

## COUPLED PARTICLE MOTION IN THE CIAE CRM PULSED INJECTION LINE\*

Shizhong An<sup>1</sup>, Tianjue Zhang<sup>1</sup>, Klaus Bongardt<sup>2</sup>, Sumin Wei<sup>1</sup>  
<sup>1</sup> China Institute of Atomic Energy, Beijing, 102413, P.R. China  
<sup>2</sup> Forschungszentrum Juelich, 52425 Jülich, Germany

### Abstract

The 10 mA, 40keV H- pulsed injection line for the CIAE 10 MeV CRM cyclotron has two main operation modes for bunched beams: delivering 5 mA CW beam or chopped pulse with more than 100uA. Chopped pulse is achieved by placing behind the 70.5 MHz bunching cavity a sinusoidal transverse deflecting cavity with frequency of 2.2 MHz, 1/32 of the bunching frequency. Particles outside the wanted  $\pm 3^\circ$  phase width @ 2.2 MHz, corresponding to  $\pm 90^\circ$  @ 70.5 MHz, are either absorbed in a 50cm drift after chopper or at round slit1, 1cm aperture. Time dependence of sinusoidal chopping field causes RMS emittance increase by a factor 3 and changes twiss parameter alpha by a factor 2 before the round slit1. Solenoid couples motion in transversal planes, but equalizes both RMS emittances. Particle tracking results are presented for the chopped pulse, showing longitudinal-transverse coupling in the deflector and equalization of RMS emittances in the solenoid. Optimised focusing strength leads to about 1% transmission efficiency for the chopped pulse. The CRM inflector receives 2.4 ns long pulse at about 4.4 MHz repetition rate, 1/16 of the RF frequency.

### INTRODUCTION

A 40 keV H- transport line for bunched and chopped beams is being constructed at China Institute of Atomic Energy (CIAE), injecting into 10 MeV Central Region Model (CRM) compact cyclotron. Radial symmetric H<sup>-</sup> beams are transported by ESQQ focusing structure to the entrance of the CRM cyclotron. Final matching for the required asymmetric phase space distributions is done by quadrupole doublet system. Same ESQQ focusing system is also used for the chopped bunch, but phase space areas are coupled by the solenoid. In order to get good longitudinal matching with the RF acceptance of the CRM cyclotron, the cyclotron frequency of 70.5 MHz is chosen as the frequency of buncher.

### CIAE'S CRM INJECTION LINE

Figure 1 shows the injection line, which is calculated by code TRACE-3D [1] for the unchopped beam. The sign of Fig.1: FC-Faraday cup, E-Three-aperture einzel lens, SOL-Solenoid, Q-Quadrupoles, STR-Steering magnets, CP-chopper, B0-buncher. This choice leads to a compact and short injection beam line. Assumed is radial

symmetric 10 mA, 40 keV H- beam from the source with total geometrical emittance of  $50\pi$ -mm-mrad. The continuous H- beam from the multi-cusp ion source is focused by the 20kV Einzel lenses into radial waist,  $\beta$  value of 0.5m at entrance of the chopper. Phase advance from chopper to the round slit 1 is  $56^\circ$  [2]. The beam is then transported to the inflector and matched into the transverse acceptances of the CRM cyclotron by the solenoid and the quadrupole doublet.

The parameters of the 70.5 MHz buncher cavity are presented in Ref. [3]. The buncher cavity with 2 cm aperture is placed before the chopper to avoid particle loss. About 1 kV voltage is required to reach upright phase space distribution at CRM injection with phase width of  $\pm 30^\circ$  @ 70.5 MHz and energy spread of  $\pm 1.5$ keV with more than 50% bunching efficiency.

For the chopped pulse, beam envelopes are the same until the entrance of the chopper cavity, radial waist with 5 mm total radius and  $\pm 10$  mrad maximal divergence. Pulse deflection is done in y-direction to limit quadrupole aperture radius to 2.5 cm in spite of  $\pm 20$  mrad kick for the wanted  $\pm 3^\circ$  pulse.

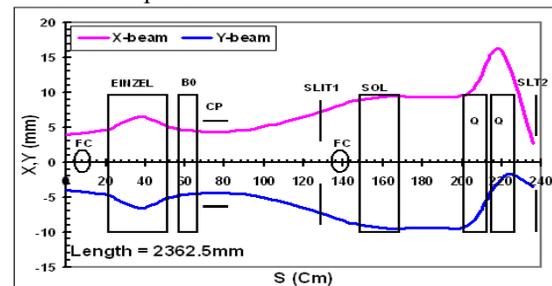


Figure 1: Layout of CRM injection line and beam envelope for the  $50\pi$  mm-mrad unchopped beam.

### LONGITUDINAL-TRANSVERSE COUPLING FOR THE DEFLECTED PULSE

Figure 2 shown geometrical parameters for the transverse deflecting structure with sinusoidal field:

$$V(t) = V_m \cdot \sin(\omega t + \varphi_0) \quad (1)$$

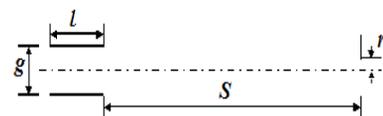


Figure 2: The structure of beam chopper.

\* Research sponsored by the National Natural Science Foundation of China, under contract 10775186.  
 Email: szan@ciae.ac.cn

The equation of motion for particles in the chopper, assuming sinusoidal deflecting field, are:

$$m\ddot{y} = e(V_m/g)\sin(\omega t + \varphi_0) \quad (2)$$

$$(0 < t < t_c)$$

$t_c = l/\beta c$  is the transit time in the chopper.

With  $vdy/ds = dy/dt$  and initial condition  $y_0 = 0, y'_0 = 0$ , we can get from equation (2):

$$\begin{cases} y(l) = \frac{eV_m}{m\omega^2 g} [\varphi_c \cos \varphi_0 - \sin(\varphi_c + \varphi_0) + \sin \varphi_0] \\ y'(l) = \frac{eV_m}{m\omega\beta cg} [\cos \varphi_0 - \cos(\varphi_c + \varphi_0)] \end{cases} \quad (3)$$

and  $\varphi_c = \omega t_c$ . Higher order terms are discussed in Ref. [4]. For CRM injection, we choose the following parameters:  $\beta=0.00923$  ( $E_0=40\text{KeV}$ ),  $c=3\times 10^8$  m/s,  $mc^2=939.28$  MeV (H-),  $f_c=2.2\text{MHz}$ ,  $V_m/g=3$  kV/cm,  $l=10$  cm.

For a sinusoidal deflecting voltage, particle at  $-\varphi_c/2$  initial phase value ends with  $+\varphi_c/2$  phase value, receiving no net angular kick, but getting smaller radial displacement. If the wanted pulse length is  $\Delta\varphi$  after chopper, the particles with initial phase values of  $\pm\Delta\varphi/2$  receive either negative or positive angular kicks. These particles around by  $-\varphi_c/2$  in phase shifted bunch center are wanted for CRM injection. Different  $\varphi_c$  means different length of chopper plate.

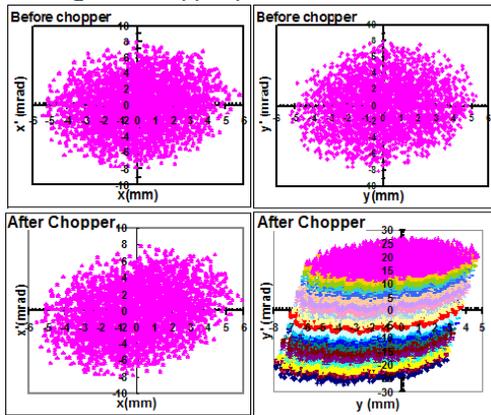


Figure 3: Distribution for the pulse length of  $\Delta\varphi=6^\circ (\pm 3^\circ)$  before and after the chopper.

The accepted bunch length of  $\pm 3^\circ$  @ 2.2 MHz or 7.6 ns is provided by a sinusoidal chopping system, causing longitudinal-transverse coupling. If we choose  $l=10\text{cm}$  and  $V_m/g=3\text{kV/cm}$ , the transit time in the chopper is  $t_c=36\text{ns}$  or  $\varphi_c=0.499$  rad ( $28.6^\circ$ ), then the obtained net kick after chopper for the bunch center is zero, but  $\pm 20$  mrad for the edge particles with the pulse length of  $\Delta\varphi=6^\circ (\pm 3^\circ)$ , twice as larger than assumed beam divergence. As consequence, 83% of the wanted particles are passing the round slit1, and less than 10% of accepted particles have larger phase value than  $\pm 3^\circ$ , therefore being outside the RF acceptance at CRM injection. Required is gap of 4 cm limits loss of particles at  $\pm 90^\circ$ ,

maximal displacement, leading to voltage amplitude of 12kV.

Obtained phase space distributions for phase width of  $\pm 3^\circ$  from single particle tracking results are shown in Fig.3 at entrance and exit of the chopper cavity. Assumed is radial symmetric initial Gaussian distribution with rms emittance of  $6.2\pi\text{-mm-mrad}$ , total one about  $50\pi\text{-mm-mrad}$ . The distribution is independent of the phase before the chopper, but it is phase dependent after the chopper. After chopper, the y-emittance is increased up to  $\sim 150\pi\text{-mm-mrad}$  for the pulse length of  $\Delta\varphi=6^\circ (\pm 3^\circ)$ , but unchanged in x direction. At the chopper entrance, assumed is radial symmetric beam with 5mm total radius and  $\pm 10$  mrad maximal divergence.

Particles outside the wanted  $\pm 3^\circ$  phase width @ 2.2MHz or  $\pm 90^\circ$  @ 70.5MHz, are absorbed in 50cm drift after chopper or at round slit1 with radius of 1cm. About 400W must be collected. Distributions after the round slit1 are shown in Fig. 4, 82.5% of particles within  $\pm 3^\circ$  are passing this slit. The red boundaries in Fig. 4 are for  $8 \times$  RMS emittances. Particles shifted by  $180^\circ$  in phase also pass slit1, but with negative kick. The CRM inflector receives 2.4 ns long pulse at 4.4 MHz.

The  $\alpha$ ,  $\beta$  and RMS emittance values for chopped and unchopped pulse are shown in Table1. For the unchopped beam, twiss parameters and RMS emittance are almost the same. But they are different for the chopped pulse, not only emittance growth, but also the  $\alpha$ ,  $\beta$  values are changing.

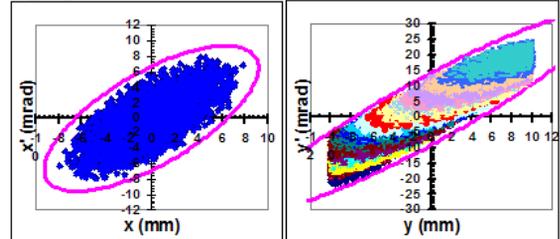


Figure 4: Distribution after the slit for the chopped pulse with length of  $\Delta\varphi=6^\circ (\pm 3^\circ)$ .

Table 1:  $\alpha$ ,  $\beta$  and RMS Emittance Values for Chopped and Unchopped Pulse after Round Slit1

		Chopped	Unchopped
$\alpha$	$\alpha_x$	-0.97	-0.98
	$\alpha_y$	-2.55	-0.99
$\beta$	$\beta_x$	1.35	1.35
	$\beta_y$	1.48	1.34
$\varepsilon_{\text{RMS}}$ ( $\pi\text{-mm-mrad}$ )	$\varepsilon_x$	6.21	6.22
	$\varepsilon_y$	20.19	6.36

## TRANSVERSE PHASE SPACE COUPLING FOR THE DEFLECTED PULSE IN THE SOLENOID

After round slit 1, the deflected pulse is matched to cyclotron injection by combination of solenoid and

quadrupole doublet focusing, see Fig 1. Parameters for solenoid: 25 cm length, 2.2kGs field. Quadrupoles are 12 cm in length, field gradient of 3 T/m, 2.5 cm aperture. Single particle tracking results are shown in Fig. 5 & 6 for the chopped and unchopped beams from round slit1 to the cyclotron inflector, unchanged focusing strength in solenoid and quadrupole doublet. Total beam envelopes are shown for  $8 \times$  RMS emittance, about  $50\pi\text{mm-mrad}$  for the unchopped beam, but changing for the chopped pulse due to transverse coupling of both phase space planes. Single particle tracking results are identical with the analytical TRACE 3D results shown in Fig. 1, as no coupling in solenoid for assumed round beam. But as phase space distribution in y-direction, where particles are deflected, is much larger than in x-direction, solenoid equalizes the RMS emittances, listed in Table 2. Four-dimensional RMS emittance is conserved inside the solenoid, whereas both 2D projections are conserved in perfect quadrupoles.

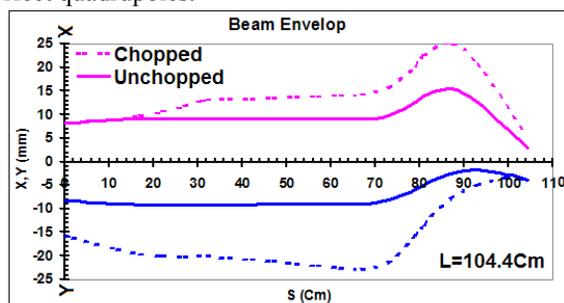


Figure 5: Total beam envelopes from slit to inflector.

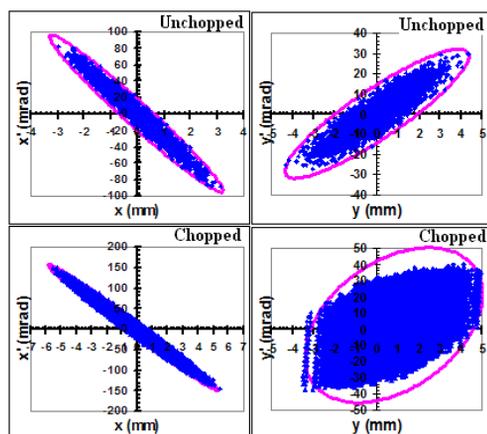


Figure 6: Phase space plots before the inflector for chopped and unchopped beam.

Table 2: RMS\_Emittance Changing for the Chopped and Unchopped Beam (unit:  $\pi\text{-mm-mrad}$ )

		Initial	After chopper	After slit	Before inflector
Chopped	x	6.22	6.22	6.21	11.24
	y	6.36	25.62	20.19	18.5
Un- chopped	x	6.22	6.22	6.22	6.31
	y	6.36	6.36	6.36	6.28

Table 2 shows the RMS emittance along the CRM injection line, unchanged for the unchopped beam, but changing for the chopped pulse. Radial symmetric Gaussian distributions with RMS emittance of  $6.22\pi\text{-mm-mrad}$  ( $50\pi\text{-mm-mrad}$  in total) are assumed as input distributions. For chopped beam, RMS emittance in y-direction is increased up to  $25.62\pi\text{mm-mrad}$  after chopper, but decreased to  $20.19\pi\text{mm-mrad}$  after round slit1, finally decreased to  $18.5\pi\text{-mm-mrad}$  by solenoid. In x-direction, RMS emittance is conserved up entrance to the solenoid, but then increased by almost a factor 2.

The accepted beam parameters for the CRM inflector are:  $\pm 120\text{mrad}/\pm 4\text{mm}$ , twiss parameter  $\alpha_x=4.86$  in x direction and  $\pm 40\text{mrad}/\pm 5\text{mm}$ , twiss parameter  $\alpha_y=-1.98$  in y direction. With unchanged focusing strength in solenoid and quadrupole doublet, for the chopped pulse in Fig. 5, resulting  $\alpha$  values are  $\alpha_x=7.56$  and  $\alpha_y=-0.43$ . Adjustment of focusing strength of the last 3 elements and use of 4mm round slit 2 leads to about 1% transmission efficiency for the chopped pulse.

## SUMMARY

The 10 mA, 40keV H- injection line for the CIAE 10 MeV CRM cyclotron has two main operation modes for bunched beams: delivering 5 mA CW beam or chopped pulse with more than 100uA. Chopped pulse is achieved by placing behind the 70.5 MHz bunching cavity a transverse deflecting cavity with frequency of about 2.2 MHz, 1/32 of the bunching frequency.

Time dependence of sinusoidal chopping field causes RMS emittance increase and changes twiss parameter alpha. Solenoid couples motion in both transverse planes, but equalizes both RMS emittances. Particle tracking results are presented for the chopped pulse, showing longitudinal-transverse coupling in the deflector and equalization of RMS emittances in the solenoid. Optimised final focusing strength leads to about 1% transmission efficiency for the chopped pulse. The CRM inflector receives 2.4nsec long pulse at 4.4 MHz repetition rate, 1/16 of the RF frequency.

## ACKNOWLEDGEMENTS

The authors would like to give the grateful acknowledge to Prof. Jingyu Tang from Institute of High Energy Physics, Beijing, Prof. Jianqin Lu from Peking University, Dr. Calabretta from LNS of Italy lots of discussions and useful suggestions from them.

## REFERENCES

- [1] K. R. Crandall and D. P. Rusthoi, TRACE 3-D Documentation, LA-UR-97-886, May 19.
- [2] K.L. Brown, Beam envelope matching for beam guidance systems, NIM 187 (1981) 51-65.
- [3] S. An, T. Zhang et al, Chinese Physics C, Vol. 32 (1), Jan. 2008.
- [4] J. Belmont, W. Joho, chopping & bunching on the TRIUMF 300 KeV Injection Line, TRI-DN-73-16, May 1973.