A COAXIALLY COUPLED DEFLECTING-ACCELERATING MODE CAVITY SYSTEM FOR PHASE-SPACE EXCHANGE (PSEX)

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Abstract

The phase space manipulation of bunched beams offers a wide range of flexibility in beam dynamics control for advanced accelerator application. In particular, the capability of exchanging the transverse and longitudinal phase spaces enables to switch the transverse and horizontal emittance or shaping the charge distribution of an electron bunch to improve acceleration gradient and transformer ratio in beam-driven accelerators. A deflecting mode cavity has been used as the most integral element in the beam control scheme as imposing a kick on particles transferred between the two phase planes. In practice, the presence of the RF element with a finite length, however, induces thick lens effect limiting the phase-space exchange (PSEX) performance based off a thin lens model. Extending the idea from [A. Zholents PAC 11], we proposed momentum compensation technique using a single accelerating mode cavity coaxially coupled with the deflecting mode one. This paper describes the composite 3.9 GHz system and presents design analysis, including tracking and particle-in-cell (PIC) simulations, and layout of feasible experiment at the Advanced Superconducting Test Area (ASTA) of Fermilab.

INTRODUCTION

Optimization of the six dimensional phase-space volume is essential to high-quality electron beam applications and the next generation of advanced accelerators. Emittance compensation of electron gun phase space with solenoidal coils [1, 2] is one such example of phase space manipulation. Here, the emittance compensation solenoid is used to align the transverse phase ellipses of the each longitudinal beam slice in the bunch to minimize the transverse emittance. Many other approaches to the modification of phase-space have been demonstrated for different applications. Phase-space manipulation of beam lines was initially considered as a means of increasing the luminosity at the collision point in B-factories [3] and to improve the performance of free-electron laser (FEL) based light sources [4] and single-pass FELs [5].

Deflecting cavities are being used for a number of accelerator applications that include particle-species separation [6], beam distribution [7], longitudinal phase space characterization [8, 9] and phase space manipulation [10]. One application, manipulation between the transverse and longitudinal phase space, has opened up new opportunities [3 – 5] and the development of single-shot, longitudinal phase space (LPS) diagnostics [8]. In order to manipulate and control 6-D electron beam phase-space, transverse and longitudinal effects have to be carefully considered. Several approaches are under development around the world including emittance exchangers (EEX) [3, 4, 5, 10] and single-shot longitudinal phase space (LPS) diagnostics [8, 9]. However, each approach has drawbacks that must be overcome to deliver the requirements of the different applications.

The first beam line proposed for EEX consisted of a simple four-dipole chicane and an RF deflecting cavity [4]. While easy to implement, the resultant emittance exchange is not complete. An improved EEX beam line using two identical doglegs was later demonstrated [5], and while this beam line does provide full emittance exchange, it does not consider thick-lens effects. These effects result in a longitudinal accelerating term in the deflecting cavity which is generally undesirable. Instead, we proposed a simple method for achieving phase space exchange (PSEX) where the emittances as well as the coordinates are exchanged – that is to say we map x to z, x' to δ, z to x, and δ to x'. This approach uses a 5-cell deflecting cavity and a single-cell fundamental mode cavity in two identical doglegs dispersive section [11 – 13].

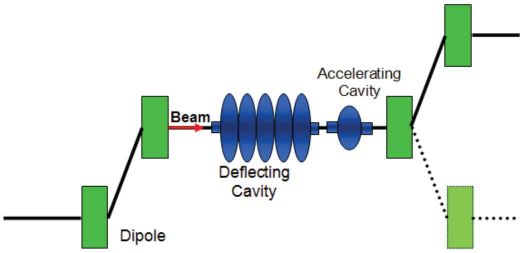

Figure 1: Proposed phase-space exchange experiment using a hybrid deflecting-accelerating radio-frequency cavity in the dispersive region of two identical doglegs (a four dipole-magnet chicane). The longitudinal energy gain in the deflecting cavity can be canceled by using the TM_{010} fundamental mode cavity.

THEORETICAL BACKGROUND

The simplest PSEX beam-line, shown in Figure 1, consists of a 3.9 GHz 5-cell horizontal deflecting cavity, operating in the TM_{110} mode, flanked by two identical horizontally dispersive sections arranged as "doglegs". The system can be arranged as the standard double-

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dogleg configuration or as a chicane (In the latter case, quadrupole magnets need to be added). The longitudinal phase space chirp accumulated in the deflecting cavity can be canceled using the single-cell accelerating cavity operated at zero-crossing.

PSEX beamline analysis is generally performed using a simple kick-approximation for the deflecting cavity. When thick-lens effects are considered, the PSEX beamline performance deviates from the ideal case and the exchange become incomplete. The remaining coupling results from the non-vanishing term between energy and time introduced by the deflecting cavity. A scheme to partially alleviate this coupling has been developed [11] but significantly impacts the PSEX beamline flexibility. A similar limitation can also affect the performance of conventional single-shot LPS diagnostics. Here, a deflecting cavity shears the beam in one direction while a dispersive beamline shears the beam in the orthogonal direction. Consequently, the final density in transverse configuration space is representative of the LPS. These techniques are prone to several limitations such as the time-energy correlation introduced by the deflecting cavity. Several methods to globally compensate for the time-energy coupling introduced by a deflecting cavity have been proposed [12] but this non-local approach is not ideal. For simplicity, we use a 4-D transfer matrix for our analysis. The transfer matrix of a thin-lens cavity is:

$$R_{k,thin} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}, \qquad (1)$$

where k is the dimensionless kick strength of the deflecting cavity. When using the thin-lens matrix for the deflecting cavity, the instantaneous energy and angular kicks as well as the length of the cavity are neglected. For a 5-cell deflecting cavity of length L_D, the thick-lens 4 by 4 transport matrix is [4]

$$R_{k,thick} = \begin{bmatrix} 1 & L_D & kL_D/2 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & kL_D/2 & k^2 L_D/6 & 1 \end{bmatrix}, \qquad (2)$$

where again k is the dimensionless kick strength. For simplicity, we ignore vertical motion because no vertical coupling is produced in the chicane to first order. The four-dimensional coordinate vector has components (x, x', z, δ), where x' and δ are the angle and energy spread, respectively. While the thick-lens transfer matrix has nonzero R_{12}, R_{13}, R_{42}, and R_{43} elements as compared to the thin-lens case, the incomplete PSEX is caused by the R_{43} term here or the R_{65} term in a 6-D transfer matrix. Using a simple RF cavity operating in the fundamental mode with

$$R_{43} = -k^2 L_D / 6 \qquad (3)$$

to compensate for the longitudinal energy gain in the deflecting cavity leads to optimal PSEX to first order when the thick-lens effect of the deflecting cavity is taken into account [4,10]. This energy gain can be canceled by using a TM_{010} mode accelerating cavity next to the deflecting cavity as shown in Figure 1, or two such cavities at half strength [11]. The time-dependent correlated energy is compensated by operating the accelerating cavity at zero-crossing with the optimal field setting to zero the 6-D transfer matrix element, R_{65} (or R_{43} in 4-D). With this simple approach, a hybrid deflecting-accelerating PSEX optimally exchanges the emittance and coordinate values. We plan to use a single-cell TM_{010} fundamental mode cavity instead of two separated TM_{010} fundamental mode cavities because the two cavities would need to be placed before and after the deflecting cavity and thus introduce complexity in the RF and accelerator system. We will also use two identical doglegs instead of the APS chicane approach for the dispersion section [11]. The matrix form of the hybrid TM_{110}-TM_{010} PSEX is

$$M_{PSEX} = M_{D2}\left(M_{TM010} \cdot M_{X115}\right) M_{D1} = \begin{bmatrix} 0 & 0 & -\frac{1}{\alpha} - \frac{3kl}{2} & \frac{2}{k} + \frac{3\alpha l}{2} \\ 0 & 0 & -k & \alpha \\ \alpha & \frac{2}{k} + \frac{\alpha l}{2} & 0 & 0 \\ -k & -\frac{1}{\alpha} - \frac{kl}{2} & 0 & 0 \end{bmatrix}, \qquad (4)$$

where α is the dipole strength, l is the length of the accelerating mode cavity, and M_{D1} and M_{D2} are the matrices of doglegs.

We plan to employ such an alternative scheme to achieve optimal PSEX in inserting the TEM-mode coaxial coupler in the beam pipe between the two cavities as shown in Figure 3. In this arrangement, RF power in the deflecting cavity is directly coupled to the accelerating cavity through the beam pipe. Signal transient simulation shows that the coupler accommodates the same level of RF power at the accelerating mode cavity, which should be tunable by adjusting its intrinsic coupling impedance.

SIMULATION MODELING ANALYSIS

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. 2(a)). 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. 2(c)), 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. 2(b), 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.

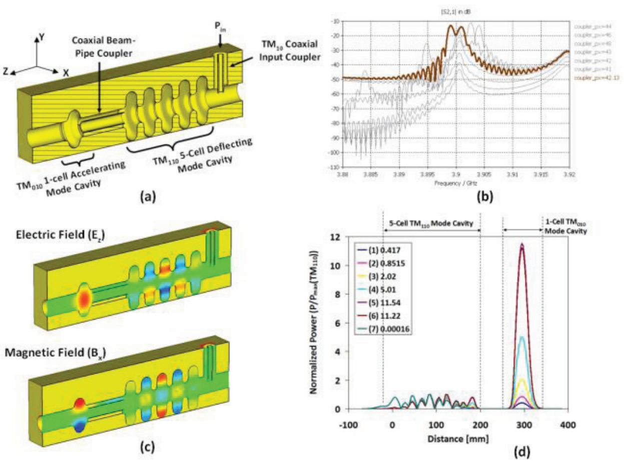

Figure 2: (a) 3D-view of RF simulation model of a hybrid TM$_{110}$-TM$_{010}$ PSEX system using the coaxial beam-pipe coupler (b) transmission spectrum (S$_{21}$) and (c) field distributions (top: E-field and bottom: H-field) of a hybrid TM$_{110}$-TM$_{010}$ mode (d) RF power distribution along the axial distance with respect to coupling parameter between the two cavities ((1) ~ (7) = P$_{max}$(TM$_{010}$)/P$_{max}$(TM$_{110}$))

The coaxial coupler couples TM$_{110,\ \pi}$ mode with TM$_{010}$ mode as shown in Fig. 2(c). The phase and amplitude of the TM$_{010}$ mode field confined in the accelerating mode cavity can be readily controlled by adjusting the coupling impedance, which is normally obtained from tweaking the relative length and radius of the antenna inside the beam-pipe coupler.

Figure 2 (d) shows the spatial power distributions of the hybrid (TM$_{110}$-TM$_{010}$) mode with respect to the levels of power coupling (η = P_{max}(TM$_{010}$)/P_{max}(TM$_{110}$)) that are determined by the antenna length relative to the beam pipe length between the two cavities. The ratio ranges from 0.417 to 11.54. The field data (E-field and H-field) from CST MWS eigenmode solver were imported into tracking and particle-in-cell simulations. For the simulations, particle data (10,000 macro-particles) of the electron bunch with 50 MeV injection energy, 20 pC bunch charge, and 36.7 ps bunch duration were imported from Impact-Z. The transverse beam emittance ($\varepsilon_{x,y}$) of the injected bunch is about 0.1 mm-mrad and transverse beam size ($\sigma_{x,y}$) is about 2 mm, as shown in Fig. 4.

Figure 3 shows preliminary tracking and PIC simulation results with the field and particle data in the various coupling conditions (η = (1) – (7)). The transverse phase space plots, (a) – (c), in Fig. 4 were obtained from tracking solver and the longitudinal one, (d) – (f), from PIC solver. The beam is deflected along x-axis with the under-coupled phase condition (η = 0.417). The orientation of deflection is, however, changed to the y-axis as the coupling becomes in-phase condition with increasing coupling strength. Once it exceeds the over-coupled condition (η = 11.54) of out-of-phase, the deflection is re-aligned to x-axis. One can thus see that the phase variation changes the deflecting direction. The energy spread is minimal with (6) η = 11.22 where the phase-space volume becomes minimal. The simulation shows that the accelerating cavity reduces the energy spread from 5.6 % to 2.8 %. We will extensively look into beam dynamics of the designed system by incorporating it with the chicane beamline model. Beam dynamics analysis will be performed to optimize and analyze the optimal phase-space exchange during beam deflection and acceleration in the cavities.

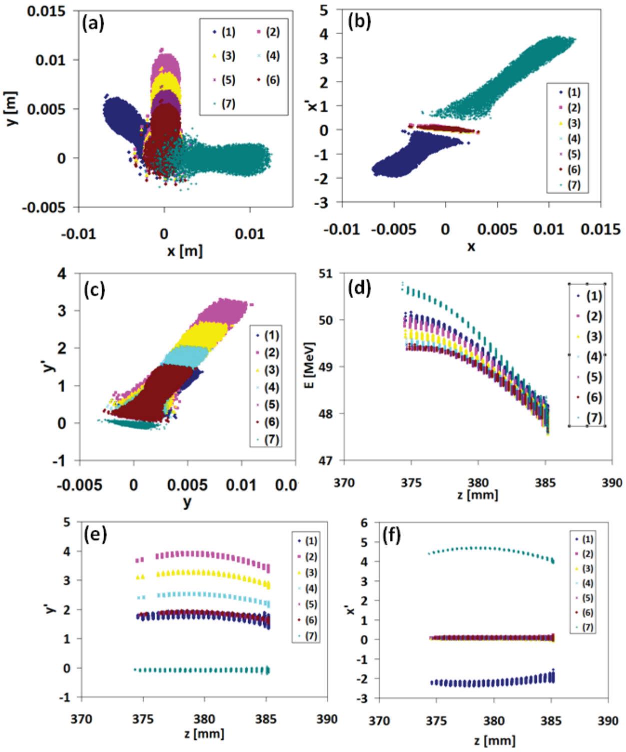

Figure 3: Tracking, (a – c), and PIC, (d – f), simulation results in the Cartesian coordinate, described in the simulation model (Fig. 2) (a) x-y (b) x-x' (c) y-y' (d) z-E (e) z-y' and (f) z-x'

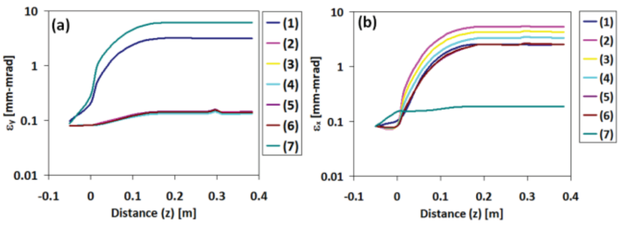

Figure 4: Transverse Beam Emittances (a) ε_y and (b) ε_x along the longitudinal direction with respect to coupling parameters (P$_{max}$(TM$_{010}$)/P$_{max}$(TM$_{110}$))

EXPERIMENTAL PLAN

An experiment aimed at demonstrating the proposed concept is currently under consideration at the ASTA facility. The key objective of this experiment is to complete the physics and conceptual engineering design of a compact PSEX system so that the system can be

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fabricated and assembled and validation experiments performed. We expect that the ASTA facility will be available for the experiment at the appropriate time.

We will begin by briefly reviewing the status and present experimental results of deflecting RF cavity systems. Once the beam physics effort has produced a baseline design for the accelerating cavity combined with the existing 5-cell deflecting cavity and we have the necessary RF coupling information, we will analyze the thermo-mechanical performance of the accelerator system using the system design package and define the required cooling approach for the system. The results will be fed back to the beam physics and RF design efforts to ensure that engineering issues, such as stress and the resultant deformations leading to frequency shifts, are acceptable, or if iteration is required. The thermal analysis will explore the stress levels in the cavity bodies and seek cooling solutions to keep the thermal stresses to manageable levels. The modified coaxial coupler is a key feature of the thermal analysis. Once the analysis is complete and a final candidate configuration exists for the accelerating structure, hybrid RF coupling and beam transport components, we will perform a conceptual design for both the accelerator structure and the balance of the PSEX system such that final engineering design. This conceptual design will address issues associated with integration at the proposed FNAL validation facilities.

For proof-of-principle experiment, the beam produced by an L-band photoinjector will be injected into the 3.9-GHz cavities. In order to measure the z-dependent energy element of the transfer map we use a difference orbit technique: the phase of the 3.9-GHz system is 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 R_{65}. The experiment will allow for a through optimization as the relative field amplitude and phase between the cavities could also be adjusted.

CONCLUSION

Beam dynamics analysis of the hybrid PSEX system has been performed to optimize and analyze the optimal phase-space exchange during beam deflection and acceleration in the cavities. The performance of this work took advantage of RF and tracking/PIC simulation solver, CST MWS/PIC code using the particle-tracking and finite-difference time domain modules. Tracking and PIC simulations incorporated with CST successfully verified the RF system of TM_{110}-TM_{010} mode cavities effectively remove energy spread. RF and tracking/PIC 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 PSEX test system. Currently, we are looking into possible ways to readily demonstrate PSEX using the hybrid deflecting-accelerating cavity system in the ASTA at Fermilab.

REFERENCES

[1] B. E. Carlsten, Nucl. Instrum. Methods Phys. Res., Sect. A 285, 313 (1989).
[2] L. Serafini and J. B. Rosenzweig, Phys. Rev. E 55, 7565 (1997).
[3] Y. Orlov, C. M. O'Neill, J. J. Welch, and R. Sieman, Proceeding of 1991 Particle accelerator Conferences, San Francisco CA, 2838 (1991).
[4] M. Cornacchia and P. Emma, Phys. Rev. ST Accel. Beams **5**, 084001 (2002).
[5] P. Emma, Z. Huang, K.-J. Kim, and P. Piot, Phys. Rev. ST Accel. Beams 9, 100702 (2006).
[6] D. A. Edwards, Editor, Fermilab TM-2060, October 1998.
[7] C. Hovater, et. al., LINAC96, Geneva, Switzerland, 77 (1996).
[8] D. Alesini, "RF deflector-based sub-ps beam diagnostics: application to FELs and advanced accelerators", in Physics and Applications of High Brightness Electron Beams (World Scientific, 2006) Erice, Sicily, 2005; see also J. T. Moody, P. Musumeci, M. S. Gutierrez, J. B. Rosenzweig, and C. M. Scoby, Phys. Rev. ST Accel. Beams 12, 070704 (2009).
[9] R. Akre, L. Bentson, P. Emma, and P. Krejcik, “A Transverse RF deflecting structure for bunch length and phase space diagnostics,” Proc. 2001 Particle Accelerator Conf., Chicago, June 2001, (2001) 2353.
[10] P. Piot, D. R. Douglas, and G. A. Krafft, Phys. Rev. ST Accel. Beams 6 030702 (2003).
[11] Zholents and M. Zolotorev, “New type of a bunch compressor and generation of a short wave length coherent radiation”, LBNL CBP Seminar (2010); see also Argonne National Laboratory Report No. ANL/APS/LS-327 (2011); see also http://accelconf.web.cern.ch/accelconf/PAC2011/talks/tuocn6_talk.pdf
[12] D. Xiang, A. Chao, Phys. Rev. ST Accel. Beam*s* 14, 114001 (2011).
[13] Y.-M. Shin, P. R.-G. Piot, and M. Church, Proc. 2012 International Particle Accelerator Conf., New Orleans, (2012), TUPPC045.

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