GHz}$$

- The wake does ~ 1 full oscillation on the bunch length: $\omega_e \sigma_z / c \sim 5$

- 2-particle model of beam break-up gives a high growth rate

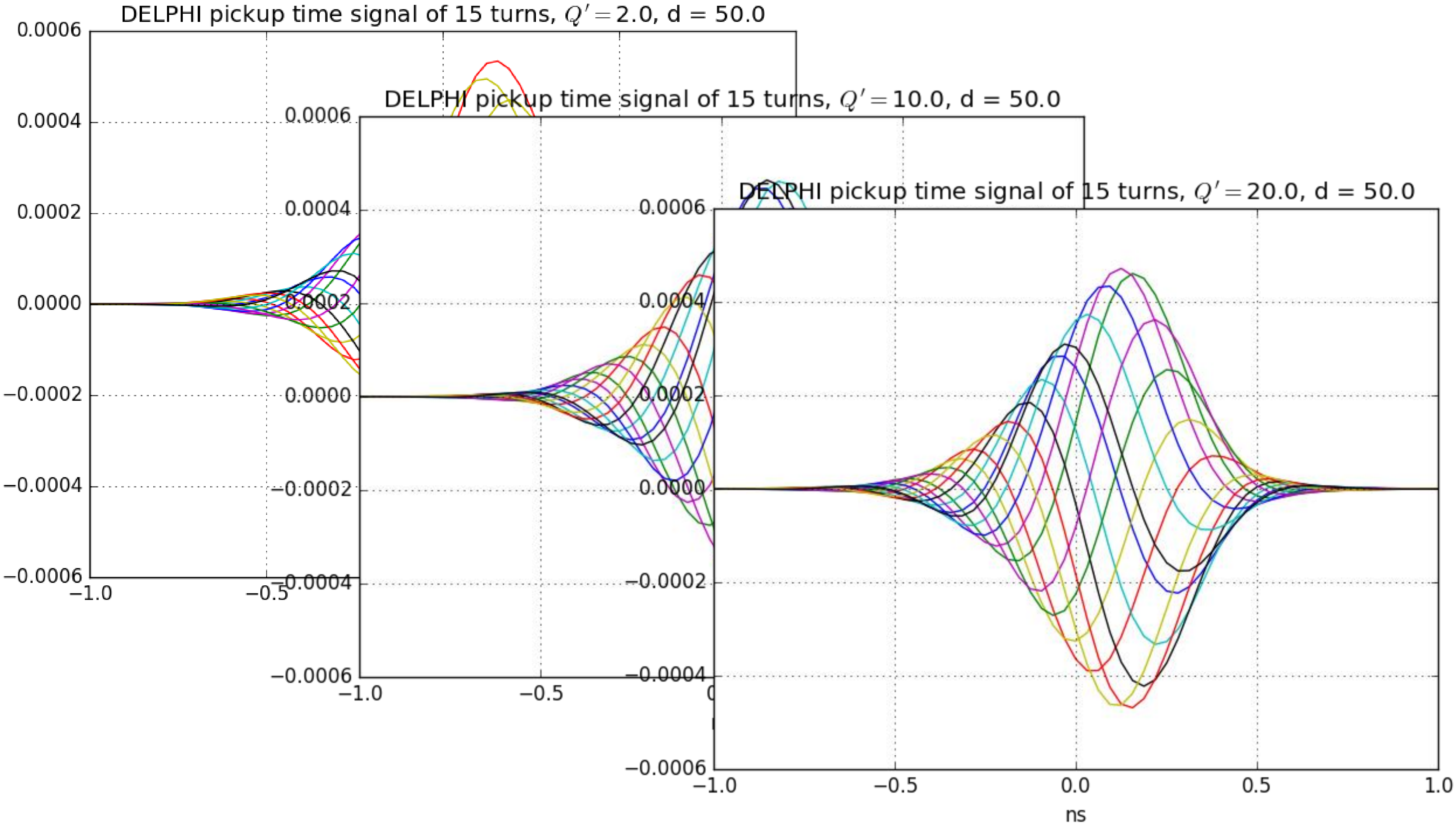
$$\tau_{BBU} \sim (2\pi r_p c n_e \beta_y / \gamma)^{-1} < 10 \quad \text{turns}$$

- Alternatively, we can consider an **"equivalent" broad-band resonator model**

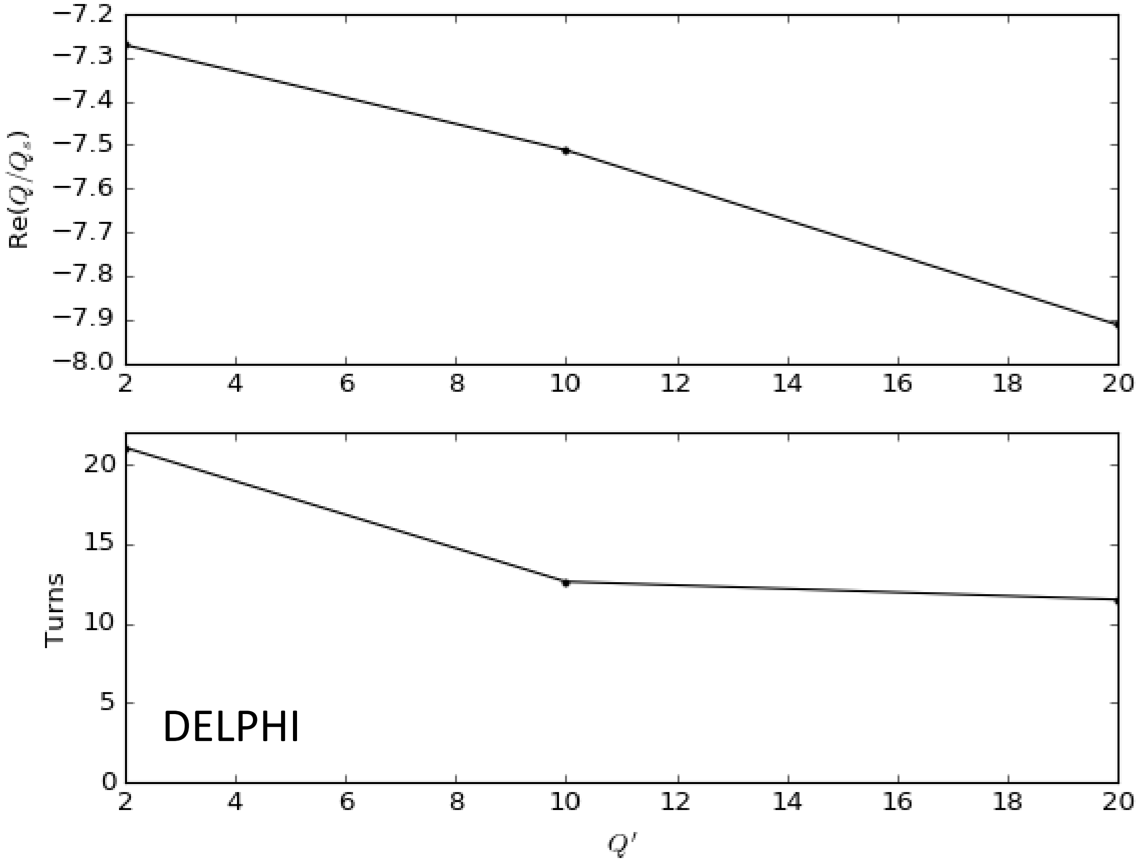
$$\boxed{\omega_R = \omega_e \qquad Q \sim 1 \qquad R_s = (150 - 500)\,\mathrm{M\Omega/m}}$$

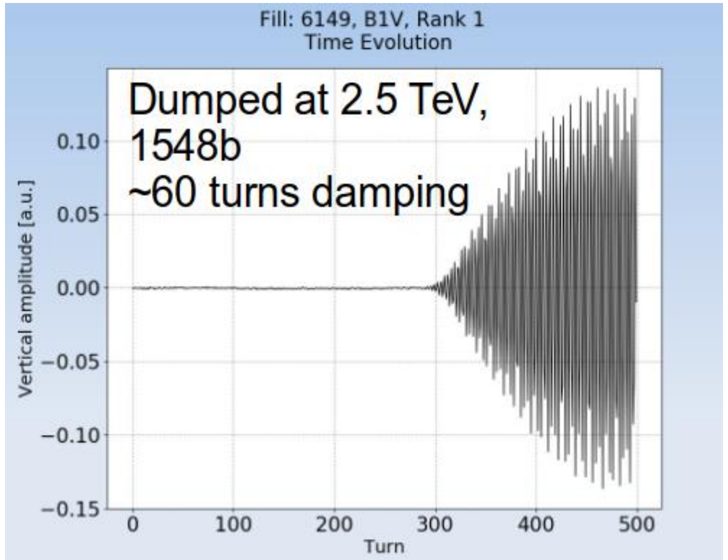
depending on the "enhancement factor"

- Much higher impedance than the other sources at this frequency
- Numerical simulations performed with DELPHI
  (latest version with pickup signals thanks to David on gitlab.cern.ch/IRIS/DELPHI)

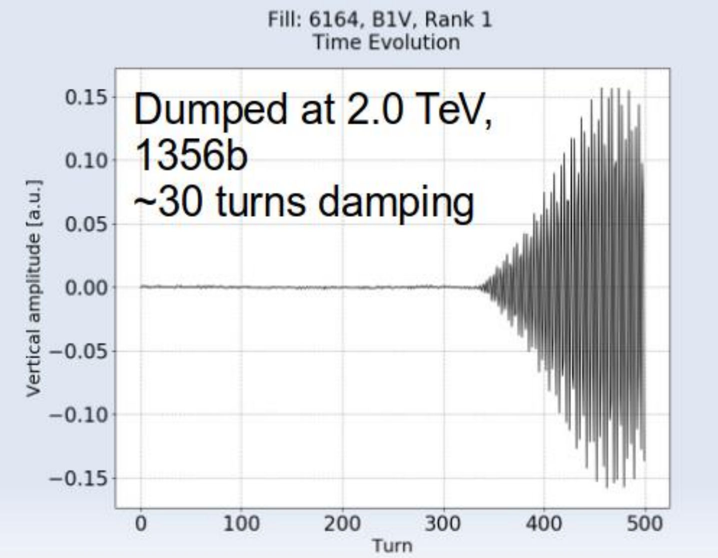

DELPHI pickup time signal of 15 turns, $Q' = 2.0$, d = 50.0
0.0006
0.0004
0.0002
0.0000
−0.0002
−0.0004
−0.0006
−1.0
−0.5
DELPHI pickup time signal of 15 turns, $Q' = 10.0$, d = 50.0
0.0006
0.0004
0.0002
0.0000
−0.0002
−0.0004
−0.0006
−1.0
−0.5
DELPHI pickup time signal of 15 turns, $Q' = 20.0$, d = 50.0
0.0006
0.0004
0.0002
0.0000
−0.0002
−0.0004
−0.0006
−1.0
−0.5
0.0
0.5
1.0
ns

Comparison with observed growth rate





Dumped at 2.5 TeV,
1548b
~60 turns damping



Dumped at 2.0 TeV,
1356b
~30 turns damping

"Update on observations of coherent motion",
X.Buffat et al. 16L2 task force meeting, 05-09-2017

Comparison with observed headtail monitor pattern

Dump at 7:14 on
31-08-2017 at 0.6 TeV

Options:
☐ Load
☑ Scale Y
☐ Show FS
☑ Repeat
☑ Baseline
☐ Compensation

5 turns acquired

Start: 0
Num: 5
Inc: 1

From: 1381
To: 1381
All

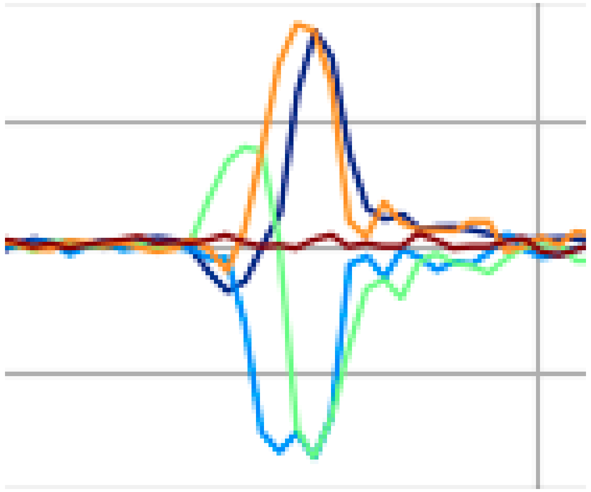
Bunch: # 1380, # 1381, # 1382, # 1383, # 1384, # 1385, # 1386, # 1387, # 1388, # 1389, # 1390, # 1391, # 1392, # 1393, # 1394

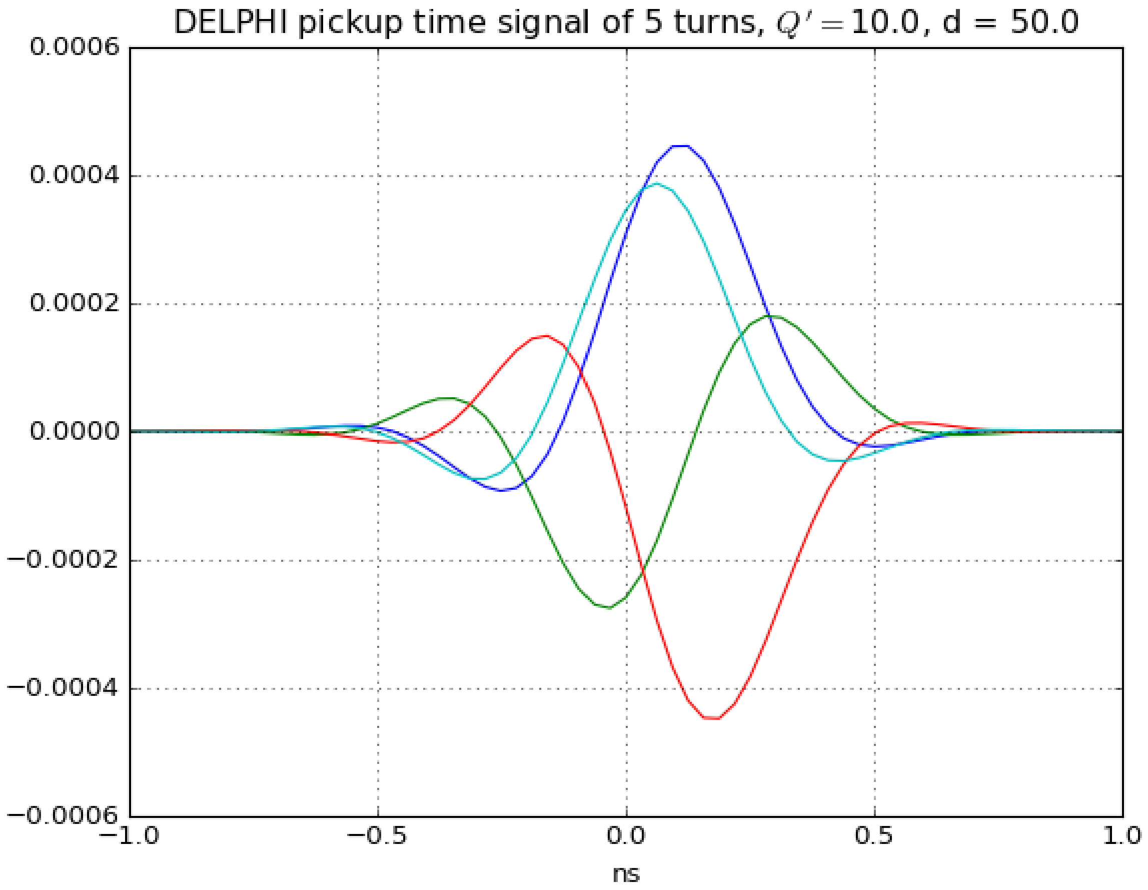
LHC.BQHT.B1_20170831_071403.h5 | 38 MB | 10.0 MS | 10 turns

See also B.Salvant, T.Levens
https://indico.cern.ch/event/657108/contributions/2677558/attachments/
1516242/2367988/Headtail_monitor_16L2.pdf

Comparison with observed headtail monitor pattern

B1V HT pickup, 5 turns, 600 GeV

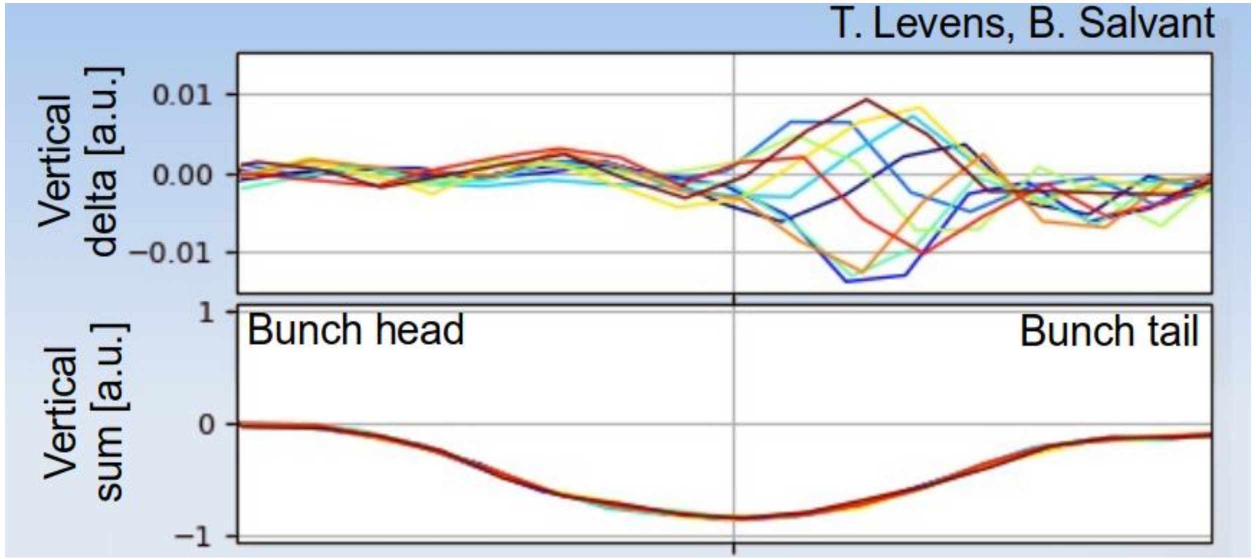


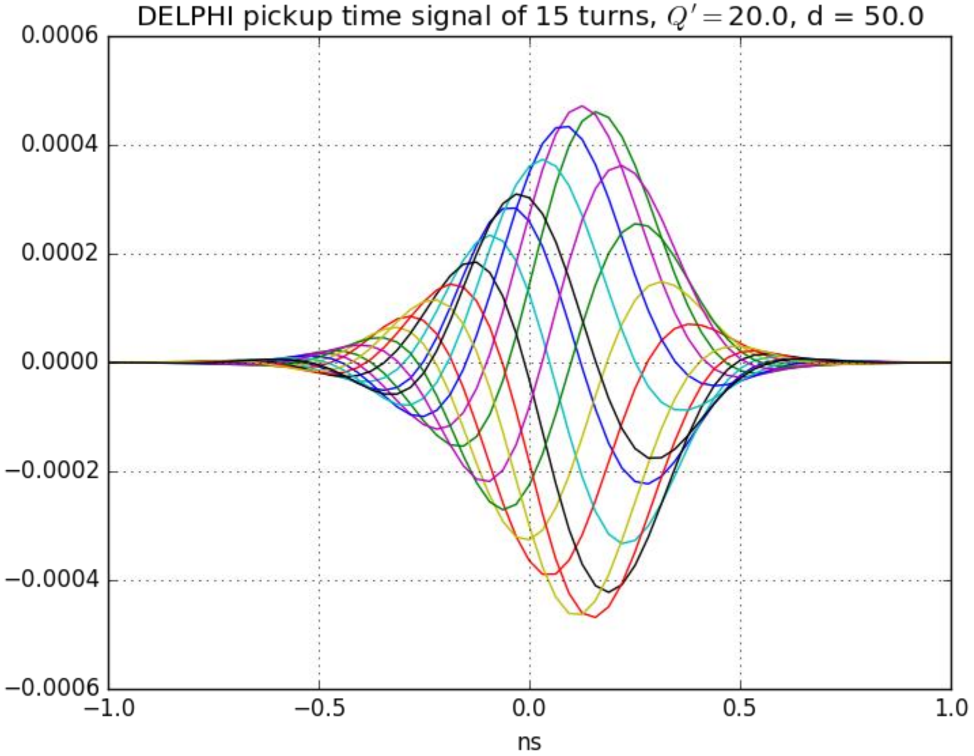


Not so far from the HT pickup acquisition!

Comparison with observed headtail monitor pattern

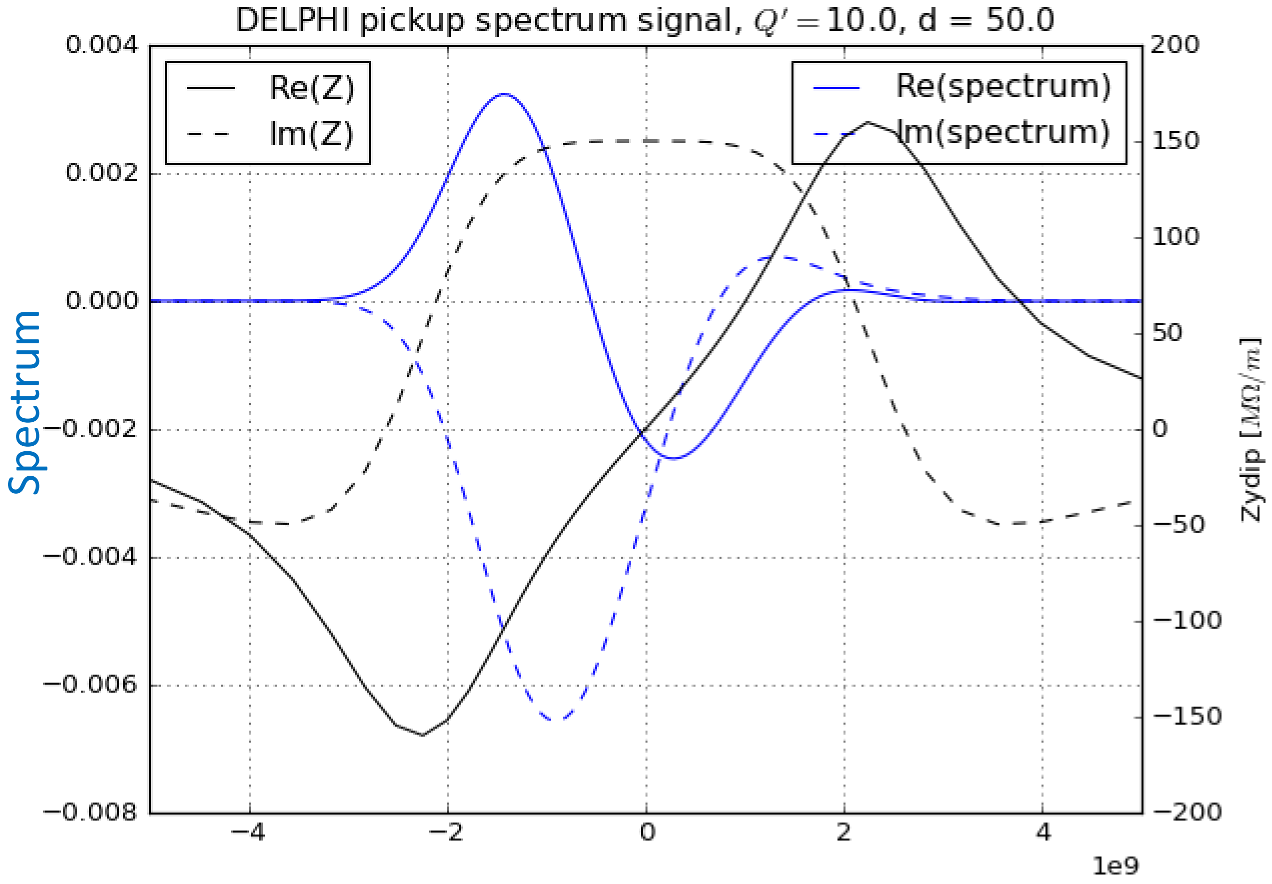
B1V HT pickup, 10 turns, 2TeV, fill 6164

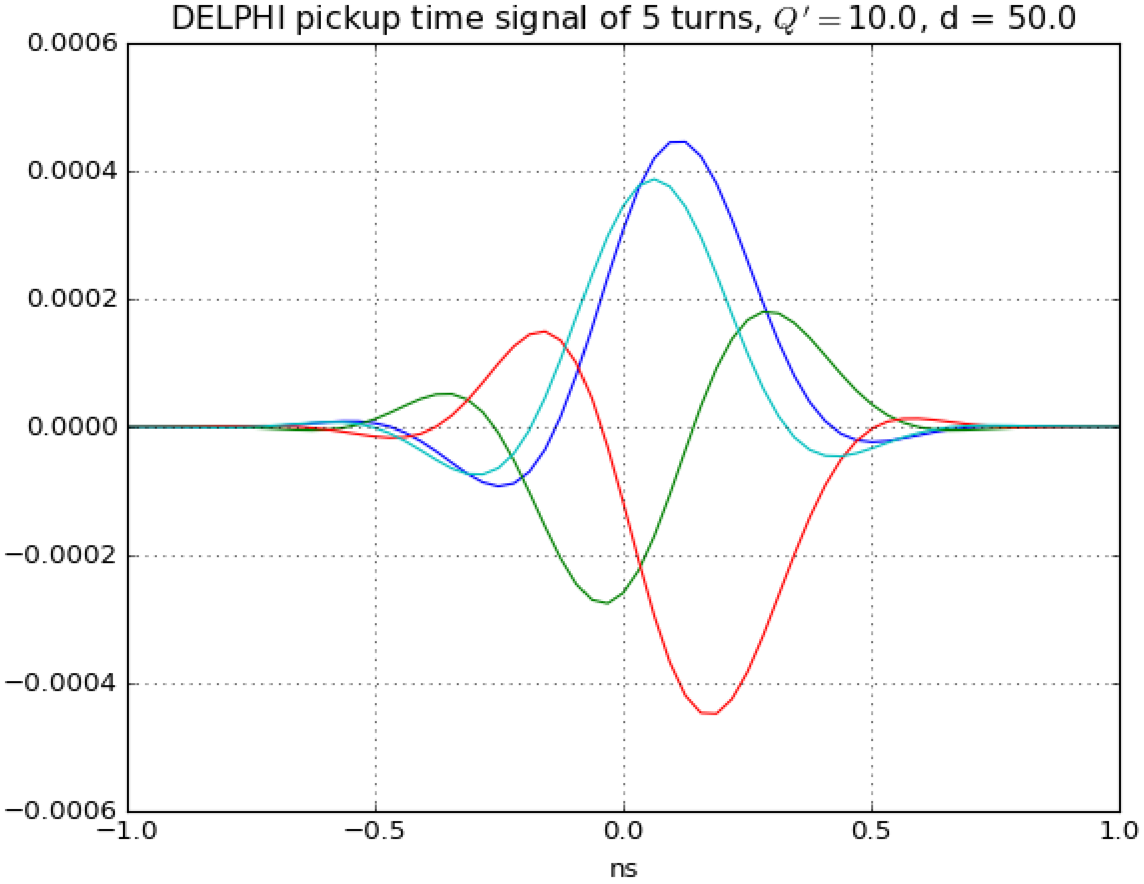




Not so far from the HT pickup acquisition!

Spectrum of most unstable mode

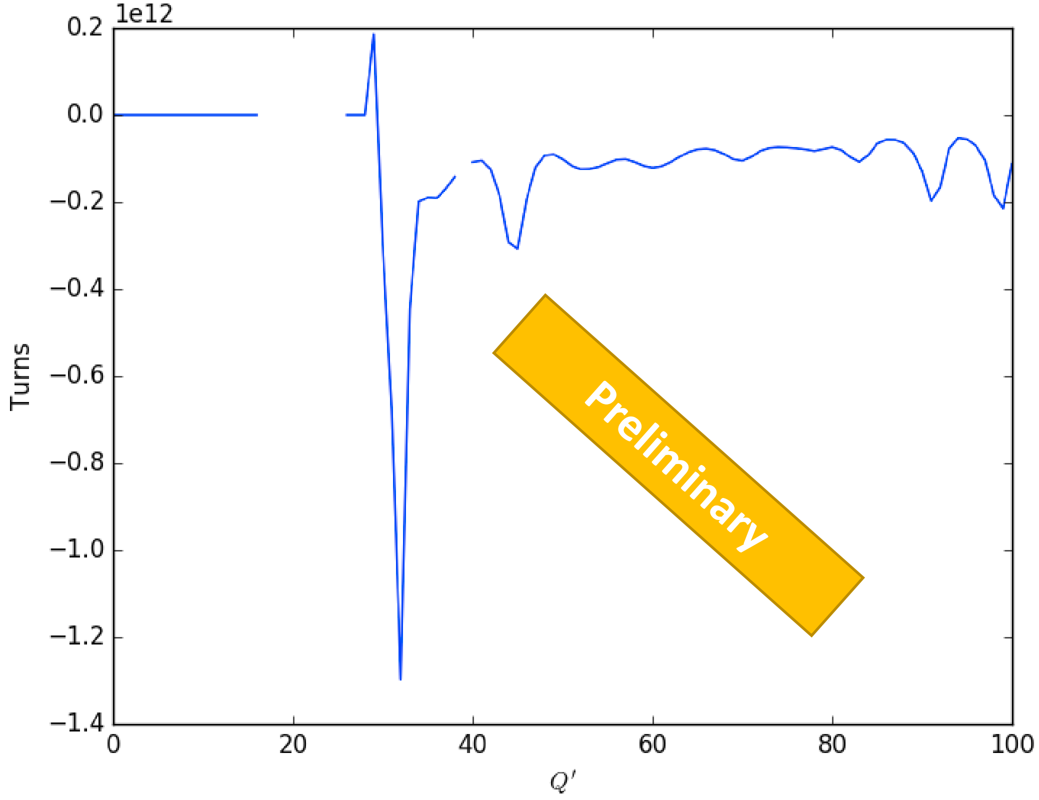




- Must be noted that the notion of azimuthal and radial modes for very large impedances (or high intensity) is far from the usual low intensity approximation.
- In general, complex eigenvalues -> complex eigenvectors

NB: In Chao, perturbation on the low intensity eigenvectors decomposition is assumed -> real spectra are shown.

Effect of chromaticity - DELPHI



- DELPHI run up to Q’ = 100.
- Instability damped for Q’>30

Warning: for some simulation there seems to be some issue with convergence -> more detailed studies needed!

Effect of chromaticity – BNS criterion

As the instability is faster than a synchrotron period, we can virtually unroll the LHC and treat is as a LINAC.

The instability we observe is compatible with a Beam Break Up (BBU) instability.

Assuming a growth rate of 20 turns at 450 GeV, the BNS criterion (e.g. Chao p.142) states a BBU instability can be stabilized by adding energy spread as:

$$\xi \frac{\Delta E}{E} = \frac{\Upsilon}{k_\beta L}$$

Growth parameter

Total phase advance during growth time

With $\frac{\Delta E}{E} \simeq 3 \cdot 10^{-4}$ and $k_\beta L \simeq N_{turns} \cdot 2\,\pi Q_y$ phase advance to grow as $\Upsilon = e$ we get

$$Q' = \frac{e}{2\pi\frac{\Delta E}{E}N} \simeq 72$$

Summary

- An equivalent resonator model for the 16L2-type instability was derived based on the tune shift observed during the instability.
- Resonator model: Rsh=150MOhm/m, f=2.6GHz and Q=1
- Simulation in DELPHI were performed at the LHC injection energy.
- The rise time of few 10 of turns is in good agreement with the post-mortem observation (range of 20-50 turns)
- The mode pattern at the HeadTail pickup has been reconstructed and it is close to the observed one.
- Stabilization with chromaticity seems to help:
  - Q’ > 72 from BNS criterion
  - Q’ > 30 from rough DELPHI simulations
- Additional simulations are on progress:
  - PyHeadtail simulations with 16L2 resonator
  - More detailed DELPHI simulations at larger chromaticities: Q’ in [20-100]