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A new beam source for free electron lasers ☆

Ming Chang Wang[a,b,*], Zhijiang Wang[b], Yu Huang[b], Lifen Zhang[b], Bin Lu[b], Junbiao Zhu[b], Jae Koo Lee[c]

[a]CCAST (World Laboratory), P.O. Box 8730, Beijing, 100080, China
[b]Shanghai Institute of Optics and Fine Mechanics, P.O. Box 800211, Shanghai 201800, China
[c]Pohang Institute of Science and Technology, Pohang, South Korea

Abstract

A high power, high current density and high voltage electron beam was generated with the pseudospark discharge (PS). This is a new approach to high brightness beam source for free electron lasers. The design and construction of the pseudospark discharge is described. The device has low cost and is easy to fabricate. The experimental results are presented, the configuration of the modified pulse line accelerator (PLA) is described. The intense electron beams with a voltage of 200 keV, a current of 2 kA, a beam diameter of less than 1 mm, a beam pulse duration of 400 ns and beam emittance of 48 mm mrad were measured. The compact free electron laser with a table size is discussed.

1. Design of the pseudospark discharge

The pseudospark discharge is a new kind of gas discharge, based on the principle of a hollow cathode discharge and has the property of a self-sustaining discharge. Several experiments with a beam voltage range of 20–50 keV have been reported. Destler of University of Maryland reported the pseudospark discharge experiments with a beam voltage of 200 keV [1].

The high quality electron beams can be produced by the pseudospark discharge, there are many advantages. The beams have an intense current density ($>10^4$ A/cm^2), narrow beam diameter (<1 mm) and very low emittance (tens of mm mrad), high brightness (10^{12} A m^{-2} rad^{-2}).

We have designed the device as a high brightness electron beam source of the Raman free electron laser and collaborated for the simulation work with POSTECH in Korea since 1993.

It is well-known that the electrical breakdown voltage in gases is described by the Paschen law $U=f(Pd)$, where P is the gas pressure and d is the distance between the cathode and anode (K–A). The Paschen law can be used in the range below 10 keV. A typical breakdown curve as a function of Pd is shown in Fig. 1 of Ref. [2]. It is characterized by near linear rise at Pd-values from 25 to 40 mbar mm. A minimum around 7 to 13 mbar m and a steep rise below the minimum. The breakdown below 10^{-4} mbar mm is called vacuum breakdown.

The condition of the hollow cathode (HC) effect can be written approximately as follows:

$$\varphi P < 133.3\ \mathrm{cm\ Pa}\,, \tag{1}$$

where φ is the internal diameter of the hollow cathode cylinder.

The cutoff voltage of single gap PS chamber is limited to about 20 kV due to local micro-discharges resulting from gas adsorption on the surface of an insulator and local field enhancement at triple points. It is necessary to consider a multi-gap geometry in order to design a high voltage (higher than 100 kV) PS source of electron beam. Generally speaking, the relation between the breakdown voltage U_b and the product of the K–A distance d and pressure P filled in the chamber obeys the Paschen experimental law, $U_b=f(Pd)$. It is experimentally shown that the PS breakdown relation in the beam voltage range 10–70 keV is a function of P^2d, not Pd. The experienced equation was given by Rhee and Ding [3] as follows:

$$U_b(P,d)=\frac{\alpha}{(P^{\beta}d)^{\delta}}\,, \tag{2}$$

where $\alpha=0.1865\pm0.0019$, $\beta=1.9952\pm0.0064$, $\delta=2.226\pm0.016$. It is seen that β is approximately 2. Will the equation be suitable to a higher beam voltage above 100 keV? Up to now, we can only rely on this equation for the design. The relation between the K–A distance d and the pressure P filled in the multi-gap geometry at fixed voltages 100–500 kV applied by our modified pulse-forming line (PFL) was calculated as shown in Fig. 2 of Ref. [2]. The K–A distance increases with the pressure value P decreasing at a constant voltage; the K–A distance drops

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* Corresponding author. Tel. +86 21 59534890, fax +86 21 59528812, e-mail mcwang@fudan.ihep.ac.cn.

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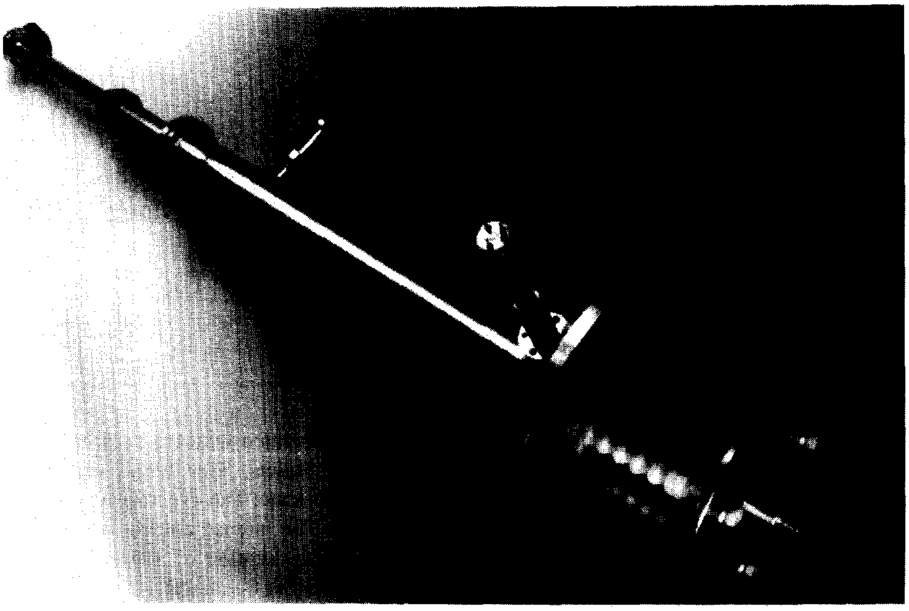

Fig. 1. The photograph of the pseudospark discharge chamber.

with the voltages increasing at a given gas pressure; in the range of 100–500 kV, the curves at higher pressure tend to be approximately 2 cm, while at the lower end of pressure, a reasonable K–A distance should be 10 cm. Therefore the K–A distance is determined to be between 2 and 10 cm depending on applied voltages and filled gas pressure, while the corresponding values of the pressure are from 20 to 7 Pa. By comparison with Eq. (1), this range meets the condition for the HC effect.

2. Configuration of the pseudospark discharge

The photograph of the pseudospark discharge chamber as an intense current density, low emittance, high brightness electron beam source is shown in Fig. 1. The design of the intermediate electrodes and insulators of the pseudospark chamber is similar to Bauer's one, which has been proven a high voltage working device [4]. The configuration parameters of the modified pulse line accelerator (PLA) are as follows.

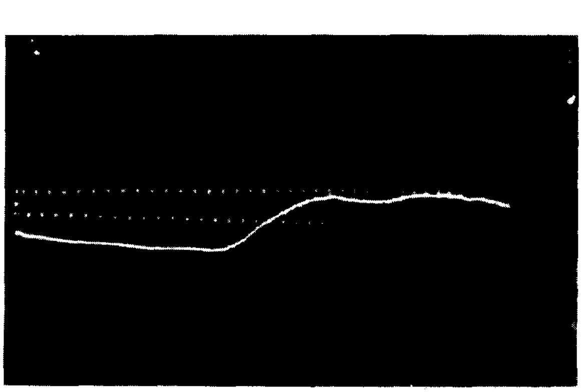

Fig. 2. The charging voltage waveform of the pseudospark discharge.

The PS hollow cavity has a 3 cm diameter and is 4.1 cm long. The discharge chamber consists of a planar cathode with hollow cavity, sets of intermediate electrodes and insulators with a common channel, and a planar anode. The electrodes are made of brass and the insulators are made of Plexiglas. The diameter of the channel is 3.2 mm. The anode–cathode gap distance is varied in 10–100 mm. A Rogowski coil, a Faraday cup was installed in the drift tube.

A 10-order Marx generator is charged to a higher pulse voltage of more than 100 kV, which has parallel charge and series discharge. After the Marx generator being triggered, the voltage is directly applied to the multi-gap PS chamber via the modified PFL. The PFL was modified to use as a water coaxial cable, by directly shorting its main switch and taking off the ground inductance. No any matching resistance was connected between the modified PFL and the PS chamber due to this low resistance and high power device.

The HC effect takes place in the HC operated at low pressure due to the injection of positive ions and the electron ionization and avalanche in it, with the explosive electron emission near the cathode hole, resulting in the step-by-step breakdown of the multi-gap PS chamber from the cathode to the anode. The protecting sheath of each insulator is set up near the discharge channel to screen various radiations due to ionization and bombardments from runaway particles, therefore effectively avoiding local micro discharges. A high power, intense current electron beam is ejected out of the anode hole due to electrostatic focusing and acceleration.

3. Experimental results and further work

High power, high current density and high voltage electron beam was generated with pseudospark discharge. The electron beams have a voltage of 200 keV, a current of 2 kA and beam diameter of less than 1 mm. The beam penetrated a 0.3 mm hole on a copper foil of 0.05 mm thickness at a distance of 5 cm from the anode and penetrated a 0.6 mm hole on a radiachromic film at a distance of 15 cm [5].

The typical pulse voltage waveform applied over the PS chamber, i.e., the output of the PLA, is shown in Fig. 2. It was photographed with an OK-19 high voltage oscilloscope. The voltage calibration is 84 kV/mm and the standard signal period is 0.3 μs. It is clear that the voltage pulse approximately is a rectangular wave with a maximum peak of 200 kV, the pulse duration about 3 μs and a rapid rising wavefront whose longer pulse duration and steep pulse front meet the requirements of pseudosparks. Fig. 3 shows the discharge waveform of the electron beam current (1 μs/div). The duration of the beam pulse current is 400 ns.

A slit type emittance meter was employed for the emittance measurement and was placed in the drift tube 5 cm downstream of the anode. The emittance meter consists of a series of parallel thin slits of 150 μm width and 450 μm spacing constructed from 1 mm think stainless steel plate, a radiachromatic film, was placed 6 mm downstream of the slit plane as the beam detector. The electron beams passing through the slits will produce an appropriate density profile on the radiachromatic film. The

Fig. 3. The discharge waveform of the electron beam current.

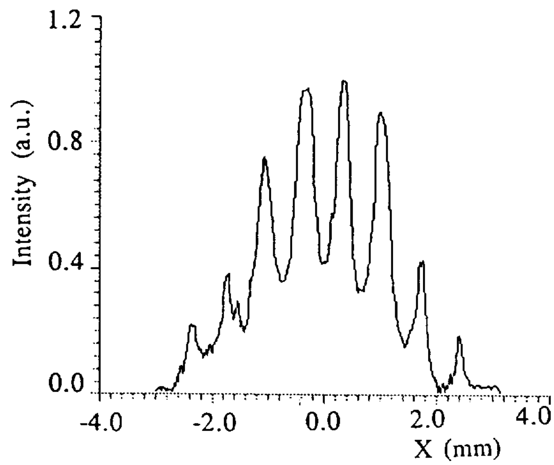

Fig. 4. The optical density profile.

density profile was obtained by scanning the film using an optical microdensitometer and is shown in Fig. 4. The measured rms (root-mean-square) emittance of the electron beam was found to be $\varepsilon = 48 \pm 10$ mm mrad. The beam normalized rms emittance was $\varepsilon_n = 47 \pm 10$ mm mrad. It is much less than before. The beam brightness of 3×10^{11} $A/(m\,rad)^2$ from the pseudospark discharge device was obtained. It is comparable to a photo-cathode source.

It is found that the emittance is sensitive to the gas pressure. The gas pressure of the chamber is controlled by a vacuum auto controller, with a measuring and control range from 0.15 to 7.5×10^7 Torr. The nitrogen gas is filled by a piezo-electric needle valve, with the pressure accuracy of $\pm 1.5\%$ (full scale) and the maximum flow $>2.25 \times 10^3$ Torr cm^3/s.

The beam current will be enhanced and the voltage will go to 300 kV. The pseudospark discharge beam source has low cost and is easy to fabricate. The design of a compact FEL with a table size is proposed [6]. The original device of a Raman FEL is shown in Fig. 5. The size of the Marx generator can be reduced and the PFL can be removed while the diode is replaced by the pseudospark discharge device. The size of a compact FEL with pseudospark as a new beam source will be reduced to $\frac{1}{4}-\frac{1}{5}$ of a traditional FEL. Whole device has the same size as a computer table.

Table 1 gives the parameters of the 3 mm wave free electron laser at SIOFM and the expectancy data of the FEL with pseudospark discharge. Now the beam diameter is about 1 mm, we can make a small period wiggler with an internal radius of 5 mm. The magnet field will be expected to increase to 3 kG with the same period of 10 mm. The efficiency of the FEL with pseudospark discharge will be increased significantly.

The pseudospark discharge has many prospective applications, it can be applied to the free electron lasers, the

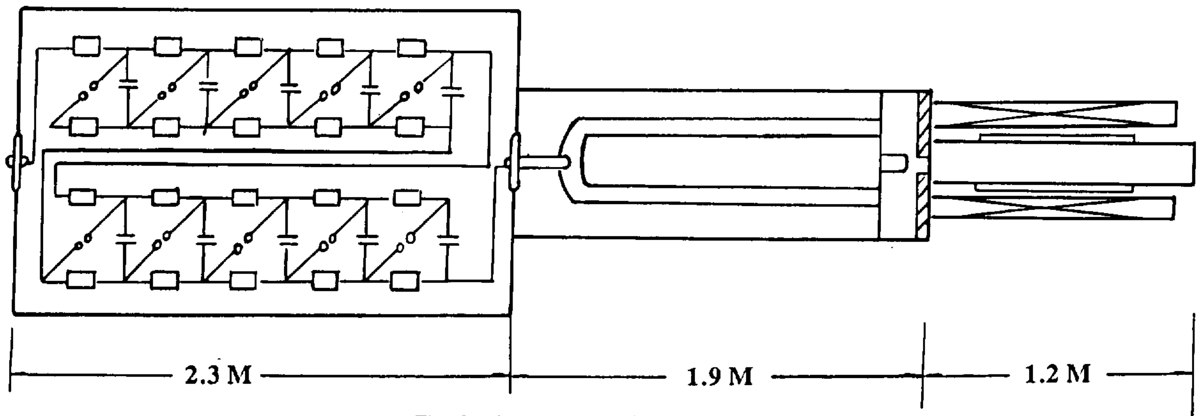

Fig. 5. The schematic of the Raman FEL.

Table 1
The parameters of the Raman FEL experiment at SIOFM expectancy data of the FEL with pseudospark discharge

		3 mm wave experiments	Expectancy with pseudospark
Accelerator			
Beam voltage	V	400 kV	350 kV
Beam current	I	400 A	1500 A
Beam radius	r_c	3 mm	1 mm
Pulse duration	τ	60 ns	400 ns
Wiggler			
Wiggler period	λ_w	10 mm	10 mm
Wiggler length	L	600 mm	600 mm
Wiggler field	B_w	1500 G	3000 G
Internal radius	r_i	8 mm	5 mm
Radiation wave			
Wavelength	λ_s	3 mm	3.3 mm
Output power	P_0	1 MW	10 MW
Pulse duration	15 ns		
Efficiency	η	0.63%	1.9%

X-ray laser pumping, the high power switch, the electron beam lithography and the plasma processing.

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