CHOICE OF ACCELERATING SYSTEM FOR UNDULATOR LINEAR ACCELERATOR

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Abstract

The undulator linear accelerators (UNDULAC) were suggested as a new type of high intensity low energy ion linac. Such accelerators can be realized in a periodical IH structure. All spatial harmonics of RF field in UNDULAC are non-synchronous with a beam. In our case an accelerating force is to be driven by a combination of the zero and the first space harmonics. The ratio of the first to the zero RF field harmonics amplitudes must be equal to 0.25 – 0.3. The effective beam bunching and focusing can be provided in this case. The geometry of UNDULAC accelerating channel is discussed to realize this ratio. The first results of the IH resonator type choice are also presented.

INTRODUCTION

The design of high intense ion linear accelerator (linac) is a challenging task of a contemporary accelerator physics and technology. Such accelerators can be used as neutron generators and for nuclear energetic, thermonuclear synthesis as well as in other applications. In a conventional radio frequency (RF) linac the beam is accelerated by a synchronous wave of an RF field. Radio Frequency Quadrupole (RFQ) structures are usually used in a buncher of linac. The current transmission coefficient in RFQ can be limited by large value of losses due to small channel aperture and powerful influence of space charge fields. Therefore, the maximum proton beam current in RFQ is 120 – 150 mA but the rate of energy gain is low (usually not greater than 300 – 400 keV/m).

An alternative method of the acceleration in electromagnetic fields without a synchronous wave was presented in [1]. Some analytical studies have already been published in [2, 3]. The acceleration mechanism is similar to the acceleration mechanism in an inverse free electron laser (IFEL), where an electron beam is accelerated by a ponderomotive force. In our case, the accelerating force is driven by a combination of two non-synchronous waves which are provided by two undulators. Here we the define undulator as any structure producing a periodic electromagnetic field in which the phase velocity significantly differs from the beam velocity. We identify a linac that uses this approach as the “undulator linear accelerator” (UNDULAC).

There are three different types of undulators that can be used to realize the required configuration of accelerating fields: magnetic (UNDULAC-M), electrostatic (UNDULAC-E) and RF undulator (UNDULAC-RF).

The numerical simulation was done for a ribbon beam of protons and deuterium D^- ions. The results of D^- ion beam dynamics simulation are discussed in [4]. Let us briefly consider the results of the proton beam dynamics simulation in UNDULAC-RF buncher and accelerator using longitudinal RF field for π mode. The simulation was done assuming the following parameters: the initial energy of protons W_{in} = 46 keV (β_{in} = 0.01), the length of accelerator channel is 1.2 m, the accelerator channel cross section size is $2a\times 2b = 0.8\times 20\ \text{cm}^2$, the wave length $\lambda = 2$ m. The effective amplitude of combined wave was chosen to be equal to $\chi E_0^2 = 0.25\left(160\,\text{kV/cm}\right)^2$. Here χ is the ratio of RF field harmonics amplitudes $\chi = E_1 / E_0$. This ratio is very impotent parameter in UNDULAC-RF. It’s optimal value can done the beam with minimal losses. In this case the output beam energy is equal to 380 keV.

The current transmission coefficient is equal to 83 %. The optimal value of χ is equal to 0.25 – 0.3, which coincides with analytically founded value. The particle losses are caused by fast oscillations of particle phases and longitudinal velocities. The rate of energy gain is equal to 600 – 700 keV/m in accelerating sub-section of UNDULAC. This value is as much again the accelerating field gradient in RFQ.

We will study the interdigital H-type (IH) periodic resonator with drift tubes as the accelerating structure for UNDULAC-RF. It is simpler than RFQ and extends the limit of the beam current and the rate of energy gain as well as it increases the transmission coefficient. The choice of the resonator form and the numerical simulation results of electrodynamics parameters are discussed in this paper.

CHOICE OF RF FIELD AMPLITUDES RATIO

The necessary χ ratio can be realized using the simple channel period. The basic parameters of one period are shown in Fig. 1. The dependence of RF field harmonics amplitudes ratio was investigated as a function of the period parameters. It was done both by analytically method and numerically.

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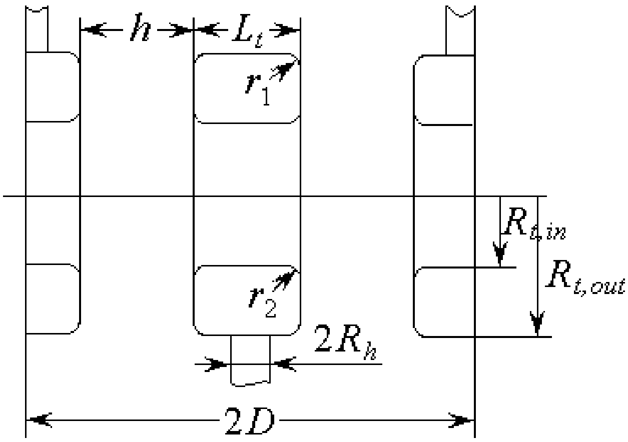

Figure 1: The parameters of UNDULAC-RF period.

As it was told the optimal ratio of RF field harmonics amplitude, χ, at the channel axis is equal to 0.25 – 0.3. We assumed that the accelerating gap width h is smaller than the electrode length L_t. In this case the z-dependence of the RF potential is the piecewise-smooth function. We can expand the RF potential in Fourier series for $y < R_{t,in}$, where $2R_{t,in}$ is the width of the aperture:

$$U(x,0,z) = \frac{4u}{\pi}(-1)^n \times \times \sum_{n=0}^{\infty} \frac{\sin(Y_n)\cosh(2Y_n y/h)\cos(2Y_n z/h)}{(2n+1)Y_n \cosh(2Y_n R_{t,in}/h)}, \tag{1}$$

where u is the voltage between the adjacent electrodes, $Y_n = (2n+1)\pi h/D$, D is the RF field period.

The field amplitude ratio can be presented as

$$\frac{E_1}{E_0} = -\frac{\sin(3\pi h/2D)\cosh(\pi R_{t,in}/D)}{3\sin(\pi h/2D)\cosh(3\pi R_{t,in}/D)}. \tag{2}$$

This expression is readily rewrites as

$$h(z) = \frac{2}{\pi}\arcsin\left(\frac{1}{2}\sqrt{3+3\frac{E_1}{E_0}\frac{\cosh[3\pi R_{t,in}/D(z)]}{\cosh[\pi R_{t,in}/D(z)]}}\right). \tag{3}$$

Thus, knowing the required field amplitude ratio and channel aperture one can choose the accelerating-gap width for different reference particle velocity values. In our case the structure period $D = \beta_s\lambda$. The dependence of accelerating gap width on period value is shown in Fig. 2 for the different values of χ. All curves are computed with aperture size $R_{t,in} = 4$ mm without the blending.

The previously results was verified by means of numerical simulation. The field distribution on the 3D grid was computed by the use of finite elements method. The RF field harmonics amplitude ratio χ was analyzed by using the FFT algorithm. The results of numerical simulation are also shown in Fig. 2 and agree with analytical study.

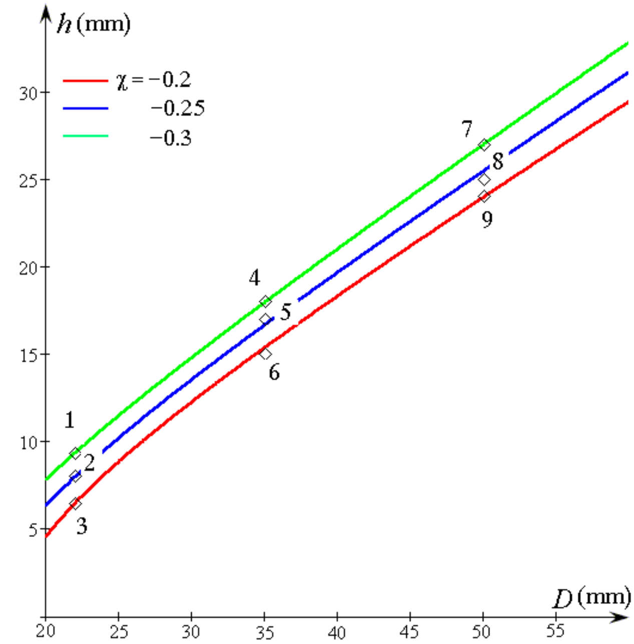

Figure 2: The dependence of accelerating gap width h on the structure period D for different χ values. The results of analytical study are shown by solid lines and the results of numerical simulation by "◇"-s:

1. $D = 22$ mm, $h = 6.45$ mm, $\chi = -0.291$;
2. $D = 22$ mm, $h = 8$ mm, $\chi = -0.234$;
3. $D = 22$ mm, $h = 9.3$ mm, $\chi = -0.178$;
4. $D = 35$ mm, $h = 15$ mm, $\chi = -0.278$;
5. $D = 35$ mm, $h = 17$ mm, $\chi = -0.244$;
6. $D = 35$ mm, $h = 18$ mm, $\chi = -0.175$;
7. $D = 50$ mm, $h = 24$ mm, $\chi = -0.287$;
8. $D = 50$ mm, $h = 25$ mm, $\chi = -0.208$;
9. $D = 50$ mm, $h = 27$ mm, $\chi = -0.169$.

The electrodes in real accelerating channel can not be fabricated without the blending. The necessary correction can be easily done by simulation. The numerical simulation shows that the influence of the blend radius on χ value is negligible. For example, if $h = 6.45$ mm and $D = 22$ mm χ value is equal to -0.291 without the blending and -0.265 with the bland radius $r_2 = 1$ mm. The ratio χ is not depended on outer electrodes size if it's value is larger than 10 mm and the gap is not sufficiently larger than outer electrodes size.

ACCELERATING CHANNEL PERIOD AND APERTURE FORM

The ribbon ion beam can be accelerated in UNDULAC-RF. The slot aperture is necessary for the ribbon beam acceleration. We discuss the RF undulator field for π mode in this paper. In this case transverse component of the RF field is zero at the axis and the dependence of RF potential on transverse coordinates can be written as

$$U(x,y) = u\cosh(h_x x)\cosh(h_y y), \tag{4}$$

where h_x and h_y are the transverse wave numbers, $h_x^2 + h_y^2 = h_z^2$. The ratio h_x/h_y is the parameter which define the electrode form and influence on the beam dynamics. In our case the optimal value is $h_x/h_y \approx 20$ and $R_{t,in} = 4$ mm. The form of aperture can be calculated as:

$$\alpha(x) = \frac{h_x}{h_z} \operatorname{arccosh}\left(\frac{2\pi X_{\max} / D}{2\pi h_x x / h_z D} \right). \qquad (5)$$

The length of undulator periods can be easily founded if the dependence of reference velocity on longitudinal coordinate z is calculated from equation:

$$\frac{\mathrm{d}}{\mathrm{d}\xi} \beta_s(z) = \left(\frac{e\lambda}{2\pi mc^2} \right)^2 \frac{E_0(z) E_1(z)}{\beta_s^2} \sin(2\varphi_s(z)). \quad (6)$$

Here e and m are the proton charge and mass, c – the velocity of light, $\xi = 2\pi z/\lambda$ is the dimensionless longitudinal coordinate. The field amplitudes $E_0(z)$, $E_1(z)$ and reference phase $\varphi_s(z)$ are increasing functions of the longitudinal coordinate in the bunching sub-section of UNDULAC-RF and the constant in the accelerating sub-section. The period of undulator $D = \beta_s(z)\lambda$ and the discrete values of period are shown in Fig. 3. In our case the period value is varying from 20 mm to 62 mm and the number of periods is equal to 38.

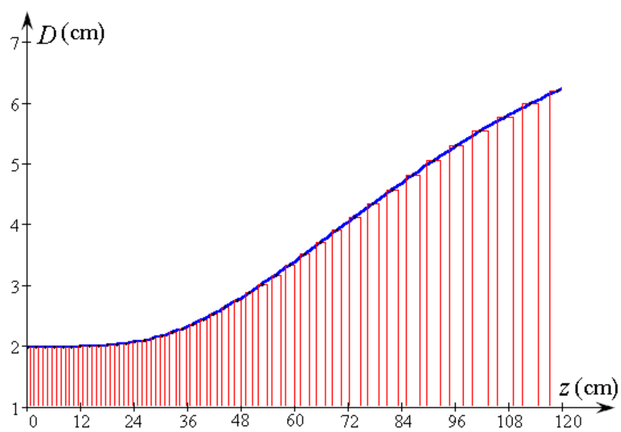

Figure 3: The period of undulator $D = \beta_s(z)\lambda$ and the discrete values of the period versus longitudinal coordinate z.

RESONATOR FOR UNDULAC-RF

The UNDULAC-RF can be realized as the periodical IH resonator. The choice of resonator type and numerical simulation of the electrodynamics characteristics are the main problems.

The well-known two-camber IH resonator was chosen for UNDULAC-RF (see Fig. 4). Such resonator is compact and has high values of the shunt impedance and the quality factor and is useful in many types of ion accelerators (for example in systems with periodical RF focusing, [5]). Geometric parameters of resonator are the following: the inner radius of resonator is 180 mm, the total length of the resonator is 1 250 mm, the distance between of the vanes is 100 mm and the vane thickness is 10 mm. The resonant frequency of the resonator is equal to 150 MHz. The shunt impedance and the Q-factor are equal to 85 MΩ and 10 500 respectively.

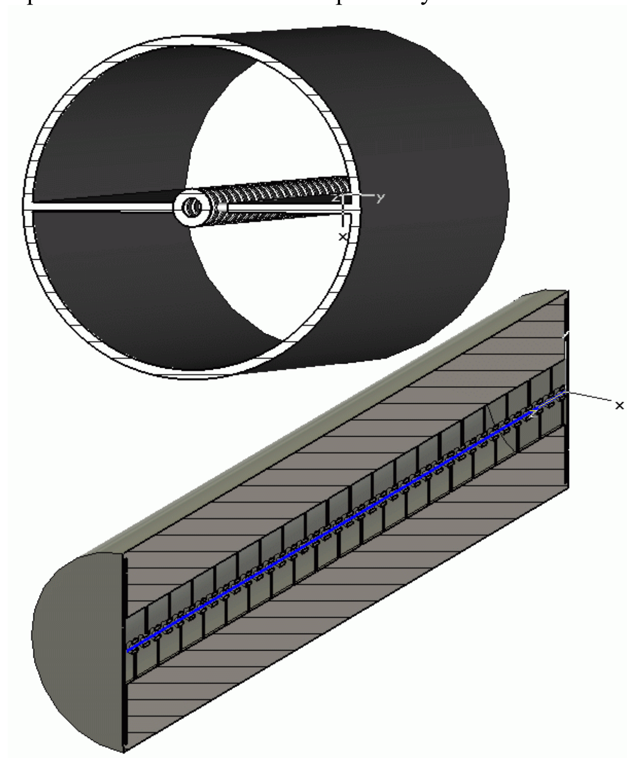

Figure 4: The schematic view of the two-camber IH resonator for UNDULAC-RF.

The important problem is to realize the necessary RF field amplitude distribution in the resonator. The amplitude of RF field in the bunching sub-section was chosen as an increasing function and the amplitude was a constant in the acceleration sub-section. This amplitude in the buncher can be easily realized because the field is distributed by sine in IH resonator. The especial form gap in the vane was used for the field amplitude alignment in accelerating sub-section.

CONCLUSION

The first results of UNDULAC-RF design prototype were presented in this paper. It was shown that the necessary RF field harmonic ratio can be realized by especial choice of the period and the tube parameters.

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