A 10 MeV L-BAND LINAC FOR THE IRRADIATION APPLICATIONS IN CHINA

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Abstract

The electron linear accelerator has wide applications, and the demands for the irradiation applications are keeping growing in China. A high beam power 10 MeV L-band Linac has been developed recently as a joint venture of Institute of High Energy Physics (IHEP) and Wuxi EL-PONT Company in China. The Thales TH2104U klystron, 2 A thermionic electron gun and 3 m long L-band disk-loaded constant impedance RF structure were adopted. A stable electron beam of 10 MeV / 40 kW has been obtained in the last April. In this paper the detailed design issues and beam commissioning results are reported.

INTRODUCTION

IHEP in China has very rich experience in the electron linac design and development. When requested to transfer the technology to industry, many S-band electron linacs have been developed for medical and irradiation applications. For the S-band irradiation linac, the beam power is limited to be ~20 kW because of the RF structure heating/cooling issues. Due to the scaling law of $P\sim f^{1}$ between the RF power consumption of the accelerating structure and the frequency, L-band structure [1][2] is usually adopted for the nature extending to much higher beam power up to ~100 kW level. For any high beam power machines the power efficiency is a concern. According to Eq. (1), the maximum conversion efficiency η_{max} of the RF power to the beam power dependents only on the attenuation factor τ[3], and smaller τ is preferred.

$$\eta_{\max} = \frac{1}{2}\left[\frac{\left(1-e^{-2\tau}\right)^2}{\left(1-e^{-2\tau}\right)-2\tau e^{-2\tau}}\right] \tag{1}$$

However, there is a compromise among power efficiency, power dissipation as well as heating, peak beam current and beam energy. It is known that τ is independent of frequency, and for SLAC type 3m long disk-loaded TW structure τ is ~0.57. Suppose a 3 m long L-band structure of 34 cavities is used, τ can be roughly estimated to be 0.57*34/86=0.225. With SUPERFISH simulation and cold test, τ is shown[4] to be 0.22, which is in good agreement with the simple scaling. By putting 0.22 into Eq. (1) one can get an efficiency η_{max} of 90%, which is very excellent. In this condition, the beam current is ~900 mA according to Eq. (2).

$$i_{\eta_{\max}} = \left(\frac{P_T}{rl}\right)^{1/2}\left[\frac{\left(1-e^{-2\tau}\right)^{3/2}}{\left(1-e^{-2\tau}\right)-2\tau e^{-2\tau}}\right] \tag{2}$$

Table 1 shows the design parameters for the 10 MeV / 40 kW L-band linac. The linac is a machine with very heavy beam loading; the beam energy range of 8 to 12 MeV can be easily controlled by simply adjusting the gun bias voltage (i.e. the gun emitting beam current), but above 10 MeV is not recommended for prevention of the neutron production.

Table 1: Design parameters for the 10MeV L-band linac

Beam energy (MeV)	10
Beam power (kW)	40
RF frequency (GHz)	1.3
Peak beam current (mA)	530
Duty cycle (%)	0.75
Klysron peak power (MW)	10

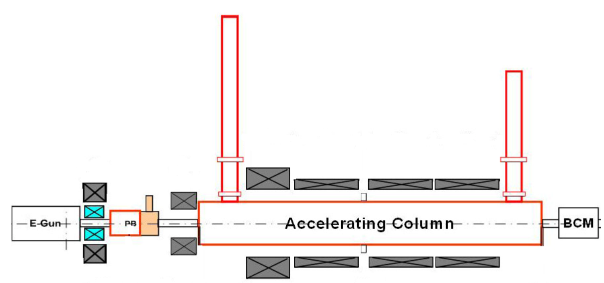

Figure 1: The schematic of the L-band linac.

DETAILED DESIGN AND SIMULATION

Figure 1 shows the schematic of the high power 10 MeV L-band linac, which mainly consists of an electron gun, an RF power source and an accelerating column. The electron gun is the 80 kV BEPC type [5] gun with 2 A Y646B cathode grid assembly. The gun system is separated from the other subsystems, which makes it easy for maintenance. The gun emitting current and the beam energy are adjustable. The RF power source is a 10 MW Thales TH2104U klystron with 130 kW average power, and the modulator was designed to make it work at 100 kW. Fig. 2 shows the Thales TH2104U klystron and its parameters.

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Frequency	1300	MHz
Output power	10	MW
Gain	> 47	%
Pulse width	> 55	μs
Duty cycle	> 1.1	%
Output average power	> 130	kW
Efficiency	45	%
Beam voltage	167	kV
Beam current	136	A

Figure 2: Thales TH2104U klystron and its parameters.

With 10 MW TH2104U klystron and a 3 m long L-band RF structure, a 10 MeV / 40 kW electron beam with a beam current of 530 mA as listed in Table 1 can be obtained. Except for the klystron, the RF structure is a key issue for the high power electron linac. The simple constant impedance structure with the cell dimension scaled from the 3 m long SLAC type disk-loaded TW structure was used, but the first 6 cells are β changed for the beam bunching requirement. Simulations with the EGUN and PARMELA codes have been conducted [6], and the simulation results were confirmed by measuring the beam performance in later commissioning. Even without the pre-buncher, a proper beam with more than 40% transmission efficiency was obtained, which is also confirmed with the machine commissioning. Fig. 3 shows the simulated beam energy spread and beam size, which are good enough for an irradiation machine.

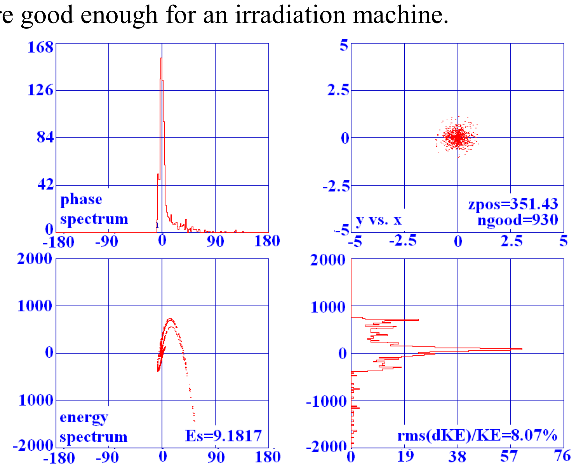

Figure 3: The simulated beam phase space.

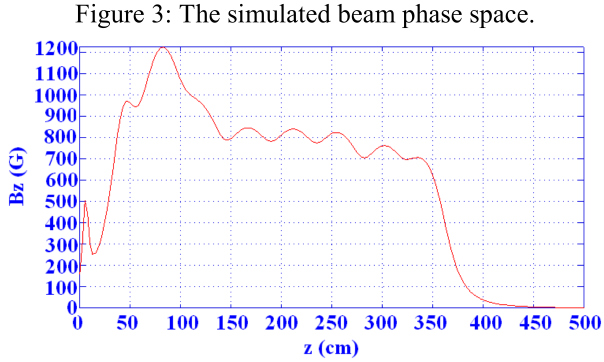

Figure 4: The solenoid magnetic field distribution along the 10 MeV / 40 kW linac.

Fig. 4 shows the designed solenoid magnetic field distribution along the whole linac. As the RF structure heating is a concern for the design of the high power electron linac, the structure iris temperature rise and its deformation were also simulated [7] and shown in Fig. 5, which indicates the maximum temperature of 62 °C under the design parameters and a tolerable deformation of ~17 μm. The cooling system is a simple water jacket around the accelerating column; A special cooling design is required if even higher beam power up to 100 kW is needed.

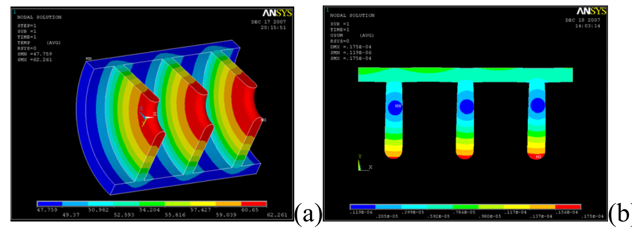

Figure 5：ANSYS results for the structure heating under the design parameters: (a) the iris temperature rise; (b) the structure deformation.

COMMISSIONING AND BEAM TEST

The machine was installed at EL PONT Company in 2009; the machine processing and commissioning were started right after the entire subsystems ready. The first beam was obtained on November 3rd, 2010. Fig. 6 is the picture of the whole linac, and Fig. 7 shows the modulator.

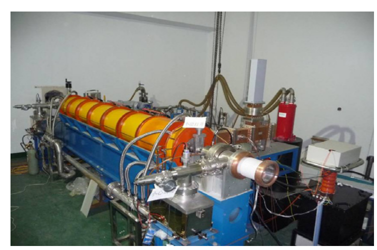

Figure 6: Picture of the L-band linac.

Figure 7: Pictures of the modulator.

Table 2 shows the milestones of the high power L-band electron linac development and commissioning progress. Almost two years were taken to get the first beam, and the main time consuming task is the klystron purchase, which takes one year and a half with almost 6 months delay. From the first beam @ 5Hz to the 40kW stable beam almost half year was taken to reach the design goal. During the high power processing process, many lessons have been learnt, such as beam instability, beam duct heating and degassing, beam loss and so on.

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Fig. 8 is the beam testing results with the beam energy of 11.2MeV at 600mA beam current shown in (a) and the beam current profile measured with BCT shown in (b), which is better than the design prediction.

Table 2: Milestones of the L-band linac development

Date	Activity
October, 2007	Proposal and design
Augeust, 2008	Manufacture, purchase
September, 2009	Assembly at EL PONT
November 3rd, 2010	First beam
November 6th, 2010	Beam at 5 Hz
March 31st, 2011	30 kW
April 24th, 2011	40 kW

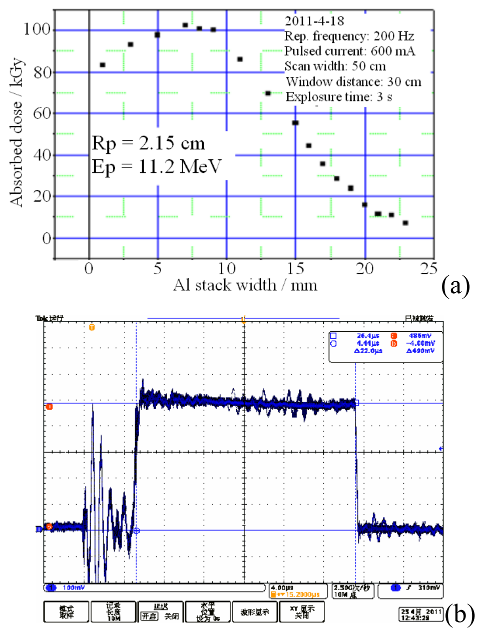

Figure 8: The beam testing results. Time-scale is 4 µs/division.

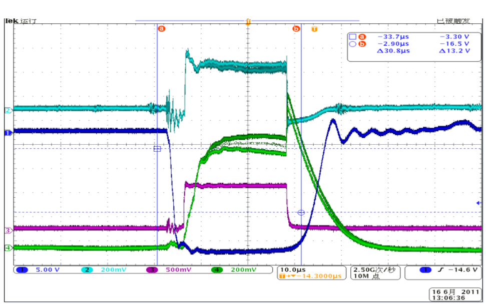

Figure 9: Machine status: blue line is the modulator high voltage waveform, turquoise the beam current from BCT, pink forward RF, and green reflected RF. Time-scale is 10 µs/division.

Many problems have been encountered during the beam testing and the machine commissioning; in particular the beam instability has very strong impact on the beam quality, the beam duct heating and the vacuum degradation, so systematic investigations were conducted for more than two months. Finally the RF driven source problem was found by monitoring the voltage standing-wave ratio (VSWR) as shown in Fig. 9, in which channel (1) in blue is the modulator high voltage waveform, channel (2) in turquoise the electron beam current from BCT, channel (3) in pink the forward RF, and channel (4) in green the reflected RF. It can be seen that the beam instability is correlated with the reflected RF (not the arcing but the VSWR change), which means the frequency is not correct even the indicator still shows 1300 MHz. After the problem was fixed, the beam instability was gone. In addition, the bunching effect of the pre-buncher was found not so strong, and taking out it would make the machine architecture much simpler.

SUMMARY

The high power 10MeV L-band electron linac is the first 40 kW irradiation linac developed and constructed in China. The first beam was obtained on November 3rd, 2010, which confirmed the design and the simulation predictions. After a few months machine processing, the designed beam parameters were achieved on April 24th, 2011. The formal beam testing was conducted by the National Institute of Metrology on December 26th, 2011, and the testing beam current is 720 mA with energy of 9.9 MeV. If the machine works at a duty cycle of 0.7% as already processed, the beam power can reach 50 kW. The conversion efficiency η from the RF power to the beam power is ~72%, a little bit lower than the theoretical prediction, which is partially because the RF power into the accelerating structure is lower than 10 MW, and/or the beam loss. Nonetheless, 72% is not bad. Now the machine has been put into operation at EL PONT Company.

ACKNOWLEGEMENT

The high beam power 10 kW / 40 MeV electron linac facility is a joint venture of IHEP and EL-PONT Company in China. Many works not mentioned here were accomplished by EL-PONT, such as infrastructure, power supply, cooling system, beam scan or deliver system and so on. Many thanks to all EL-PONT staffs for their contributions to the machine design, development, commissioning and operation.

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