MODELING INVESTIGATION ON A DEFLECTING-ACCELERATING COMPOSITE RF-CAVITY SYSTEM FOR PHASE SPACE BEAM CONTROL

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Abstract

Phase space manipulations between the longitudinal and transverse degrees of freedom hold great promise toward the precise control of electron beams. Transverse-to-longitudinal phase space exchange has been shown to be capable of exchanging the transverse and horizontal emittance or controlling the charge distribution of an electron bunch for beam-driven advanced accelerator methods. The main limitation on the performance of this exchange mechanism stems from the external coupling nature of a realistic deflecting cavity, compared to a thin-lens model. As an extended idea from [A. Zholents, PAC11], this paper presents the design of a composite 3.9-GHz RF system consisting of a deflecting and accelerating-mode cavity. The system design analysis is discussed with particle-in-cell (PIC) simulations of the device performance.

INTRODUCTION

Deflecting cavities have found an increasing number of applications in accelerators including particle-species separation [1], beam distribution [2] , longitudinal phase space characterization [3] and phase space manipulation [4]. One of applications, phase space manipulation between the transverse phase spaces and the longitudinal phase space, has opened new exciting opportunities. Initially proposed in the context of a B-factory [5], these methods were subsequently explored as possible candidates for improving the performance of single-pass free-electron lasers (FELs) [6]. More recently their application as pulse shaper was proposed [7] and demonstrated [8, 9]. A typical phase-space-exchanger (PEX) beamline consists of a deflecting cavity flanked by two dispersive sections [10]. The simplest solution devised to date consists of a horizontally deflecting cavity, operating in the TM110 mode, flanked by two identical horizontally dispersive sections arranged as “doglegs". Most of the PEX beamline analysis is generally performed using a simple kick-approximation for the deflecting cavity. When thick-lens effects are considered, the PEX beamline performance deviates from the ideal case and the exchange become incomplete. The remaining coupling results from the non-vanishing coupling term between energy and time introduced by the cavity. A partial scheme to alleviate this coupling has been developed [11, 12] but significantly impacts the PEX beamline flexibility.

A similar limitation can affect the performance of conventional single-shot longitudinal phase space (LPS) diagnostics. In these LPS diagnostics, a deflecting cavity shears the beam in one direction while a dispersive beamline shears the beam in the orthogonal direction. Therefore the final density in the transverse configuration space is representative of the LPS. These techniques are prone to several limitations and one of them stems from the time-energy correlation introduced by the deflecting cavity. Several methods to globally (over the beamline) compensate for the time-energy coupling introduced by a deflecting cavity have been proposed [13, 14]. One correction method recently suggested in Ref. [15] proves an efficient local correction with a wide range of applications as discussed below.

The purpose of the accelerating cavity, operated at zero-crossing, is to remove the time-dependent correlated energy introduced by the deflecting cavity. In the six-dimensional trace space (x, x', y, y', z, δ) the matrix of a RF system composed of a deflecting cavity followed by an accelerating cavity is

$$\mathrm{M_c} = \begin{bmatrix} 1 & L_c & 0 & 0 & \kappa\left(L_a + \frac{L_d}{2}\right) & 0 \\ 0 & 0 & 0 & 0 & \kappa & 0 \\ 0 & 0 & 1 & L_c & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & \kappa & \frac{\kappa L_d}{2} & 0 & 0 & 0 \end{bmatrix} \quad (1)$$

where $L_c \equiv L_a + L_d$ (L_a and L_d are the lengths of the accelerating and deflecting cavities, respectively) and the normalized deflecting strength is $\kappa \equiv \frac{ekV_\perp}{\varepsilon}$ with $V_\perp$ and ε being the deflecting voltage and beam energy respectively, and $k \equiv 2\pi/\lambda$ where λ is the mode wavelength. The accelerating cavity is operated at zero crossing with its normalized accelerating strength $\chi \equiv \frac{ekV_\|}{\varepsilon}$ (where $V_\|$ is the accelerating voltage) set to $\chi = -L_c\kappa^2 = 2$ such to zero the $M_{c,65}$ element.

BEAM DYNAMICS SIMULATION FOR THE 3.9-GHZ HYBRID SYSTEM

We now explore the expected cancellation of the M_{65} term in a realistic configuration. The hybrid cavity system is composed of a 5-cell deflecting mode cavity [16] followed by a single-cell accelerating cavity. Both cavities operate at 3.9 GHz and have an elliptical shape. The tracking studies are performed with ASTRA (a space charge tracking algorithm) [17] using a three-dimensional field map of the electromagnetic field of the deflecting cavity obtained from HFSS [18, 19]. The accelerating cavity is described by its axial electric field obtained from CST Microwave Studio [18] and the associated radial electric and azimuthal magnetic fields are obtained from a third-order radial expansion in ASTRA. The effects of input and high-order-mode couplers are not taken into account in these simulations as the cavities are taken to be axis-symmetric. To compute the transfer matrix of the system, a macro-particle distribution consisting of 7 macro-particles, each offset along one of the phase space coordinate was used. The final offset with respect to the reference particle was used to directly compute the transfer matrix of the RF system. The final offset with respect to the reference particle was used to directly compute the transfer matrix of the RF system. The beam total energy was set to 40 MeV. The resulting M_{65} as a function of E_a, the peak accelerating field in the accelerating cavity, and for different value of κ are shown in Fig. 1. As predicted from the transfer matrix analysis, the M_{65} cancelation occurs for $E_a \propto \kappa^2$ (a fit from the simulation gives a slope of 1.98).

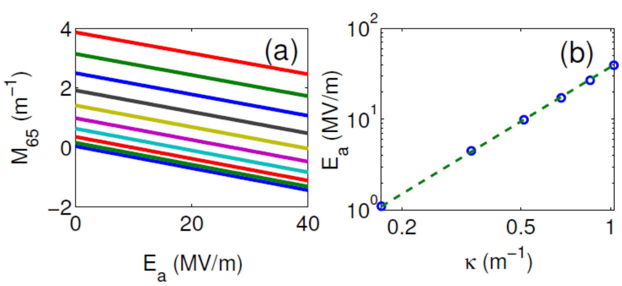

Figure 1: M_{65} as a function of the peak field in the accelerating cavity for deflecting field amplitude (a) and needed accelerating field to cancel the M65. In (a) the traces correspond to equidistant variation of κ from 0.17 (lower trace) to 1.7 (upper trace). The beam energy is 40 MeV.

RF MODELING ANALYSIS OF DEFLECTING MODE (TM_{110}) CAVITY

The 3.9 GHz 5 cell deflecting mode (TM_{110}) cavity has been commissioned for beam-control and beam physics study in A0 photoinjector lab for many years. The cavity, designed for π-mode operation with out-of-phase longitudinal field distribution, was made out of OFHC copper, which has beam operated in the LN_2-cooling module. Under the LN_2-ambient temperature (= 80K), OFHC copper has ~ 6 times higher conductivity ($\sigma = 35 \times 10^7\ \Omega^{-1}m^{-1}$) that leads to 2.5 times higher Q (Q_0 = ~ 35,600) compared to room temperature. We re-investigated the cavity system design using CST MWS to check if there is room for further optimization of cavity performance (deflecting strength) since it has been suspected that the cavity has problems with input power coupling and axial field flatness. The cavity parameters, obtained from simulation data, are used to calculate the normalized deflecting strength, κ, defined from Panofsky-Wenzel Theorem, as follows,

$$\kappa = \frac{eV_L}{\rho E} = \frac{V_L}{\rho V_e} = \left(\frac{1}{V_e}\right)\frac{\omega}{c}\sqrt{2\left(\frac{R}{Q}\right)PQ_0\,\frac{4\beta}{(1+\beta)^2}}\,, \quad (2)$$

where R/Q is the cavity impedance, Q_0 is the ohmic Q, V_e is the beam voltage, β is the power coupling coefficient (= Q_0/Q_e, Q_e is the external Q), and P is the klystron power. The computational result on the deflecting strength with respect to field uniformity/cell, calculated with 40 MeV (= V_e) beam energy and 3.9 GHz operating cavity frequency, shows that the deflecting strength reduction is only ~ 5.7% even with 50% decrease of power coupling coefficient. On the other hand, the kick efficiency falls off more steeply with loss of field uniformity. It is shown that ~ 28% of the kick is lost with 40 % deviation of field flatness. However, EM simulation showed the designed cavity has < 10 % deviation of field uniformity, corresponding only to < 8.4% of kick reduction, which thereby proved that the cavity design is nearly optimized for maximum deflecting strength with the given klystron power.

EXPERIMENT PLAN

An experiment aimed at demonstrating the proposed concept is currently under consideration at the HBESL facility using a ~ 4-MeV electron beam. The beam produced by an L-band photoinjector will be injected into the 3.9-GHz cavities described in the previous section; see Fig. 2. In order to measure the <δ|z> element of the transfer map we use a difference orbit technique: the "gang" phase of the 3.9-GHz system is perturbatively varied around its nominal value and the corresponding change in mean energy is measured downstream of dipole magnet with a beam position monitor (BPM). The linear correlation between the perturbed phase and impressed energy change is representative of the M_{65}. The experiment will allow for a through optimization as the relative field amplitude and phase between the cavity could also be adjusted.

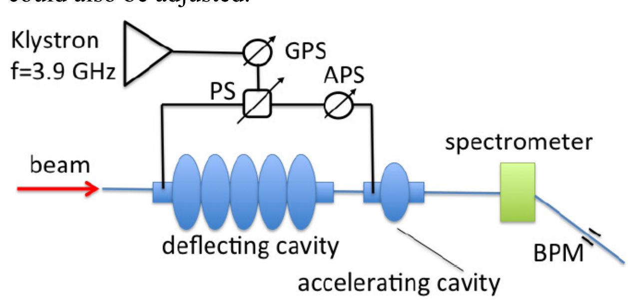

Figure 2: Overview of the planned experiment to measure M_{65}. The legend is as follows: "GPS" and "APS" are respectively the gang and accelerating phase shifters, and "PS" is a power splitter.

ISBN 978-3-95450-115-1

COAXIAL POWER COUPLER VIA BEAM PIPE FOR SIMPLE POP EXPERIMENT

A full experimental setup requires various RF components such as power divider, phase shifters, and waveguides. We are currently exploring a feasible way to feed the klystron power into the accelerating cavity without an additional coupler. One of our considerations is to insert the TEM-mode coaxial coupler in the beam pipe between the two cavities (Figs. 3(a) and (b)). In the system, RF power in the deflecting cavity is directly coupled to the accelerating one through the beam pipe. Signal transient simulation shows that the coupler accommodates the same level of RF power at the accelerating mode cavity (Fig. 3(c) and (d)), which could be also tunable by adjusting its intrinsic coupling impedance. S-parameter and field analyses on simulation result show that the accelerating field of TM_{010} mode appears comparable with the deflecting one of TM_{110}, as shown in Fig. 3(e), whereas there is no leakage field present inside the coupler. This power coupling scheme needs to be carefully investigated as it may simply enable a POP experiment without building any extra RF beam line.

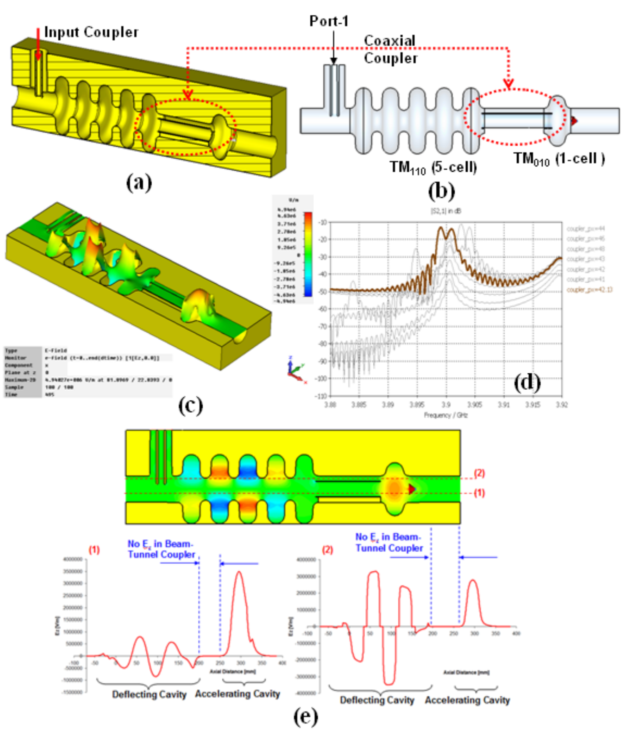

Figure 3: Hybrid deflecting-accelerating cavity PEX system using the beam-pipe coaxial coupler (a) 3D view (b) cross sectional view (c) field distribution (e) S21 between input coupler and antenna receive near the accelerating cavity (e) Ez contour plot (top) and 1D axial E-field distribution (bottom)

CONCLUSION

Our theoretical analysis shows that M_{65} term can be canceled by the hybrid RF system comprised of a 5 cell deflecting mode cavity followed by a single gap accelerating mode cavity. Tracking simulations (ASTRA) incorporated with CST and HFSS successfully verified the RF system of TM_{110}-TM_{010} mode cavities effectively remove energy spread. RF simulations (CST MWS) verified that the klystron power can be coupled into the accelerating mode cavity via the beam tube with a half-filled coaxial power coupler. This power coupling scheme is under consideration for constructing the hybrid deflecting-accelerating PEX test system. Currently, we are looking into possible ways to readily demonstrate PEX using the hybrid deflecting-accelerating cavity system in the HBESL at Fermilab.

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