LONGITUDINAL FOCUSING OF SPACE-CHARGE DOMINATED BEAMS IN THE UMD ELECTRON RING[*]

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Abstract

Longitudinal focusing is of great importance in space-charge-dominated bunched beams. The bunches lengthen rapidly due to the strong space-charge forces during transport. The UMD electron ring[1] is designed to operate with bunches having rectangular and parabolic profiles. Three induction cavities along the ring will be employed for longitudinal focusing. In this paper, we first briefly review the longitudinal dynamics of parabolic and rectangular bunches. The design of the induction cavities with their high repetition rate modulators is then presented. The preliminary test results of lower voltage and repetition rate version of two different modulators and the SPICE simulation results show that modulators work well.

1. INTRODUCTION

The longitudinal focusing of space-charge dominated beam is of great interest in recirculator systems for applications in high energy physics, heavy ion inertial fusion, spallation neutron sources and so on. Longitudinal expansion due to the strong space-charge force will result in rapid change in the beam profile. An initially rectangular profile of a drifting beam does not remain rectangular, thus, so-called “ear-field” must be applied to the edges of the beam to focus the expanded beam back to the rectangular shape. A linear force should also be applied to focus a parabolic beam. Three induction modules will be employed for longitudinal focusing in order to maintain a proper beam profile in the UMD electron ring. The focusing voltages for beams with rectangular and parabolic profiles are given in section 2. The design of the induction cavity and its pulse modulators, as well as preliminary results of low voltage version test are presented in this paper. More details on the development of a full-voltage, MHz-repetition-rate modulator will described elsewhere later.

2. LONGITUDINAL EXPANSION OF BUNCHED BEAMS WITH RECTANGULAR AND PARABOLIC LINE CHARGE DENSITY DISTRIBUTIONS

The particles in the leading edge of bunched beams will be accelerated, and particles in the trailing edge will be decelerated due to the space-charge force. The line charge density and the velocity distributions along the bunches will change with drifting distance *S*.

For an initial rectangular beam with a uniform velocity, the line charge density and velocity in the beam frame can be obtained from the solution of one-dimension cold-fluid equations[2,3,4] in the simple wave region,

$$\frac{\lambda}{\lambda_0} = \begin{cases} 1 & |t| < t_1 \\ \left[\dfrac{2}{3} + \dfrac{S_{cusp}}{3S}\left(1 - \dfrac{2|t|}{\tau_0}\right) \right]^2 & t_1 \le |t| \le t_2 \\ 0 & |t| > t_2 \end{cases} \qquad (1)$$

$$\frac{v}{C_s} = \begin{cases} -\dfrac{2}{3}\dfrac{|t|}{t}\left[1 - \dfrac{S_{cusp}}{S}\left(1 - \dfrac{2|t|}{\tau_0}\right)\right] & t_1 \le |t| \le t_2 \\ 0 & t_2 < |t| < t_1 \end{cases} \qquad (2)$$

$$t_1 = \left(\frac{1}{2} - \frac{S}{2S_{cusp}}\right)\tau_0, \qquad t_2 = \left(\frac{1}{2} + \frac{S}{S_{cusp}}\right)\tau_0,$$

$$S_{cusp} = v_0^2 \tau_0 / 2C_s, \qquad C_s = \sqrt{\frac{egI_i}{4\pi\varepsilon_0 m v_0 \gamma^5}}$$

where λ is the line charge density, v is the velocity in the beam frame, ε_0 the permittivity of free space, e/m is the ratio of charge to mass of the particles, γ is the Lorenz factor, g is a geometry factor in the order of unity. I_i is the initial beam current, v_0 is the beam velocity, τ_0 is pulse width of beam.

According to Eq. (1), a 10 keV, 0.1A, 50ns rectangular beam in the UMD ring will reach the “cusp” point after about three turns[4]. In order to maintain a good beam profile during transportation, an external force must be applied to the beam before the “cusp” point.

For a parabolic bunch, the line charge density and velocity distributions can be expressed as follows[5] if $z_m - z_i << z_i$

$$\lambda(z,S) = \frac{I_i z_i}{\beta c z_m}\left(1 - \frac{z^2}{z_m^2}\right) \qquad (3)$$

$$v \approx E_i \frac{4\alpha g S}{I_0 \beta^4 m v_0 c} t \qquad (4)$$

where

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$$\alpha = \frac{4gI_i}{\beta_0^3 I_0 \gamma^5} \qquad z_m \approx \frac{gI_i}{I_0 \beta^3 Z_i}\frac{C}{N_g} + z_i$$

z_i is the initial bunch length, E_i is the beam energy.

3. DESIGN OF LONGITUDINAL FOCUSING IN THE UMD RING

3.1 Voltages for longitudinal focusing in the UMD ring

Because the equations of motion are time reversible[3], we could restore the beam profile by tilting the beam velocity distribution in the beam frame properly in very short time. This can be realized by applying a voltage pulse from a small induction gap, during which the transition time of the particles could be negligible.

From Eq. (2), we can derive the voltage for restoring the rectangular bunch

$$V(t) = \frac{4t}{3e|t|} m v_0 C_s [1 - \frac{S_{cusp}}{S}(1 - \frac{2|t|}{\tau_0})] \qquad t_1 < |t| < t_2$$

$$0 \qquad , \quad t_2 < |t| < t_1$$

In the UMD ring design, three induction modules will be employed for longitudinal focusing for good beam profiles. In this case, the expansion distance S is 1.92 m. For an initial rectangular beam of 10keV, 0.1A, 50 ns, the voltage waveform for restoring the beam after the expansion distance S is plotted in Fig. 1

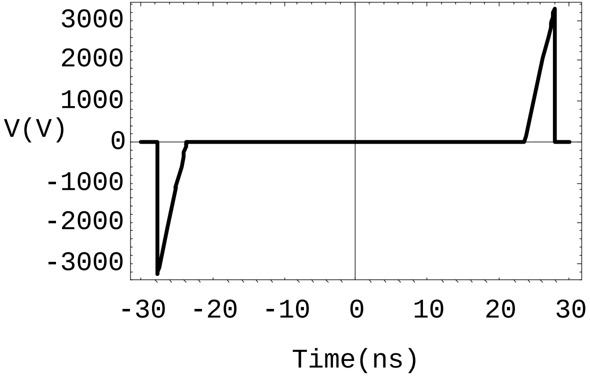

Fig. 1 "Ear-field' for focusing rectangular bunch

This is the so-called "ear-field". The particles in the leading edge will be decelerated by the negative "ear",while the particles in the trailing edge will be accelerated by the positive "ear". The beam profile will be restored after another distance of S. This process repeats periodically, so that the longitudinal beam envelope will oscillates along the ring.

For a matched space-charge dominated beam bunch with a parabolic profile, we get the voltage for restoring the beam profile from the equation of longitudinal beam envelope [6],

$$V(t) = \frac{2cgI_i \quad C}{I_0 N_g \gamma^2 (z_m / Z_i)^3} \frac{mc^2}{q} t \tag{5}$$

Where C is the circumference of the UMD ring. N_g is the number of the induction gaps along the ring. To focus the parabolic bunch, the voltage waveform is as the follows:

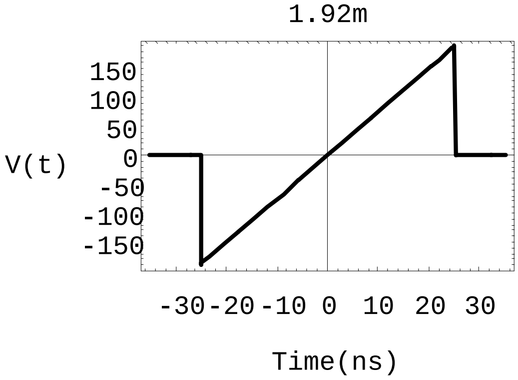

Fig. 2 Voltage for focusing parabolic bunch

Due to the short revolution time of the UMD ring, the repetition rate of both voltage pulses should be 5.08 MHz. This is very tough for the pulse switch technology, especially for the fast rise/fall time "ear-field".

3.2 Longitudinal matching

Longitudinal matching is also important in longitudinal focsing. In order to match the beams between the injection and the ring, the distance between the electron gun and the first focusing cavity should be 1.92 m.

4. DESIGN AND DEVELOPMENT OF COMPACT INDUCTION MODULE

The principle of induction cavities has been described in many places[7,8]. Here we just describe some special requirements on the induction cavity design for the UMD ring.

4.1 Special requirements on the cavity design

4.1.1 High frequency response

Due to the high rep-rate and the fast rise/fall time of the ear field, most magnetic materials cannot be used. A special Nickel-Zinc ferrite toroid of material CMD5005 ,which can run in frequency range up to more than 100 MHz with low core loss and high permeability, has been chosen for the cavity design. The initial permeability of the ferrite is 1600 and the maximum flux density is 3200 Gauss. The dimensions of the ferrite toroids are 6" OD, 2.1" ID, 1.3" Height.

4.1.2 High vacuum and bakable

The ring must be capable of vacuum as low as 10^{-10} Torr and must be bakable. To meet these requirements, a glass-metal seal has been designed for the induction gap, so the cavity is outside the vacuum. This not only avoids the possible problems which could occur if the ferrite be put in vacuum, but also makes the special mechanical design possible which makes a cavity bakable by splitting the ferrite toroid and its housing (see Fig . 3)

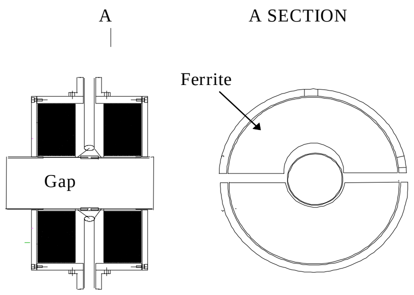

Fig. 3 Mechanical design of the compact cavity

The C-type toroids can be taken out before the system is baked.

4.1.3 The transverse focusing due to the gap voltages

The induction gap voltage plays a role in transverse focusing[6]. The focusing length depends on the gap voltage[9]. In the case of the "ear-field", the focus length varies from infinite to 25 m with the "ear" from 0V to V_{peak}. The minimum focus length is about 1500 m[10] for parabolic bunch. So the effects on transverse focusing in both cases are negligible.

4.2 Modulator design for driving the cavity

A circuit that generates the "ear-field" has been designed for the rectangular bunch. A triangular pulses have been generated to focus the parabolic bunch. PSPICE simulations and low voltage tests of the circuits have been carried out. Preliminary results show that the circuits work well. More details about developments of the full high voltage, MHz-rep-rate modulators will be described elsewhere.

5. CONCLUSIONS

The line charge density and velocity distributions of both rectangular and parabolic bunches after expansion have been given. The voltages for focusing the rectangular and parabolic bunches have also been derived individually. A compact, bakable induction module for high frequency response, has been designed and developed.

REFERENCES

[1] J.G. Wang, S. Bernal, J.J. Deng, Y. Li, M. Reiser, H. Suk, M. Venturini, T. Godlove, Design and Development of an Electron Recirculator, in this proceeding.
[2] A. Faltens, E.P. Lee, and S.S. Rosenblum, Beam end erosion, J. Appl. Phys. 61(12)(1987)5219-5221.
[3] D.D. Ho, S.T. Brandon,and E.P. Lee, Part. Accel. 35,15(1991).
[4] D.X. Wang, J.G. Wang, M. Reiser, Phys. Rev. Vol. 73, No.166-69(1994).
[5] D.X. Wang, J.G. Wang, D. Kehne, M. Reiser,Appl. Phys. Lett. 62(25),1993
[6] M. Reiser, Theory and Design of Charged Particle Beams, Wiley, New York, 1994.
[7] R. J. Briggs, Linear Induction Accelerator, LINAC'86 (1986), 10-13
[8] J.G. Wang, D.X. Wang, E. Boggasch, D. Kehne, M. Reiser, T. Shea, Nucl. Instru. Meth. in Phys. Res. A301(1991) ,19-26.
[9] Y.B. Chen, M. Reiser, J. Appl. Phys. 65(9)(1989), 3324-3328.
[10] J.J. Deng, Technical note, E-Ring-96-18