DESIGN OF INJECTION AND EXTRACTION BEAMLINES FOR THE ALPHA PROJECT*

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Abstract

The Advanced eLectron-PHoton fAcility (ALPHA) is under construction to support Crane Naval Center's radiation effect testing program. This paper reports the design of injection and extraction beamlines for the ALPHA facility and discusses the nonlinear beam folding which is used to convert a transverse Gaussian beam distribution into an uniform rectangular beam distribution.

INTRODUCTION

The ALPHA facility consists of an electron linac and an electron storage ring to provide uniform intense beams for radiation test, and it has a potential to be a future X-Ray source. The ring uses four dipoles from the Cooler Injection Synchrotron (CIS) [1], which was constructed for proton acceleration from 7 MeV to 240 MeV. The circumference of the ALPHA storage ring is 20 m, and its lattice has an adjustible momentum compaction factor by changing the field strength of a pair of gradient damping wigglers [2]. For the proof of working principles, we use a refurbished 20 MeV CLINAC as the injector. The CLINAC will be upgraded to a 50 MeV linac by the end of 2011. Two operation modes (debunching and accumulation modes) [3] are currently planned for the ALPHA facility. For the debunching mode, two magnetic kickers are located at symmetric positions with respect to the Lambertson magnet. When the magnetic kickers are turned at 24 mrad, the closed orbit of the storage ring passes through the Lambertson magnet, and thus the injected beam is extracted in a single pass. In this case, the storage ring can be considered as a big α–magnet for debunching. For the beam accumulation mode, the magnetic kicker's power supply is designed to have 500 ns decay time (beam revolution time in ring is 66 ns). The closed orbit is gradually moved back to designed orbit during injection so that multi-turn accumulation can be achieved in this way. In this paper, we describe the design concepts of the injection and extraction beamlines to maximize beam transport and to satisfy desired beam properties.

INJECTION BEAMLINE

Figure 1 shows the layout and components of injection beamline, and its beam parameters are summarized in Table 1. The beamline consists of two 45° horizontal dipoles, a 20° vertical bending magnet, a 20° Lambertson magnet and nine quadrupoles for optical matching. The Lambertson septum magnet is located at the center of the ALPHA storage ring. The injection channel is about 32 mm away from the center of the beam orbit. The height of linac beamline is determined by the 20° dipole in the injection beamline. Two 45° dipoles are used to accomodate the linac in a limited tunnel space. The vacuum chamber aperture in the 20° dipole is 23.4 mm, while it is 47.6 mm in most other regions of the injection beamline.

Table 1: Parameters for Injection Beamline

Parameter	Value
at the entrance of the injection beamline	
minimum beam energy	20 MeV
charge	50 pc
energy spread $\Delta E/E$ (peak-to-peak)	20%
normalized emittance (rms)	5 mm-mrad
horizontal β-function	50 m
vertical β-function	50 m
transverse beam distribution	Gaussian
at the exit of the injection beamline	
charge with phase-II linac	$\geq$ 23.8 pc
minimum beam energy	20 MeV
maximum beam diameter	22.3 mm
horizontal dispersion	1.583 m
vertical dispersion	0 m
energy acceptance $\Delta E/E$ (peak-to-peak)	1.4%
horizontal β-function	0.533 m
vertical β-function	3.378 m

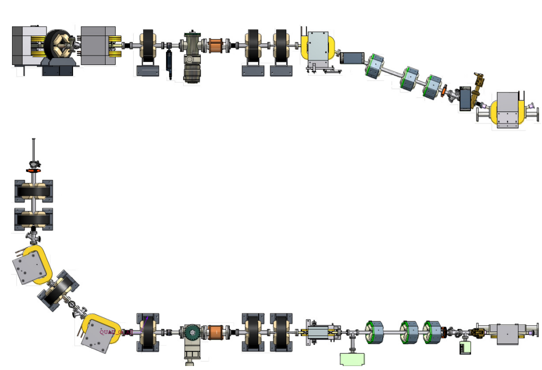

Figure 1: Side-view (top) and top-view (bottom) of the injection beamline from linac (left) to Lambertson (right).

Beams from medical linac have a large energy spread and a large emittance. This makes the design of our injection beamline more difficult. Generally, beam size is a function of the emittance and the dispersion by σ =

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$\sqrt{\beta\epsilon + D^2\delta^2}$, where β is the β-function, ϵ is the unnormalized emittance, D is the dispersion function, and δ is the energy spread. The estimated energy spread of a typical medical linac is about 20% (peak-to-peak) as shown in Table 1. Thus the beam size is dominated by the momentum spread, and we need to minimize the dispersion function throughout the beamline while match it to the ring. Since the momentum acceptance is 1.4% (peak-to-peak) at the Lambertson magnet due to the large horizontal dispersion of 1.583 m, we collimate the large beam energy spread by a slit located between two 45° dipoles.

We use MAD [4] and ELEGANT [5] codes to carry out beamline design. The optimized lattice is shown in Fig. 2. In Table 1, there are our assumed linac parameters for optics matching and design of the injection beamline. But during commissioning, the injection beamline will be re-optimized by using the measured linac parameters. As shown in Figs. 1 and 2, we keep β-functions small before collimation to reduce the chromatic effect. A screen is installed between the second quadrupole and the first 45° dipole to measure the transverse emittance by quadrupole scanning method. Two 45° bending magnets steer the beam orbit to the left by 90°. A third quadrupole is used to control horizontal dispersion downstream and can be scanned to measure the energy spread with a screen located between the third quadrupole and the second 45° dipole. A differential pumping area starts from the fifth quadrupole to the seventh quadrupole thus beam size is strictly controlled by the three quadrupoles between 45° horizontal bending magnet and 20° vertical one. As shown in Fig. 2, dispersion and β-functions are minimized in the differential pumping area. The last three smaller quadrupoles are used to minimize the maximum dispersion and match the Twiss parameters to ring. A wall current monitor is installed between the fourth and the fifth quadrupoles to measure beam current and the third screen is installed between the last quadrupole and the Lambertson magnet for the final beam steering.

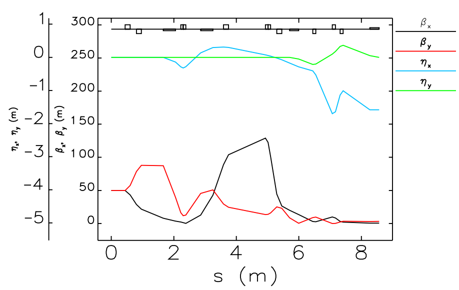

Figure 2: Twiss parameters along the injection beamline from linac to ring.

Many issues are being considered. Magnets alignment and power supply jittering are studied by performing error simulations and we found that their impact is small. One important thing is the chromatic effect before the slit due to the large energy spread. It increases the transerve emittance and gives a limitation in our emittance measurements. Longer distance between the first quadrupole and the screen will improve the situation. Within 2010, we will measure the beam emittance and momentum spread of the linac beams for the optics matching between linac and the ALPHA storage ring.

EXTRACTION BEAMLINE

For radiation effect tests, it is preferable to prepare beams with a uniform transverse beam distribution. Our design goal is to provide a square beam with at least 4 cm $\times$ 4 cm transverse beam size, and beam intensity fluctuation across this area should be within $\pm 10\%$. We choose to use octupoles for nonlinear beam folding instead of the collimation method. This method can increase the uniformity and avoid radiation background due to the collimation.

Similar to the injection beamline, dispersion and β-functions are matched between ring and extraction beamline and controlled by quadrupole triplets and doublets. Figure 3 shows the Twiss parameters along the beamline. Two octupoles at 7.8 m and 9.2 m are placed in a long straight section with zero dispersion as shown in Fig. 3. Since the folding angle by octupoles is proportional to the cubic power of displacement ($\Delta x' \propto x^3$) [6], the ratio between the horizontal β-function and vertical β-function should be large at these octupole positions to fold beam only in one direction. Figure 4 shows the calculated beam envelope along the extraction beamline. The optimized beam distributions of nonlinear folding are shown in

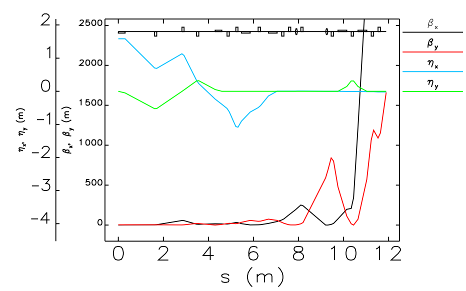

Figure 3: Twiss parameters along the extraction beamline from ring to test area.

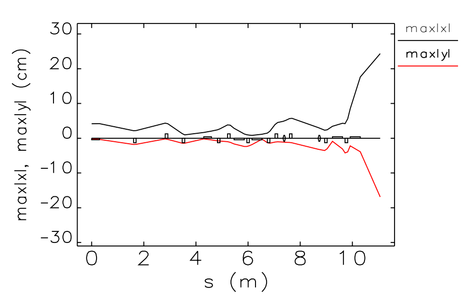

Figure 4: Beam envelope along the extraction beamline.

Fig. 5, where Gaussian beam distribution was assumed to carry out tracking simulation. We optimized the lattice for the extraction beamline to keep beam intensity fluctuation within $\pm 10\%$ in the central region. As shown in Fig. 4, the

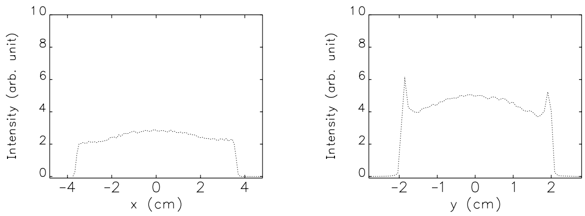

Figure 5: Transverse beam profile: horizontal (left)-vertical (right) on the test area.

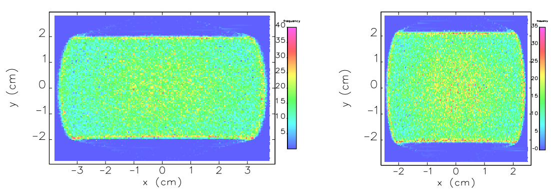

Figure 6: 2D-histograms of transverse beam distribution on the test area when the final two quadrupoles are off (left) and on (right).

large beam size in the last two vertical dipoles induces difficulties in magnet fabrication. We tried to reduce the beam size in dipoles and further added two quadrupoles at downstream of the last bending magnet. Figure 6 shows the 2D histograms at test area when the last two quadrupoles are turned off and on. As shown in Fig. 6, we can control the final beam size on the test bench by adjusting the last two quadrupoles.

COMMISSIONING PLAN AND STATUS

Since March 30 2010, we have been working for the commissioning of the injection beamline. The beamline has been installed and the beam was transported downstream to reach the Lambertson. Figure 7 shows the first beam observed on the first screen. During the emittance measurements for the optics matching, we met the beam steering problem due to a big misalignment of the scanning quadrupole. To figure out this misalignment, we scanned the quadrupole and measured offset on the screen according to a relation $\Delta x = K_1 L x_{\rm co} s$, where $K_1 L$ is the integrated field strength of the scanning quadrupole, Δx is the offset at the screen, s is the distance from the quadrupole to the screen and $x_{\rm co}$ is the closed orbit offset at the quadrupole with respect to the center of quadrupole. Figure 8 shows the measured steering angle θ versus $K_1 L$. The slope is the misalignment of quadrupoles. The measured misalignments are 2.4 mm in the horizontal direction

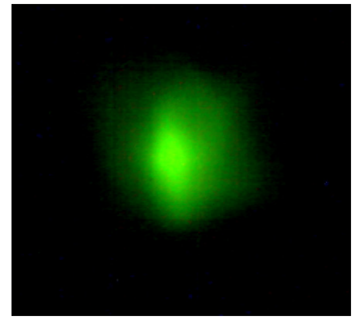

Figure 7: Beam image at the first screen right before the first 45 degree dipole.

and 1.5 mm in the vertical direction as shown in Fig. 8. After aligning the quadrupole according to the measured values, beam steering due to quadrupole misalignment was corrected. Therefore, we can measure the beam transverse emittance properly by scanning the quadrupole.

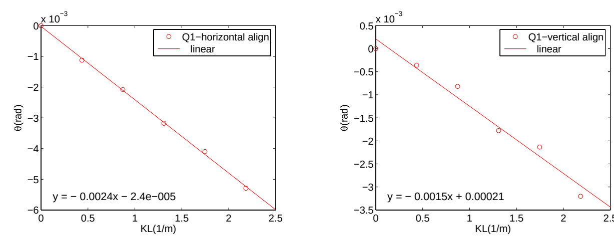

Figure 8: Steering angle vs integrated quadrupole strength: the horizontal (left) and vertical (right) misalignment of the first quadrupole.

SUMMARY

For the ALPHA project, we have designed the injection beamline to keep the beamsize along the transport line small and to get an optics matching from the exit of the linac to the entrance of the Lambertson magnet. To reduce the chromatic effect due to a large energy spread of 20% (peak-to-peak), we keep Twiss parameters small and strength of quadrupoles weak along the beamline. A nonlinear beam folding method is used in the extraction beamline to provide uniform beam profiles for the radiation effect testing experiments. We will reduce the rabbit ears at the edges to improve the uniformity. Commissioning of the ALPHA project is on-going.

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