RESIDUAL ION DYNAMICS IN ThomX ELECTRON STORAGE RING *

A. Gamelin†, C. Bruni, LAL, Orsay, France

Abstract

ThomX is a compact Compton Backscattering Source (CBS) which is being built in Orsay, France. Ions produced from residual gas in the storage ring can induce several instabilities. However the electron beam stability is crucial to attain the nominal performances foreseen. In order to prevent instabilities ion cleaning is considered. Complete studies of the beam effect on the ions have been undertaken. It shows that there are preferential ion accumulation points depending on the storage ring lattice. This paper will detail the ion longitudinal and transverse dynamics considering the optics of ThomX storage ring.

INTRODUCTION

Ions produced from residual gas can significantly degrade the performance of a machine and produce various beam instabilities like the conventional ion trapping (CIT) or the fast beam-ion instability (FBII) [1]. The coupled dynamics between the ions and the beam can lead to fast rising transverse instabilities which can be difficult to manage. To cure more effectively these problems it is important to understand the ions dynamics in the accelerator. The ions undergo the effect of the electron beam crossing and go through strong transverse oscillations. But the beam has also an important longitudinal effect on the ions which can induce accumulation points in the ring. The beam-ion interaction can be described by using the beam-beam interaction theory under the 'strong-weak' approximation [2], the ions are considered as a very weak beam which will not disrupt the electron beam. In that case it is possible to express analytically the effect on the ions of a beam with a Gaussian transverse distribution and supposed infinitely short in the longitudinal dimension. The transverse beam-ion force can then be calculated from the Bassetti-Erskine formula [3] and the longitudinal part is given by Sagan formula [4]. The beam-ion force will be different depending on the position, longitudinal and transverse, of the ion in the accelerator. It is therefore the beam Twiss parameters and the lattice design that will completely determine the ion motion in the accelerator.

ThomX STORAGE RING

ThomX is a compact and low energy accelerator aiming to produce hard X-rays which is under construction at LAL, Orsay, France. The machine is a Compton Backscattering Source (CBS) which is composed of a laser based electron gun, a warm Linac, a 18 m circumference storage ring, an extraction line and an X-ray beam line for users. The 50 MeV electron beam collides with a laser beam from a Fabry-Perot cavity at each turn in the storage ring to produce the X-rays. Then after 20 ms the beam is too degraded by collective effects, intrabeam scattering (IBS) and Compton interaction so it is extracted and dumped while a new one is injected. An important characteristic of ThomX is that due to the short storage time, the electron dynamics is not damped. Also contrary to usual storage rings, ThomX has an Interaction Point (IP) where beam size is minimal in order to carry out electron-photon interaction. For symmetry reasons there is a second IP, called IP bis, where beam size is minimal but there is no Compton interaction. The Twiss parameters β_x, β_y, dispersion η_x and beam sizes σ_x and σ_y are shown for half of the ring in Fig. 1. A more detailed description of the project is available in the TDR [5].

BEAM-ION INTERACTION IN ThomX

Transverse Component

The beam-ion interaction can be expressed in terms of velocity kick felt by the ions during the beam crossing. The transverse components Δv_x and Δv_y are known in the case of a Gaussian beam from the Bassetti-Erskine formula [3]:

$$i\Delta v_x + \Delta v_y = \frac{-NK\sqrt{\pi}}{\sqrt{2\left(\sigma_x{}^2-\sigma_y{}^2\right)}}\left(w\left[\frac{x+iy}{\sqrt{2\left(\sigma_x{}^2-\sigma_y{}^2\right)}}\right]\right.$$
$$\left. -exp\left[-\left(\frac{x^2}{2\sigma_x{}^2}+\frac{y^2}{2\sigma_y{}^2}\right)^2\right]w\left[\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2\left(\sigma_x{}^2-\sigma_y{}^2\right)}}\right]\right) \tag{1}$$

With $\sigma_x = \sqrt{\epsilon_x\beta_x + \eta^2\sigma_\epsilon{}^2}$ the horizontal beam size, $\sigma_y = \sqrt{\epsilon_y\beta_y}$ the vertical beam size, $K = \frac{2r_p c}{A}$, N is the number of electrons in a bunch, r_p the classical proton radius, A is the atomic mass of the ion, c the speed of light, x and y the ion transverse coordinates, ϵ_x and ϵ_y the horizontal and vertical emittance, η and $\eta\prime$ the dispersion functions, σ_ϵ the relative energy dispersion and $w(z)$ the complex error function [6].

The real part of Eq. (1) gives Δv_y and the imaginary part gives Δv_x. The velocity kicks that the ions will undergo depend explicitly on the ion position x and y but also on the value of the Twiss parameters at their longitudinal position. Figure 2 shows the horizontal kick Δ_x variation in the horizontal plane, in the $x > 0$ part $\Delta v_x < 0$ and in the $x < 0$ part $\Delta v_x > 0$. So at first order, the horizontal effect of the beam will push the ions back to the cavity center and toward the beam. This effect is very important when the ion is close to the beam, typically of the order of σ_x. The ions will then undergo very large transverse oscillations with speeds of the order of 100 m/s.

In Fig. 3 positive speeds are shown in red and negative speeds in blue. As the $x > 0$ part is mainly blue and the

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† gamelin@lal.in2p3.fr

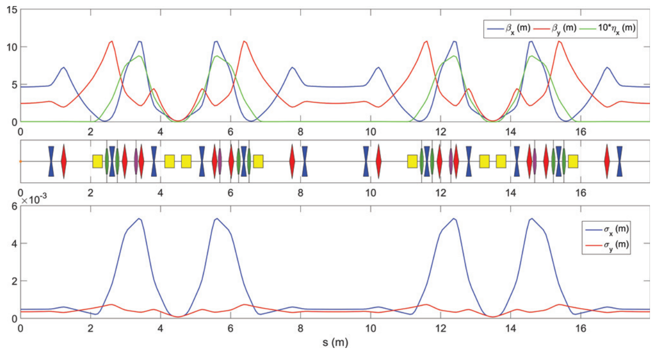

Figure 1: Top: Twiss parameters β_x in blue, β_y in red, horizontal dispersion $10 \times \eta_x$ in green versus longitudinal position s for half the storage ring. Middle: Scheme of the first half of ThomX elements, x focusing quads are in red, x defocusing quad in blue, dipoles in yellow and sextupoles in green and pink. Bottom: Horizontal beam size σ_x in blue and vertical beam size σ_y in red versus longitudinal position s for half the storage ring. Beam parameters: Horizontal emittance $\epsilon_x = 5 \times 10^{-8}$ m.rad, vertical emittance $\epsilon_y = 5 \times 10^{-8}$ m.rad, and relative energy spread $\sigma_\epsilon = 0.6\%$.

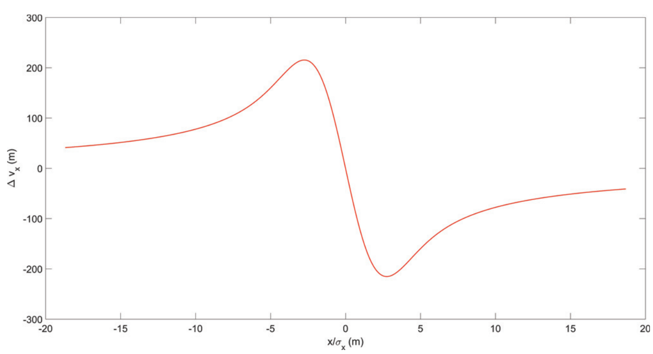

Figure 2: Horizontal kick Δv_x vs horizontal position x at longitudinal position $s = 0$ and vertical position $y = 0$ for CO^+ ions (A=28).

$x < 0$ part is mainly red then ions are focused toward the beam. However Δv_x has a longitudinal structure with minimums at s = 3.2 m and s = 5.8 m that correspond to maximums of ${\sigma_x}^2 - {\sigma_y}^2$, the red curve in the bottom plot of Fig. 3. These points are close to dipoles, the non-zero dispersion within these ranges leads to a significant increase of ${\sigma_x}^2 = \epsilon_x \beta_x + \eta^2 {\sigma_\epsilon}^2 \approx 10^{-5}$ m² with respect to ${\sigma_y}^2 = \epsilon_y \beta_y \approx 10^{-7}$ m². This increase is caused by the energy dispersion $\sigma_\epsilon = 6 \times 10^{-3}$ which is big compared to a usual ring where the electron dynamics is damped. As the velocity kick is inversely proportional to ${\sigma_x}^2 - {\sigma_y}^2$, see Eq. (1), so in these areas the ion focusing is less intense. The velocity kick maximum at s = 4.5 m corresponds to the IP where β_x is minimal, the green curve in the bottom plot of Fig. 3. In the central region, $\frac{x^2}{{\sigma_x}^2} + \frac{y^2}{{\sigma_y}^2} \leq 1$, transverse kicks variation is linear and can be approximated as Eq. (2) [4]. As Δv_x changes like $\frac{1}{\sigma_x}$ then a minimum of β_x leads to the

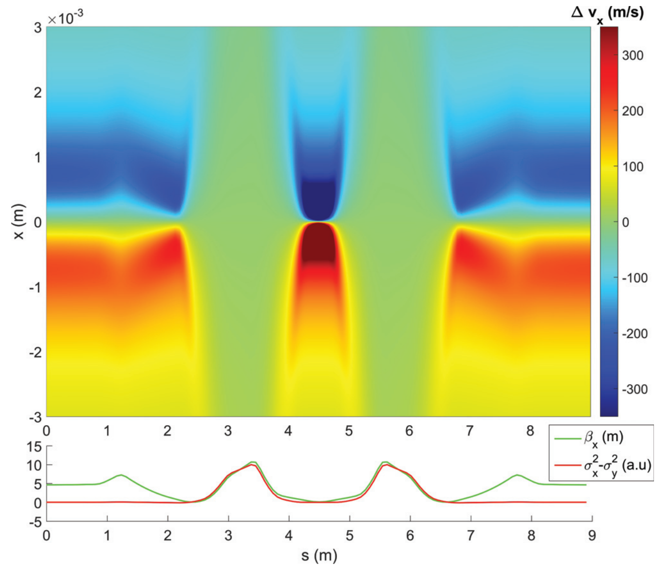

Figure 3: Top: Color map of the horizontal kick Δv_x vs horizontal position x and longitudinal position s along half ThomX ring. For CO^+ ions (A=28). Bottom: Twiss parameter β_x in green and ${\sigma_x}^2 - {\sigma_y}^2$ in red (arbitrary units) vs longitudinal postion s along half ThomX ring.

maximum of Δv_x observed at the IP.

$$\Delta v_{x,y} = \frac{-2Ncr_p}{A\sigma_{x,y}(\sigma_x + \sigma_y)}(x, y) \quad (2)$$

The same kind of longitudinal structures are observed for Δv_y. However the intense areas at s = 2.2 m and s = 6.8 m observed for Δv_x in Fig. 3 produced by minimums of β_x at these points disappear for Δv_y. Likewise for the relatively low intense areas at s = 1.2 m and s = 7.8 m which are caused by local maxima of β_x at these points. The electron beam has a focusing effect toward the beam central region on the ions. The focusing is stronger at the IP, the areas before and after the IP, where a dipole singlet is located, are areas where the focusing will be very low.

Longitudinal Component

The longitudinal kick Δv_s can be evaluated in terms of the transverse kicks with Sagan formula [4] :

$$\Delta v_s = [-\alpha_x \epsilon_x + (\eta \sigma_\epsilon)(\eta' \sigma_\epsilon)] \frac{\partial \Delta v_x}{\partial x} - \alpha_y \epsilon_y \frac{\partial \Delta v_y}{\partial y} \quad (3)$$

The order of magnitude of longitudinal kicks is of 1 m/s compared to 100 m/s for the transverse kicks but Δv_s is not negligible. The longitudinal kick effects can accumulate over several hundred turns whereas transverse kick effects often cancel out after a few turns because of the ion transverse oscillations. In Fig. 4 the color map of Δv_s is drawn, positive kicks (toward the right) are shown in red and negative kicks (toward the left) are shown in blue. One can deduce that the IP is an accumulation point for the ions, on the left of the IP at s = 4.5 m there is $\Delta v_s > 0$ and on the right of the IP

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$\Delta v_s < 0$, so the ions will be pushed to the IP and trapped to this point. At s = 2.5 m and respectively at s = 6.5 m there are expulsion points, the ions in these areas will be pushed back by the strong Δv_s to the yellow area at s < 2.5 m and respectively pushed back to the green area at s > 6.5 m. The ion trapping at these points is expected to be less important than at the IP because of the uneven strength of the forces creating this potential well.

In ThomX case the longitudinal kick Δv_s is dominated by the $(\eta\sigma_\epsilon)(\eta'\sigma_\epsilon)\frac{\partial\Delta v_x}{\partial x}$ term of Eq. (3) as shown in the bottom plot in Fig. 4. For a typical storage ring the value of the relative energy dispersion σ_ϵ would be lower and all the terms of Eq. (3) would have equivalent weight. From s = 2.1 m to s = 6.8 m the term $(\eta\sigma_\epsilon)(\eta'\sigma_\epsilon)\frac{\partial\Delta v_x}{\partial x}$ is of the order of 10^{-5} m/s which allows high values of Δv_s in this region. At s = 2.5 m, s = 6.5 m and around the IP Δv_s is especially intense because of the quick variation of Δv_x along x at these points.

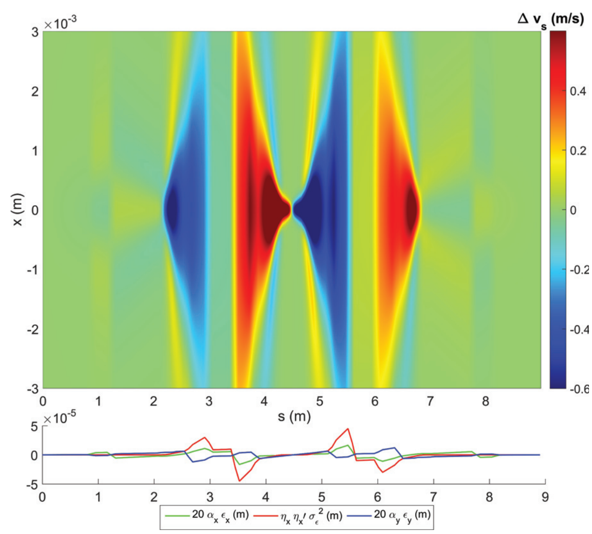

Figure 4: Top: Color map of the longitudinal kick Δv_s vs horizontal position x and longitudinal position s along half ThomX ring for CO^+ ions (A=28). Bottom: $\alpha_x\epsilon_x$ in green, $\eta_x\eta_x\prime\sigma_\epsilon{}^2$ in red and $\alpha_y\epsilon_y$ vs longitudinal postion s along half ThomX ring.

Simulations

Simulations of the ion dynamics using this beam-ion kick model have been undertaken and corroborate previous findings about ion trapping. Figure 5 shows the final longitudinal distribution of 20 000 CO^+ ions after 30 000 turns in ThomX ring. This simulation shows that IPs (s = 4.5 m and s = 13.5 m) and expulsion points (s = 2.5,6.5,11.5 and 15.5 m) behave as expected from the beam-ion interaction kick maps. The ions which are produced near the IP are trapped there and accumulate over time. The expulsion zones around the IPs push back the ions produced there to regions where the longitudinal kicks are weaker. In these zones (from s = 6.5 to s = 11.5 m and from s = 15.5 m to s = 2.5 m) the ions move back and forth but there is an additional weak trapping at s = 1.5,7,11 and 16 m.

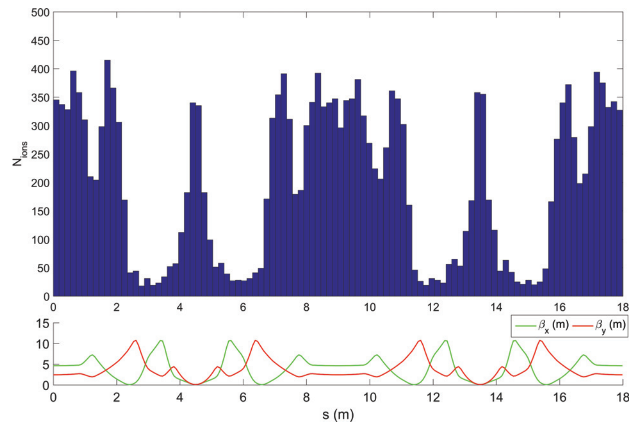

Figure 5: Top: Histogram of the ions final longitudinal position after 30 000 beam-ion interactions. Bottom: β_x in green and β_y in red vs longitudinal position s.

CONCLUSION

Use of the beam-ion kick model given by Sagan, Bassetti and Erskine to ThomX storage ring shows that the interaction point (IP) is a stable equilibrium point for the ions. There are also two expulsion points, where the ions are stable transversely but unstable longitudinally. These two expulsion points are consequences of the high relative energy dispersion caused by the undamped electron dynamics in ThomX storage ring. Ion trapping is expected at these points and cleaning electrodes have been placed along the ring to prevent it. Future studies will include ion dynamics along the ring using this beam-ion model taking into account cleaning electrodes and ion trapping by magnetic elements.

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