BEAM OPTICS DESIGN FOR A DUAL BEAM IRRADIATION SETUP

S. K. Srivastava, K. G. M. Nair, K. Suresh, B. K. Panigrahi, P. Magudapathy, S. Chinnathambi
Materials Science Group, Indira Gandhi Center for Atomic Research, Kalpakkam-603102

Abstract

A dual beam irradiation facility is being setup at Materials Science Group, IGCAR for carrying out radiation damage studies. This paper describes the details of the ion optical design of the dual beam irradiation setup. First order beam optics calculations using transport matrix method has been adopted to design beam line. A MATLAB based program was written and used for optimizing the beam transmission through the beam line and to obtain a focused beam spot on the target [1].

METHOD OF CALCULATION

In this facility, heavy ion beam from 1.7 MV Tandetron accelerator will be used for irradiation and helium ion beam from a 400 kV accelerator will be used to simultaneously inject helium into the samples. The beam line from 1.7 MV Tandetron accelerator to the dual beam irradiation chamber is already built and is functional. The fabrication of the beam line from 400 kV accelerator to the dual beam irradiation chamber is in progress. NEC built RF-charge exchange ion source is used which is having emittance 6.5 mmmrad-MeV$^{1/2}$ at 25 keV [2] and it produces approximately 4 mm of beam waist at 1 m from gap lens [3]. Distance between gap lens and entrance of accelerating tube is 0.9 m. Accelerating tube is having 17 electrodes with 2" apart from each other making 16 sections and a total length of 32". The maximum accelerating voltage is 400 kV which is reduced to zero in equal steps from first to 16th electrode. Irradiation chamber and 400 kV accelerator are at right angle so the beam will be steered 90^0 using a rectangular magnet with entrance and exit angle 26.6^0 and bending radius 0.4 m. This magnet will also act as mass analyzing magnet. Center of the magnet is 7.5 m away from target and 3.3 m away from the exit of accelerating tube. A 0.7 m long differential pumping section with 2 cm aperture size is incorporated to achieve vacuum isolation between dual beam irradiation chamber which is at vacuum of 10^{-9} mbar and the rest of the beam line which will be at vacuum of 10^{-7} mbar. Differential pumping section must be placed al least 2.5 m away from dual beam irradiation chamber in order to provide enough space for beam scanner, neutral trap and beam diagnostic elements. Matching of the beam optics has to be has to be optimized to achieve maximum beam transmission through the differential pumping unit and also to obtain a focused narrow beam spot on the target. This was achieved using two electrostatic quadrupole triplets (QPT). These quadrupole triplets have effective length 130-20-180-20-130 mm with maximum potential gradient 3.3 kV/cm^2. Now the whole problem turned in to finding the appropriate position for two quadrupole triplets in the beam line.

The invariant emittance ellipse is given by

$$\gamma y'^2 + 2\alpha\beta yy' + \alpha y^2 = \varepsilon \qquad (1)$$

Where,

$$\gamma(s) = \frac{1+\alpha^2(s)}{\beta(s)} \qquad (2)$$

Where ε is beam emittance; α, β and γ are twiss parameters [1].

The beam envelope at s is given by

$$E(s) = y_{max}(s) = \pm\sqrt{\varepsilon\beta(s)} \qquad (3)$$

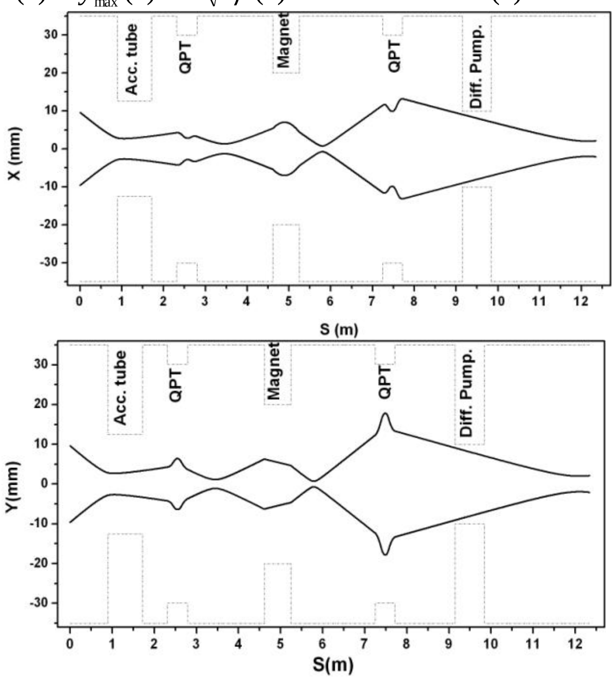

Figure 1: Beam envelope (thick solid line) in horizontal and vertical planes and the aperture sizes (dotted line) of the beam line elements.

So if $\beta(s)$ and ε is known, then the beam envelope E(s) can be determined throughout the beam line. Emittance for the ion source is known which is conserved up to the accelerating tube but in the accelerating tube normalized emittance (eqn.4) is constant and geometrical emittance within accelerating tube is derived from the normalized emittance [1]. After accelerating tube emittance remains constant throughout the beam line.

$$\varepsilon_N = \left(\frac{p_0}{m_0 c}\right)\varepsilon \qquad (4)$$

The twiss parameters(α, β, γ) at s_0 can be related to the twiss parameters $(\alpha_0, \beta_0, \gamma_0)$ at s using the transformation [1]:

$$\begin{bmatrix} \beta \\ \alpha \\ \gamma \end{bmatrix} = \begin{bmatrix} C^2 & -2SC & S^2 \\ -CC' & SC'+S'C & -SS' \\ C'^2 & -2S'C' & S'^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{bmatrix} \quad (5)$$

Where C, S, C' and S' are the elements of the matrix which relates position (y) and the divergence (y') of a single particle at s to the position (y_0) and divergence (y'_0) at s_0

$$\begin{bmatrix} y \\ y' \end{bmatrix} = \begin{bmatrix} C & S \\ C' & S' \end{bmatrix} \begin{bmatrix} y_0 \\ y'_0 \end{bmatrix} \quad (6)$$

In a circular accelerator$(\alpha_0, \beta_0, \gamma_0)$ can be determined at a symmetric point of machine where derivative of beta vanishes but here there is no symmetric point in the machine. The derivative of beta also vanishes at beam waist. So if the beam waist and emittance is known then twiss parameters at the beam waist $(\alpha_w, \beta_w, \gamma_w)$can be determined. NEC built RF- charge exchange ion source which is used here is having emittance 6.5 mmmrad-MeV$^{1/2}$ (90% particles) at 25 keV [2] and it produces approximately 4 mm of beam waist at 1 m from gap lens [3].

$$\mathrm{E} = 2 \times 10\text{-}3\,\mathrm{m}$$

$$\alpha_w = -\beta'/2 = 0, \quad \beta_w = E^2/\varepsilon = 0.2482,$$
$$\gamma_w = 1/\beta_w = 4.0287$$

$$\begin{bmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{bmatrix} = \begin{bmatrix} C^2 & -2SC & S^2 \\ -CC' & SC'+S'C & -SS' \\ C'^2 & -2S'C' & S'^2 \end{bmatrix}^{-1} \begin{bmatrix} \beta_w \\ \alpha_w \\ \gamma_w \end{bmatrix}$$
$$= \begin{bmatrix} 4.2770 \\ 4.0287 \\ 4.0287 \end{bmatrix} \quad (7)$$

Here $\begin{bmatrix} C & S \\ C' & S' \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$ is the drift space between gap lens of ion source and the beam waist. In this way the initial twiss parameter at the end of gap lens of ion source is determined. Twiss parameters at the end of one element become the initial twiss parameter for the next element. Now using the transformation (5) and eqn. (3), the beta function and thus beam envelope at a step of one mm is determined throughout the beam line and accelerating tube which can be seen in figure 1.

Simulation starts from the end of gap lens of ion source with initial twiss parameters (7) and beam passes through the drift space up to the entrance of accelerating tube. Accelerating tube is divided in to 16 sections of equal length 2”. The potential difference is kept equal in every section so that ions are accelerated by equal energy (800/16=50 keV) in each section. The transformation matrix used is given in eqn. (8) [1]. Here l is length of accelerating section, $p_0$is the momentum with which ion enters in to the accelerating section and Δp is the momentum gain in the section.

$$M_{ac} = \frac{1}{\sqrt{\dfrac{p_0}{p_0 + \Delta p}}} \begin{bmatrix} 1 & \dfrac{p_0}{\Delta p}.l.\ln\left(1 + \dfrac{\Delta p}{p_0}\right) \\ 0 & \dfrac{p_0}{p_0 + \Delta p} \end{bmatrix} \quad (8)$$

Now $p_0 + \Delta p$ becomes the new p_0 for next accelerating section.

Standard transfer matrices for drift space, rectangular magnet and quadrupole have been used [1]. Quadrupole triplets were arranged in FODOF in one plane and DOFOD in another plane. Astigmatism correction was incorporated by changing the potential gradient of central quadrupole with respect to outer quadrupoles. Focusing strength is given by [4],

$$K = qG/2E \quad (9)$$

Where q is the charge of ion, G is the potential gradient and E is the energy of ion.

One quadrupole triplet was kept in between accelerating tube and rectangular magnet and another was kept in between rectangular magnet and differential pumping. It was found that if the first QPT is kept very close to the accelerating tube then transmission through differential pumping is low and if it is placed away from accelerating tube then beam spot on target increases. It is found that 0.6 m is the optimum distance between accelerating tube and first QPT. Rectangular magnet provides very hard focusing in both planes and produces the beam waist just 0.5 m away from the exit of magnet. After this, beam diverges strongly in both planes. To provide beam focusing on target, second QPT is placed between the beam waist produced by magnet and differential pumping unit. QPT can not be placed very close to the beam spot because of large magnification but it can also not be placed close to the differential pumping unit since differential pumping will obstruct beam envelope and reduce the beam transmission. 2.0 m from the exit of magnet is found the optimum position for second QPT. With the above QPT configuration, it is found that 60% of the emittance (90% particles) is only passing through the differential pumping unit, this emittance contains 70% of particles [2]. Finally 4mm of beam size on the target and 70% transmission is achieved by this beam optics design.

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