STUDY OF SMITH-PURCELL FREE ELECTRON LASER USING ELECTRON BUNCH PRODUCED BY MICRO-PULSE ELECTRON GUN

Jifei Zhao*, Deyu Yang, Ziqin Yang, Weiwei Tan, Yujia Yang, Xiangyang Lu†
Institute of Heavy Ion Physics, Peking University, Beijing100871, China

Abstract

A Micro-Pulse electron Gun (MPG) with the frequency of 2856 MHz has been designed, constructed and tested. Some primary experimental studies have been carried out and electron beam with the average current of 18 mA has been detected which holds promise to use as an electron source of Smith-Purcell Free Electron Laser (SP-FEL) to produced Coherent Radiation. It is well known that Smith-Purcell radiation is one of the achievable ways to produce FEL. After many years study in theory and experiment, lots of new mechanisms and appearances have been discovered. Coherent Smith-Purcell Radiation was discovered in 1990s as well. Obviously, MPG is one of ideal electron sources of CSPR for that S-band electron source can increase energy density and produce frequency-locked SP radiation at these frequencies. And this will be displayed in the simulation of this article.

INTRODUCTION

Since the multipacting effect was firstly discovered by Farnsworth in 1934[1], it has been deeply investigated in many areas, such as RF structure related accelerator [2-5], high power microwave generators [6, 7]. Some applications of the multipacting effect require suppressing the secondary-electron emission electron while the others, crossed-field devices for instance, need to enhance the emission [8]. Micro-Pulse electron Gun (MPG) which has been proposed by Mako for more than two decades [9] needs to select the materials judiciously. Due to its self-bunching property and choosing suitable secondary-electron-emission material, MPG is capable of providing high Pulse Repetitions Frequency (PRF) which means high current and short pulse electron beams [10]. The features of high PRF and short pulse make MPG one of the most appropriate electron sources to do some research of frequency locked Coherent Smith-Purcell Radiation (CSPR) which was discovered in 1990s.

This paper presents studies on the steady state multipacting in a MPG and the simulation of Smith-Purcell FEL using electron bunch produced by MPG. In the first section, the requirements for the steady multipacting are proposed by analyzing the self-bunching effects and conditions of secondary electron emission. In the second section, the primary experimental results are obtained through the experiments carried out on a 2.856 GHz MPG cavity. Finally, the further experimental arrangements are given. And Smith-Purcell FEL is investigated by using Particle In Cell (PIC) simulation method.

* Email: zjf@pku.edu.cn
† Corresponding author, email: xylu@pku.edu.cn

REQUIREMENTS FOR STEADY STATE MULTIPACTING

The MPG Model

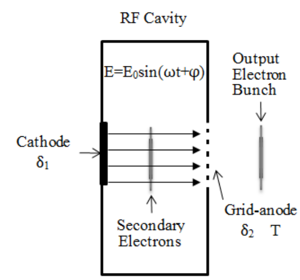

Figure 1: The schematic diagram of MPG model.

The MPG model is shown in Fig. 1. It consists three parts: an pill-box RF cavity working TM_{010} mode, a secondary emission surface with Secondary Emission Yield (SEY) δ_1, a grid-anode, SEY δ_2 and transmission coefficient T, which is opaque to the microwave field but let the electrons partially go out the RF cavity. When MPG working, the microwave electric field -anode changes as sine wave with time. And the secondary electrons move between cathode and grid under the action of electric field.

The Self-bunching Effects

The self-bunching effects have been reported in many articles [11, 12]. They can be explained by the following ways.

Firstly, we divide the cavity length into N parts and every part is dz. The electric field acting on every electron in nth can be expressed

$$E_n = E_0 \times \sin(\omega \sum_{i=1}^{n-1} t_i + \varphi) \tag{1}$$

where t_i is the travelling time of electron in ith part. And the acceleration can be written (non-relativistic electrons)

$$a_n = \frac{E_n e}{m} \tag{2}$$

Then the travelling time is

$$t_n = \frac{(v_{n-1}^2 + 2a_n dz)^{\frac{1}{2}} - v_{n-1}}{a_n} \tag{3}$$

where v_{n-1} is the velocity of electron in (n-1)th part.

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The velocity of electron in nth and is

$$v_n = a_n t_n + v_{n-1} \tag{4}$$

The time of different initial phase electrons take to go across one cavity length in a specific MPG is obtained through carrying out recursive process above. Figure 2 shows travelling time versus the initial phase of different electrons for cavity length d=2mm, RF frequency f=2.856GHz (half a period is 171ps), N=10000, initial energy ε=2eV, in the case of E_0=0.7MV/m, E_0=0.8MV/m, E_0=0.9MV/m, E_0=1.0MV/m, E_0=1.1MV/m, E_0=1.2MV/m.

Taking example for E_0=1MV/m, one can clearly see there are two crossover points between the t=171ps (half a period) and the E_0=1MV/m curve. And the abscissa value of left one corresponds to the initial phase of synchrotron electron φ_c because it means that if an electron which was emitted from the emission surface with this phase it just can reach the grid in half a period. While the abscissa value of right one corresponds to the cutoff point of self-bunching effects.

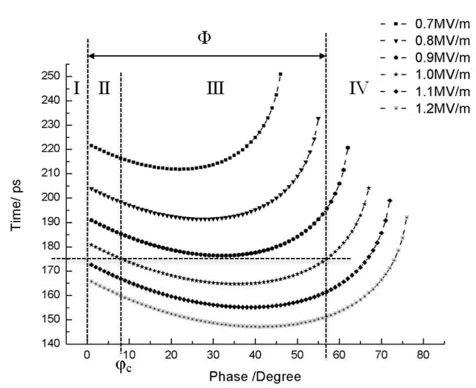

Figure.2: The travelling distance of electron vs its phase.

The integrated interval of self-bunching can be confirmed by comparing the time of different electrons take in a cavity length. In conclusion, the phase range of self-bunching is (0-Φ). Another piece of information Fig. 2 gives us is that there must exist two crossover points between the half a period time line and the electric field curve to make the MPG running stably-that is the electric field must be chosen properly for a parameters given MPG in order to produce self-bunching effects.

The Requirements of Secondary Electron Emission

Basically, the higher the electric field is, the more energy the electrons will be gained. According to the basic empirical SEY formula of common metal materials Eq. 8 [13], the SEY curve versus the energy of the incident electron can be got.

$$\frac{\delta}{\delta_{\max}} = (\nu e^{1-\nu})^k \tag{8}$$

where δ is the SEY of the material, δ_{max} is the maximum value of δ, $\nu=(E_i-E_0)/(E_{max}-E_0)$, in which E_{max} is the impact energy corresponding to δ_{max}, E_0 is the initial energy of secondary electrons and k=0.62 for ν<1; k=0.25 for ν>1.

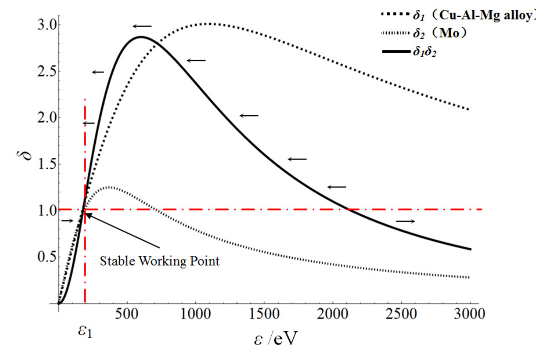

Figure 3: The effective SEY curve versus impact energy for Mo, Cu-Al-Mg ally and total of them.

The effective SEY curve versus impact energy for Mo, Cu-Al-Mg ally and total of them are shown in Fig. 3. Where the δ_{max} for Mo and Cu-Al-Mg ally are respectively 1.25 and 3 and corresponding ε_{max} are 375eV and 1000 eV. The stable working point is the crossover point in this figure because if there are power fluctuations, the working point can return to the stable working point. That is, there are power feedback mechanisms at this point.

Requirements for Steady State Multipacting

As was mentioned above, the impact energy must working at the stable working point and the electron bunch must produce self-bunching effects. In conclusion, to obtain steady state multipacting in the MPG, there must be a good match between the accelerating field required by self-bunching effects and impact energy. The accelerating field can be adjusted by frequency f and cavity length d to produced self-bunching effects. While the stable working point can be adjusted by changing δ of the cathode and the grid-anode as well as the transmission factor T.

PRIMARY EXPERIMENTS

Based on the requirements of steady state multipacting, two MPG cavities (PKUMP-I and PKUMP-II) with frequency of 2.856GHz have been designed and the RF parameters have been listed in Table 1. The PKUMP-I has been constructed and applied to do some primary experiments.

The schematic diagram of the experimental platform is shown is Fig. 4. The output electron beams are collected by a faraday cup which is connected to a 50 Ω resistance in parallel way. So the beam current can be detected by a oscilloscope.

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Table 1: The Designed RF Parameters of the MPG Cavities

RF parameters	PKUMP-I	PKUMP-II
Resonant frequency f (GHz) :	2.856	2.856
Cavity length (mm)	1.8	1.75
Unloaded quality factor Q_0	100	~400
Shunt impedance r_{shunt} (MΩ)	0.036	~0.03
Unloaded coupling coefficient β_0	1.25	3~4

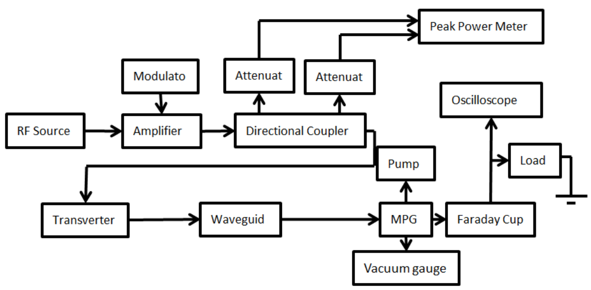

Figure 4: The schematic diagram of the experimental platform.

Three different materials have been tested as grid-anode by the platform using PKUMP-I. And the materials of different transmission are shown is Fig. 5. The test result is shown in Table 2. Form this table we can make some conclusion: (1) The higher the transmission is, the more electrons the MPG could produce. (2) Oxy free copper is a more appropriate choice for getting relatively large current. Although Grid-anodes of Stainless Steel and Molybdenum could not produce more electrons, they are useful for steady state multipacting. Taking the MO3 for example, the measured average current is 0.4 mA, just as what is shown in Fig. 6, but the stable working time is more than 70min.

Table 2: The Measured Current for Various Grid-anode

Materials	NO.	Transmission Coefficient	Measured Average Current (mA)
Stainless steel	SS1	6%	0.2
	SS2	18.3%	3.8
Oxy free copper	OFC1	6%	4
	OFC2	18%	9
	OFC3	25%	18
Molybdenum	MO1	11%	4
	MO2	14.125%	6
	MO3	30.65%	0.4

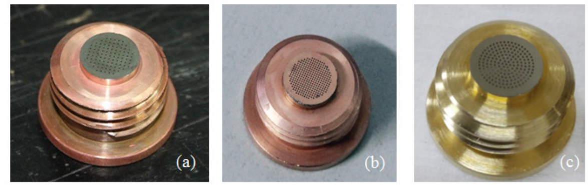

Figure 5: Three different grid-anodes (a) is stainless steel grid, (b) is Oxy Free Copper grid, (c) is Molybdenum grid.

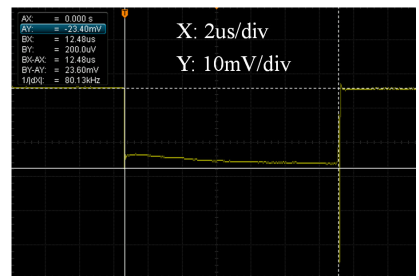

Figure 6: The output beam average current (≈0.4 mA) when the grid-anode is MO.

SIMULATION OF SMITH-PURCELL FEL

When a charged particle passes over a periodic grating, the Smith-Purcell Radiation (SPR) which was first observed in 1953[14] occurs. For electron bunch, the wavelength of the radiation is

$$\lambda = \frac{1}{n}\left(\frac{1}{\beta} - \cos\theta\right) \qquad (9)$$

where n is the order of the radiation, l is the granting period, β is the ratio of the electron bunch velocity to the speed of light, and θ is the observation angle.

According to the feature of the electron bunch produced by MPG, the simulation of SP-FEL is carried out by PIC simulation method. The main setting parameters of the simulation are show in Table 3.

Table 3: The Main Parameters of the Simulation

Parameters	Value
Electron beam energy	100keV
Average current	18mA
Beam thickness	0.5mm
Frequency	2.856GHz
Beam length (longitudinal)	5ps
Grating period	1mm
Grating groove depth	1mm
Grating groove width	0.5mm
Number of periods	200
External magnetic field	2T

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After the MPG, there is an accelerating gap between the MPG and the grating. And the voltage of the gap is -100 keV which can accelerate the electron beam to about 100 keV. The beam is supposed a parallel-beam and the emittance of it is 0 mm·mrad. The number of periods is assumed 200 with the grating period is 1mm so that there are three electron bunches passing over the grating at least. Figure 7 is the X-Y contour map of B_z obtained at 1.271 ns. Four electron bunches is passing over the surface of the grating. We can see the interference fringes apparently. And there are two cylindrical waves radiated from both ends of the grating appear. We conclude that those waves should be attributed to the so called evanescent wave radiation. The evanescent wave radiate at the ends of a grating where it undergoes partial reflection and partial diffraction. Figure 8 shows the Time signal of *Bz* and corresponding FFT from a detector placed at 35°. It can be clear seen from Fig. 8 that there are seven electrons arrived the terminal of the grating because there are seven nodes and the interval of the node is 350 ps corresponding to the period of the beam. The FFT from a detector strongly shows the frequency-locked SP radiation occurred and the frequency is 54.25 GHz corresponding to 19th harmonic of the rf frequency.

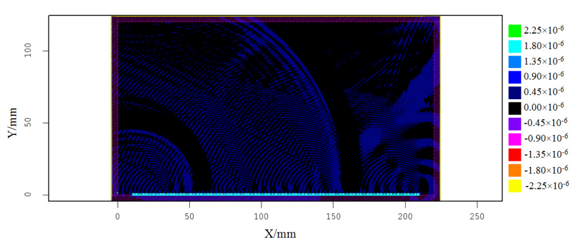

Figure 7: the x-y contour map of B_z obtained at 1.271ns.

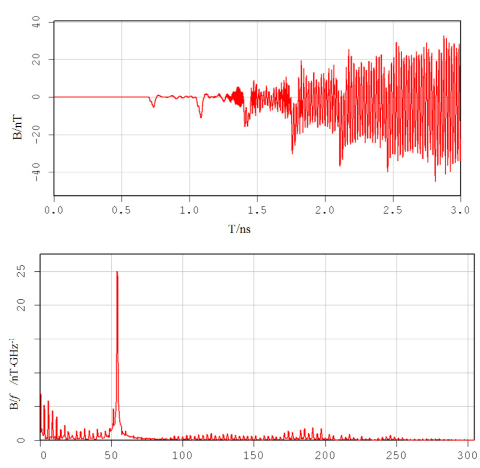

Figure 8: Time signal of B_z and corresponding FFT from a detector placed at 35.

CONCLUSION

In summary, the self-bunching effects and the requirements of secondary electron emission were investigated in theory. And the theoretical analysis shows that to obtain a steady state multipacting, a good match between the accelerating field and impact energy is required. According the theory, the experimental exploration was carried out with the PKUMP-I one of the two MPG designed by Peking university. Three different metal grid materials were used in the experiments. A maximum of 18mA with OFC3 was detected by a faraday cup and a more than 70 min of stable output with MO3 was got. To study the application of the electron bunch produced by MPG in SP FEL, the simulation was carried out by PIC method. The results show that the electron bunch could produce frequency-locked SP radiation.

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