ANALYSIS AND OPTIMIZATION OF COUPLER KICK IN APEX*

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Abstract

A high repetition rate (~MHz) and high brightness photoinjector, based on VHF band CW normal conducting (NC) RF gun, is being developed under Advanced Photoinjector EXperiment (APEX) at Lawrence Berkeley Lab. A NC 30 MeV L-band linac system will be added after the gun to demonstrate beam brightness with lower repetition rate (~10 Hz). In this paper, coupler kicks from APEX buncher and acceleration cavities are evaluated by 3D RF simulation, analytical model and beam tracking, and coupler cells are optimized to minimize emittance dilution due to coupler kicks.

INTRODUCTION

The Advanced Photo-injector Experiment (APEX) is for demonstration of MHz repetition rate high brightness electron beam (~300 pC, ~0.6 mm mrad) injection for the next generation high repetition rate X-ray free electron lasers [1]. APEX is staged in 3 phases. In phase 0, the VHF-band normal conducting RF gun was successfully conditioned to achieve CW operation at nominal beam energy (750 keV) with low vacuum pressure performance (10^{-11} – 10^{-9} Torr). In phase I, a 6D beam phase space characterization will be conducted at 750 keV in CW mode. In phase II, a NC 30 MeV linac will compress and accelerate the beam to reduce space charge effects, so that beam brightness will be more reliably characterized. The APEX beamline is shown in Fig. 1.

The designs of buncher cavity and booster cavity are based on the ALS harmonic cavity and the ANL-AWA acceleration cavity respectively [2, 3], as shown in Fig. 2, both of which are not optimized for low energy and low emittance photoinjectors in terms of coupler kick. The RF input coupler breaks cylindrical symmetry of acceleration field and induces RF multipoles, which may perturb beam alignment and emittance compensation. Such effects can be even worse for beam near the gun due to relatively lower beam energy and thus bigger beam sizes, and has been taken care of in previous low emittance photoinjectors [4-9].

In the following, the RF coupler kicks will be evaluated for the APEX buncher and acceleration cavities through both simulations and simplified analytical models, and geometry modifications are suggested and evaluated.

ANALYTICAL EVALUATION OF COUPLER KICK EFFECT

RF coupler induced emittance growth has been well investigated during the development of low emittance photoinjectors [4-9]. Here a simplified analytical model is used to summarize the coupler kick effects when beam travels through a coupler cell (Fig. 2). Inside the model, only RF force is considered and beam size inside the cell is assumed to be relatively constant. The longitudinal paraxial electric field is expressed as follows:

$$E_z(x,y,z,t) = E_z(x,y,z)e^{i(\omega_0 t+\varphi_0+\Delta(x,y,z))}. \quad (1)$$

where amplitude asymmetry is included in $E_z(x,y,z)$,and phase asymmetry is included in $\Delta(x,y,z)$. $\varphi_0 = 0$ is defined as maximum acceleration phase.

Considering first order phase asymmetry and amplitude asymmetries induced by dipole and quadrupole, RF phase and amplitude can be expressed as,

$$\Delta(x,y,z) = k_y y . \quad (2)$$

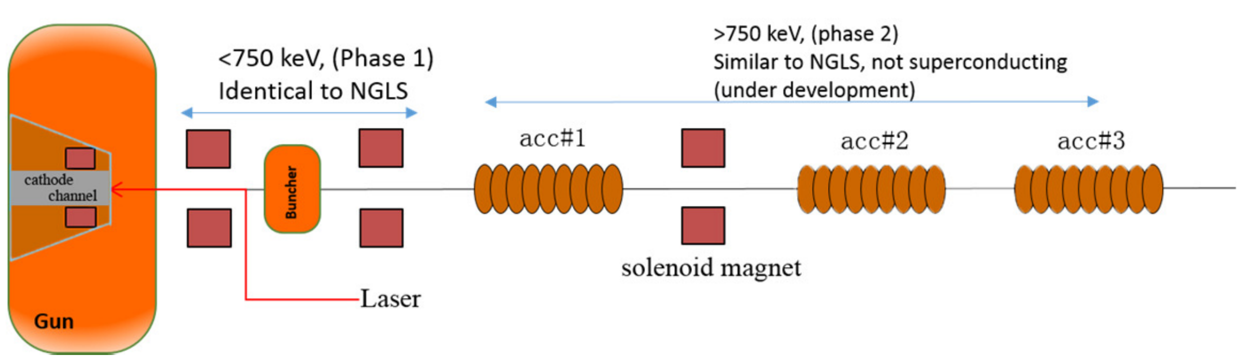

Figure 1: Schematic of the APEX injector beamline. Phase 1 is currently under operation. Phase 2 under development.

**This work was supported by the Director of the Office of Science of the US Department of Energy under Contract no. DEAC02-05CH11231

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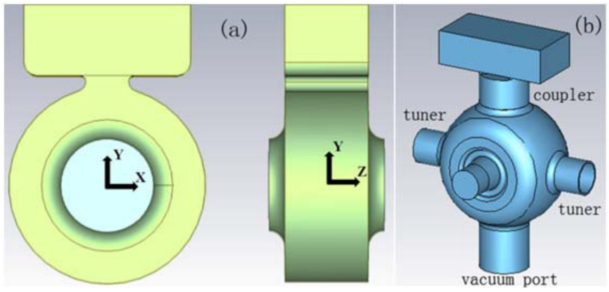

Figure 2: (a) Coupler cell of ANL-AWA cavity, (b) APEX buncher scaled from ALS harmonic cavity.

$$E_z(x,y,z) = E_0 \cos(kz)(1 - a_0(x^2+y^2) + a_1\, y - a_2(x^2-y^2)) \quad (3)$$

where E_0 is the peak axial acceleration field, a_0, a_1 and a_2 are monopole, dipole and quadrupole coefficients, k_y is first order phase gradient.

RMS normalized projected emittance growth can be formulated as,

$$\Delta\varepsilon_{n,x}^{monopole} = \Delta\varepsilon_{n,y}^{monopole} = a_0\alpha\lambda\sigma_x^2\sigma_\varphi \cos\varphi_0 . \quad (4)$$

$$\Delta\varepsilon_{n,y}^{dipole} = \frac{1}{2} a_1\alpha\lambda\sigma_y\sigma_\varphi \cos\varphi_0, \;\; \Delta\varepsilon_{n,x}^{dipole} = 0 . \quad (5)$$

$$\Delta\varepsilon_{n,x}^{quadrupole} = \Delta\varepsilon_{n,y}^{quadrupole} = a_2\alpha\lambda\sigma_x^2\sigma_\varphi \cos\varphi_0 . \quad (6)$$

$$\Delta\varepsilon_{n,y}^{phase} = \frac{1}{2} k_y\alpha\lambda\sigma_y\sigma_\varphi \sin\varphi_0 \;\; \Delta\varepsilon_{n,x}^{phase} = 0 . \quad (7)$$

where $\alpha = \frac{eE_0}{2mc^2k}$, λ is RF wavelength (twice coupler cell length), k is RF wave number, σ_x and σ_y are transverse RMS beam sizes, σ_φ is longitudinal RMS bunch length measured by RF phase. The total emittance growth is,

$$\Delta\varepsilon_{n,x} = \Delta\varepsilon_{n,x}^{monopole} + \Delta\varepsilon_{n,x}^{quadrupole} . \quad (8)$$

$$\Delta\varepsilon_{n,y} = \sqrt{\begin{array}{l}(\Delta\varepsilon_{n,y}^{monopole} - \Delta\varepsilon_{n,y}^{quadrupole})^2 \\ +(\Delta\varepsilon_{n,y}^{dipole} - \Delta\varepsilon_{n,y}^{phase})^2\end{array}} . \quad (9)$$

RF SIMULATIONS

The preliminary APEX buncher cavity design (1.3 GHz) is scaled from ALS harmonic cavity (1.5 GHz), as shown in Fig. 2, and has a single waveguide coupler, a symmetric vacuum port and two RF tuner ports. The ANL-AWA cavity is a 1.3 GHz 7-cell standing wave cavity, and the RF power is fed into the cavity by a single waveguide coupler (Fig. 2). In order to feed the 7 cells, the coupling slot is big, which is expected to greatly distort the cylindrical field symmetry in coupler cell.

Coupler Kick Evaluation

CST Microwave studio is used to simulate 3D RF field map, and RF field in the middle plane of coupler cell is used to extract amplitude and phase asymmetry coefficients, as shown in Table 1. Eq. (5) to (7) are used to do a quick emittance growth evaluation based on Table 1 and one specific beamline optimization solution for 300 pC operation from ASTRA simulation [10, 11], as shown in Table 2.

Table 1: Amplitude and phase asymmetry coefficients

	Buncher	**AWA cavity**
a_1 (m^{-1})	0.007	0.9
a_2 (m^{-2})	8.7	1.4
k_y (mrad/m)	3.0	17

Table 2: Emittance growth (in mm mrad) evaluations for one APEX solution with 300 pC beam charge

	Buncher	**ACC #1**	**ACC #2**	**ACC #3**
$\Delta\varepsilon_{n,y}^{dipole}$	0.02	4.9	1.4	1.2
$\Delta\varepsilon_{n,x\ or\ y}^{quadruple}$	0.28	0.02	0.003	0.002
$\Delta\varepsilon_{n,y}^{phase}$	0.03	0.005	0.06	0.03

Table 2 shows coupler kick gives significant emittance growth in both buncher and acceleration cavities. Buncher cavity is dominated by quadrupole, and AWA cavity is dominated by dipole.

Coupler Cell Optimization

To minimize quadrupole in buncher cavity, tuner ports are made to be the same size as coupler port and vacuum port, and tuners are removed or retracted. To minimize dipole and phase asymmetry in AWA cavity, symmetric dual RF coupler is added (Fig. 3), and coupler size is tuned to restore the original power coupling factor. CST simulations show though dipole is minimized, quadruple is enhanced by an order of magnitude, so two dummy ports are added at 90 degree relative to coupler port to suppress quadrupole. Comparison between original and modified AWA coupler cell is displayed in Fig. 3.

After coupler cell optimization, with the same beamline settings as in Table 2, Eq. (5) to (7) predict coupler induced emittance growth are well below 0.05 mm mrad for both buncher and acceleration cavity.

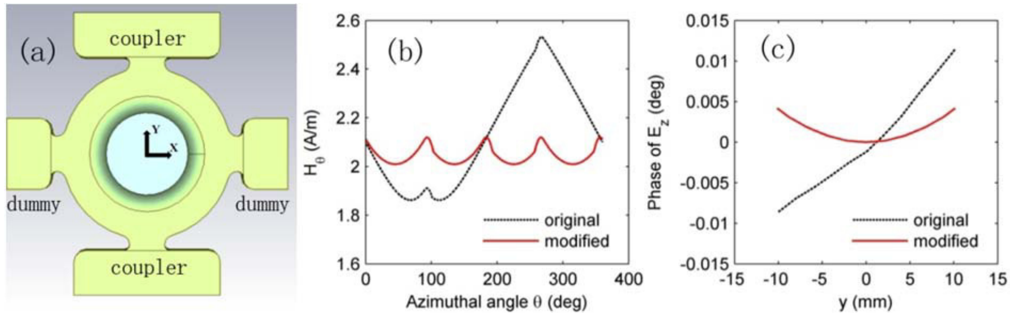

Figure 3: (a) 4-port optimization of AWA coupler cell, (b) azimuthal magnetic field amplitude at radius of 10 mm in central plane of coupler cell (z=0), (b) RF phase of E_z along line x=0 in plane z=0.

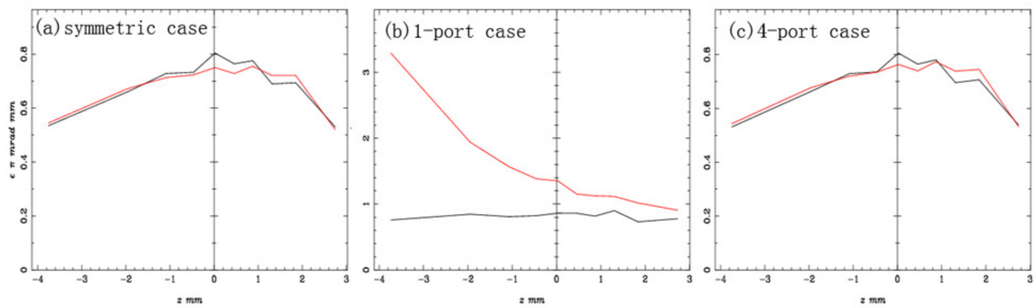

Figure 4: Slice emittance (x: blac, y: red) at ACC #3 exit (~14 MeV) for (a) symmetric map, (b) 1-port map, (c) 4-port map

BEAM TRACKING SIMULATIONS

To include both RF and other forces (space charge, solenoid focusing et al.), the 3D RF field maps from CST can be used in ASTRA simulations of the APEX beamline. In the following, three field maps of AWA cavity are used for one solution of the ongoing optimization process for the APEX beamline, as shown in Fig. 4. The "symmetric" case is based on input of the on-axis E_z field in ASTRA. In this case, ASTRA expands the fields E_r and B_φ around the axis up to 3rd order. This is by construction azimuthally symmetric and no emittance growth due to multipole field is possible. The "1-port" and "4-port" cases refer to 3D field maps based on the optimization described previously. Fig. 4 confirms the original AWA cavity (1-port) will cause huge emittance growth and the optimized AWA cavity (4-port) almost removes all coupler kicks.

CONCLUSION

Coupler kicks in the APEX injector are studied by RF simulation, analytical model and beam tracking, and huge emittance growth is found due to improper coupler cell designs of buncher and acceleration cavities. After symmetry optimization of coupler cell, coupler kicks are minimized and confirmed by ASTRA simulations.

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ISBN 978-3-95450-138-0