A TRANSVERSE RF DEFLECTING CAVITY FOR THE FERMI@ELETTRA PROJECT

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Abstract

The layout of FERMI@Elettra includes a high energy transfer line (TL) which brings the accelerated electron bunch to the FEL undulator chains. The TL optics has been designed according to several space constraints and with the purpose of including diagnostics for the complete characterization of the electron bunch just before the FEL process starts. Basing on such optics, this paper reports the study of the electron bunch deflection at nominal energy of 1.2 GeV for the measurement of the bunch length, of the transverse slice emittance and of the slice energy spread, coupled to a downstream dipole. The effect of the cavity on the electron beam was simulated by tracking code and the specification on the deflecting voltage was thus confirmed. Furthermore the RF design and electromagnetic simulations are also presented here.

INTRODUCTION

The layout of FERMI@Elettra includes a high energy transfer line (TL) designed according to several space constraints and with the purpose of including diagnostics for the complete characterization of the electron bunch just before the FEL process starts [1]. Using such optics as a base, this note reports the study of the electron bunch deflection at approximately 1.2 GeV for the measurement of the bunch length and of the transverse slice emittance. The well-known formulas contained in [2, 3, 4] concerning the dynamics of the bunch deflection as function of the RF deflector parameters and of the optical Twiss parameters are here used. Perturbations to the ideal case due to in the finite transverse emittance is also considered. Then, some of the basic formulas have been manipulated in to evaluate the measurement resolution, which depends on the transverse finite emittance and on the screen resolution. Specification for the high energy RF deflector in FERMI is given. The analytical predictions are verified by the particle tracking [5]. Furthermore tracking section also includes some considerations about the single bunch beam break up (BBU) instability acting in the main Linac. In the last section RF design and structure parameters for the deflector are addressed.

OPTICS

It is supposed here that the RF deflector alternately operates in both transverse planes to allow the measurement of the horizontal and vertical transverse slice emittance. In addition, this allows the BBU instability to be observed in both planes ([6] and references therein). The RF deflector is placed in a drift section 2.5 m long and it is followed by a (multi) 5-screen emittance measurement section. The quadrupole magnets in between the five OTR screens are separated by $\pi/4$ phase advance in both planes. The betatron phase advance over the cavity length is small, thus the phase advance in the cavity is approximated by its average value ($\beta_D = 18m$ and $\beta_S = 4.5m$ are beta function at the deflector and at the screens, respectively). Since the efficiency of the bunch deflection at the chosen observation point depends on $sin(\Delta\psi_{D,S})$ (see next section), a null vertical deflection occurs at $\Delta\psi_{D,4} = 180deg$ (OTR4), the maximum deflection is at $\Delta\psi_{D,2} = 78deg$ (OTR2) and a poorly deflection occurs at $\Delta\psi_{D,1} = 25deg$ (OTR1) both in the vertical plane. The parameters concerning the Medium Length Bunch option (MLB) [7] used are: bunch charge $0.8nC$, average energy of $1.14GeV$, total normalized emittance of $2\mu mrad$ and RMS bunch length of $90\mu m$.

BASICS

In the approximation of pencil beam (null transverse emittance, $\sigma_{y,0} = 0$), the RMS beam size at the screen location when $\varphi_{RF} = 0$ (the centroid remains on the axis trajectory) is:

$$\sigma_{y,S} = \frac{eV_\perp}{E}\sigma_z \left[\frac{\omega_{RF}}{c}\right]\sqrt{\beta_D\beta_S}\sin(\Delta\psi_{DS}) \qquad (1)$$

where $V_\perp$ is the total transverse voltage of the deflecting structure and σ_z is the bunch length before the action of the deflection.

Finite Transverse Emittance

If the finite transverse emittance of the bunch is taken into account, then the RMS beam size at the screen after the deflection is estimated by the quadratic summation of the RMS non-deflected particle transverse size distribution and of the RMS beam size in the pencil beam approximation:

$$\sigma_{y,S,\epsilon} = \sqrt{\frac{\epsilon_N\beta_S}{\gamma} + \left[\frac{eV_\perp}{E}\sigma_z\frac{\omega_{RF}}{c}R_{34}\right]^2} \qquad (2)$$

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RESOLUTION

Resolution from beam finite emittance

Eq. 2 describes the increase of the beam size measured at the screen in the presence of a finite transverse emittance. This perturbation is negligible if $\sigma_{y,S} >> \sigma_{y,0}$. If it is $\sigma_{y,S} = \kappa\sigma_{y,0}$ then:

$$\sigma_{y,S,\varepsilon}(\kappa) = \sqrt{\sigma_{y,0}^2 + \sigma_{y,S}^2} = \frac{\sqrt{1+\kappa^2}}{\kappa}\sigma_{y,S} \qquad (3)$$

and the relative error on the beam size is:

$$\frac{|\sigma_{y,S,\varepsilon} - \sigma_{y,S}|}{\sigma_{y,S}} = \frac{\Delta\sigma_{y,S}}{\sigma_{y,S}}(\kappa) = \left|\frac{\sqrt{1+\kappa^2}}{\kappa} - 1\right| \qquad (4)$$

Notice that the measurement of the horizontal slice emittance is not affected by a vertical enlargement of the beam size at the screen as the horizontal width of the beam spot is only of interest. Eq. (2) shows that if $V_\perp$ is sufficiently large, the bunch RF deflection satisfies the approximation of pencil beam. Once κ has been fixed accordingly to the relative error given by eq. (3) and eq. (4), then the minimum peak voltage of the RF deflector (when $\varphi_{RF} = 0$) providing such an error is given by:

$$V_{\perp,\min} = \kappa\frac{E}{e}\frac{1}{\sigma_z}\sqrt{\frac{\varepsilon_N}{\gamma\beta_D}}\left(\frac{c}{\omega_{RF}}\right)\frac{1}{|\sin(\Delta\psi_{DS})|} \qquad (5)$$

with ϵ_N the total normalized emittance of the non-deflected bunch. Figure 1(left) plots eq. (5) with varying κ.

As an example, an RMS intrinsic relative error on the bunch length measurement $\Delta\sigma_z/\sigma_z$ of about 3% is guaranteed by the error parameter $\kappa = 4$ (in absence of other perturbations to the deflection). The minimum RF deflector peak voltage $V_{\perp,MIN}$ required by this specification is something less than $6MV$ (see figure 1 (left)).

Maximum peak voltage specification

The measurement of the transverse slice emittance requires short portions of the bunch length to be resolved at the screen after the bunch is deflected. That is, the resolution of the measurement system has to provide the necessary sensitivity to the intensity contrast. Then, the CCD camera detecting the screen will be able to distinguish density clusters. The OTR screen resolution is estimated to be $10\mu m$ RMS, while in this handling we have not taken in account the CCD pixel size. Figure 1 (right) shows the measured beam size as a function of $V_\perp$ according to eq. (2) (worse phase advance of the OTR1 screen for the bunch vertical deflection). The deflected RMS beam size at the screen for $V_\perp = 20MV$ is $380\mu m$.

A first estimate of the minimum slice length detectable as a function of the deflecting voltage can be obtained by using the following simple approach. A portion of the longitudinal density distribution of the electron bunch is modeled by two identical Gaussians with different centers at a given distance Δx; the sigma of the Gaussians is the instrumental RMS resolution. This is sketched in figure 2 (left). Then, the intensity contrast is defined by: $IC = (A-B)/A$ (see figure 2 (left)). Thus, by fixing the specified intensity contrast, a minimum distance between the density peaks is determined; this can be taken in turn as the minimum detectable slice length. The intensity contrast as a function of centers distance Δx can be plotted for different screen resolutions (see figure 2 (right)). Assuming $10\mu m$ RMS resolution of the screen, a contrast of 70% allows for the detection of about a $40\mu m$ slice length. This correspond to 30 slice in the MLB if we consider the approximation of a uniform bunch current distribution and taking a peak voltage of $18MV$. According to figure 1 (right), the RMS beam spot size at the OTR1 screen is about $350\mu m$.

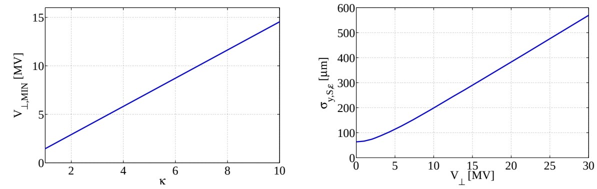

Figure 1: Left: Minimum deflecting voltage as a function of the error parameter κ. It has been assumed a beam size measurement at the OTR2 screen location. Right: The measured beam size at the OTR1 screen location as a function of the deflector peak voltage $V_\perp$. The curve represents the less efficient vertical deflection over the available screens.

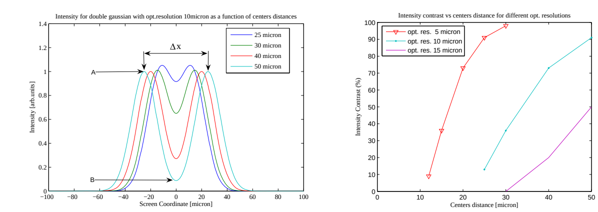

Figure 2: Left: Intensity contrast for a double Gaussian particle distribution as a function of the centers distance. Right: Intensity contrast vs. distance between the centers of the double Gaussian particle distribution for three RMS resolution of the OTR screen.

PARTICLE TRACKING

The vertical deflection has been applied to the MLB option. Particle distributions of the deflected bunch observed at the OTR2 screen are shown in figure 3. The beam spot size obtained is about $3mm$ in height. The on-axis bunch deflection has been performed with a peak voltage $V_\perp = 20MV$ and it is observed at the OTR2 screen location. This can be compared with the analytical result where a $20MV$ peak voltage provides an RMS beam spot size on the OTR2 screen of about $840\mu m$. This correspond to a $\sqrt{12}\cdot 840\mu m = 2.9mm$ full width of the image for an ideally uniform particle distribution, namely a good agreement between theory and particle tracking.

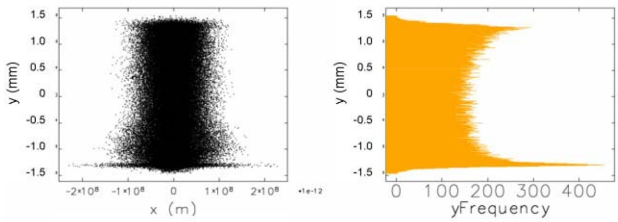

Figure 3: Particle distribution of the deflected bunch observed at the OTR2 screen. On the top left, particles in the x-y plane; the vertical extension contains information on the bunch length. The other plot shows the particle distributions in the vertical plane.

Single bunch beam beak-up instability

The geometric wake fields in the accelerating structures upstream of the RF deflector [8] induce a BBU instability in both the transverse planes; as a result, the bunch tail is laterally displaced with respect to the head in the plane of action of the wake field and the bunch assumes a typical "banana shape" [6]. If the bunch distortion is in the horizontal plane, then the vertical deflection will show it in the x-y plane of the screen. In such a way the BBU instability in the main Linac can be checked and compensated locally by means of trajectory management. Figure 4 shows the "banana shape" at the OTR2 location induced by the horizontal transverse wake field in the Linac. No special wakefield compensation is implemented. Notice that in the previous figure 3 the local trajectory bumps have been implemented in the simulation.

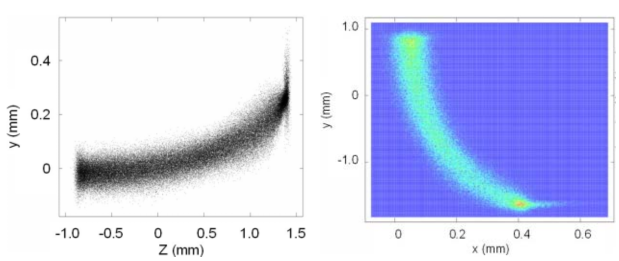

Figure 4: "Banana shape" induced by the Linac horizontal transverse wake field. Before (left) and after (right) the vertical deflection of the bunch.

RF DEFLECTOR DESIGN

The RF design and the choice between different options was done taking in account the following constrains:

- the required deflecting voltage $V_\perp = 18MV$;
- the working RF frequency $f_{RF} = 2998MHz$;
- filling time $t_f \leq 3\mu s$;
- the available space of about $2m$
- the available RF power $P_{RF} = 15MW$;

The required deflecting voltage $V_\perp = 18MV$ is normally achieved by travelling wave (TW) structure. The optimization of the RF structure is extensively handled in the reference [9]. Table 1 lists the main RF and structure parameters of the deflector which has a phase advance for cell of $2\pi/3$. Geometric parameters are iris radius a, iris thickness t, period L and cavity radius b while RF parameters are quality factor Q, normalized group velocity $\beta_g = v_g/c$, attenuation constant α, $r_\perp/Q = (v_g/\omega_{RF})(F_\perp/e)^2/P_{RF}$ and $r_\perp = (F_\perp/e)^2/(dP/dz)$. Let us note that the group velocity is negative which means that the mode in the deflector is a backward wave. Thus the RF power will be fed in at the coupler at the downstream end of the structure. The connection between RF power and transverse deflecting voltage for the deflector $2m$ long was calculated in [9] and is given by:

$$V_\perp = 0.941\sqrt{r_\perp P_{RF}} \quad (6)$$

Table 1: Main RF and structure parameters of the transverse deflector.

L	$33.33\ [mm]$	β_g	-0.0157
b	$59.33\ [mm]$	α	$0.1480\ [m^{-1}]$
a	$12.50\ [mm]$	$r_\perp/Q$	$2074\ [\Omega/m]$
t	$8\ [mm]$	$r_\perp$	$28\ [M\Omega/m]$
f_{RF}	$2.998\ [GHz]$	t_f	$0.425\ [\mu s@2m]$
$Mode$	$2\pi/3$	P_{RF}	$15\ [MW]$
Q	13500	$V_\perp$	$19.3\ [MV@2m]$

CONCLUSION

In this paper the study of the electron bunch deflection at around $1.2GeV$ for the measurement of the bunch length and of the transverse slice emittance is performed. Some of the basic formulas have been manipulated to evaluate the measurement resolution in the presence of a transverse finite emittance and on the screen resolution at the observation point. As a conclusion, a peak voltage of $18MV$ for the RF deflector is completely satisfactory for the bunch length measurement. The same specification allows for a resolution of 30 slices over the MLB with an intensity contrast of about 70% The analytical predictions have been verified by the particle tracking.

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