HALF-MINI BETA OPTICS WITH A BUNCH ROTATION FOR WARM DENSE MATTER SCIENCE FACILITY IN KEK*

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Abstract

A half-mini beta optics is studied for a warm dense matter science facility in KEK. The irradiation onto a target at a small focal spot ($<$ a few mm) with a short pulse duration ($\sim$100 nsec) is required. The final focus is carried out through a half-mini beta beamline placed after the kickout from the 500 MeV Booster improved. The space charge effect is evaluated for the beamline in the high current beam. The beam optics concerned with the effects of space charge and a large momentum spread during the half-mini beta system is investigated for the study of the warm dense matter science in KEK.

INTRODUCTION

A research field on high energy density physics (HEDP) and warm dense matter (WDM) sciences [1] driven by heavy ion beam illuminations require the generation of a high-current heavy ion beam [2] .

A concept of an induction synchrotron was proposed for a purpose of nuclear physics study, high energy physics research, high-current beam generation, and so on [3]. Recently, the experimental demonstration of the induction synchrotron was reported in the KEK proton synchrotron [4]. Induction voltage modulators have a repetition capability and a precise waveform controllability for high-current charged particle beams.

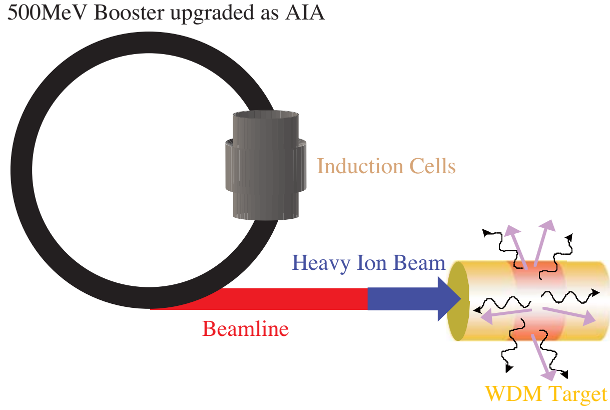

Figure 1: Outline of the 500 MeV Booster improved as the AIA and the beamline for the WDM experiment.

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An all-ion accelerator (AIA) is one of attractive and useful applications of the induction synchrotron, and the 500 MeV Booster upgraded as the AIA is under construction in KEK [5, 6, 7, 8, 9]. The AIA is a quite interesting device as a driver to explore a WDM state. The irradiation onto a target at a small focal spot ($<$ a few mm) with a short pulse duration ($\sim$100 nsec) is required to create an interesting WDM state. The final focus is carried out through a half-mini beta beamline placed after the kickout from the AIA as shown in Fig. 1.

The half-mini beta beamline should be designed with the space-charge effect due to the high current beam. The effect of a large momentum spread caused by a fast bunch rotation is investigated. The beam optics concerned with the space charge effect during the half-mini beta system is designed for the WDM science in KEK AIA Facility.

BEAM PARAMETERS REQUIRED FOR WDM EXPERIMENTS

The WDM state is in a solid density with 0.1$\sim$10 eV temperature regime [1, 2]. For the creation of the WDM state, high power beam is required. The beam power is proportional to the product of kinetic energy and beam current. However the ions with high kinetic energy have the long distance for a stopping range. For this reason, the kinetic energy of the beam should be limited for the WDM application, and heavy ions have an advantage for the short stopping range.

Consider an aluminum target illuminated by an uranium (U) ion beam with 80 MeV/u kinetic energy [10]. The deposition energy of 1 kJ/g in the aluminum target is achieved at the beam radius 2 mm at the target, and is converted to 0.12 eV target temperature. When the minimum beam radius of 0.5 mm can be achieved, the target temperature increases to 1 eV. Consequently, we aim to design the minimum beam radius less than 1 mm at the target for the WDM study.

ESTIMATION OF SPACE CHARGE - EMITTANCE RATIO FOR HALF MINI-BETA SYSTEM IN WARM DENSE MATTER APPLICATION

The beam radius r_b along the transport distance s is described by [11]

$$\frac{d^2 r_b}{ds^2} = -k_0^2 r_b + \frac{K_t}{r_b} + \frac{\varepsilon^2}{r_b^3}, \quad (1)$$

where k_0 is the focusing parameter applied by an external magnetic force, ε is the unnormalized emittance, and K_t is the transverse perveance as

$$K_t = \frac{2}{\beta^3\gamma^3}\frac{I_b}{I_0}, \tag{2}$$

where β is the beam velocity divided by speed of light c, γ is the relativistic factor, I_b is the beam current and I_0 is the characteristic current. The characteristic current is given by

$$I_0 = \frac{4\pi\epsilon_0 m_0 c^3}{qe}, \tag{3}$$

where ϵ_0 is the permitivity in vacuum, m_0 is the ion mass of the beam, q is the charge state of the beam ion and e is the elementary charge.

In this study, the beam parameters produced from the 500 MeV Booster replaced as the AIA are assumed as follows. The beam current I_b is 0.6 A (the pulse duration is 100 ns), the beam ion species is $^{238}U^{92+}$ and the kinetic energy is 80 MeV/u, i.e., $\beta = 0.389$ and $\gamma = 1.09$ in this condition.

From Eq.(1), $K_t\, r_b^2/\varepsilon^2$ can be defined as the ratio of the space-charge force to the diffusion force by the emittance. The ratio as a function of the beam radius with each emittance is calculated as shown in Fig. 2. As shown in Fig. 2, the space charge effect can be neglected at the focal point.

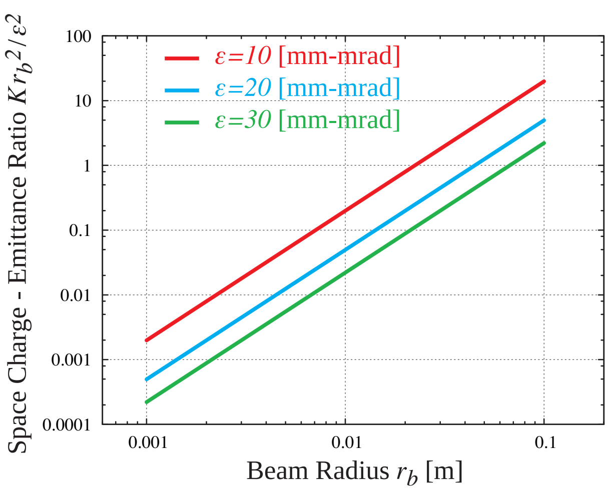

Figure 2: Ratio of space-charge effect to emittance term.

DESIGN OF THE BEAMLINE FOR WDM EXPERIMENTS BY BEAMOPTICS

BeamOptics [12] is a useful tool for the beamline design. The beta functions, which are β_x for the horizontal direction and β_y for the vertical direction, along the beamline determined by the *BeamOptics* are shown in Fig. 3. In this case, the last three quadrupole magnets are replaced for the half-mini beta optics, and the maximum magnetic field gradient is required as 47.5 T/m.

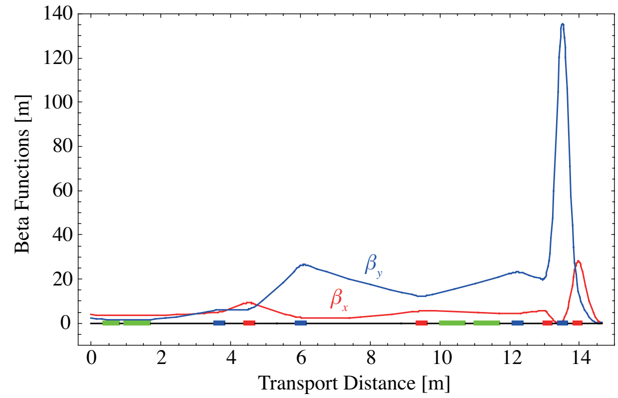

Figure 3: Beta functions and lattice components in the focus line for WDM experiments.

BEAM ENVELOPE CALCULATION WITH SPACE CHARGE EFFECT

The beam radii $r_x = \sqrt{\beta_x\varepsilon_x}$ and $r_y = \sqrt{\beta_y\varepsilon_y}$ along the transport distance s are described by [11]

$$\frac{d^2 r_x}{ds^2} = -k_x^2 r_x + \frac{2K_t}{r_x + r_y} + \frac{\varepsilon_x^2}{r_x^3}, \tag{4}$$

and

$$\frac{d^2 r_y}{ds^2} = -k_y^2 r_y + \frac{2K_t}{r_x + r_y} + \frac{\varepsilon_y^2}{r_y^3}, \tag{5}$$

where k_x and k_y are the horizontal and vertical focusing parameters applied by external magnets, ε_x and ε_y are the unnormalized horizontal and vertical emittances.

The focusing parameters are given as $k_x^2 = k_0^2$ and $k_y^2 = -k_0^2$ at each magnet. The relation between *k-value* and the magnet focusing parameter k_0^2 is defined by

$$K = \frac{1}{B\rho}\frac{\partial B}{\partial x} = k_0^2, \tag{6}$$

where $B\rho$ is the magnetic rigidity.

Solving the coupled equations, we can obtain the beam envelope with the space charge effect during the focus beamline. Figure 4 shows the numerical calculation result with $\beta\gamma\varepsilon_x = 30$ mm-mrad and $\beta\gamma\varepsilon_y = 15$ mm-mrad. As shown in Fig. 4, the minimum beam radius less than 1 mm at the focal point and the maximum radius less than 10 cm in the beamline can be achieved. In this case, the space charge effect did not affect to the beam envelope as shown in Fig. 2, because the beam radii are always less than 8 cm during the beamline.

ESTIMATION FOR PULSE COMPRESSION

To increase the beam power, the pulse compression is needed in the beamline. A head-to-tail velocity tilt is applied to the beam bunch, and the accelerated beam tail can

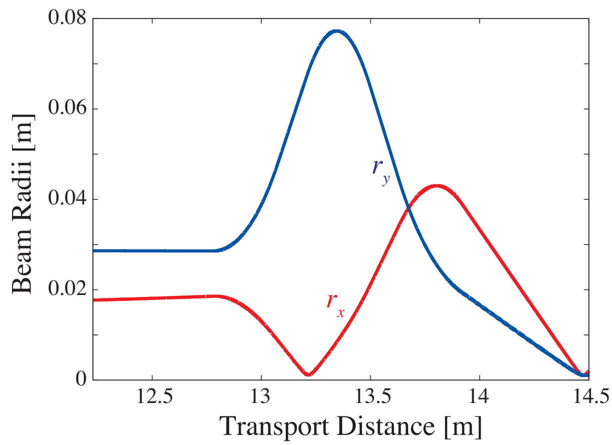

Figure 4: Beam envelope including the space charge effect around the focal position.

close to the decelerated beam head as shown in Fig. 5. However the large momentum spread causes a misalignment of the focal point. In this case, since the space charge effect is not so strong, the repulsive force around the stagnation point is small in the longitudinal direction. As a result, the head-to-tail velocity tilt is limited by the final focus requirement.

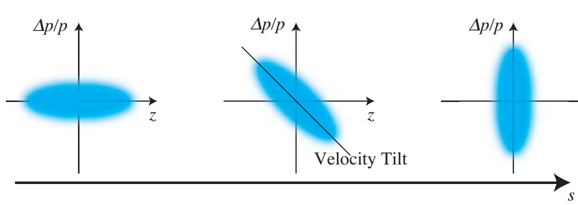

Figure 5: Bunch compression scenario with a head-to-tail velocity tilt in a phase space of a momentum spread $\Delta p/p$ and a longitudinal direction z along the transport distance s.

The beam pulse is assumed by 100 ns after the extraction from the 500 MeV Booster AIA. Figure 6 shows the head-to-tail velocity tilt as a function of the required drift space [13] to obtain the pulse duration of 50 ns by the bunch compression, i.e., the compression ratio is 2. If the momentum spread at the final focus is restricted as less than 1 %, the 600 m length for the drift compression is required to suppress the large momentum spread. The required voltage for the head-to-tail velocity tilt is 2.28 MV in this case.

CONCLUSIONS

The beam optics during the half-mini beta system was investigated for the WDM science in KEK AIA facility. The ratio of the space charge effect to the emittance term was evaluated in the beam radius. The beamline from the 500 MeV Booster improved as the AIA to the target for

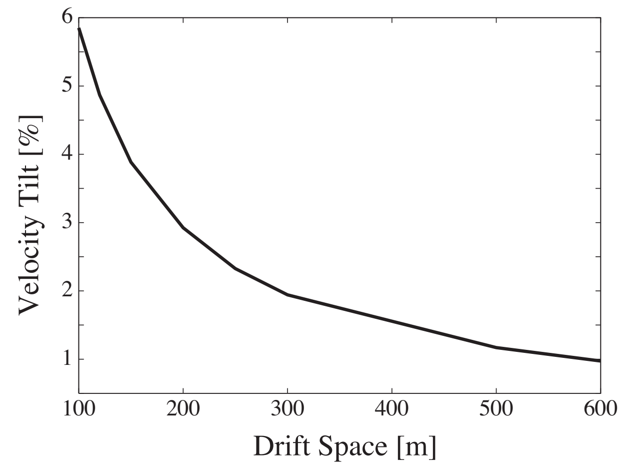

Figure 6: Required head-to-tail velocity tilt for the twice compression of the pulse duration as a function of the drift space.

the WDM experiments was designed by using *BeamOptics*. The envelope calculation with the space charge effect was carried out, and it is found that the space charge effect cannot be affected in this designed beamline, if focusing magnets with high magnetic field gradient are equipped. The pulse compression during the beamline was also estimated, but the long drift space is needed from the viewpoint of the momentum spread restricted at the final focus design.

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