Beam Loading Simulations in LINACs with RF-Track

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Abstract

Linear Accelerators technology is evolving towards compactness and high intensity. As a consequence, these devices are becoming suitable for several industrial and medical applications, such as the upgrade of light sources to the so-called 4-th generation or the design of high-dose rate radio-therapy facilities. In such scenarios, intensity-dependent collective effects can arise and compromise the LINAC performance. This work focuses on the Beam Loading effect, which induces a reduction of the available accelerating gradient of the structure as a consequence of the interaction of the beam with the cavity. A power-diffusive model for the Beam Loading effect has been derived and implemented into the tracking code RF-Track. With this, transient scenarios in both standing-wave and travelling-wave LINACs have been studied. Good agreement has been found with experimental measurements carried out in the CLEAR facility at CERN.

Beam Loading Effect

The beam loading (BL) effect effectively reduces the gradient of an accelerating structure due to the beam's interaction with the surrounding cavity [1].
A partial differential equation was derived by considering energy conservation in the accelerating structure. Its expression:

- For TW structures is:

$$-\frac{\partial G_{\text{eff}}}{\partial t} = \left(-\frac{v_g}{r/Q}\frac{\partial (r/Q)}{\partial z} + \frac{\omega}{Q} + \frac{\partial v_g}{\partial z}\right)\frac{G_{\text{eff}}}{2} + v_g\frac{\partial G_{\text{eff}}}{\partial z} + \frac{r}{Q}\frac{\omega \tilde{I}}{2}, \quad (1)$$

- For SW structures is:

$$-\frac{\partial G_{\text{eff}}}{\partial t} = \frac{\omega}{Q}\frac{G_{\text{eff}}}{2} + \frac{r}{Q}\frac{\omega \tilde{I}}{2} - \frac{P_{\text{input}}}{L}. \quad (2)$$

Beam Loading in TW structures

- **Reliable gradient calculation.**

Gradient reduction for a 120 MV/m structure has been calculated when a beam of $\langle I \rangle$ = 1.02 A and length 152 ns enters CLIC Accelerating Structure. The results are shown in Fig 1. and they show good agreement with Fig. 2.

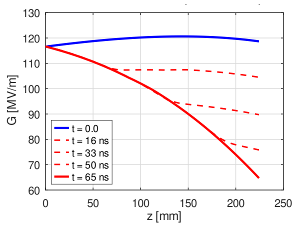

Figure 1: RF-Track calculation for gradient reduction in CLIC AS after the injection of a beam with $\langle I \rangle$ = 1.02 A and length 152 ns.

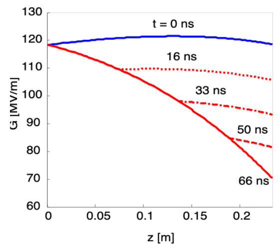

Figure 2: Analytical calculation for gradient reduction in in CLIC AS after the injection of a beam with $\langle I \rangle$ = 1.02 A and length 152 ns [3].

- **Tracking under transient gradient.**

A long train is injected in CLIC PETS and a transient effect is observed as energy loss is different from bunch to bunch as shown in Fig. 3.

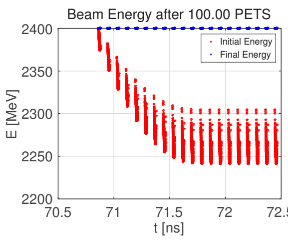

Figure 3: Beam Energy after 100 PETS.

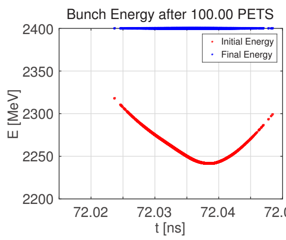

Figure 4: Single bunch energy distribution after going through 100 PETS.

Acknowledgements

We thank Alexej Grudiev for the useful discussions on the BL effect and the CLEAR OP team for the material provided as well as the valuable discussions on the operation of the gun.

Beam Loading in RF-Track

The BL effect is evaluated on flight during tracking and its effect can be calculated and superposed in parallel with other contributions to the particle's dynamics.
How?: The resolution of Eqs. (1,2) via the Finite-Difference Method has been implemented as a self-consistent module in RF-Track [2].
Features: Fast computation, flexibility.

- Attachment to RF-fieldmaps, drift spaces, analytic structures
- Superposition with other collective effects.
- RF Information: r/Q calculation, input/output power, loaded gradient.

Beam Loading in SW structures

- **Reproducible results for BL in CLEAR photo-injector.**

A train of 150 bunches injected in CLEAR photo-injector and a charge-dependent energy loss from bunch-to-bunch is observed and accurately predicted by RF-Track.

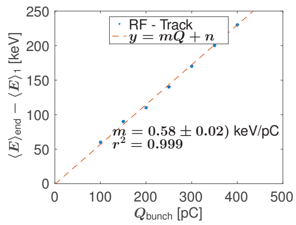

Figure 5: First-To-Last Energy Loss of a train of 150 bunches with variable Q_{bunch} per bunch. RF-Track simulation.

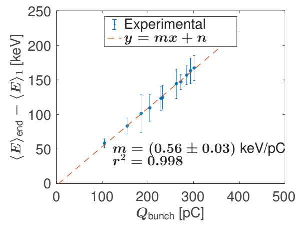

Figure 6: First-To-Last Energy Loss of a train of 150 bunches with variable Q_{bunch} per bunch. Measurement @ CLEAR.

- **Reproducible results for BL in CLEAR Start-to-End**

The same train is tracked towards the end of CLEAR accelerating structures and good agreement with measurements is found as shown in Figs. 7 and 8.

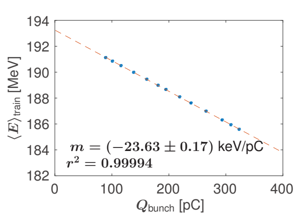

Figure 7: Mean energy of a train of 50 bunches as a function of its charge per bunch. RF-Track simulation.

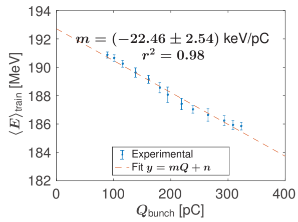

Figure 8: Mean energy of a train of 50 bunches as a function of its charge per bunch. Measurement @ CLEAR.

Conclusions

Starting from basic principles, a BL module has been developed for the tracking code RF-Track. It allows:

- Gradient reduction calculation due to ohmic losses, power flow and BL in TW structures. Bunches can be tracked under such transient effect.
- BL simulations for SW photo-injectors, showing good agreement with measurements at CLEAR.
- Start-to-end simulations including BL in all accelerating structures.

References:

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