DESIGN AND FIELD MEASUREMENTS OF A LINEAR ACCELERATOR ENDOWED WITH SINGLE FEED WITH MOVABLE SHORT COUPLER

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Abstract

Field asymmetries in the rf coupler of accelerating structures degrade the projected beam transverse emittance, especially at low energy. This paper presents an alternative single feed coupler design that reduces the dipolar and the quadrupolar field components by exploiting a movable short circuit placed on the opposite waveguide. The structure has been simulated and optimized with the Ansys HFSS simulation code. RF measurements on an aluminum prototype machined in the "Elettra - Sincrotrone Trieste S.C.p.A.", are here presented. Such results are in good agreement with the simulations.

INTRODUCTION

FERMI@Elettra is an S-band linac-based Free Electron Laser (FEL) facility [1, 2]. Successful FEL lasing relies on the generation of a high brightness electron beam at the photo-injector. The FERMI photo-injector mainly consists of the radiofrequency (rf) gun and of two travelling wave S-band rf sections, working at 2998.01 MHz, which accelerate the beam up to 100 MeV. Actually the rf power feed consists of a single-feed coupler which results in a field asymmetry that induces a transverse kick along the bunch and causes transverse emittance degradation [3]. In order to reduce or eliminate the field asymmetries in the coupler cavity, dual feeding or a dual feed with the racetrack geometry are proposed in several laboratories [4, 5, 6]. In this paper we evaluate the performances of a new type of single feed coupler endowed with an adjustable short-circuit (SC) (see Fig. 1) on the opposite side [7] to reduce the dipolar field component and with a racetrack (RT) geometry [5, 6] to reduce the quadrupolar component as well. The proposed coupler provides the same field magnitude distribution as that of the dual feed coupler (DF), with the advantage of avoiding the use of power splitters. The transversal dynamics of the particle can be evaluated with the following equation [3]:

$$p_{\perp} = \frac{q\,E_{z,0}\,l}{2\,a\,\omega}\left(\overline{\Delta\varphi_d}\cos(\varphi_{RF}) + \frac{\overline{\Delta E_d}}{E_{z,0}}\sin(\varphi_{RF})\right) \quad (1)$$

where φ_{RF} is the rf phase, l is the coupler length, $2a$ is the beam aperture, $\overline{\Delta\varphi_d}/2a$ is the dipolar phase gradient of E_z, and $\overline{\Delta E_d}/2a$ is the dipolar amplitude gradient. The last two quantities are averaged along the z-axis of the coupler, taking the transit time factor into account. Since the first accelerating section is usually operated very close to the crest ($\varphi_{RF} = 0$), according to (1), the dipolar phase gradient is mainly responsible for the transversal kick of the bunch centroid, while the dipolar amplitude gradient deflects each electron depending on its longitudinal position along the bunch, i.e. on its rf phase φ_{RF}. This results in a head-tail beam emittance degradation, given by [5]:

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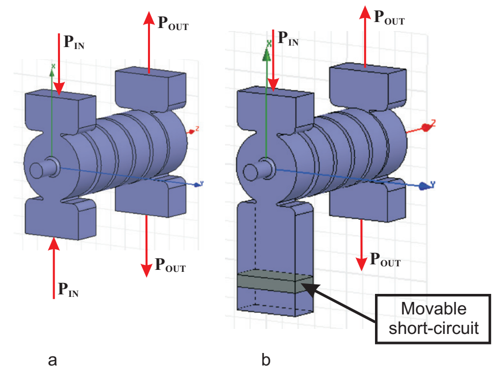

Figure 1: Dual feed (a) and Single feed with movable short-circuit (b).

$$\varepsilon_{n,f} = \sqrt{\varepsilon_{n,i}^2 + \sigma_x^2\left(\sigma_{\Delta\gamma\beta_\perp}\right)^2} \quad (2)$$

where $\varepsilon_{n,i}$ and $\varepsilon_{n,f}$ are the initial and final normalized transverse emittance, respectively, σ_x is the rms beam spot size at the coupler, and $\sigma_{\Delta\gamma\beta_\perp}$ is the rms transversal kick along the bunch.

MICROWAVE DESIGN

We designed and analyzed with HFSS [8] the following different couplers: Single feed (SF), Single feed translated (SFT), Dual feed (DF), Dual feed with racetrack (DF-RT), Single feed with movable short-circuit (SF-SC), Single feed with movable short-circuit and racetrack (SF-SC-RT)).

We designed the accelerating structures in order to reduce the dipolar component $|\Delta E_d/E_z| \leq 0.1$ % in the structures (SFT)-(SF-SC)-(SF-SC-RT) (In (DF)-(DF-RT) $|\Delta E_d/E_z| = 0$). In the structures (DF-RT)-(SF-SC-RT), also the quadrupolar component has been reduced as follows: $|\Delta E_q/E_z| \leq 0.1$ %.

For the structures (SF)-(SFT)-(DF)-(DF-RT) the coupler design is standard [3, 5], while we describe the optimization process of the structures (SF-SC)-(SF-SC-RT). The

ISBN 978-3-95450-122-9

optimization is made by searching the position of the SC parameter that minimizes the dipolar component, and then for the structure (SF-SC-RT) the quadrupolar component has been reduced by exploiting the racetrack geometry (see Fig. 2a). Fig. 2b shows how the dipolar component varies with the SC parameter. By setting the RT offset at 7 mm,

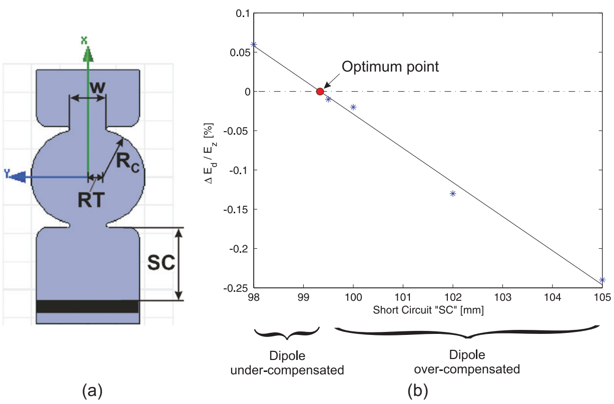

Figure 2: Racetrack geometry applied to the single feed coupler with movable short-circuit (a) and plot of the dipole component for a small variation of the parameter "SC" (b).

the quadrupolar component is $|\Delta E_q/E_z| = 0.01$ %.

In the SFT case the dipolar field has been reduced by translating the coupler along the $-x$ axis of 1.3 mm. However, the dipolar component $|\Delta E_d/E_z|$ increases of 0.1% every 20μm of coupler translation, leading to a very stringent constrain in the machining process.

MICROWAVE MEASUREMENTS

In the Elettra - Sincrotrone Trieste S.C.p.A. laboratories, an aluminum prototype of the linac has been machined. It is composed by a SF and by a SF-SC coupler. We measured the couplers field asymmetries with the bead-pull method, by placing the bead in the center of the coupler and moving it transversally, recording the S_{11} parameter. According to [9], the electric field magnitude is given by: $|E_z(x)| = \alpha\sqrt{|S_{11}(x)|}$, where x is the bead position and α is a constant.

The normalized electric fields, measured in the midplane of the two couplers, are depicted in Fig. 3. We measured a dipolar component $|\Delta E_d/E_z|$ of about 6% for the SF coupler and 0.1% for the SF-SC coupler (with SC = 101 mm), that is very close to the measurement resolution limit.

EVALUATION OF THE BEAM DYNAMICS IN THE COUPLERS

This section describes the results of the particle beam tracking in the designed input couplers. The algorithm discretizes and integrates the relativistic Lorentz force [5]:

$$\vec{F} = \frac{d\vec{p}}{dt} = m_0 c \frac{d(\gamma\vec{\beta})}{dt} = e(\vec{E} + c\vec{\beta}\times\vec{B}) \qquad (3)$$

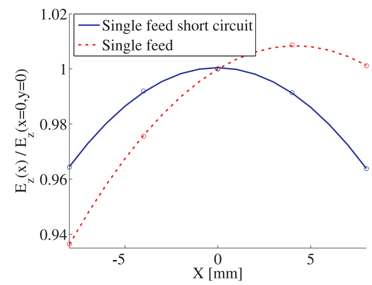

Figure 3: Normalized magnitude of the electric field on axis as a function of the transverse coordinate x.

where the electric field $\vec{E}$ and the magnetic induction $\vec{B}$ are given by the simulator. The transversal kick can be decomposed in multipoles as:

$$\begin{cases} \gamma\beta_x = A_0\cdot x + D_x + Q\cdot x + S\cdot y + O_x(x,y) \\ \gamma\beta_y = A_0\cdot y + D_y - Q\cdot y + S\cdot x + O_y(x,y) \end{cases} \qquad (4)$$

where: A_0 is the RF focusing, D_x and D_y are the dipoles oriented in the x and y direction, Q is the quadrupole, S the skew quadrupole, $O_x(x,y)$ and $O_y(x,y)$ are higher-order infinitesimal terms.

We assume that the beam energy at the input coupler is 5 MeV and that the linac accelerating gradient is 20 MeV/m. The dipolar beam transversal kick, analyzed on the "Single feed" type accelerating structures, is shown in Fig. 4, while the effect of the quadrupolar kick, analyzed in all the structures, is shown in Fig. 5.

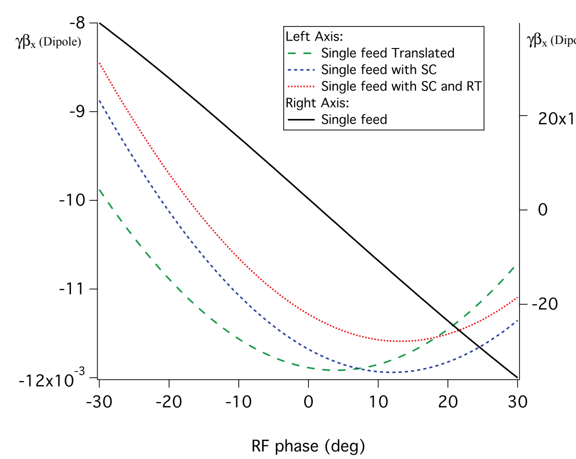

Figure 4: Plot of the dipole kick calculated varying the rf phase.

We calculate the difference between the momentum of two particles that have different rf phase values. We consider a 10° S-band long bunch, whose centroid is accelerated -3° off-crest, with σ_x = 0.5 mm and a normalized initial emittance of 0.65 mm mrad [2]. By using the simulation results of Figs. 4-5, it is possible to evaluate the dipolar (ΔD_x) and the quadrupolar (ΔQ) peak-to-peak kick for the analyzed couplers. In Fig. 4 the minimum of the dipole

ISBN 978-3-95450-122-9

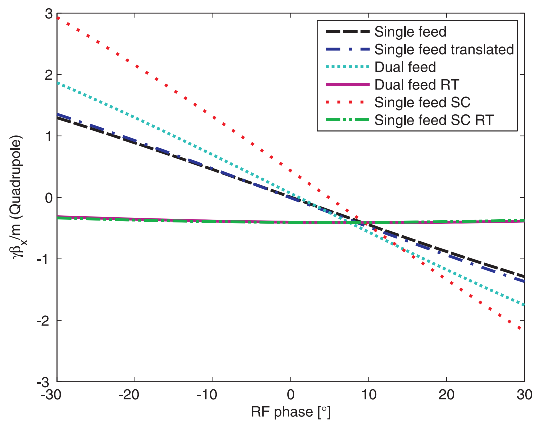

Figure 5: Plot of the quadrupole kick calculated varying the rf phase.

kick for the SF-SC-RT structure occurs at about 13°, so at the operating rf phase of -3° the electron bunch samples an high peak-to-peak kick (Situation called: SF-SC-RT (1)). However, such minimum can be shifted back to -3° by introducing a dipolar amplitude gradient by moving the SC position in order to compensate the dipolar phase gradient (see Eq. (1)). By setting $\Delta E_d/E_z$ = -0.5%, it is possible to move the minimum of the dipole kick at -3° that is the operating rf phase (SF-SC-RT (2) case). The racetrack geometry needs to be slightly adjusted. The results are listed in Table 1. The dipolar and the quadrupolar emittance growth have been calculated by using Eq. (2), where in the quadrupolar case we have assumed $\sigma_{\Delta\gamma\beta_\perp} = \sigma_x \Delta Q$.

Table 1: Dipolar and quadrupolar effects calculated for the analyzed input couplers. The emittance growth is calculated with a normalized initial emittance of 0.65 mm mrad.

	ΔD_x (dip.)	$\Delta\varepsilon/\varepsilon_i$ (dip.)	ΔQ (quad.)	$\Delta\varepsilon/\varepsilon_i$ (quad.)	$\Delta\varepsilon/\varepsilon_i$ Total
Unit		(%)	(m^{-1})	(%)	(%)
SF	13e-3	905	450e-3	1.5	905
SF T	0.25e-3	2	474e-3	1.6	3.5
DF	-	-	630e-3	3	3
DF RT	-	-	16e-3	2e-3	2e-3
SF SC	0.54e-3	8	885e-3	5.6	13
SF SC RT (1)	0.56e-3	9	10e-3	1e-3	9
SF SC RT (2)	5.4e-5	0.08	26e-3	5e-3	0.1

CONCLUSIONS

In the single feed structure with a movable short-circuit the electric field asymmetry can be controlled by searching the short-circuit position that ensures the minimum dipolar amplitude gradient. This feature has been verified with HFSS simulations and bead-pull measurements on a linac prototype machined in the Elettra laboratory, confirming the results of the simulations. Moreover by applying the racetrack geometry it is possible to compensate the quadrupolar component of the electric field.

The dynamics of the electron bunch inside the linac has been studied with an in-house developed tracking software, that provides the position and the momentum of the particles, for different accelerating phases.

The residual dipolar peak-to-peak kick can be further compensated by intentionally introducing a dipolar amplitude gradient with an optimized SC position.

Finally, the proposed compact single feed coupler design represents a good alternative to the typical dual feed structures, which are more invasive and expensive, especially for long accelerating facilities.

ACKNOWLEDGMENT

This work was funded by the FERMI project of Elettra-Sincrotrone Trieste S.C.p.A., partially supported by the Ministry of University and Research under grant numbers FIRB-RBAP045JF2 and FIRB-RBAP06AWK3. Thanks to Ivan Cudin, Maurizio Barnaba, the mechanical workshop and all the staff of Elettra - Sincrotrone Trieste S.C.p.A. for the support in the production of the linac prototype. The PhD of Massimo Dal Forno in the “Department of Engineering and Architecture” of the University of Trieste, Italy, has been supported by Elettra - Sincrotrone Trieste S.C.p.A., Italy.

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