EMITTANCE EXCHANGE BEAMLINE DESIGN IN THU ACC LAB

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Abstract

Emittance exchange (EEX) provides a novel tool to enhance the phase space manipulation techniques. This study presents a beamline design for exchanging the transverse and longitudinal emittance of an electron bunch based on the Tsinghua Thomson scattering experimental facility. This beamline consists of a 2.856 GHz half-one-half cell deflecting cavity with no axis offset and two doglegs. In this paper, by optimizing the beam envelope parameters for Tsinghua Thomson scattering source, we report the theoretical analysis and a good particle tracking simulation result about emittance exchange and longitudinal shaping.

INTRODUCTION

Since the emittance exchange (EEX) concept was firstly came up with in 2002 [1], lots of researches have been developed to optimize the exchange result for different applications. Theoretical analysis for identical dogleg-type exchanger presented an exact result contrast to chicane-type in 2006 [2]. A proof-of-principle transverse and longitudinal emittance exchange experiment conducted at Fermi Lab demonstrates the feasibility of EEX theory [3]. Although the initial motivation for EEX aims to attain an optimized transverse emittance for FEL, a significant innovation proposed in [2] and [4] which provide a novel tool for advanced phase space manipulation really extends the application of EEX and incites a new term research in bunch shaping for many kinds of accelerators. In the wakefield acceleration, a short and low energy but high current drive beam can create high gradient fields to accelerate trailing bunch. A novel shaped drive bunch to enhance the transformer ration which can extremely increase the acceleration efficiency has been proposed in Argonne AWA group based on EEX [5]. Now the experiment to achieve this specific shaped bunch is being conducted at Argonne. A similar beam shaping using emittance exchanger is presented in LANL [6].

Tsinghua University has been constructed a Thomson Scattering X-ray (TTX) beamline in 2009 [7], which aims at an ultra-fast, high flux, and tuneable X-ray source for advanced imaging applications. Based on this experimental facility, we design an EEX beamline to use RF deflecting cavity for bunch longitudinal shaping. Whether to shape electron bunch for wakefield accelerator or for tuneable subpicosecond electron bunch train generation [8], this EEX technique can be the spectacular tool in accelerator physics.

This paper is organised in three parts, firstly we report

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the theoretical design of EEX beamline based on TTX, and secondly we introduce the half-one-half deflecting cavity designed for EEX, finally the particle tracking simulation of emittance exchange and bunch shaping using this beamline is presented.

ANALYTIC TRANSFER MATRIX

Generally, two identical doglegs sperated by a deflecting cavity consist the main components of EEX beamline. The transfer matrix of dogleg and deflecting cavity in first order can be written as

$$M_{DL} = \begin{bmatrix} 1 & L_{DL}/2 & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi/2 \\ 0 & 0 & 0 & 1 \end{bmatrix}, M_C = \begin{bmatrix} 1 & L_C & kL_C/2 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & kL_C/2 & k^2 L_C/n & 1 \end{bmatrix} \quad (1)$$

Where $L_{DL}, \eta, \xi, L_c, k$ denote respectively the whole length of two doglegs, dispersion, compression of one dogleg, and length, dimensionless strength of deflecting cavity. The factor n is related to the effective deflecting cavity length, and n equals 4 for one pill-box cavity. When particles pass through the dogleg, their horizontal and longitudinal momentum has an impact of dispersion η on their longitudinal and horizontal position respectively. Similarly, deflector relates the initial longitudinal and horizontal position to final horizontal and longitudinal momentum. On the condition that $1 + k\eta = 0$, this dogleg type EEX transfer matrix is

$$M_{EEX} = M_{DL} M_C M_{DL} = \begin{bmatrix} 0 & \dfrac{L_C}{n} & m_{13} & m_{14} \\ 0 & 0 & k & \dfrac{k\xi}{2} \\ \dfrac{k\xi}{2} & m_{32} & \dfrac{k^2 \xi L_C}{2n} & \dfrac{k^2 \xi^2 L_C}{4n} \\ k & m_{42} & \dfrac{k^2 L_C}{n} & \dfrac{k^2 \xi L_C}{2n} \end{bmatrix} \quad (2)$$

Where m_{ab} represents the function of parameters in expression (1). In order to achieve the exact phase space exchange (PSEX), additional quadrupoles are needed before the first dogleg so that we can shape the bunch to some specific shape. Figure 1 is the schematic of this beamline. In our design, by using four quadrupoles, we can transform the left bottom sub matrix of matrix M to an approximate identical matrix, so the final transfer matrix of our beamline can be written as

$$M_{PSEX} = \begin{bmatrix} 0 & m_{12} & m_{13} & m_{14} \\ 0 & 0 & m_{23} & m_{24} \\ m_{31} & 0 & \sim 0 & \sim 0 \\ 0 & 1/m_{31} & \dfrac{k^2 L_C}{n} & \dfrac{k^2 \xi L_C}{2n} \end{bmatrix} \quad (3)$$

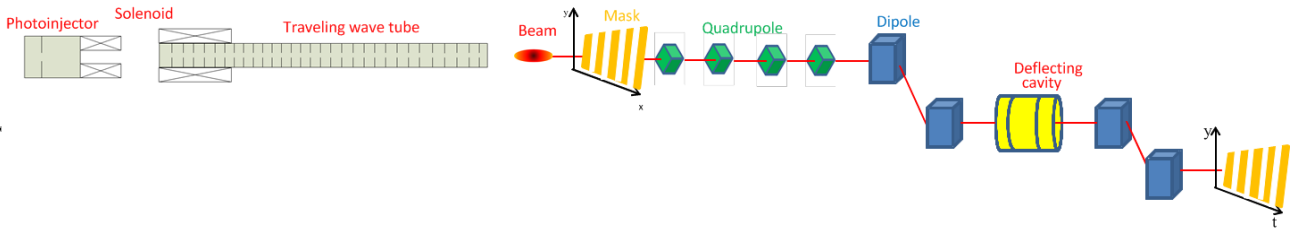Where ~0 denotes a small quantity approximating zero. Eq.3 explains that on the first order approximation, initial

Figure 1: The schematic of EEX beamline desgin in THU.

beam profile in x position can be projected to final z position with a stretch factor m_{31}.

$$z_f = m_{31} x_i \qquad (4)$$

It implies that if we want to shape the bunch longitudinally, we can shape it transversely with some masks instead, which has more flexibility and feasibility.

DEFLECTOR DESGIN

The reference particle transverse motion in a TM110 mode deflector can be described as:

$$\frac{dp_x}{dz} = -\frac{kW}{c} \sin\left(\frac{2\pi}{\lambda} z\right) \qquad (5)$$

For a $\lambda/2$ pill-box cavity, integrate (5)

$$x - x_{in} = \frac{k\lambda^2}{4\pi^2} \qquad (6)$$

It shows that an off-axis effect has influence on the reference particle trajectory, which will result in an inexact exchange. This off-axis effect is proportional to the strength of deflector which is determined by the beam energy. To achieve an exact transverse and longitudinal profile exchange, we designed a half-one-half type S-band deflector as shown in Fig.2 to compensate this effect [9]. Figure 3 is the reference particle trajectory in this deflector.
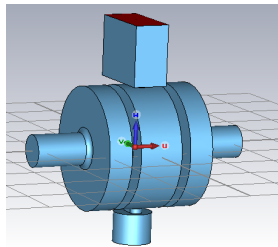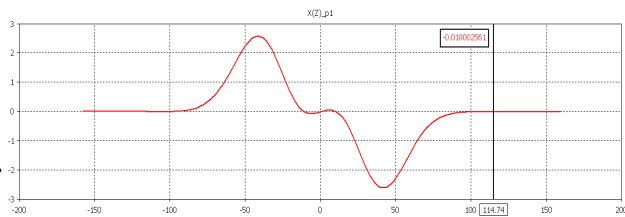

Figure 2: S-band deflecting cavity for EEX.

Figure 3: No off-axis reference particle trajectory.

SIMULATION RESULT

As shown in Fig. 1, there are an S-band 1.6 cell photocathode RF gun and a 3-meter long travelling wave

accelerating tube with 85 cells working at $2\pi/3$ mode in TTX platform. Based on these facilities, we simulate the beam dynamics of EEX using Parmela code. During the simulation, the space charge effect is taken into consideration, and however, CSR is not included. Considering the room space limitation, this EEX beamline is more compact with whole length not exceeding 3 meters. The parameters of some crucial components are listed in Table 1:

Table 1: Parameter of EEX

No.	Element name	Length (mm)	Value of parameters
1	Quadrupole	100	942.38 gauss/cm
2	Quadrupole	100	526.41 gauss/cm
3	Quadrupole	100	-610.39 gauss/cm
4	Quadrupole	100	464.67 gauss/cm
5	dogleg	700	Bending angle 20 deg, Bend length 150 mm, Drift length 400 mm
6	Deflector	218	2.44 MV

Using these parameters, we can figure out the dispersion and compression in dogleg

$$\begin{cases} \eta = \dfrac{L_D \sin\theta + 2\rho\cos\theta(1-\cos\theta)}{\cos^2\theta} = 0.2112\, m \\[2mm] \dfrac{\xi}{2} = -2\beta^2\theta\rho + 2\rho\tan\theta + L_D\tan^2\theta = 0.0661\, m \end{cases} \qquad (7)$$

L_D, β, θ, ρ denote respectively the drift length in dogleg, relative velocity, bend angle and bend radius. By utilizing a gaussian laser in cathode, the bunch parameters after TWT list as below:

Table 2: Parameter of Beam after TWT

Parameter	Value	Parameter	Value
Twiss α_x	-1.31	$\gamma\varepsilon_x$	2.61 um
Twiss β_x	1.10 m	$\gamma\varepsilon_y$	2.61 um
Twiss α_z	-0.11	$\gamma\varepsilon_z$	62.51 um
Twiss β_z	0.44 m	Charge	500 pC
Energy W_0	30.2 MeV		

Comparing the phase space at input and output of EEX, we observed that transverse position profile is transformed into final longitudinal position profile. A grating structure mask is placed before the first quadrupole, which can cut the beam to slices in x direction. Figures 4 and 5 present a desirable result that

the slice structure has exchanged to longitudinal position. And the particles density statistics of final z direction is extremely similar to initial x direction. Actually, according to the numerical matrix analysis, the relationship between z_f and x_i is

$$z_f \approx 0.89 x_i \qquad (8)$$

It proves that specific longitudinal profile can be easily attained by modulating transverse profile proportionally.
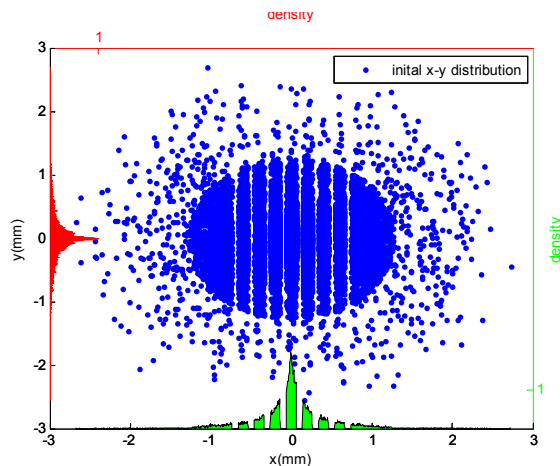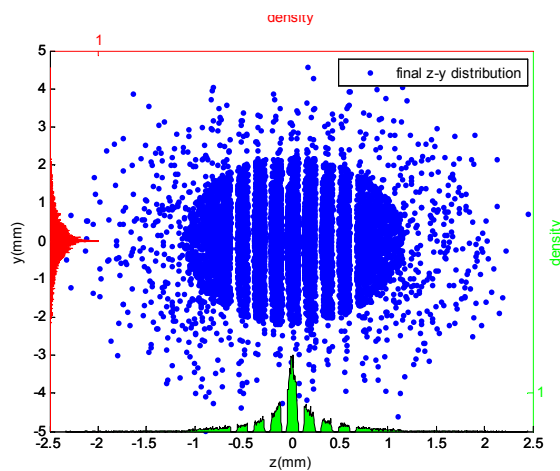

Figure 4: x-y plane beam profile at input of EEX.

Figure 5: z-y plane beam profile at output of EEX.

DISCUSSION

The simulation of this EEX design indicates that with this compact beamline in THU accelerator lab we can generate specific longitudinal profile of the electron bunch to promote accelerator application. For example, if the interval of the mask refered to in Fig. 4 is at the range of 0.1 mm, the bunch train at the output of EEX can be used to gernerate THz radiation.

Due to the condition that $1 + k\eta = 0$ and the deflector dimensionless strength k is proportional to the deflecting voltage, the power of deflector is constrained by dogleg dispersion for the same electron energy. Considering our lab room space limitaion, the dispersion can not expand by lengthen drift in dogleg. So the only way for us the

decrease the deflector power is to enlarge the bend angle. Now we already have two doglegs in THU accelerator lab, and the max design bend angle, which is used in the simulation, is 20 degrees.

We also have simulated larger charge such as 1 nC using the same structure, the EEX result preforms well in spite of the enhancement of space charge effect. However, if manipulating a larger charge, the CSR must take into account. If the interval is too fine, it may be not distinguished on the output longitudinal profile. Although first order analysis points out that the beam profile parameters (Twiss parameter) at the input have little influence on the performance of transvers and longitude exchange, high order calculation will impact it indeed. So it is better to select a proper phase for TWT to force the bunch α_x and α_z approaching zero to attain a small divergence in transverse and longitudinal phase space.

We use the matrix calculation to figure out the each quadrupole strength, and find that for a specific stretch factor m_{31} the strength of four quadrupole can only be selected in a specific range. So it seems that we need a new approach to assure the strength when conducting experiment. We also find that in our simulation, if the strench factor m_{31} is too large, there will be some particles lost in the deflecting cavity and the strength of quadrupole is too large. The reason for that phenomenon may be that the four quadrupoles has defocusing the beam spot in y direction so that the beam spot is larger than the deflector beam pipe. So it is better to design the beam pipe of deflector as big as possible. In our simulation, we choose m_{31} to be 0.9 for a reasonable quadrupole strength and beam pipe size.

CONCLUSION

We have designed a compact EEX beamline in Tsinghua University accelerator lab based on the TTX facility. The simulaiton result shows a good agreement with the matrix analysis. We can shape the bunch longitudinal profile as we want. It can be an applicable tool for us to enhance the beam phase space manipulation and to extend the application of accelerators in our lab. We already have two doglegs and the deflector will be completed design soon, the experiment is planned to proceed at the end of this year.

ACKNOWLEDGMENT

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