S-BAND ACCELERATING STRUCTURE FOR HIGH-GRADIENT UPGRADE OF TTX

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Abstract

Thomson scattering x-ray source is an indispensable scientific X-ray imaging tool in various research fields. The 3-meter S-band linac in Tsinghua Thomson scattering X-ray source (TTX) has been running at an accelerating gradient of 15 MV/m so far. The gradient will be upgraded to 30MV/m by replacing the old structure with a shorter linac. Detailed optimization of the RF design of the new S-band linac structure is presented in this paper. Finally, further research on energy upgrade with X-band structures are also discussed.

INTRODUCTION

Advanced X-ray sources, such as X-ray free-electron lasers [1] and Thomson scattering facilities, are constructed in the world. These facilities can produce X-ray photos in keV energy. This will be widely used in biology, chemistry and material sciences with X-ray imaging technology. We have built the compact Thomson X-ray scattering source with mono-energetic electron beams and TW laser beam, which can get 10^7 photos in one single shoot [2]. The present beam line layout of TTX is showed in Fig. 1 (a).

The operating proposal is to replace the old S-band travelling wave (TW) tube with a shorter one working in higher gradient and add two X-band accelerating structures after the structure. Upgrading layout of beam line is showed in Fig. 1 (b).

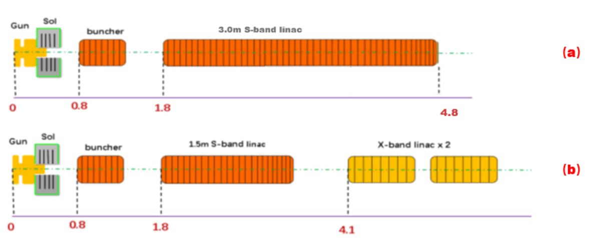

Figure 1: Present linac layout and upgrade proposal.

New design of S-band TW tube in 3π/4 mode has been adopted through electromagnetic calculation to get nearly 30 MV/m in the accelerating structure. The following section we will present electromagnetic design process of constant gradient structure design and its dual-feed coupler.

ELECTROMAGNETIC DESIGN

Completely procedure of designing the S-band TW tube starts with a single cell design. Simultaneously, optimizing the iris shape and thickness is essential in order to reduce iris surface field and lower breakdown rate. After single cell structure design finished, parameters adjustments of each cell separately is to achieve constants accelerating gradient in whole tube. Then, individually designing process of dual-feed coupler meet the demand of the cellchain design as microwave input/output port.

In the overall design a continuous feedback between the electromagnetic design and realistic mechanical manufacturing procedure has been necessary.

Cell Design

Main RF parameters of the single cell such as shunt impedance, group velocity and attenuation decide performance of TW tube. When constructing high gradient accelerating field, we have been studied as a function of the iris diameter, cell outer thorough the simulation.

An originally model shown in Fig. 2 [3], and two fillets has been adopted in cell, aiming to enhance the quality factor Q. Different phase advanced mode from 2π/3, 3π/4, 5π/6 has been simulated in the same working frequency conditions by adjusting period length and cell outer radius to get higher acceleration efficiency according to shunt impedance.

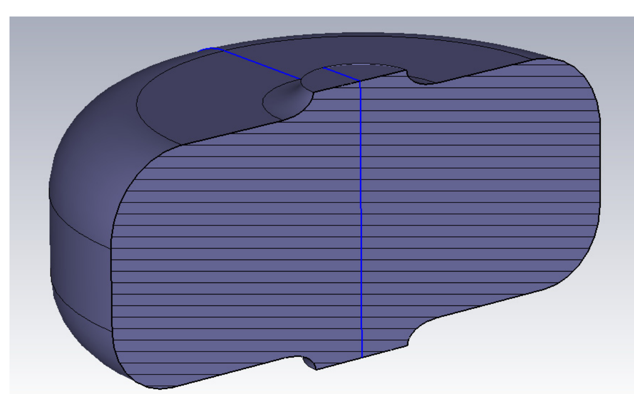

Figure 2: Original 3D model of single cell in simulation.

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The simulation results are shown in Table 1 and phase advanced of 3π/4 in single cell has been chosen as practical accelerating mode because of its higher impedance.

Table 1: Phase Advance Mode Comparison

Parameters	1#	2#	3#
Iris half aperture/mm	8.00	8.00	8.00
Phase advance per cell	2π/3	3π/4	5π/6
Frequency/MHz	2856	2856	2856
Unloaded quality factor Q	15130	16438	17582
Group velocity (v_g/c)	0.00368	0.00296	0.00208
Shunt impedance/MΩ·m^{-1}	70.1	71.6	70.9

Elliptical iris optimization will get better performance surface compared to the round profile, which is essential for high gradient application. In the design we reference an elliptical cross-section with an aspect ratio 1.8/1 [4]. To reduce breakdown rate, we adjust iris thickness based on the original single cell model in constant phase advance to smooth surface field. Surface electric distribution along with elliptical shape in various iris thickness has showed in Fig. 3. Considering lower maximum surface field value contrast to accelerating gradient and ratio of electric field along surface to peak electric gradient, we choose 9.54mm for long axis and 5.3mm for short axis in elliptical iris.

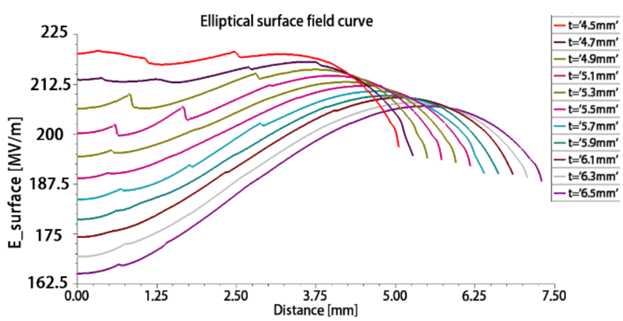

Figure 3: Surface electric field analysis result along with elliptical shape of iris in various thickness.

The RF parameters of single cell with optimistic iris thickness has showed in Table 2

Table 2: Single Cell Design Parameters

Parameters	Value
Frequency	2856.00MHz
Phase advance per cell	3π/4
Period	39.36mm
Iris half aperture	8.00mm
Cell radius	42.14mm
Unloaded quality factor Q	16566
Group velocity (v_g/c)	0.00321
Shunt impedance	72.7 MΩ/m

Realistic manufacturing procedure of TW tube with copper has slightly error in cell outer radius and iris half aperture, having an influence on harmonic frequency shifting. Simulation in sensitivity of parameter changes about frequency shifting has showed here.

Table 3: Frequency Sensitivity with Respect to the Cell Main Parameters

Parameter	**Sensitivity**
Iris half aperture	10kHz/μm
Iris thickness	5kHz/μm
Cell outer radius	-70kHz/μm
Cell length	-5kHz/μm

Constant Gradient Structure Design

In TW accelerating structure, Equation (1~4) [5] have described that power in each cell with its loss, shunt impedance and quality factor Q decide accelerating gradient, group velocity and attenuation factor α. For disk loaded linac, group velocity mainly depends on iris half aperture in a periodic cell.

To maintain 30MV/m acceleration gradient in whole structure to get nearly 50MeV electron beams within TW tube short than 1.5 meter, individual simulation for each cell with separated parameters must do. Low electron beam loading in current simplify the analysis of power attenuation when beams pass through TW tube.

$$P_{loss} = \frac{E^2}{Rs} \quad (1)$$

$$\alpha = \frac{P_{loss}}{2P} \quad (2)$$

$$\upsilon_g = \frac{\omega}{2Q\alpha} \quad (3)$$

$$P = P_{input} \exp^{-2\alpha} \quad (4)$$

Make discretization by cell number, equations (2~4) changes into different form shown as equations (5~7), and subscript n references numbers of cell.

$$\alpha_n = \frac{P_{loss}}{2P_n} \quad (5)$$

$$\upsilon_{g,n} = \frac{\omega}{2Q\alpha_n} \quad (6)$$

$$P_{n+1} = P_n \exp^{-2\alpha_n} \quad (7)$$

Setting different iris half aperture for every single cell and retuning the cell radius to keep working frequency in 2856MHz. Calculating group velocity and impedance, we plot trend of accelerating gradient and power attenuation with cell numbers in Fig. 4.

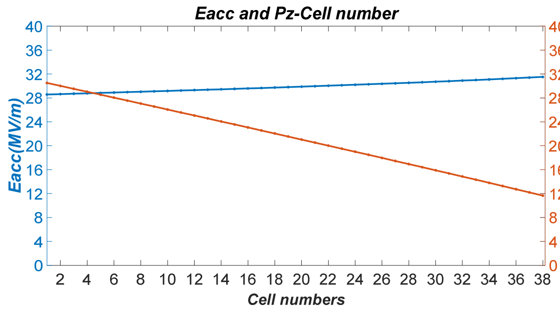

Figure 4: Accelerating gradient and power attenuation change with cell numbers.

The simulated parameters of S-band TW tube without couplers are showed in Table 4.

Table 4: Complete Parameters of S-band TW Tube

Parameters	Value
Frequency	2856.00MHz
Phase advance per cell	3π/4
Length	1.493m
Cell numbers	38
Period	39.36mm
Iris half aperture	10.57mm~8.00mm
Cell radius	42.58mm~42.14mm
Elliptical iris long axis	9.53mm
Elliptical iris thickness	5.3mm
Filling time	893ns
Group velocity (v_g/c)	0.00898~0.00321
Shunt impedance	65.5MΩ/m~72.7MΩ/m
Input power	31MW
Gradient	28.6MV/m~31.5 MΩ/m

Coupler Design

The input and output couplers have been designed in order to implement the power feeding into structure. We have adopted dual-feed coupler structure and its separated model with four cells are showed in Fig. 5.

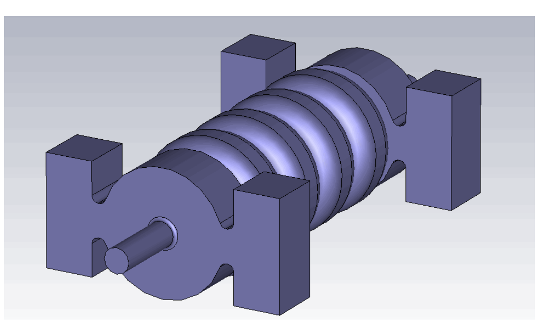

Figure 5: Individual coupler model with four cells.

Optimizing the radius of coupler cell and the size of coupling port is to match the waveguide mode TM01 in working frequency of 2.856GHz. The reflection coefficient of individual input/output coupler with four cells are showed in Fig. 6.

The quadrupole field components are ignorable compared with accelerating gradient in simulation results.

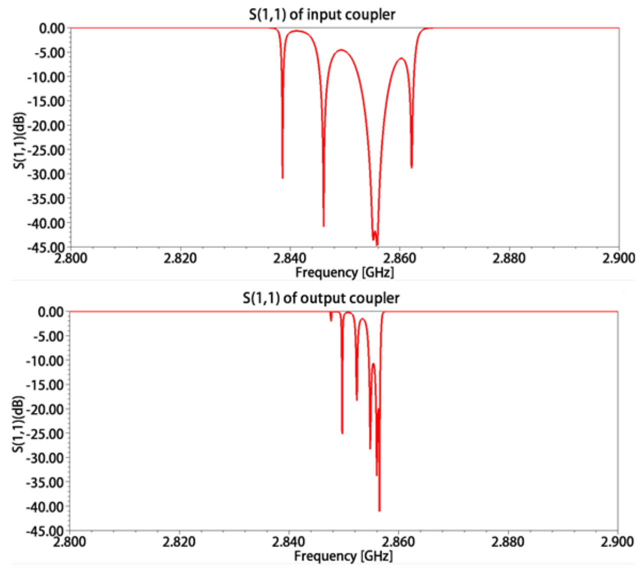

Figure 6: S(1,1) parameter of input/output coupler.

Mechanical drawing and fabricating is constructing in progress.

CONCLUSION

The design of S-band TW tube with nearly 1.5m length is finished and parameter details have mentioned in previous table. Mechanical drawing and manufacturing are in progress. Next several months, high power test of the structure will proceed in TTX platform and experiment results will be analysed to characterize the performance of tube.

Upgrading plan has concentrated on structure optimization to improve electron beam energy into 150 MeV. As the part of plan in energy upgrading, structure design of another two X-band accelerating tube is in progress synchronically. Furthermore, mechanical drawing of X-band structure keeps pace with the fabrication of X-band TW tube.

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