IMPACT OF ELECTROMAGNETIC FIELDS IN TESLA RF MODULES ON TRANSVERSE BEAM DYNAMICS

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Abstract

Transverse electric fields in TESLA rf modules exist on one hand because of deformations of the longitudinal accelerating field in the presence of rf structure misalignments or in the vicinity of asymmetrically machine parts like input couplers. On the other hand, the beam itself induces transverse wake fields if it does not travel through the center of a perfectly rotationally symmetric structure.

Transverse deflecting fields deflect beam particles. The average deflection causes a change in the beam trajectory; the phase dependence of the transverse field leads to a variation of the transverse kick along the longitudinal position of the bunch and thus in general to a change in projected emittance. If the strength of the transverse field component varies along the transverse direction itself, slice emittance will be affected.

We will present the amplitudes and spatial variations of transverse fields generated by the mechanisms described above, and discuss their impact on beam trajectories and shape.

INTRODUCTION

Coupler Kicks

A TESLA module consists of eight superconducting radio-frequency cavities running at 1.3 GHz. Each of these standing wave cavities include one rf input coupler and two high order mode (HOM) couplers. The HOM couplers are placed one at each side of the cavity and they absorb the energy associated to the HOM field that is excited when the beam travels through the module. Figure 1 shows an overview of a TESLA cavity, where the allocations of the couplers are indicated.

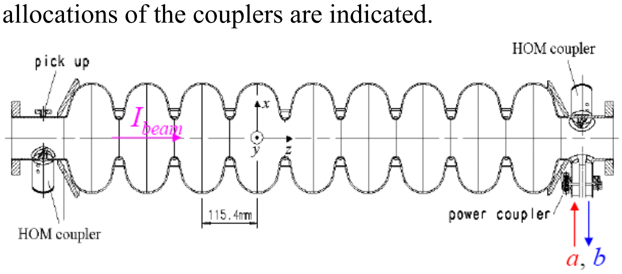

Figure 1: Overview of a TESLA rf cavity. Total length is about 1.2 m. Upstream region (left) includes a HOM coupler and downstream region (right) the main and a HOM coupler. The iris radius is 35 mm.

Both power and HOM couplers induce transverse kicks. The kick produced by the main coupler is horizontal and depends on the penetration depth, the quality factor Q and the SWVR. On the other hand, the HOM-couplers induce kicks in both horizontal and vertical directions and depend only on the cavity field.

We have calculated the distortions on the electromagnetic field induced by the coupler regions with the eigensolver MAFIA. Taking into account a penetration depth of 8mm, the induced voltage by the upstream coupler region on the centre of the cavity is:

$$\frac{V_x}{V_z}\cdot 10^6 = -59.065 + 9.373i \qquad (1)$$
$$\frac{V_y}{V_z}\cdot 10^6 = -43.218 - 1.847i$$

And the transverse voltage induced by the downstream coupler is:

$$\frac{V_x}{V_z}\cdot 10^6 = 11.367 + 48.623i \qquad (2)$$
$$\frac{V_y}{V_z}\cdot 10^6 = 45.459 - 2.770i$$

The real part corresponds to a net kick experienced by the whole bunch, which produces a trajectory deviation to the beam. For instance, assuming an rf field of 20 MV/m and taking into account that a TESLA cavity is 1.0362 m length, the horizontal voltage induced for the upstream couplers would be about 1.2 KV. This is equivalent to a kick of 12 μrad for an electron beam of 100 MeV.

On the other hand, the imaginary part corresponds to a kick which depends on the phase seen by each particle. This time-dependent kick induced by the couplers distorts the longitudinal slices of the beam by a different amount, which results in an increase of the projected emittance.

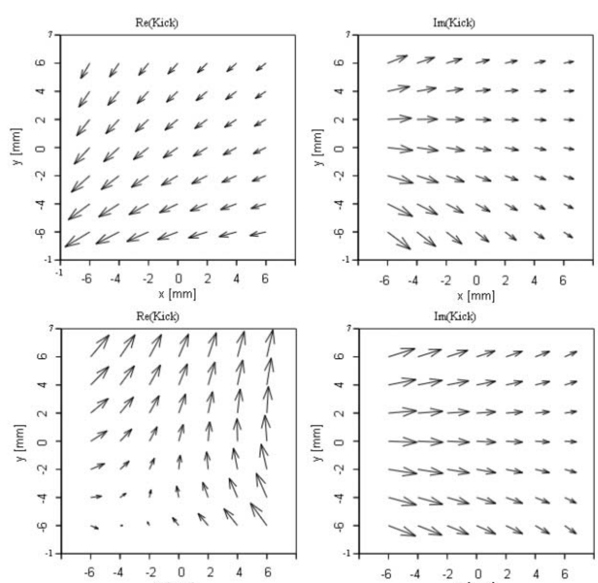

Figure 2: Voltage map induced for the upstream and downstream coupler regions.

The coupler kicks depend also on the transverse position of the beam respect to the cavity axis. Figure 2 shows the voltage map induced by the coupler regions; i.e. the voltages for different horizontal and vertical beam positions. Left and right maps correspond to the real and imaginary part of the kick, respectively. The voltage at the centre of the map correspond to the kick induced on-axes (equations 1 and 2). The offset-dependence of the coupler kicks causes an increase of the slice emittance.

Wakefields

The electron beam induces wakefields when passes through a non symmetric structure or when travels off-axes through a perfectly rotationally symmetric element. These EM fields act on the electrons arriving later and produce distortions in the longitudinal and transverse directions.

The transverse wakefields can be generally characterized by wake functions. In our case, we distinguish between the wakes generated by the TESLA module itself (symmetric structure) and the wakefields created by the input and HOM couplers (non-symmetric elements).

The transverse wake functions per a TESLA cryomodule have been obtained fitting numerical data to analytic expressions [1]:

$$w_T = 10^{15}\left(1-\left(1+\sqrt{\frac{s}{0.92\cdot 10^{-3}}}\right)\cdot e^{-\sqrt{\frac{s}{0.92\cdot 10^{-3}}}}\right)\cdot\begin{pmatrix}\mathrm{x[m]}\\ \mathrm{y[m]}\end{pmatrix}\left[\frac{V}{C}\right] \qquad (3)$$

where s is the longitudinal position along the bunch (s>0, s=0 corresponds to the head of the bunch). The kick produced by the wake of a TESLA module is proportional to the transverse deviation of the beam and is null if the bunch travels on-axis. Since a TESLA module consists of eight 9-cell cavities, we can get the equivalent wake function per accelerator cavity dividing equation (3) by eight.

On the other hand, the wake function induced by the couplers of a TESLA cavity is [2]:

$$w_C(s) = H(s)\cdot 10^{12}\left(\begin{pmatrix}-0.042\\ -0.038\end{pmatrix}+\begin{pmatrix}8.6 & 0.14\\ 0.06 & -1.8\end{pmatrix}\cdot\begin{pmatrix}\mathrm{x[m]}\\ \mathrm{y[m]}\end{pmatrix}\right)\left[\frac{V}{C}\right] \qquad (4)$$

The coupler wake has two components: one independent of its transverse coordinates and one which depends on the centroid position of the beam.

The wake function of the couplers is constant along the bunch and the resulting kick factor does not depend on the bunch length. However, it can be seen that the constant wake function given by equation 4 can overestimate the kick factor for short bunches [3].

MODELLING IN ELEGANT

Coupler kicks can be implemented in elegant [4] as transverse deflecting cavities – with the same frequency as the accelerator structure (1.3 GHz). We can model the coupler kick as two independent cavities: one with zero degrees of phase (net kick given to the bunch) and one with ninety degrees off-crest (phase dependent part of the kick).

The orbit dependence of the coupler kick can be solved iteratively. First of all we track the beam assuming on-axes coupler kicks for all the cavities. This gives a trajectory deviation which we use to determine new values for the coupler kicks. Then we track the beam again and repeat this procedure until the result converges. Usually between two and four iterations are required to get an orbit convergence better than 1 μm.

On the other hand, both structure and coupler wakefields can be implemented in elegant giving to the program the corresponding green functions (i.e. the wake functions).

Example

We have analyzed with elegant the kick factor produced by the module and the coupler wakes. For a Gaussian beam with an rms length of 300 μm, the effect of the coupler wake on axis is equivalent to the impact of the module wake with a horizontal and vertical beam offset of 2.9 and 2.6 mm. In both cases the resulting kick factor is 0.021 V/pC for the horizontal plane and 0.019 V/pC for the vertical one. We have obtained the same results using analytical calculations.

Figure 3 shows horizontal and vertical kick along the bunch due to module and coupler wake effects for this example.

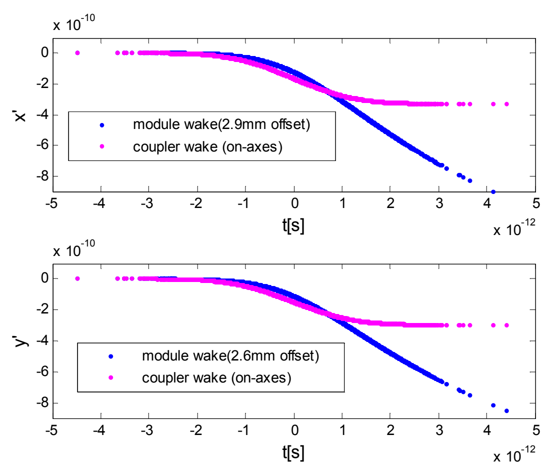

Figure 3: Comparison between transverse kicks generated by structure wake (with the indicated off-sets) and coupler wakes (on-axes) for a Gaussian beam of 300 μm length. Both wakes induce the same kick factor.

IMPACT OF ORBIT BUMPS TROUGH TESLA MODULES AT FLASH

FLASH (Free Electron LASer in Hamburg) is a SASE FEL user facility at DESY, Hamburg [5]. It serves also as a pilot project for the European XFEL. FLASH uses presently six TESLA superconducting modules to accelerate the electron beam up to 1 GeV. Figure 4 shows a schematic layout of FLASH.

We have analyzed the degradation of the beam quality due to the wakes and coupler kicks of the TESLA modules at FLASH. For that we have measured the emittance as a function of the trajectory through the different accelerator modules.

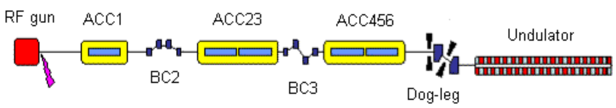

Figure 4: Schematic layout of FLASH.

Figure 5 shows measurements and simulations of emittance increase for different horizontal orbit bumps through ACC23. The amplitude of the bump refers at the orbit read at the BPM11DBC2 – a beam position monitor placed just upstream these accelerator modules. The bumps were closed downstream ACC23 before the second bunch compressor (BC3). All the accelerator modules were working at on-crest operation. Electron beam charge was 0.6 nC. Final electron energy was 700 MeV.

For each bump the emittance was measured using five OTR screens in front of the undulator section. A reference was taken before and after the measurements. Emittance values for the initial and final references were similar (3.2 and 2.8 μm). Vertical emittance was not affected for all the different bumps. The beam was not matched for the different emittance measurements – the mismatch parameter is shown at Figure 5. The error bars of the plots show the statistical error of beam size measurements required for the emittance calculation.

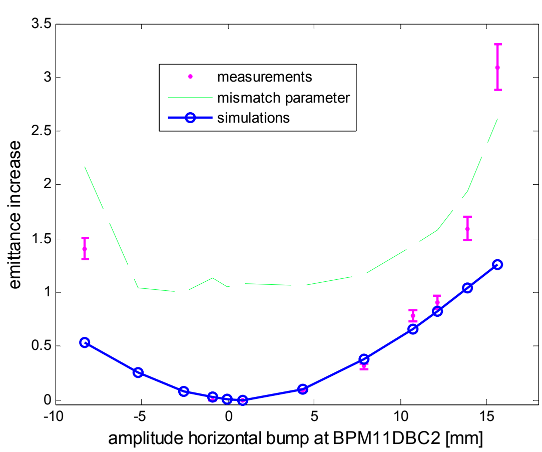

Figure 5: Measurements and simulations of emittance increase for different bumps through ACC23.

Simulations have been done from the exit of the first accelerator module to the entrance of the undulator using elegant. A Gaussian distribution of 10^5 particles has been used as an input beam. Module and coupler wakefields as well as coupler rf kick effects have been taken into account.

There is a qualitative agreement between measurements and simulations. For moderate bumps the simulations fit well with the measurements. However, for the extreme cases (i.e. -8.3, 13.9 and 15.7 mm) simulations predict much weaker effect than what we measured. On one hand, the measured mismatch parameter for these cases was big (>1.5), a fact which increases the effective error of the measured emittances. On the other hand, we have calculated the kicks induced by the coupler kicks in a limited area of ±6mm around the couplers regions (see Figure 2). Our model extrapolates the kicks induced outside this limited area. This extrapolation probably underestimates the effects of the couplers when the beam travels out of this ± 6x6mm region.

Other measurements done during different days at ACC23 and ACC456 with moderate bumps have shown good agreement with simulations.

SUMMARY

We have described and quantified the transverse wakefields and the coupler kicks effects concerning the TESLA accelerator modules. We have explained how to implement these effects into elegant.

We have presented measurements and simulations of trajectory bumps through ACC23 at FLASH. Simulations agree with measurements for moderate bumps but not for bigger ones. The disagreement can be explained mostly by the underestimation in our simulations of the coupler effects for the severe cases.

REFERENCES

[1] T. Weiland and I. Zagorodnov, "The Short-Range Transverse Wake Function for TESLA Accelerating Structure", TESLA Report 2003-19 (2003)
[2] I. Zagorodnov and M. Dohlus: "Coupler Kick", https://indico.desy.de/contributionListDisplay.py?confId=177
[3] M. Dohlus et al, these proceedings.
[4] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation", Advanced Photon Source LS-287, September 2000.
[5] J. Rossbach, "A VUV free electron laser at the TESLA test facility at DESY", Nuclear Instruments and Methods in Physics Research Section A, Volume 375, p. 269-273 (1996).