Circular Beam Scanning of Large Targets

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Abstract

Circular sweep of the beam over a large target for making a uniform irradiation zone is suggested. The scanning pattern is an untwisted spiral if the beam is z-uniform or a collection of concentric circles if the beam consists of bunches of particles. Deflection voltage is provided by RF cavities with orthogonal transverse fields shifted in time by $\pi/2$. The amplitude of deflection voltage as a function of time and the optimal beam scan frequency with respect to RF frequency of accelerator are given.

1 INTRODUCTION

Irradiation facility can be divided by scanning systems [1,2] where the beam of particles is unfolded in time to cover a target in one or two dimensions and static systems [3] where the time-independent extension of the beam is used. High uniformity of the irradiation dose over a target is very important for many applications including ion implantation and microfilters production. Usual scanning systems use linear X-Y scanning in two orthogonal directions created by saw-like deflecting magnetic field. Irradiation of large targets by short bunches of particles accelerated in RF linac requires a high value of scanning frequency and large amplitude of deflection field. For such a case it could be convenient to use electromagnetic field with harmonic dependence on time provided by RF cavities as a deflection voltage.

2 ONE DIMENSIONAL BEAM SCANNING

Consider the beam of non relativistic particles with charge q and mass m which oscillates along x-axis of a target with a frequency ω and amplitude R

$$x = R \sin \omega t \tag{1}$$

The beam current is

$$j = q \frac{dN}{dt} \tag{2}$$

where dN is a number of particles which irradiate the target during the time dt. Let us define the particle distribution along the x-axis. From equation of motion (1) the time interval dt is connected with dx by

$$dt = \frac{dx}{\omega R \sqrt{1-\left(\frac{x}{R}\right)^2}} \tag{3}$$

After substitution (3) in (2) the particle distribution along the irradiated line is given by:

$$\frac{dN}{dx} = \frac{j}{\omega R q \sqrt{1-\left(\frac{x}{R}\right)^2}} \tag{4}$$

The singularity in (4) for x=R is avoided if transverse sizes of the beam are taken into account. From (4) it follows that the distribution along the axis is close to uniform only in the center of a target and has strong nonlinear peaks near it's boundaries. It is clear from eq.(1) that the particles move more slowly near the boundaries than in the center of a target therefore the number of particles near the boundaries is larger .

3 TWO DIMENSIONAL BEAM SCANNING

Consider the beam which draws a circle at the target and Cartesian coordinates of the particles obey the equations

$$x = r \sin \omega t$$
$$y = r \cos \omega t \tag{5}$$

In such a case particle density along the circle is a constant

$$\frac{dN}{dl} = \frac{j}{qr\omega} \tag{6}$$

For uniform irradiation of a large target let us change the radius of the beam trajectory slowly in such a way that the increasing of the area dS irradiated by the beam per one revolution is a constant:

$$dS = 2\pi\, r(t)\, dr(t) = \text{const} \tag{7}$$

The equation (7) is a condition of uniform irradiation of a target in radial direction while the equation ω=const is the condition of a uniform irradiation in azimuth direction. After combining the equation (7) with equation of rotation $d\varphi=\omega dt$ the radius of beam trajectory is given by

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$$r = \sqrt{\frac{dS}{d\varphi}\frac{\omega t}{\pi}} \qquad (8)$$

The value $dS/d\varphi$ can be defined from the condition that after N revolutions (i.e. during the period of irradiation $T=2\pi N/\omega$) the beam radius reaches it's maximum value r=R equals to the radius of a target:

$$\frac{dS}{d\varphi} = \frac{R^2}{2N} \qquad (9)$$

Finally the equation for increasing of beam radius with time for a uniform irradiation of a target is

$$r = R\sqrt{\frac{t}{T}} = R\sqrt{\frac{\omega t}{2\pi N}} \qquad (10)$$

Equation (10) describes the untwisted spiral trajectory of the beam which starts in the center of a target. Cartesian coordinates of particles are changing according to

$$x = R\sqrt{\frac{t}{T}}\ \sin\omega t$$

$$y = R\sqrt{\frac{t}{T}}\ \cos\omega t \qquad (11)$$

It is clear that for better uniformity of irradiation the number of revolutions of the beam which covers the target should be much larger than unit N>>1 and the increasing of beam radius at every revolution should be smaller than the transverse size of the beam.

4 DEFLECTION VOLTAGE

Let us estimate the required electric field for making necessary beam trajectory (11). Let the beam passes through the narrow gap of the length d with the deflecting field

$$E_x = E(t)\sin\omega t$$
$$E_y = E(t)\cos\omega t \qquad (12)$$

followed by drift space with the length z >> d .We assume that the beam is on-axis in the gap. According to equation of motion of particle inside the gap

$$\frac{d^2x}{dt^2} = \frac{q}{m}E_x(t) \qquad (13)$$

the beam obtains the transverse velocity $v_x = \beta_x c$ in the gap

$$v_x = E(t)\frac{qd\sin(\theta/2)}{mc\ \beta_z\ (\theta/2)}\sin\omega t \qquad (14)$$

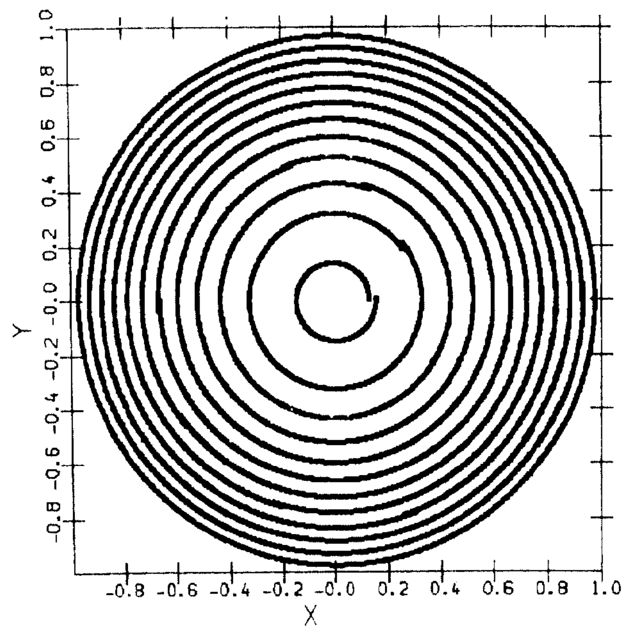

Figure 1. Bunched beam scanning of a target.

analogously for v_y, where θ is a transit time angle

$$\theta = \frac{\omega d}{c\beta_z} \qquad (15)$$

After the drift the deviation of the beam at the target is

$$x = z\frac{\beta_x}{\beta_z} \qquad (16)$$

Combining eqs.(11), (14) and (16) the required deflecting voltage U=Ed to produce untwisted spiral beam trajectory at the target is

$$U_x(t) = U_0\sqrt{\frac{t}{T}}\ \sin\omega t$$

$$U_y(t) = U_0\sqrt{\frac{t}{T}}\ \cos\omega t \qquad (17)$$

where U_0 is a amplitude value of gap voltage

$$U_0 = 2\frac{W}{q}\frac{R}{z}\left(\frac{\theta/2}{\sin\theta/2}\right) \qquad (18)$$

and W is a kinetic energy of the beam.

5 TARGET IRRADIATION BY BUNCHED BEAM

The suggested technique of uniform target irradiation is suitable for the beam consisting of short bunches.

Suppose the value of RF frequency of particle accelerator is f and the phase length of bunches after acceleration is $\delta\Phi=\Delta\Phi/2\pi$. To provide necessary beam trajectory at the target every bunch has to be turned into a circle during the illumination of the target by the bunch (see fig. 1). It gives the following expression for the frequency of deflecting voltage

$$\omega = \frac{2\pi f}{\delta\Phi} \tag{19}$$

Longitudinal particle distribution inside the bunch is not a uniform because of the shape of a separatrix which defines the phase stability region of RF accelerator. This non-uniformity will be transformed into azimuth non-uniformity of a beam at the target. To smooth this effect the frequency of scanning field can be chosen slightly different from the value (19):

$$\frac{\omega}{2\pi f} = \frac{1}{\delta\Phi} + \varepsilon \tag{20}$$

where $\varepsilon < 1$ is a small mismatching between frequencies . Inserting of a small mismatching means that every bunch will be displayed at the target in a shifted angle from the previous one (see fig. 1) As a result the azimuth non-uniformity of particle distribution will be smoothed from overlapping of the neighboring bunches and the final distribution of the particles at the target will be more flattened.

6 CONCLUSION

The uniform target irradiation by circular beam sweeping is suggested. The scan pattern is an untwisted spiral for a continuos beam or a family of concentric circles for a bunched beam. The required value of deflecting voltage and scan frequency to provide necessary beam trajectory are found. The considered method of target irradiation can be useful in different applications of charged particle beams where the large amplitude of deflection voltage and high uniformity of irradiation are required.

7 REFERENCES

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