A 4 MEV STANDING WAVE ELECTRON LINAC WITH ON-AXIS COUPLER

Lin Yuzheng, Tong Dechun, Hu Yumin
Li Derun, Feng Jianian, Liu Andong, Xu Guanghua, Luo Weiyi
Physics Department, Tsinghua University
Beijing, P.R. China

Abstract

Programs are made to optimize the on-axis coupling SW cavity and study the longitudinal and transverse dynamics. Transient process with the beam loading under the resonance or the detuning condition is studied. The formula for optimum delay injection time is presented. Two on-axis coupling SW (OCS) accelerating tubes were built. Experiment results on delay injection time and beam characteristics are also given out.

Introduction

Since the first side-coupling SW accelerating structure (SCS) was proposed by E.K. Knapp in 1964,[1] many kinds of SW accelerating structures have been developed. In all kinds of SW accelerating structures, the SCS structure was considered as the most successful structure, which has been used in many therapy and radiography machines. But SCS structure is a non-cylindrical sysmmetry structure, which causes somewhat inconveniences in fabricating, assembling, welding and tuning. So, much work has been dedicated to the cylindrical structures. One of the successful structures among them is on-axis magnetic coupling structure (OCS).[2] The OCS not only has the conveniences in fabricating, welding and cooling, but also has smaller diameter and considerable shunt impedance which can compete with SCS.[3]

Since 1978, we have been working on the OCS,[4] the work covers the optimization of cavity, the manufacture of cavity, the technology of welding, the longitudinal and transverse dynamics, the microwave measurement and tank tuning, the design of coupler and the study of transient process, the stable transmission of microwave power supply and so on.

Two OCS accelerating tubes (tube 1 & tube 2) have been successfully made in Tsinghua University. Tube 1 is to be used to study the beam properties. Tube 2 is to be used in the radiography field.

In this paper, the optimization design of cavity, the longitudinal and transverse dynamics design, the transient process, the formula of optimum injection time, the measured results of the beam properties and so on are reported.

Cavity Optimization

Progam COSC has been developed to optimize the geometry parameters of cavity and study their influnces on the shunt impedance and other microwave parameters. In order to get a higher shunt impedance, the following measures have been taken:

Reduce the thickness of coupling cavity and the thickness between coupling and accelerating cavity;

Optimize the geometry parameters of cavity;

Study the coupling slot position and dimension's influnces on the shunt impedance, coupling coefficient between cavities, and Q value.

And the actual efficient shunt impedance reaches 85 Mohm/m at last.

Longitudinal Dynamics

In order to obtain higher capture efficiency and improve the energy spectum of beam, we adopted two cavitie as bunching section in both two tubes. Program DOSC has been developed to study the longitudinal dynamics.

Both tubes consist of two-cavity bunching section and four-cavity accelerating section respectively. For tube 1, its injection voltage is 40 KV, and two bunching cavities's Beta value is 0.75 and 0.9. For tube 2, injection voltage is 22 KV, the Beta value of two cavities in bunching section is 0.68 and 0.90. The Beta value of accelerating cavity in both tubes is 1.0. The designed energy of the two tubes is higher than 4 Mev. A two MW S-band ($f=2998$ MH_z) magnetron is to be used as power sources.

Transverse Dynamics

The method of solving beam envelope equation is to be used to study the transverse behavior of beam. The following beam envelope equation is obtained by linearizing the paraxial field $E_r(Z)$ and H (Z) in cavity.

$$\frac{d^2R}{dZ^2} + \frac{(\beta\gamma)'}{\beta\gamma}\frac{dR}{dZ} + \frac{N(Z)}{\beta\gamma} - \frac{\mathcal{E}^2}{(\beta\gamma)^2R^3} = 0 \qquad (1)$$

Where R: beam envelope dimension
Beta: normalized velocity
γ: normalized energy
$\mathcal{E}$: initial emittance of injected beam
N(Z): term related to RF field and space charge

$$N(Z) = \frac{1}{\beta}\frac{e}{m_oc^2}E_r(Z)\mathrm{Sin}(\varphi+\varphi_o) + \frac{e}{m_oC}\mu_oH_\varphi(Z)\cos(\varphi+\varphi_o) - \frac{3eIT\mu_r}{4\pi\varepsilon_o m_oc^2\beta\gamma^2R_s{}^2a_z} \qquad (2)$$

For both tubes, calculation results in computer indicates that, if the initial emittance is small, properly select the negative angle to inject(eg. $\psi=-2^o$--3^o), better focusing beam can be got without using external focusing coils. For instance, in tube 2, the measured value of the initial emittance is 35--55 mm.mrad, namely normalized emittance is 0.01~0.016mm.m_oc, injection angle is -2^o, the spot diameter is 2.0 mm at the target of accelerating tube.

Transient Process

By equivalent circuit method and the principle in energy conservation, we obtain the energy gain (we) formula for different injection time (t_b), which can be written as

$$W_e = \frac{e}{1+\beta}\, 2\sqrt{P_oZT^2L\beta(1-e^{-t/t_F})} - IZT^2L[1-e^{-(t-t_b)/t_F}] \qquad (3)$$

Where β is the coupling constant which is measured as the VSWR with the beam off. I is the beam pulse current. P_o is the input power. ZT^2 is the shunt impedance. L is the length of the accelerating structure. From Fig.1, we can see that there exists an optimum delay injection time t_{opt}. When the beam is injected into the tube at t_{opt}, the beam's energy is almost not varied with the time, and the energy dispersion is the narrowest at the same time. The t_{opt} is equal to

$$t_{opt} = \ln\left(\frac{2\beta}{\beta+1}\right) \cdot t_F \quad (4)$$

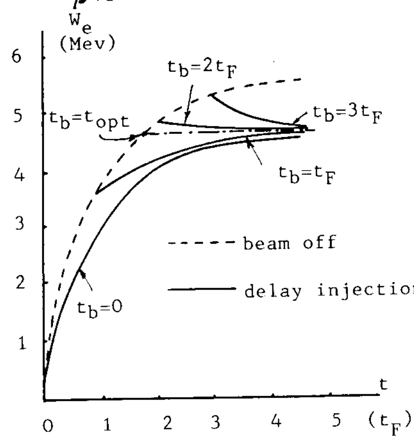

Fig.1. The relation between energy gain and injection time

On the other hand, different injection time also affects the VSWR at power entry of the accelerating tube. Their relations can be obtained by the following equations:

$$\rho = \frac{1+|\Gamma|}{1-|\Gamma|} = \begin{cases} Y_{in} & (Y_{in} \geqslant 1) \\ Y_{in}^{-1} & (Y_{in} < 1) \end{cases} \quad (5)$$

$$Y_{in} = Q_e \left[\frac{1}{Q_o} + \frac{1}{w_o U}\left(P_b + \frac{dU}{dt}\right)\right]$$

$$U = \frac{4Q_L^2 P_o}{W_o Q_e}\left\{(1-e^{t/tF}) - \frac{I}{2} N_1 \left[1-e^{-(t-t_b)/tF}\right]\right\}^2 \quad (6)$$

Where $N_1 = (I^2 ZT^2 L Q_e / 4P_o Q_o)^{1/2}$. U is the energy stored in the accelerating structure.
Similarly, the relative curve between VSWR and the delayed injection time t_b is shown in Fig.2.

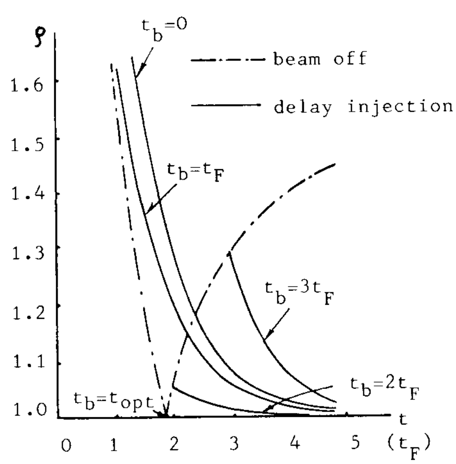

Fig.2 The relation between VSWR and delay injection time

From Fig.2, it is obvious that there also is an optimum delay injection time. When the beam is injected at that time, the accelerating structure can be maintained in the state, $\rho=1$, all the time, that means all power is feeded into accelerating tube without reflection. It can be proved that both optimum delay injection times mentioned above is the same.

The experiment has been done to investigate the above theoretical analyses in the Institute of Beijing Medical Equipment. The experiment results are well in agreement with the theoretical analyses; by hitting the target, the dose rate of x-ray is varied with injection time as shown in Fig.3, the dose rate almost reaches the maximum at t_{opt}.[5]

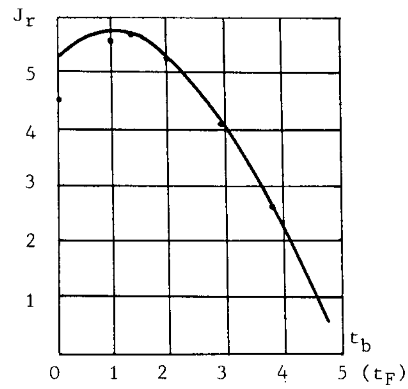

Fig.3 The experiment result of dalay injection

The transient process with beam loading under the detuning condition is also studied. According to the energy conservation law, the transient stored energy can be expressed as

$$\frac{dU}{dt} + \frac{w_o U}{Q_L} + I\left(\frac{ZT^2 L w_o U}{Q_o}\right)^{1/2} - \left[\frac{4P_o w_o U}{Q_e} - \left(\frac{\delta w_o U}{Q_L}\right)^2\right]^{1/2} = 0 \quad (7)$$

where $\delta = 2Q_e \frac{\Delta\omega}{\omega_o}$, is call as frequency detuning parmeter.
Formula for transient energy gain, We, is got by making some approximations based on equation(7).

$$\frac{We}{Wem} = \left[(1-N_1)(1-f(t)\right]\left\{1-M\left[(1-N_1)+(1+N_1)f(t)\right]\right\} \quad (8)$$

where $M=2Q_L^2 \left(\frac{\Delta\omega}{\omega_o}\right)^2$, expresses the detuning degree

$$f(t)=\exp\left[-(1+2M^2)\frac{t}{t_F}\right]$$

$W_{em}=e\sqrt{P_o ZT^2 L}$, is energy gain at stable state without beam loading.
It is evident that both beam loading and frequency detuning will lead to the reduction of energy gain.

If the delay injection is taken into account at the same time, the equation (8) may be written as

$$\frac{W_e}{W_{em}} = [1-f(t)] - N_1[1-f(t-t_b)] + 2M\Delta V(t_b)$$

where

$$\Delta V(t_b) = f(t)[f(t_b)-1] - \frac{1}{2}[1-f(t)-N_1(1-f(t-t_b))]^2 - f(t)[f(t_b)-N_1][1-f(t-t_b)] \quad (9)$$

According to the equation (8) and (9), the transient energy gain we/w_{em} is drawn in Fig.4. It shows the effects of beam loading and detuning as well as delay injection on the energy gain. From Fig.4, it is conclued that the beam energy reaches its stable value more quickly in the detuning case.

Beam Characteristics

General Desciption

A 2MW M5125 tunable magnetron is used as power source. A circulator with an isolation of 30dB and an insertion loss of 0.3dB is inserted between the magnetron and the accelerating tube. The Q_o value of the accelerating tube 1 is equal to 14400. The coupling coefficient of the tube 1 to feeding waveguide, β ,1.46. The pulse length of the line pulse modulator is avout 3 μsec. The pulse length of the accelerated electron beam is about 2.4 μsec as shown in Fig.5. Fig.6 shows the waveform of the reflected RF power.

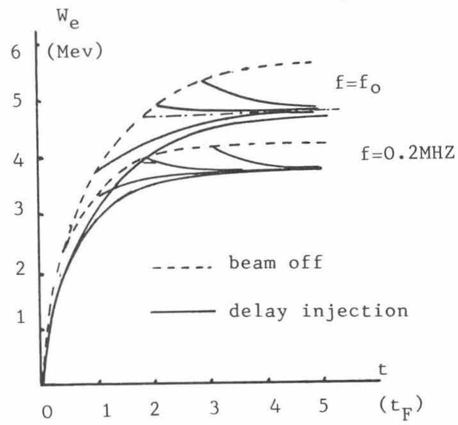

Fig.4. The detuning effect on the energy

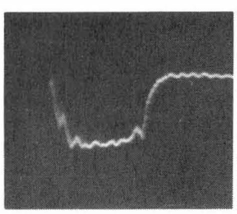

Fig.5 The waveform of beam

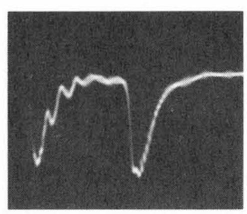

Fig.6 The waveform of reflected RF power

Electron Beam Energy

The approximate beam energy is estimated by measuring the range of electron beam in aluminium and measuring the Half-Value Layer for steel. The measured range in aluminum is 9 mm, that means the corresponding beam energy is about 4.6 Mev. And the first Half-Value Layer for steel is 27.5 mm, that indicates the beam energy is larger than 4Mev according to the standard data, 25 mm.

Dose Rate

By hitting the 2 mm tungsten target, the dose rate of about 500 rad/min.M is measured with Farmer Dose Meter.

X-Ray intensity angle distribution

The measured result of X-Ray intensity angle distribution is shown in Fig.7. The detector is put at 1m away from the target. From Fig.7, obviously the beam energy is higher than 4 Mev.

Spot Diameter

Using sandwich method, the spot diameter is measured, which is about 2 mm. The result is in agreement with the measured result by the extraced electron beam hitting the colorific plastic film.

Microwave power characteristic

The microwave power's effect on X-Ray intensity is shown in Fig.8.

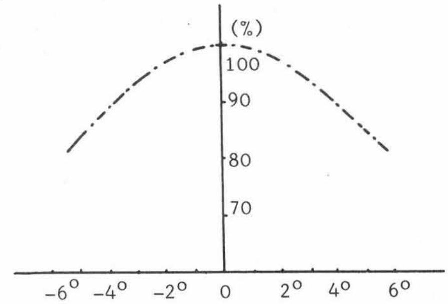

Fig.7. X-Ray intensity angle distribution

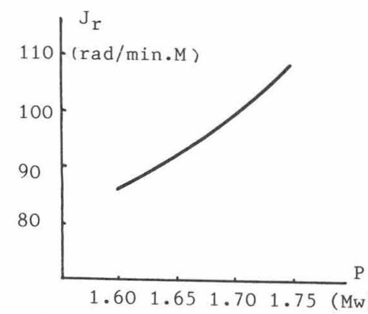

Fig.8 The relation between Dose Rate and microwave power

Frequency characteristic

X-Ray intensity is sensitive to microwave frequency but the beam current is not so much (see Fig.9).

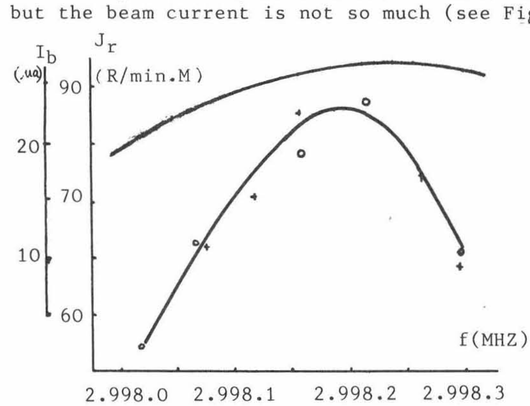

Fig.9. Frequency property

Acknowledgement

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