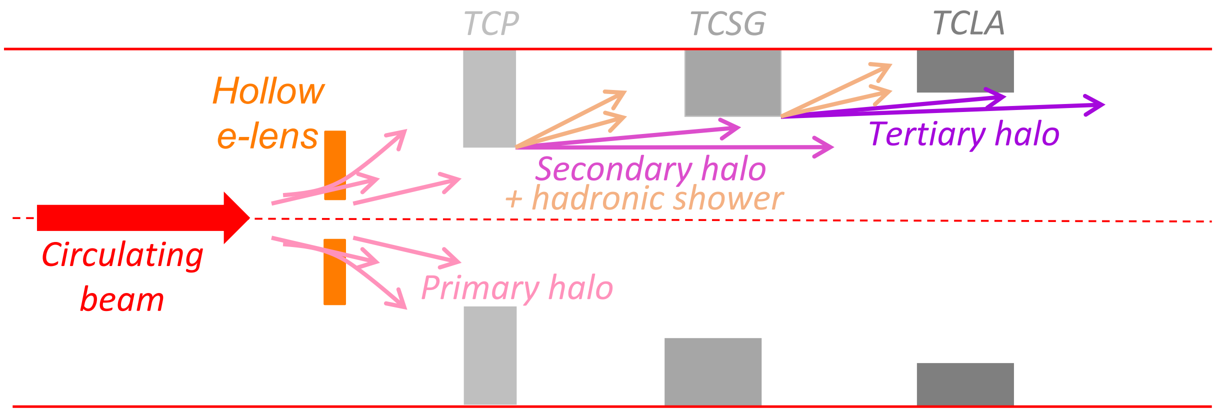
Progress on HEL impedance

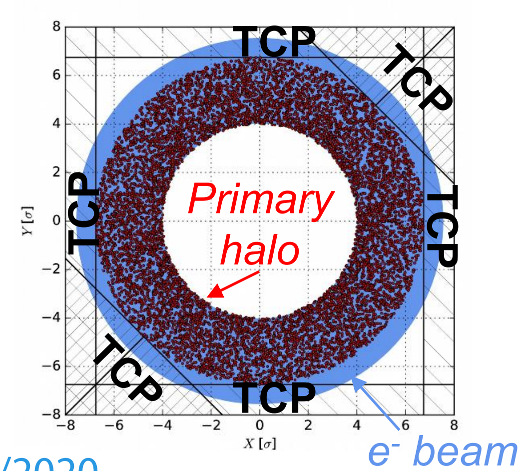
N. Mounet, C. Zannini & B. Salvant

Acknowledgements: X. Buffat, R. De Maria, A. Kolehmainen, D. Mirarchi, D. Perini, C. Rakotoalivony, G. Rumolo.

The hollow electron lens

- Since 2020, the hollow electron lens (HEL) is in the HL-LHC baseline:





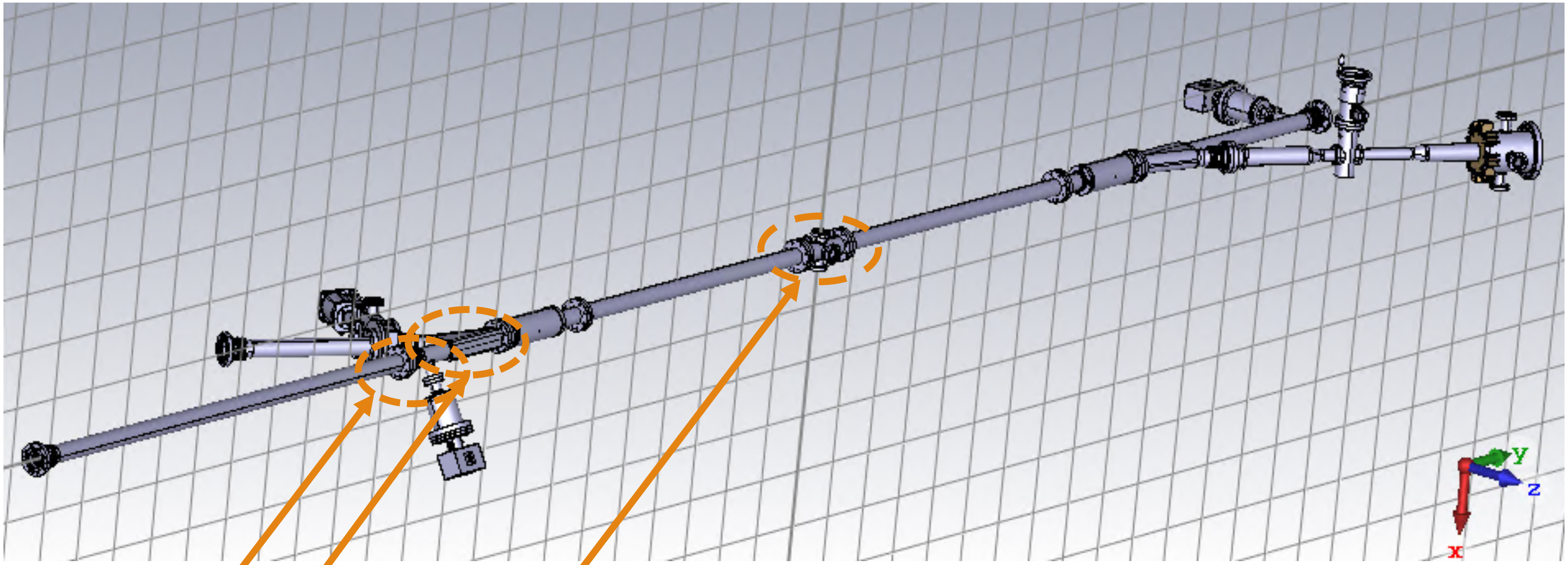
From ***D. Mirarchi***, [WP2/WP5 15/09/2020]

- Regarding impedance & stability, several potential impacts:
  - Depletion of transverse distribution tails, reducing Landau damping ⟶ taken into account in all stability predictions (tails cut at **3.2σ**)
  - Impedance of the physical device
  - Impedance from the electron beam

Impedance of the physical device

- New design (August 2020):

Provided by ***Antti Kolehmainen*** from CERN/EN-MME



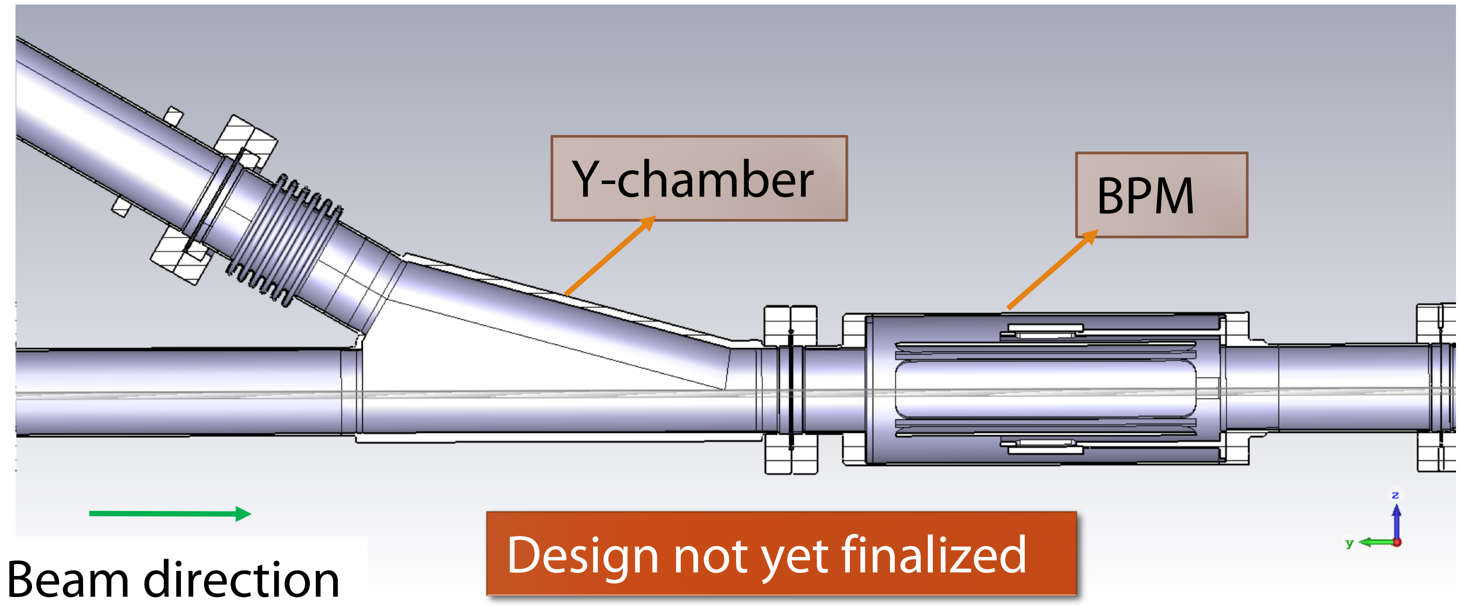
Comments from **Impedance Working Group**:

- Bellow / pump should be shielded.
- Copper coating should be applied.
- Y chamber volume could be reduced.
- Beam-Gas Curtain (BGC) design not yet available + request to have two additional bellows around it ⟶ to be studied (under discussion with EN-MME).

C. Zannini and ***B. Salvant***, WP2/WP5 23/02/2021

Impedance of the physical device

- Simulation model:



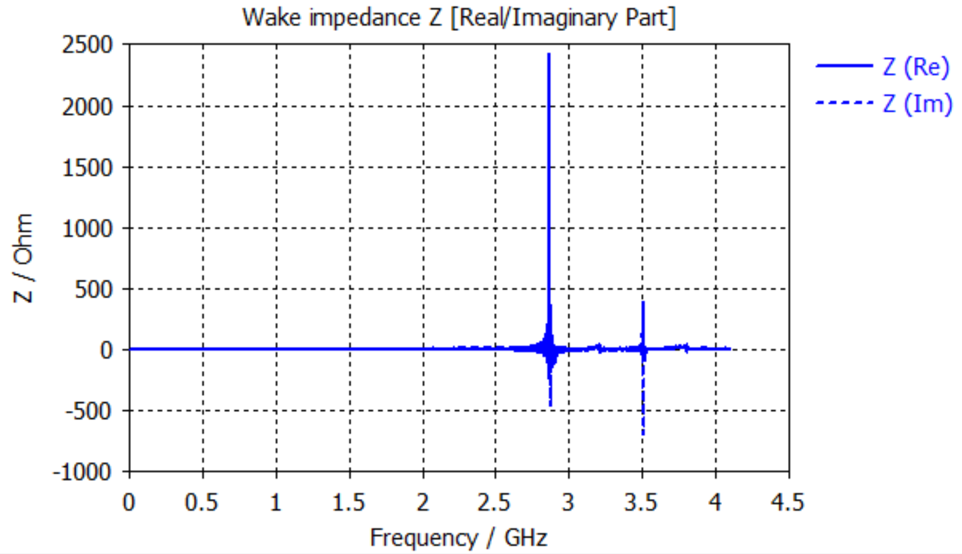
Geometric impedance of the hollow electron lens:

$Z_{G\text{-}elens} \approx 2*\text{Ychamber} + 2*\text{BPM} + \text{BGC}$

Longitudinal impedance

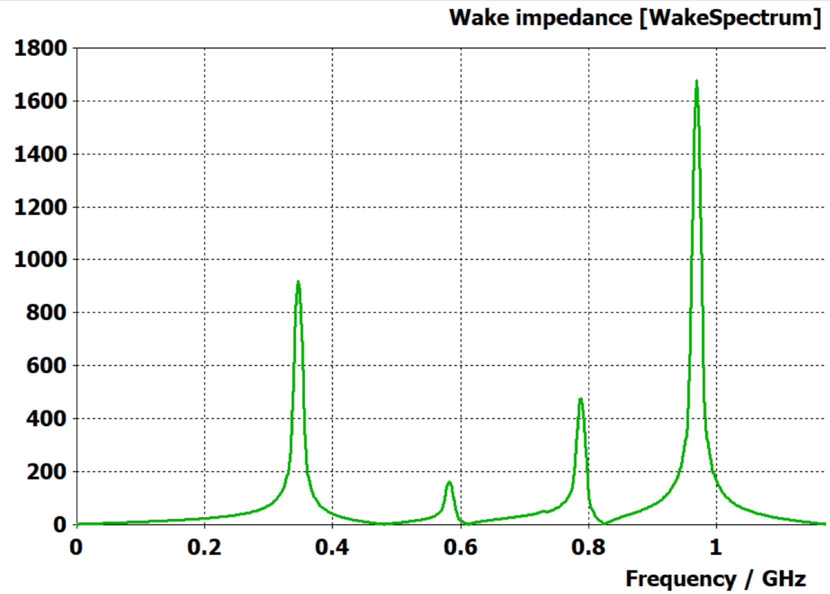
Y-Chamber

- First mode at 2.86 GHz (18 kOhm and Q=18,000 if copper coated, 2 kOhm and Q= 2800 if not)
- Im(Z/n)^{eff} ~ 0.02 mOhm for 1 Y chamber (vs. 90 mOhm for full LHC)



BPM

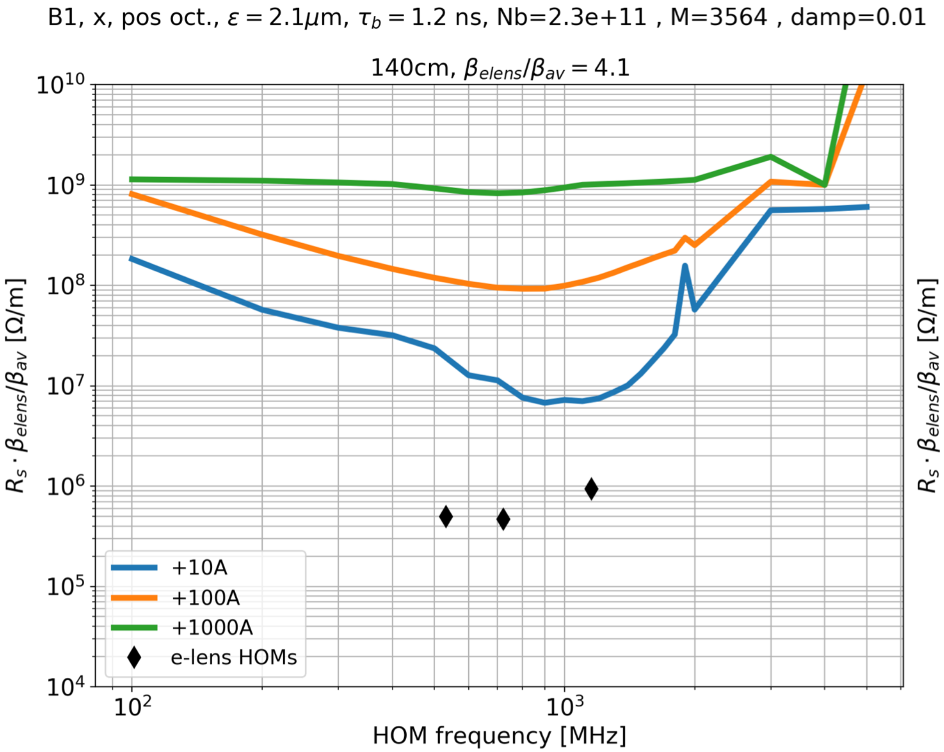
- The shunt impedance of the modes is well below the longitudinal stability threshold (200 kOhm).



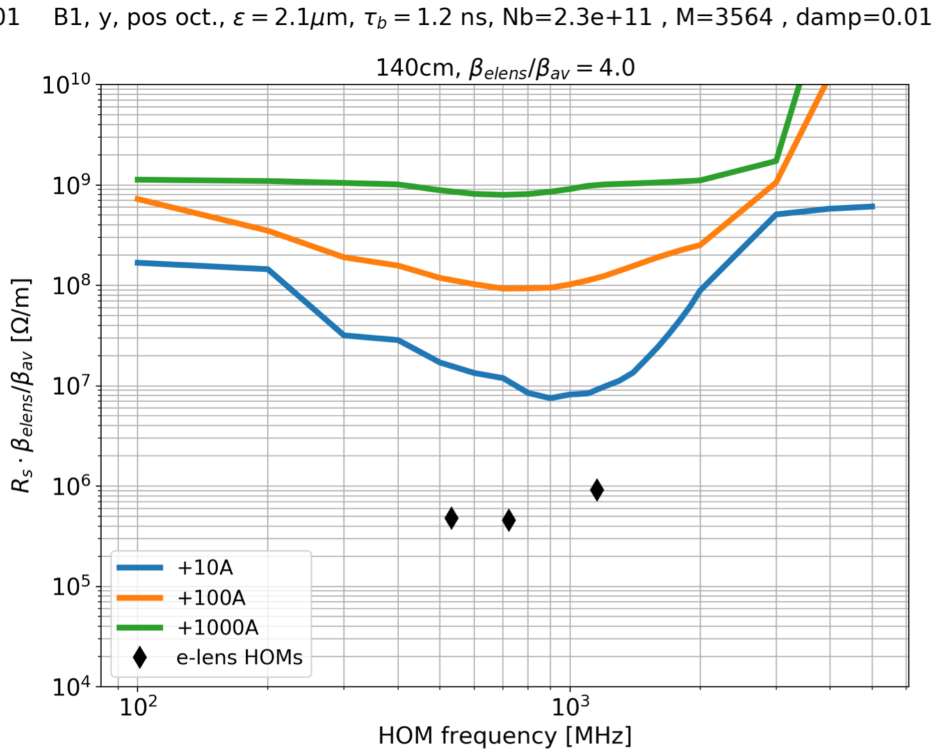
Transverse impedance - HL-LHC stability

- **Broadband impedance less than 2%** for the full broadband part of the model (itself a small part of the total impedance).
- **Large margin on the shunt impedance** for the three main HOMs:

Horizontal



Vertical



- **Caveat: the impedance of the BGC remains unknown.**

Electron beam Impedance

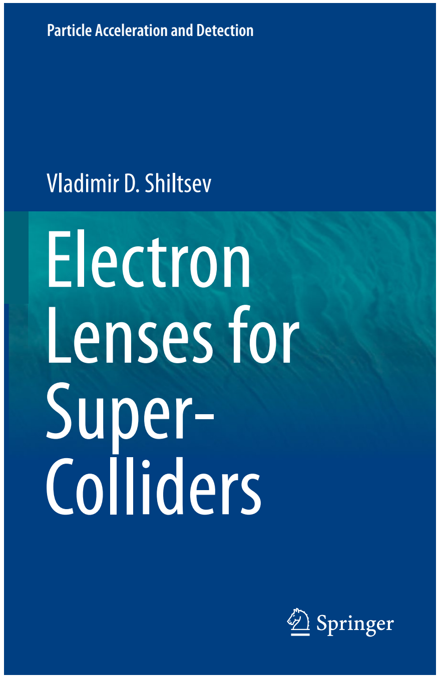
- **The issue**: electrons in the HEL are kicked by displaced protons and will in turn kick the following protons.
- To give an idea of the order of magnitude of the effect (from ***G. Stancari*** et al, CERN-ACC-2014-0248):
  - Charge density in the HEL ~ 6.5 mC/m^3
  - corresponds to ~ 4.10^{16} electrons / m^3
  - same number of electrons per unit area as an **e-cloud of 1.5 10^{12} electrons / m^3 over the full LHC circumference**, but over a length of 3 m.
- The issue was studied, within the **impedance** framework, by ***A. Burov*** et al in 1999:

PHYSICAL REVIEW E VOLUME 59, NUMBER 3 MARCH 1999

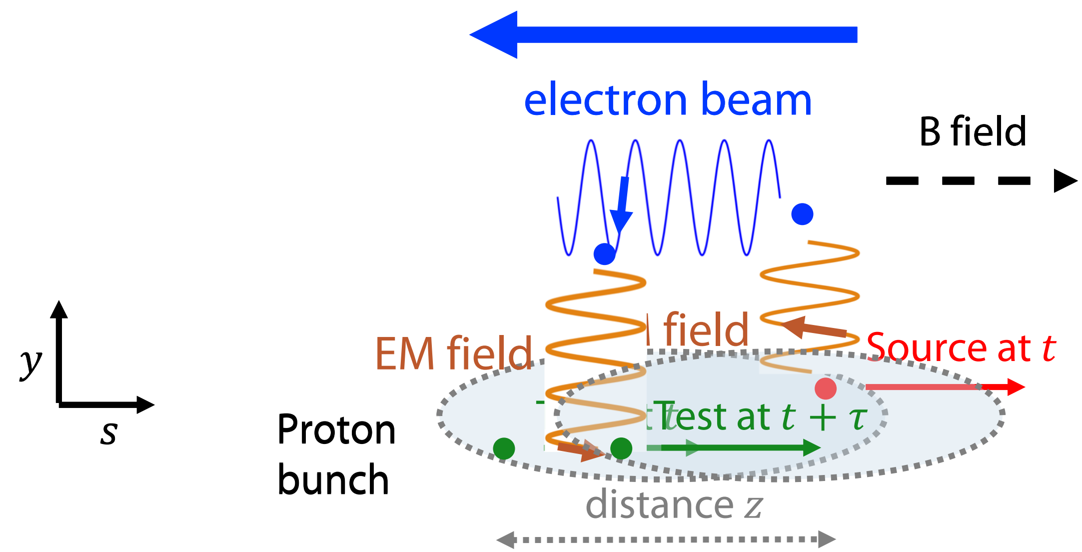
Transverse beam stability with an "electron lens"

A. Burov,* V. Danilov,† and V. Shiltsev
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 29 July 1998)

- This study is partly reproduced in **V. Shiltsev**'s book, and is the basis of what we will show now.



Electron beam impedance



- If a proton passes by with an offset, it kicks the electrons which are at the same longitudinal position.
- The electrons start spiraling under the action of the solenoid field.
- At a later time, a "test" proton behind the initial one, will in turn see offset electrons and receive a kick (in both the x and y directions ⟶ coupling).

A simple model for the wake

- Assuming both proton and electron beams are uniform and of same radius a_e, and looking only at the first order perturbation of the beams space-charge fields (i.e. keeping everything linear),
- electrons are kicked by a displaced proton slice, then move transversely under the sole effect of the solenoid field (Larmor oscillations), and finally kick the protons behind, at a later time.

⟹ we get **wake functions**: for a source proton displaced by Δx and Δy

Coupled terms

$$W_x = W sin(kz)\,\Delta x - W(1-\cos(kz))\,\Delta y$$

$$W_y = W(1-cos(kz))\,\Delta x + W sin(kz)\,\Delta y$$

See ***A. Burov*** et al, PRE 59, 3 (1999) (converted to SI units and using PyHEADTAIL sign convention)

with $$W = -\left(\frac{1}{4\pi\varepsilon_0}\right)^2 \frac{4L_e I_e}{a_e^4 \beta_e c^2 B} \frac{\left(1+\beta_p\beta_e\right)^2}{\beta_p+\beta_e},$$

$$k = \frac{\omega_L}{(\beta_p+\beta_e)c}, \qquad \omega_L = \frac{eB}{m_e\gamma_e}$$

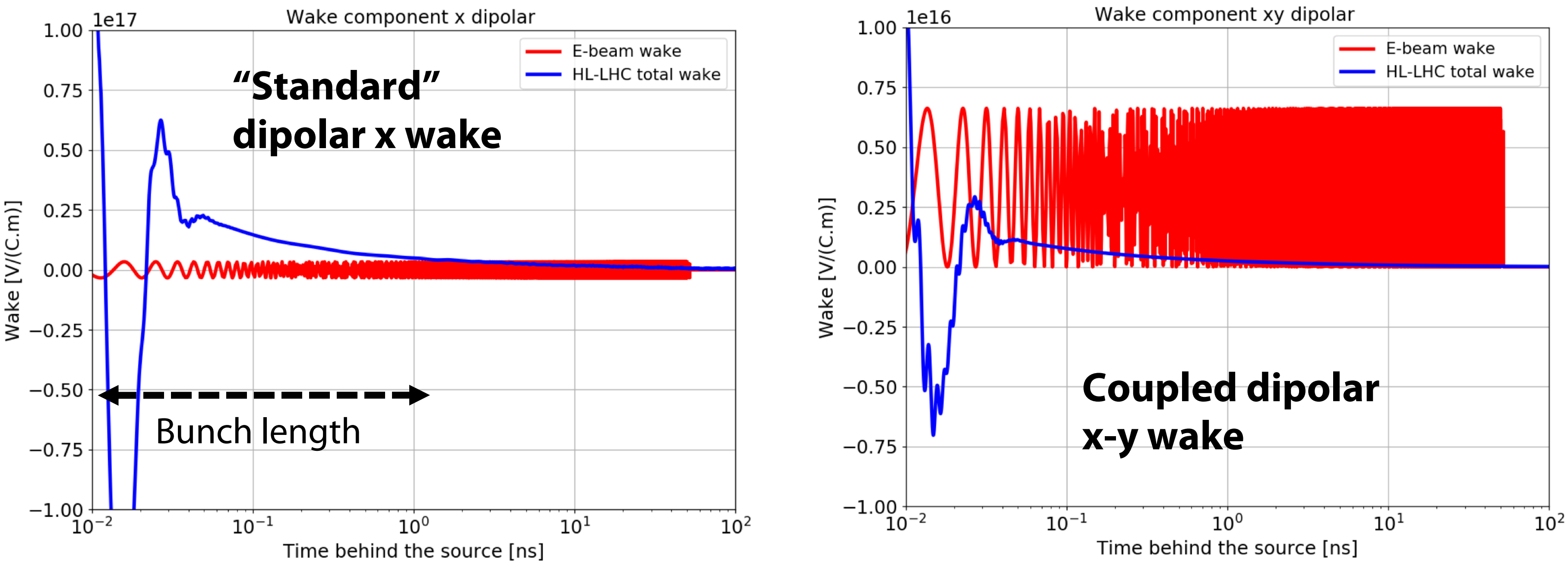
Absent from original formula

$L_e = 3$ m,
$I_e = 5$ A,
$\gamma_e = (1-\beta_e^2)^{\frac{-1}{2}} = 1.029$ (15 keV e⁻),
$\beta_p \approx 1$ (top energy)
$B = 5$ T
$a_e = 2.9$ mm (9.4 σ with 2.5 µm emittance).

(Parameters from ***D. Mirarchi***)

Electron beam wake vs. total budget

- Comparing the total wake of the HL-LHC model (latest update, retracted collimators, see WP2 28/07/2020) with the electron-beam wake model:

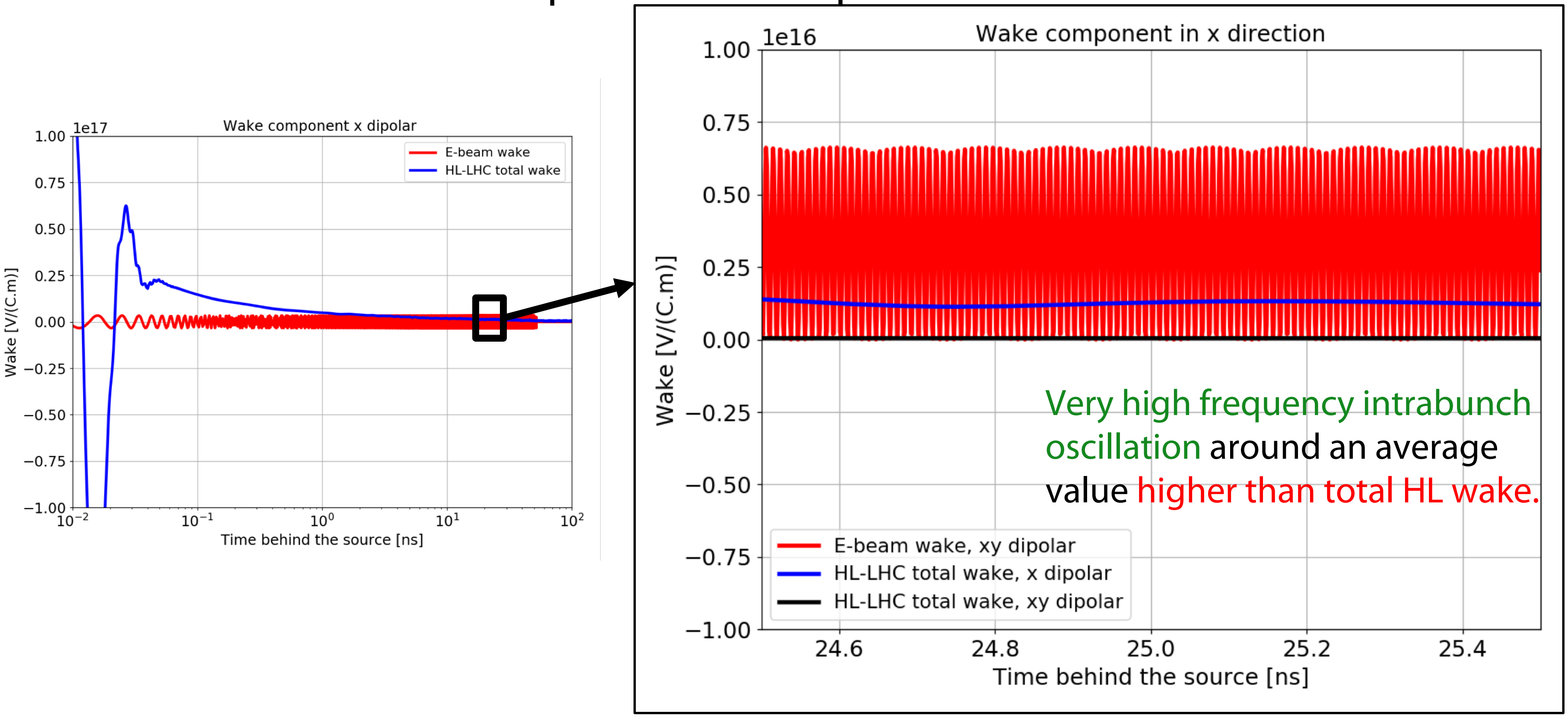


⟹ significantly smaller than the dipolar total wake (x or y) within the bunch,

⟹ but coupled terms much stronger than the rest of the wake.

Electron beam wake vs. total budget

- The wake extends up to ~52 ns ⟶ potential **multibunch** effects.

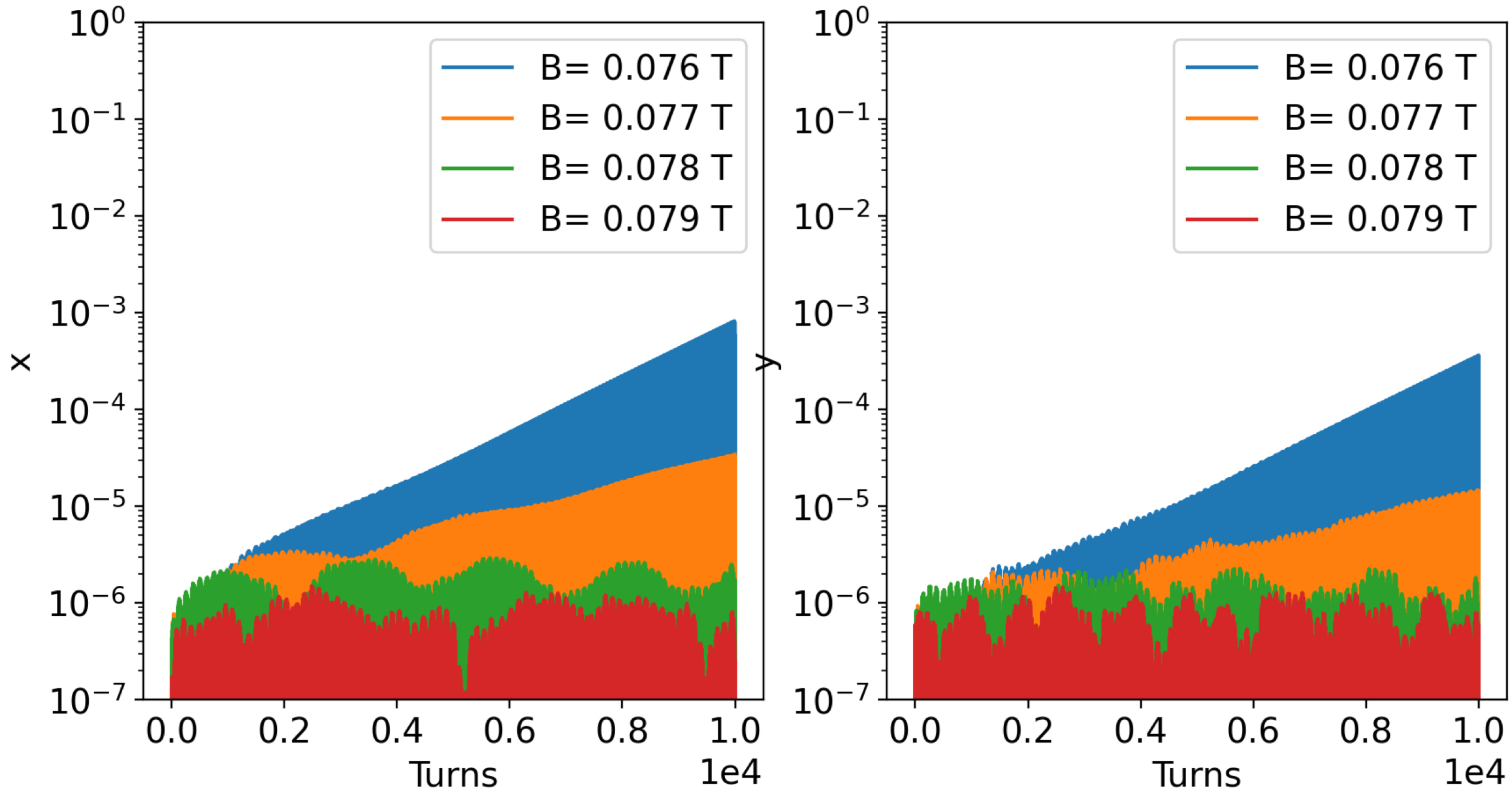


⟹ coupled terms at 25 ns are stronger than standard dipolar impedance.

⟹ potential impact on multibunch stability (ongoing simulations, still inconclusive).

E-beam TMCI with PyHEADTAIL

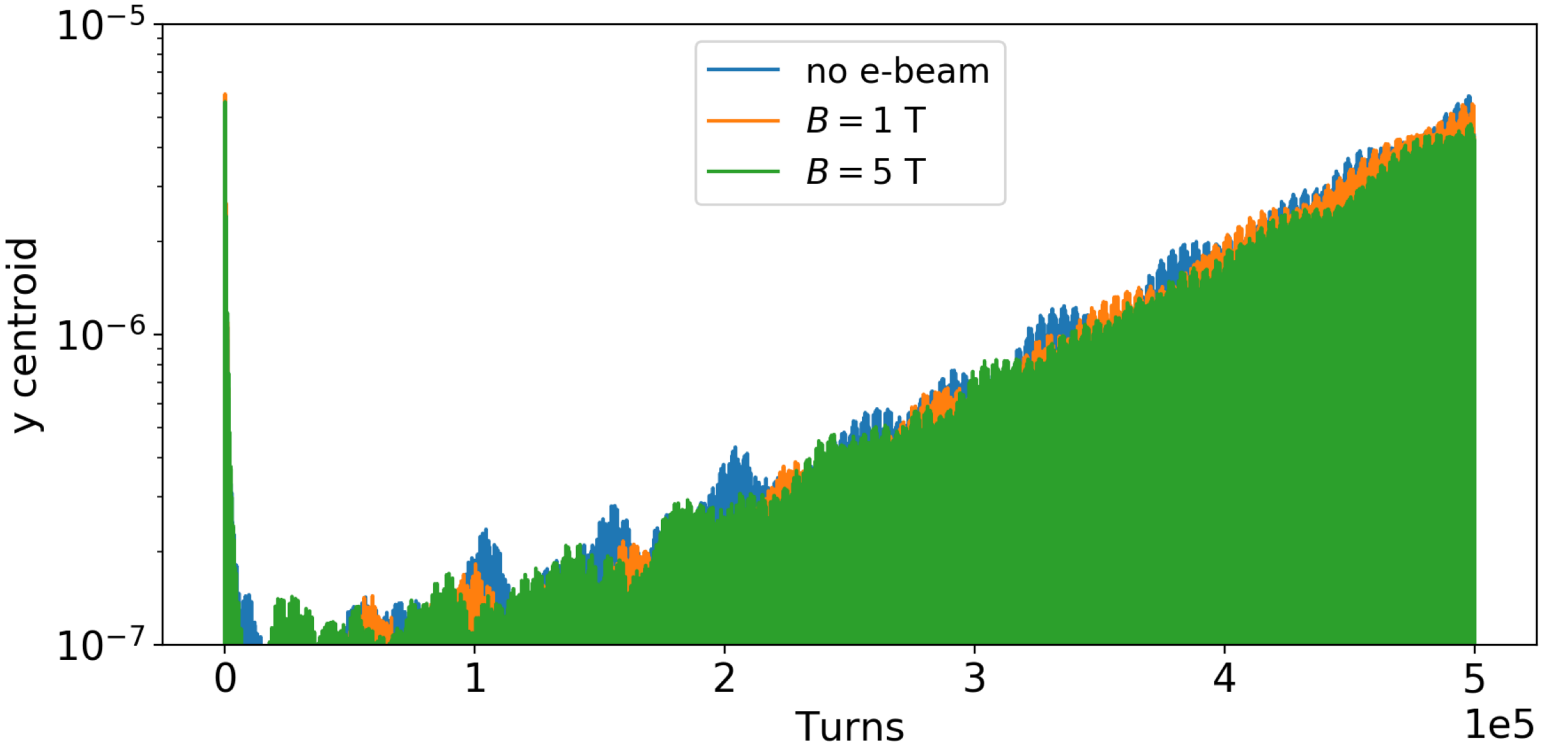
- Checking the TMCI threshold with PyHEADTAIL, in terms of B field (at fixed intensity N= 2.3 10^{11} p+/bunch, with only e-beam impedance):



$B_{thr} \approx 0.077$ T $\Longrightarrow$ comfortable margin w.r.t. nominal B=5 T.

Impact of e-beam on single-bunch stability

- In a standard operational configuration (Q'=15, 100 turns damper), adding the wake from the electron beam on top of the full HL-LHC model (both dipolar and coupled terms):



⟹ no strong impact on the most unstable plane (y), even at a lower B field and at a lower x-y tune difference (rise times stay within ~10%).

Conclusion

- The geometric impedance of the HEL device is *a priori* not a concern
  - ✗ … but the BGC remains to be evaluated
- The electron beam also exhibits an impedance:
  - simple wake model shows that coupled terms in the e-beam wake are larger than those of the full HL-LHC model, and this effect is even stronger at distances corresponding to the inter-bunch spacing (25 ns).
  - In single bunch:
    - ✓ Strongly unstable without B field (TMCI-like) at Q'=0 with 2.3 10^{11} p^{+}/b.
    - ✓ Strong mitigation of TMCI from e-beam alone with as low as B=0.1 T.
    - ✓ Single-bunch instabilities in a standard operational configuration (Q'=15, damper 100 turns) are not strongly affected by e-beam.
  - Still to be addressed:
    - ✗ shortcomings of the wake model,
    - ✗ potential multibunch effects.

Appendix

A simple model for the TMCI

- In absence of chromaticity and of any other kind of impedance, a simple formula can be found for the transverse mode coupling instability threshold, in terms of B field:

$$B_{thr} \approx 39 \frac{eN_p\sqrt{\xi_x\xi_y}}{a_e^2\sqrt{Q_s|Q_x - Q_y|}},$$

From ***A. Burov*** et al, PRE 59, 3 (1999) (converted to SI units)

with the figures of merit of the e-lens defined as

$$\xi_x = \frac{\beta_x L_e r_p I_e(1+\beta_e)}{2\pi a_e^2 \gamma_p e \beta_e c}, \quad \xi_y = \frac{\beta_y L_e r_p I_e(1+\beta_e)}{2\pi a_e^2 \gamma_p e \beta_e c}$$

$\beta_x = \beta_y = 280$ m,
$Q_s = 2.1\times10^{-3}$,
$|Q_x - Q_y| = 0.01$,
$N_p = 2.3\times10^{11}$ p+/bunch,
$r_p = 1.535\times10^{-18}$ m,
$\gamma_p = \left(1-\beta_p^2\right)^{\frac{-1}{2}} = 7460.52$,
$\xi_x = \xi_y = 1.8\times10^{-3}$.

- In HL, one gets stability as soon as

$$\text{B} > B_{thr} \approx 0.07\ \text{T}$$

Even multiplying by the extra factor found $\left(1+\beta_p\beta_e\right)^2$ (see previous slide), one gets $B_{thr} \approx 0.1$ T.

$\Longrightarrow$ comfortable margin w.r.t. the nominal $B = 5$ T.

Electron beam wake vs. total budget

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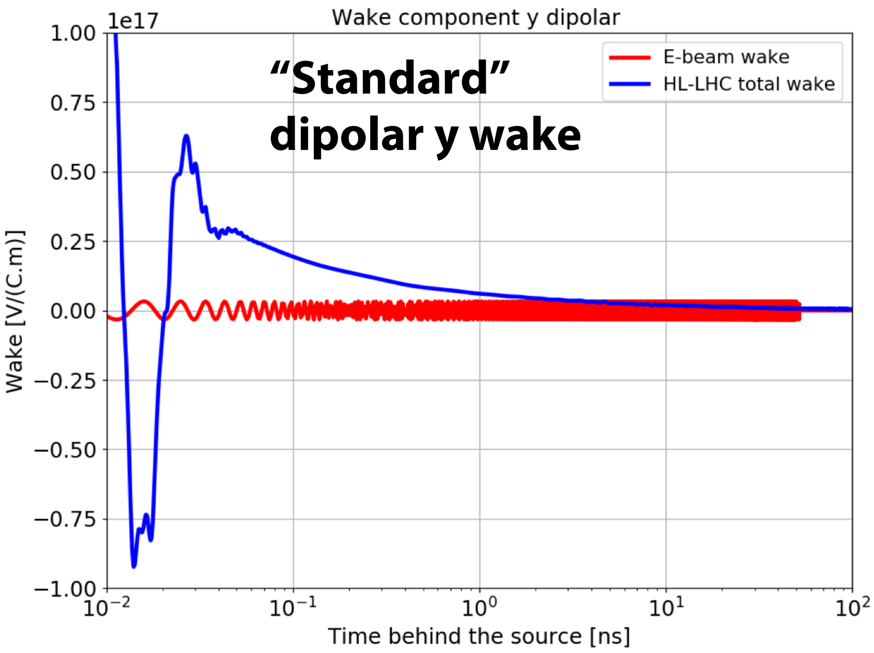
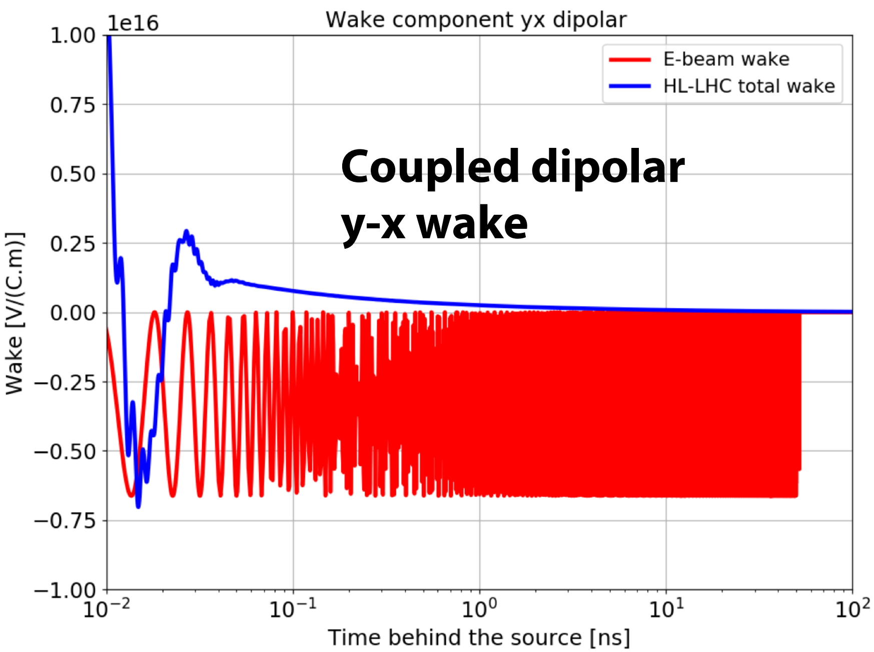
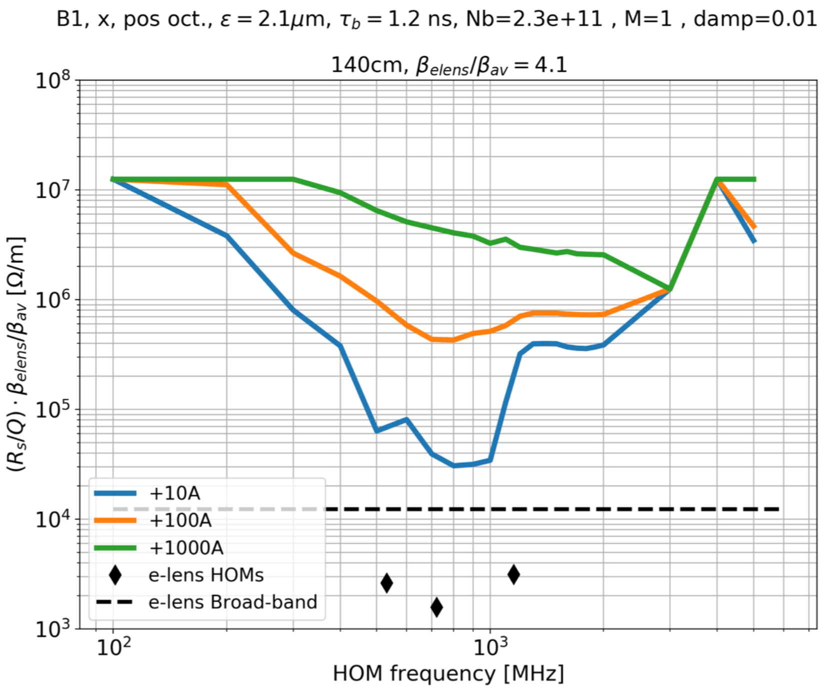




⟹ significantly smaller than the dipolar total wake (x or y) within the bunch,

⟹ but coupled terms much stronger than the rest of the wake.

Single bunch stability (HOMs from device)



Single bunch stability (HOMs from device)