A BUNCH LENGTH MONITOR FOR JLAB 12 GeV UPGRADE*

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Abstract

A continuous non-invasive bunch length monitor for the 12 GeV upgrade of Jefferson Lab will be used to determine the bunch length of the beam. The measurement will be done at the fourth dipole of the injector chicane at 123 MeV using the coherent synchrotron light emitted from the dipole. The estimated bunch length is 333 fs. A vacuum chamber will be fabricated and a Radiabeam real time interferometer will be used. In this paper, background, the estimated calculations and the construction of the chamber will be discussed

INTRODUCTION

In recent days, many accelerators use short electron bunches. Measuring bunch length is important for operating and characterizing the accelerator. Bunch length measurement can be classified as invasive techniques such as zero-phasing [1] and deflecting cavity [2] or non-invasive techniques such as electro-optical sampling [3] and interferometers [4],[5]. In Jefferson Laboratory (JLab), we are going to measure the bunch length for the 12 Gev upgrade using the radiabeam Real time interferometer (RTI) [6]. The RTI is a solid state, compact and non-destructive. The experiment will be based on the Synchorotron light which will be emitted from the last bending magnet of the injector chicane. When the bunch length of the electron beam is shorter than the radiation wavelength, the electrons radiate in phase and the radiation power becomes proportional to the square of number of electrons per bunch (N^2) [7].

$$P_{total}(\lambda) = P(\lambda)[N + N(N-1)f(\lambda)] \quad (1)$$

where $P(\lambda)$ is the power radiated by single electron and $f(\lambda)$ is the form factor given by

$$f(\lambda) = |\int S(z)exp(\frac{-2\pi iz}{\lambda})dz|^2 \quad (2)$$

where S(z) is the normalized longitudinal distribution function, z is the longitudinal position of the electrons and λ is the radiation wavelength. The form factor equals zero when the radiation is incoherent & equals one when the radiation is coherent.

COMPRESSION CALCULATION

In accelerator beam optics, the equation for an ellipse is normalized so ϵ the area of ellipse divided by π is on the right hand side. The general equation is given by

$$\gamma(\Delta\phi)^2 + 2\alpha(\Delta\phi)(\Delta E) + \beta(\Delta E)^2 = \epsilon \quad (3)$$

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By compression, we desire to convert a horizontal upright ellipse to a tilted ellipse. The transformation array is given by

$$\begin{bmatrix} \Delta\phi' \\ \Delta E' \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{bmatrix} \begin{bmatrix} \Delta\phi \\ \Delta E \end{bmatrix} \quad (4)$$

Equation(4) can be written as

$$\begin{bmatrix} \Delta\phi \\ \Delta E \end{bmatrix} = \begin{bmatrix} (M^{-1})_{11} & (M^{-1})_{12} \\ (M^{-1})_{12} & (M^{-1})_{22} \end{bmatrix} \begin{bmatrix} \Delta\phi' \\ \Delta E' \end{bmatrix} \quad (5)$$

Substituting by the values of it from eq.(5) into equation(3) and adding the terms of $(\Delta\phi')^2$, $(\Delta E')^2$ and $\Delta\phi'\Delta E'$, then the tilted ellipse twiss parameters will be

$$\gamma_1 = (M_{11}^{-1})^2\gamma_0 + 2(M_{11}^{-1})(M_{21}^{-1})\alpha_0 + (M_{21}^{-1})^2\beta_0 \quad (6)$$

$$\alpha_1 = (M_{11}^{-1})(M_{12}^{-1})\gamma_0 + \left[(M_{11}^{-1})(M_{22}^{-1}) + (M_{12}^{-1})(M_{21}^{-1})\right]\alpha_0 + (M_{21}^{-1})(M_{22}^{-1})\beta_0 \quad (7)$$

$$\beta_1 = (M_{12}^{-1})^2\gamma_0 + 2(M_{12}^{-1})(M_{22}^{-1})\alpha_0 + (M_{22}^{-1})^2\beta_0 \quad (8)$$

Assume that the longitudinal phase space distribution is a horizontal upright ellipse before compression with $\sigma_{\phi 0}$ and σ_{E0} as initial values for the bunch length and energy respectively. After the compression it will be $\sigma_{\phi,opt}$ and $\sigma_{E,opt}$ as shown in figure(1). let M be the magnification factor, so the bunch length will be compressed by a factor $\frac{1}{M}$ and to achieve the maximum minimum energy spread after compression, M must equal $\frac{\sigma_{\phi 0}}{\sigma_{\phi,opt}}$.

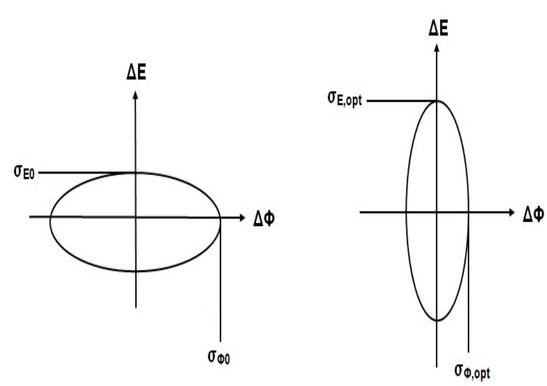

Figure 1: Phase space before & after compression.

When there is a chirp, the horizontal upright ellipse will transform into a tilted ellipse and the transformation equation is given by

$$\begin{bmatrix} \Delta\phi_1 \\ \Delta E_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -s & 1 \end{bmatrix} \begin{bmatrix} \Delta\phi_0 \\ \Delta E_0 \end{bmatrix} \quad (9)$$

Where $s = V \sin\phi$, V is the cavity offset voltage from the crest and ϕ is the offset phase from the crest in radians. Using the same technique as discussed before in equations [6,7 & 8] and notice that $\alpha_0 = 0$ when the ellipse was horizontal upright, then the new twiss parameters are

$$\gamma_1 = \gamma_0 + s^2\beta_0 \quad (10)$$

$$\alpha_1 = s\beta_0 \quad (11)$$

$$\beta_1 = \beta_0 \quad (12)$$

Since the amplification factor M is defined as "the new vertical distance divide by the old vertical distance" or "old horizontal distance divide by new horizontal distance", so $M = \sqrt{\frac{\gamma_1\epsilon}{\gamma_0\epsilon}}$.

Since $\epsilon = \sigma_{\phi 0}\sigma_{E0}$ $\quad \sigma_{\phi 0} = \sqrt{\beta_0\epsilon}$ $\quad \sigma_{E0} = \sqrt{\gamma_0\epsilon}$

$$\beta_0 = \frac{\sigma_{\phi 0}}{\sigma_{E0}} \quad (13)$$

$$\gamma_0 = \frac{\sigma_{E0}}{\sigma_{\phi 0}} \quad (14)$$

Square M and substitute by the previous values of γ_1, γ_0 and β_0

$$M^2 = 1 + s^2\frac{\beta_0}{\gamma_0} = 1 + s^2\frac{\sigma_{\phi 0}^2}{\sigma_{E0}^2} \quad (15)$$

The linear transfer matrix for the chicane is given by

$$\begin{bmatrix} \Delta\phi_2 \\ \Delta E_2 \end{bmatrix} = \begin{bmatrix} 1 & \frac{2\pi M_{56}}{\lambda E_{inj}} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta\phi_1 \\ \Delta E_1 \end{bmatrix} \quad (16)$$

Where λ is the RF wavelength and E_{inj} is the energy at which the compression is done. Again using the same procedure as mentioned before, the final twiss parameters will be

$$\gamma_2 = \gamma_1 \quad (17)$$

$$\alpha_2 = -K\gamma_1 + \alpha_1 \quad (18)$$

$$\beta_2 = K^2\gamma_1 - 2K\alpha_1 + \beta_1 \quad (19)$$

Where $K = \frac{2\pi M_{56}}{\lambda E_{inj}}$. Since the ellipse transforms into a vertical upright ellipse, so $\alpha_2 = 0$, and from eq.(18) the maximum compression condition becomes

$$K = \frac{\alpha_1}{\gamma_1} = \frac{s\beta_0}{\gamma_0(1 + \frac{s^2\sigma_{\phi 0}^2}{\sigma_{E0}^2})} \quad (20)$$

$$M_{56} = \frac{\lambda E_{inj}}{2\pi} \times \frac{s\sigma_{\phi 0}^2}{\sigma_{E0}^2(1 + \frac{s^2\sigma_{\phi 0}^2}{\sigma_{E0}^2})} \quad (21)$$

From equation(15) $\quad M^2 - 1 = \frac{s^2\sigma_{\phi 0}}{\sigma_{E0}^2}$ $\quad$ and finally

$$M_{56} = \frac{\lambda E_{inj}}{2\pi s}\frac{M^2 - 1}{M^2} \quad (22)$$

CALCULATIONS

The Jlab injector chicane consists of nine quads and four dipole magnets with bending radius 3.125 m, the magnetic field is 1.3128 kG, the length of magnet is 30 cm and the bending angle is 5.5^0 as shown in figure(2). One would like

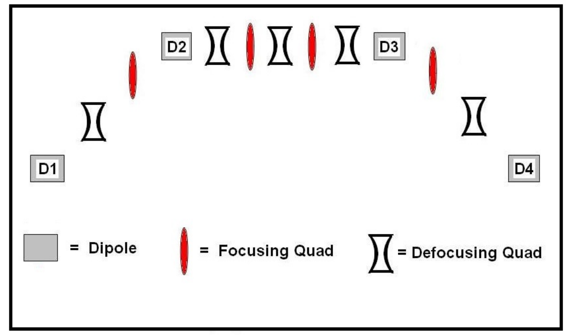

Figure 2: The Chicane.

to compare the bunch length at the third and fourth dipoles of the chicane in order to decide which place is better to do the experiment. Since the value of λ is 20 cm, E_{inj} is 67×10^6 keV and ϵ is 98.25 eV.rad then the bunch length will be calculated as follows.

For the fourth dipole, substituting with $M_{56} = 24$ cm in equation (21) and solving for s, one would find two values for s either 0.635×10^6 eV/rad or 8.256×10^6 eV/rad. Substituting from equations (10, 11 & 12) into equation (19), then

$$\beta_2 = K^2(\alpha_0 + s^2\beta_0) - 2Ks\beta_0 + \beta_0 \quad (23)$$

Substituting with s values, γ_0, β_0 and K value for $M_{56} = 24$ cm in equation (23), then β_2 is 0.031×10^{-6} rad/eV. Doing the same for $M_{56} = 12$ cm, then β_2 is 0.133×10^{-6} rad/eV. Substituting with the those values in $\sqrt{\epsilon\beta_2}$, the bunch length is 1.745×10^{-3} rad for ($M_{56} = 24$) and 3.6×10^{-3} rad for ($M_{56} = 12$). From these result, one can conclude that the bunch length will almost compress to its half value after the 3^{rd} dipole and compress fully after the 4^{th} dipole, then the best place to do the experiment is after the 4^{th} dipole.

A plane mirror will be used to deflect the synchrotron radiation to the RTI and it will confront a 3.25 degrees out of 5.5 degrees of the synchrotron radiation fan. The total energy per unit angular frequency emitted by a single electron moving on a circular orbit is given by [8]

$$\frac{dE}{d\omega} = \frac{9\sqrt{3}}{8\pi\omega_c}\frac{e^2\gamma^4}{3\rho\epsilon_0}y\int_y^\infty K_{5/3}(x)dx \quad (24)$$

where e is the electronic charge, γ is the relativistic factor, ρ is the bending radius, ϵ_0 is the free space permittivity,$K_{5/3}$ is the modified Bessel function and $y = \frac{\omega}{\omega_c}$, where $\omega_c = \frac{3}{2}\gamma^3\frac{c}{\rho}$ is the critical angular frequency. Since the radiation will be collected by a mirror at an angle $\Delta\theta = 3.25$ then

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the energy between two angular frequencies ω_1 and ω_2 is

$$E = \frac{3.25}{360}\frac{9\sqrt{3}}{8\pi}\frac{e^2\gamma^4}{3\rho\epsilon_0}\int_{y_1}^{y_2} y \int_{y}^{\infty} K_{5/3}(x)dxdy \quad (25)$$

Since the repetition rate in JLAB is 500 MHz, power can be estimated by assuming the form factor is a Gaussian distribution, multiplying eq.(24) by $\frac{3.25}{360}$ and using equations (1), (2) then the estimated calculations for the power distribution as a function of wavelength for different bunch lengths is shown in fig (3).

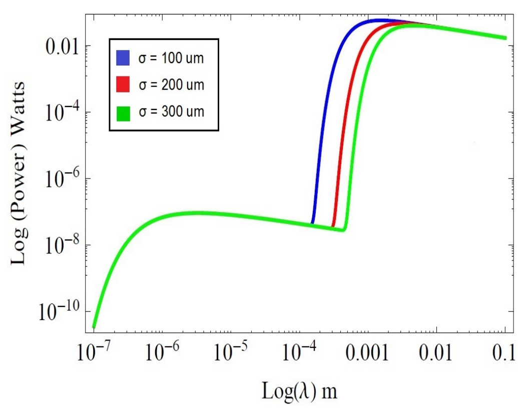

Figure 3: Power spectrum for different bunch lengths.

CONSTRUCTION OF THE CHAMBER

The old chamber and its component is shown in fig(4a) while the new one is shown in fig(4b). The new chamber is built with four additional ports, two of them are for the laser alignment assembly and the Synchorotron light (SL) assembly, while the other two is for the insertable mirror assembly. The difference between the new and old line is that the spool section is removed. The new chamber is made from 316 stainless steal with the same thickness as the old

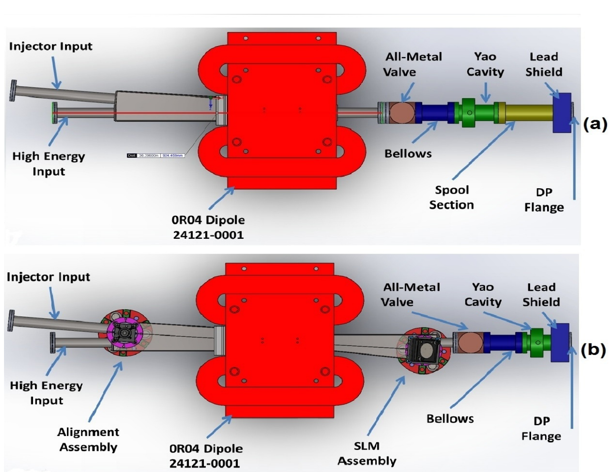

Figure 4: Old and new chamber.

one so, it will have the same magnetic permeability. The chamber elastic limit is measured under vacuum and found to be 70 MPa which is much less than the elastic limit of the stainless steel.

The four assemblies are mounted on a rotatable flange with jacking screws to provide small angular correction as shown in fig(5). The alignment laser assembly has a cage

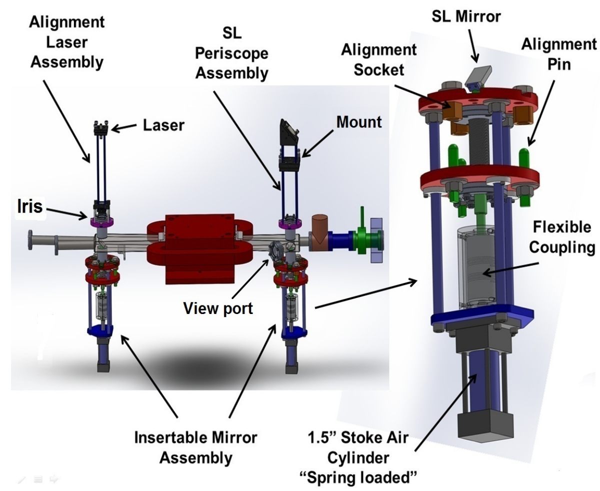

Figure 5: Chamber with laser & SL assembly.

system with a laser diode to help in the alignment. The insertable mirror assembly has a mirror in each one, one to help in the laser alignment while the other is to receive the synchorotron light and reflected upward to the RTI. Both assemblies are attached to stroke air cylinder which is a spring loaded to fail out in case losing air or electrical signals. Also, the chamber has a view port to make sure that the initial laser alignment is on the right spot.

CONCLUSION

The chamber will be installed by the end of the year and as the upgrade finishes, the RTI will be installed. The measurements will be taken in the second phase of the upgrade as JLAB will be operated for one cycle and the results will be compared to the zero-phasing technique used in the north linac.

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