STUDY OF BEAM BREAK UP IN IRRADIATION LINACS

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Abstract

Many recent experiments of the irradiation linacs produced at Tsinghua University and Nuctech indicate that beam power is limited by beam break up (BBU). Limits exist while the beam current or the pulse width is increased. In this paper, we illustrate the bream break up phenomenon in the cases of both the 10 MeV travelling-wave linac and 10 MeV backward travelling-wave linac. The main modes in the linacs are analysed and the wake fields are calculated both with theoretical analysis and numerical simulations. The BBU threshold of these structures has been studied, by computing the wake fields and their impact on the beam transport along the structures.

INTRODUCTION

High energy X-ray and γ-ray have been widely used in irradiation disinfection and sterilization for food and medical supplies. Thus the corresponding linear accelerators used for irradiation are in high demand. In the past years, many irradiation linacs, both travelling-wave and backward travelling-wave, have been studied and manufactured by Tsinghua University and Nuctech. Recent experiments indicate that beam power is limited by beam break up (BBU). It is clear that a better understanding of this phenomenon is needed to overcome this issue.

Beam break up is one of the most important and common beam transverse instabilities in RF electron linacs. As early as 1957, the phenomenon was observed in a 25 MeV electron linac with 1 A rated current in the Atomic Energy Research Establishment, Harwell, Britain. When the beam current came up to the range of 500~600 mA, the tail of the pulse would be lost. This means that there will always be a threshold current for a given pulse length. [1].

To study this phenomenon, more experiments have been carried out in backward travelling-wave linac. We have observed the beam break up and explored the influence of pulse width and the current on BBU. In addition, the physical mechanism of BBU has been investigated. Dispersion curve and microwave parameters have been calculated by simulating the period structure in CST. Finally, a preliminary model has been established to describe the process according to the wake field obtained by CST simulations.

EXPERIMENT EXPLORATION

Experiments were done in a 10 MeV backward travelling-wave accelerator system. The main components of this system are: modulator, klystron, electron gun, focusing and oriented magnets and a water target, see Fig.1. The pulse width can be controlled by the modulator and the current can be changed in the electron gun circuit. The current of the focusing and oriented coils is adjustable and the output pulse can be showed in a four-channel oscilloscope.

Figure 1: Picture of the accelerator system.

We scanned different pulse widths and beam current values in order to observe and compare the output pulse waveform. When one of the pulse width or beam current reaches certain threshold, the beam break up occurs, see Fig.2. The channel 1 and 4 show the input and output pulses, respectively. The output pulse is obviously shortened. And the pulse width given by modulator is 17.4 µs and the output beam current is 231 mA.

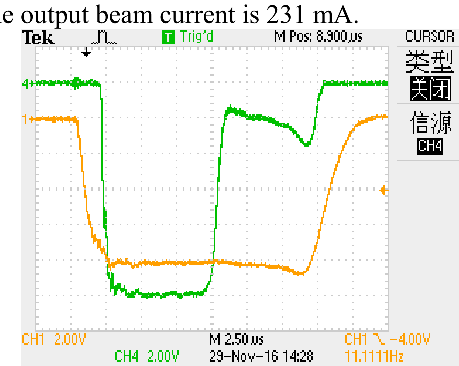

Figure 2: The input (orange) and output (green) pulses for 17.4 µs pulse width, 231 mA beam current.

Different pulse width or beam current lead to different degree of beam loss. The shorter the pulse width, the smaller the proportion of the output pulse is lost. The same goes for beam current. According to the experiment data, the pulse loss proportion increases with the pulse

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width while the voltage of electron gun remains unchanged.

If the pulse width remains unchanged, there exists a threshold current at which the beam break up phenomena will occur. We scanned some pulse widths and find out the corresponding maximum beam current before BBU, see Fig.3. As the pulse width increases, the maximum beam current decreases. It means that pulse width and beam current are both important factors for beam break up and there is a clear connection between these two.

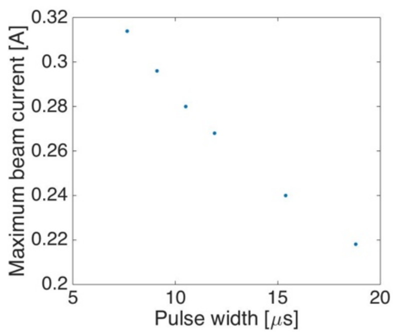

Figure 3: Relation of the pulse width and current.

PHYSICS MECHANISM

As we all know, a charged particle will interact electromagnetically with the accelerating cavity wall when it goes through it. An electromagnetic field called wake field will be generated in the interaction. In many applications, we are most interested in the modes so called m=0 longitudinal wake field and the m=1 transverse wake field. The beam will be influenced by the m=1 transverse wake force in case the beam is off centre, inducing a transverse deflection of the bunch. For a high-intensity beam, the motion of the bunch will be seriously disturbed, leading to the beam break up [2].

In more detail, the beam goes into the cavity with offset because of misalignment of the components or oscillation of the beam, leading to the generation of deflecting dipole wake field. The following electron enters the structure and interacts with the transverse deflecting force. The beam will be decelerated by the deflecting field and energy is transferred to the field. As a consequence, the noise-generated dipole wake field can be amplified by the beam itself as soon as it has been brought off-axis. The amplified wake field will interact repeatedly on the following pulse, inducing an even larger offset. So, the energy given by the beam to the deflecting mode increases. Finally, if the corresponding power exceeds the power losses into the walls, the wake field and the beam deflection will grow exponentially, leading to a transverse instability, so-called beam break up [3].

MODES AND PARAMETERS CALCULATION

As described above, the beam break up is caused by the interaction between the beam and the dipole mode in the accelerator. To study this phenomenon, the deflecting field pattern and parameters should be determined firstly. Secondly the field distribution, amplitude and phase should be calculated. One period of the accelerating structure of the two linacs have been modeled using the CST, according to the designed engineering drawings, see Fig.4.

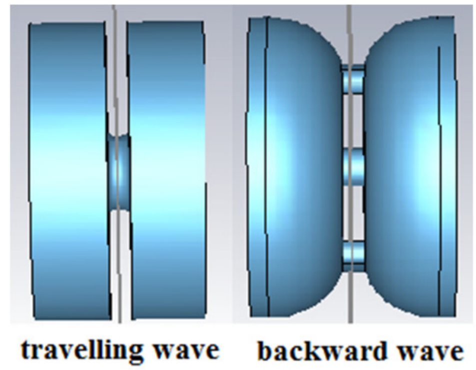

Figure 4: Period structure model in CST.

Ten engine modes have been calculated for these two structures in CST. Different modes have been verified according to the electromagnetic field pattern. For these two linac structures, the previous three modes are TM01, TM11 (0), TM11 (90). There are two TM11 modes here because of polarization degeneracy. The main deflecting mode is a sort of TM11-like mode. Here we study the TM11 mode first in engine modes.

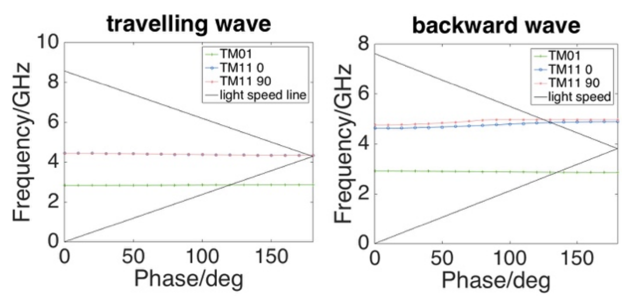

Figure 5: Dispersion curves for the two structures.

Dispersion curves have been obtained for the two accelerating structures by scanning the angles of period in CST, see Fig.5. We find that the TM11 mode can be a backward wave in a travelling wave structure and also a travelling wave in a backward wave structure. The point of intersection for the dispersion curve and the speed of light line is the working point of the accelerating cavity. Microwave parameters for TM11 (0) have been calculated in CST and showed in Table 1.

Table 1: Part of Parameters for Two Structures

Parameter	Travelling wave	Backward wave
Frequency(GHz)	4.338	4.857
Phase(degree)	177.8	229.4
Period length(mm)	35	39.36
k(/m)	90.86	101.72
Phase velocity(/c)	1.025	1.76
Group velocity(/c)	-0.001	0.075
Q	14158	15882

PRELIMINARY MODELLING AND SIMULATION

Wake Field

Wake field are generated when a beam is going through the chamber with an offset. According to the definition of the wake function, the expression can be written as follows:

$$W_{\perp}(z) = -\frac{f}{eI}\int_{-L/2}^{L/2} dz \cdot q\left(E_{\rho} - v \times B_{\phi}\right)$$
$$W_{\parallel}(z) = -\frac{f}{eIx}\int_{-L/2}^{L/2} dz \cdot qE_z \tag{1}$$

$W_{\perp}(z)$, $W_{\parallel}(z)$ represent the transverse and longitudinal wake function separately. L is the period length and the I is the beam current. If substituting the expression of dipole wake field component into the definition formula, we can get the general expression of wake function in disk-loaded waveguide [Eq. (2)]. But the parameter should be determined by the initial and boundary conditions.

$$W(s) = Ae^{-j\beta_0 s}e^{-\frac{\omega}{2Q}t} \tag{2}$$

On the other hand, wake function can be calculated using CST. Disk-loaded waveguide model for the two accelerators have been completed and the wake potential, impedance have been calculated. The wake field can be decomposed in terms of multipole components according to the impedance spectrum. It means that the wake function can be expressed in the form of composition of several impedance frequency components. Hence a more precise wake function expression has been derived.

Modelling

On the basis of the physics mechanism of BBU and the beam dynamics, an interaction model for travelling wave accelerating structure has been built. A pulse can be considered as a composition of several ten thousand of micro-pulses, being a micro-pulse a bunch. The number of bunches depends on the pulse width. So, the n-th bunch is influenced by the wake field generated by the (n-1) bunches ahead. The acting force for the n-th bunch is the accumulation of the wake force of all the foregoing bunches. Eq. (3) describes the equation of motion of the i-th bunch.

$$\frac{d(\gamma_i\beta_i mc)}{dt} = F_{z,i} = Re\left[\sum_{j=1}^{i-1} eLW_{z,j}\right]$$
$$\frac{d(\gamma_i\beta_i mx_i)}{dt} = F_{x,i} = Re\left[\sum_{j=1}^{i-1} exLW_{x,j}\right] \tag{3}$$

$W_{x,j}$, $W_{z,j}$ represent the transverse and longitudinal wake function generated by j-th bunch, acting on the i-th bunch. We rewrite this equation using the finite difference method, dividing the accelerating structure into many slices. The recursion expression is shown in Eq. (4). We can calculate the transverse position of bunches with the wake function and initial parameters [4].

$$x(z+L) = \frac{1}{1+\frac{eW_zL}{2\gamma(z)mc^2}}\left[\left(\frac{eW_zL}{2\gamma(z)mc^2} - 1\right)x(z-L) + 2x(z) + \frac{eW_xL^2}{\gamma(z)mc^2}\right]$$
$$\gamma(z+L) = \gamma(z-L) + \frac{2eW_z}{mc^2}L \tag{4}$$

Simulation Results

According to the model and the Eq. (4), we can ignore the influence of the longitudinal wake field and write a code in MATLAB to simulate the motion of electron in travelling wave accelerator. The change of offset is considered while the wake field of different bunches is accumulated. The initial offset and the beam current are the parameters which to be scanned. But for an aligned accelerating system, the offset is limited and assessable. We focus on the initial current and simulate for enough bunches. The maximum transverse offset is nearly in exponential growth with initial current as shown in Fig.6. We can get the threshold current for a given initial offset.

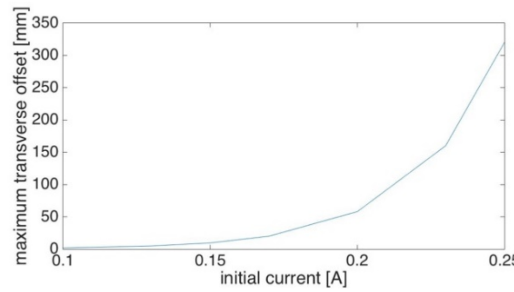

Figure 6: Relation of offset and current.

CONCLUSION

Beam break up (BBU) is limiting the maximum beam power in some irradiation linacs in Tsinghua University and Nuctech. More experiments were carried in the 10 MeV backward travelling-wave accelerator system and the relation of pulse width and current were found. The physics mechanism was studied and the modes and parameters of the accelerating structures were obtained. The deflecting mode was found and the wake field was focused studied in detail. Preliminary modelling and simulation were completed and threshold can be roughly estimated for a travelling wave cavity. But more work still need to be done to precisely model the cavity and further and more accurate simulation are needed.

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