HIGH BRIGHTNESS INJECTOR OF FEL

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1 INTRODUCTION

FELs require very good quality electron beams. A low emittance is necessary to obtain short wavelength. A high peak current provides a good gain. The quality of electron beam is mainly decided by injector of accelerator. Since conventional injectors have nearly reached their limits, a new RF gun was used as a bright electron source. C.H.Lee et al.(1) reported that very high current densities coulde be obtained from photo-cathodes. The first demonstration of a FEL driven by electrons RF gun with photocathode was made in 1988 at Stanford (2). Since that time, many laboratories have undertaken the necessary effort to design and build an RF gun with or without a photocathode. In order to further increase the brightness of electron beam, the RF guns with superconducting cavities have been used.

2 SEVERAL TYPES OF RF GUN

The electric accelerating fields obtained in an RF cavity are much higher than DC fields. This property is very favourable since at low energy, the brightness produced by RF gun is mainly limited by two effects:

The emittance growth due to space charge forces, caused both by the non linear transverse component of the space charge field and by its variation versus the longitudinal position inside the bunch.

The emittance blow-up due to time (or phase) dependence of the RF transverse forces, which generate a transverse momentum at the gun exit strongly correleted to the longitudinal position inside the bunch (i.e. the phase). This correlation is responsible for the so called fan-like shape of the transverse phase.

It must be noticed that the non linear transverse components of the RF field give also a contribution to the emittance blow-up, introducing a distortion of the phase space distribution. Therefore, the general scaling laws for the total emittance growth in RF guns tell us that, once chosen the frequency and field, for a fixed bunch charge some optimum values for the bunch length and radius can be found which minimizes the emittance growth.

There are several types of RF gun according to the cathodes and cavities that are used.

2.1. Thermionic RF gun

In thermionic RF gun, electrons are continuously emitted by a thermionic cathode but can only be extracted and accelerated during the accelerating half an rf cycle. The electrons, emitted during the accelerating half cycle, but with a too large phase do not have enough energy to reach the cavity output and are accelerated backward to the cathode, which would destroy the cathode and shorten the lifetime of cathode.

The electron pulse that actually comes out the cavity is very long (about one fourth of the rf period) and has a very large energy spread. It is thus must to place behind the gun a momentum analyzer (e.g. an "α-magnet") to reduce the pulse length, increase the peak current and select a given spectrum. The thermionic RF gun with L_aB_6 cathode is celected by Institute of High Energy Physics to provided electron beam for BFEL. This RF gun, after being momentum analyzed, has pulse width of a few picoseconds, so that the time-dependent RF field effects can be minimized. In order to reduce emittance growth, high rf field with linear radial field distribution has been used. In order to increase the life-time of cathode by reduce electron backbombardment, a transverse magnetic field at the anode is used. The physical parameters of BFELs RF gun are shown as follow:

$I_p = 10/20$ A $\qquad \epsilon_n \leq 30\pi$ mm·mrad

$\bar{I} = 110/220$ mA $\qquad f = 2856$ MHz

$E = 0.9 \pm 0.1$ MeV $\qquad \Delta f/f \leq 10^{-6}$

$\tau_{micr} = 4$ ps $\qquad \Delta\gamma/\gamma \leq 0.5\%$

$\tau_{macr} = 4\ \mu s$

As mentioned earlier, thermionic RF gun suffer from the backbombardment problem. The extra heat due to the backbombarded electrons increases the peak current during the RF macropulse which is not good for FEL operation. It also limits the duty cycle. Adding a transverse magnetic field improves the situation since the most energetic electrons come back on the cavity wall beside the cathode. If more current and higher duty cycles are needed, the backbombardment problem will still be a limitation.

2.2 Laser-driven RF guns with conventional cavity

The photocathode RF gun is illuminated by a laser which delivers short pulse. Therefore as electron beam leave the cathode, electrons are already bunched.

Besides the obvious advantages(high field, bunched beam), laser-driven guns have other good features. The pulse format is more flexible than that of conventional injectors and that of thermionic RF guns. It mainly depends on the laser pulse format which can be varied over a wide range. Photocathodes can deliver much high current densities than thermionic cathodes: more than 500 A/cm² has been obtained.

The optimum photocathode (good quantum efficiency, long lifetime, good ability to withstand high field) has not yet been found. An important issue for any type of photocathode is the dark current (current due to field emission). This current depends on the photocathode material and the field level in the cavity. In case of cw operation, this dark current could carry a significant power.

The laser used to illuminate the photocathode should provide very short pulses, at the wavelength corresponding to the photocathode spectral response, and should be synchronized to the RF, i.e. the laser micropulse should correspond to a determined phase of RF signal. This phase should be repeated from pulse to pulse with a timing jitter much less than the pulse length. The laser micropulse should be as uniform as possible in both transverse and longitudinal directions. Recently, lasers suitable for RF gun operation have been developed. A lot more work is required to improve some of the performances. The most critical issues are the uniform pulse shape, the phase and amplitude stability and the very high micropulse repetition rate.

For laser-driven guns, the micropulse length is taken as $4\sigma_b$, where σ_b is the rms bunch length. Because the laser pulse was quite long(60～100 ps), the "α-magnet" was still necessary. In 1985 LANL demonstrated the possibility of extract high current density from Cs_3Sb photocathode illuminated by a frequency doubled Nd YAG laser. The cavity shape was designed to minimize the radial electric field. This gun produced a 1 MeV beam of 70 ps pulses with a peak current of 200 A and a normalized brightness of 2.5×10^{10} A/(m² · r²) (3). A second cavity independently powered and phased then was added to the original one. Meanwhile, the adjunction of a pulse compressor to the laser allowed to generate 16 ps optical pulses. This new gun tested in 1987～1988 provided a 2.7 MeV beam with peak current of 600 A. But the lifetime of Cs_3Sb photocathode was very short and dependent on the operating conditions. The photocathode lifetime was significantly improved by replacing Cs_3Sb with CsK_2Sb. Though the lifetime remained very dependent on the operating conditions, especially the vacuum conditions.

2.3 Laser-driven RF guns with superconducting cavities

In order to improve the operating conditions and increase the electric accelerating fields, the superconducting RF cavity was used.

As SC photoemission source appears to be promising in producing high current 、low emittance 、low energy spread, it is suggested to develop a high brightness SC RF gun with photocathode by joint efforts of China Academy of Engineering Physics and IHIP of Peking Univ. The proposed parameters of this SC RF gun is presented in table 1.

A big effort has been done to design photocathode. Alkaly cesium antimonide CsK_2Sb photocathode will be first investigated. It is characterized by high quantum efficiency and by a relative low sensitivity to the residual gas contamination. In order to increase the lifetime of cathode, LaB_6 photocathode will be investigated too, which is illuminated by a tripled Nd:YAG laser.

Table 1 Projected parameters of SC. RF gun

	I Phase	II Phase
Cathode	CsK_2Sb	LaB_6
Laser type	Nd:YAG	Nd:YAG
wavelength (nm)	533	355
micropulse length (ps)	60 ~ 90	60 ~ 90
micropulse energy (μj)	4 ~ 10	50 ~ 100
Number of cavities	1 1/2	1 1/2
Frequency (MHz)	1300	1300
Max. on-axis field (MV/m)	25	25
Macropulse length (μs)	10 ~ 50	50 ~ 1000
Micropulse length (ps)	15	15
Micropulse frequency (MHz	50 ~ 100	50 ~ 100
Peak current (A)	100 (300)	20 ~ 50
Norm. brightness (A/m^2r^2)	10^{11}	$5 \cdot 10^{10}$

The schematic layout of SC. RF gun is presented in fig. 1.

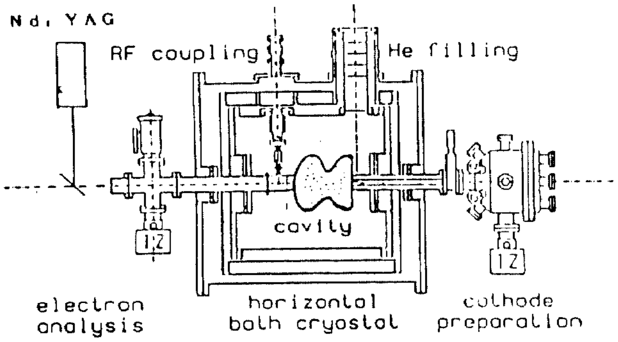

Fig. 1. schematic layout of SC. RF gun

The emittance blow-up due to time (or phase) dependence of the RF transverse forces, which generate a transverse momentum at the gun exit strongly correleted to the longitudinal position inside the bunch (i.e. the phase). This correlation is responsible for the so called fan-like shape of the transverse phase.

The general scaling laws for the total emittance growth in RF gun tell us that, in a standart RF gun it is not possible to reduce the emittance symply by decreasing the bunch density, since the RF field induced emittance blow up becomes the dominant effect.

It is well known that the basic mechanism of the RF induced emittance blow up consists in the correlation existing at the gun exit between the transverse momentum and the injection phase, as given by formula(4)

$$P_r = \alpha k r \cdot (\sin\langle\phi\rangle + \Delta\phi\cos\langle\phi\rangle - \frac{1}{2}\Delta\phi^2\sin\langle\phi\rangle) \qquad (1)$$

where r is the radial position of a generic electron in the bunch, whose exit phase ϕ is supposed to be slightly distributed around an average exit phase of the bunch $\langle\phi\rangle$, such that $\phi = \langle\phi\rangle + \Delta\phi$ The dimensionless parameter $\alpha = eE_0/2mc^2k$ has been introduced, where E_0 is the peak RF electric field at the cathode surface and $k = 2\pi/\lambda_{rf}$. The formula (1) represents the transverse phase space distribution observed at the gun exit.

The condition of minimum emittance is guarantied when $\langle\phi\rangle = 90^o$, under this condition the emittance blow up is due to the second order term which is left in the correlation. This effect on the transverse phase space is accompanied by a strong non-linear behaviour of the energy gain versus phase relationship, which gives a significant degradation of the longitudinal emittance. The final longitudinal momentum at the gun exit (when $\langle\phi\rangle = 90^o$) can be written as

$$P_z = \alpha\ (\pi(N+1/2)(1-\tfrac{1}{2}\cdot\Delta\phi^2) - \Delta\phi\ ) \qquad (2)$$

where N+1/2 is the number of cells in the RF gun structure, For vanishing non linear terms in the energy curve, a multi mode RF gun would be investigated.

3 CONCLUTION

The comparison of several types RF gun has been made. The SC RF gun is a best one for obtaining a high quality electron beam (high current, low emittance , low energy spread)and is designed by CAEP and IHIP. It will then be possible to test the different types of photocathodes in the SC accelerator environment. It can be expected to obtain a high brightness RF injector.

5 REFERENCES

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