DESIGN OF AN ULTRAFAST ELECTRON DIFFRACTION SYSTEM WITH AN L-BAND PHOTOCATHODE GUN

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Abstract

Ultrashort electron beams or X-rays can be used for investigating ultrafast dynamics of physical, chemical or biological systems. Compared to X-rays, electron beams are less destructive to material and the scattering cross section is larger, however it is difficult to decrease the electron beam pulse length due to space charge forces. One way of overcoming this difficulty is by means of a photocathode RF gun, which allows the beam energy to be rapidly increased immediately after the electron emission from the photocathode, therefore minimising the pulse lengthening due to space charge force. For time-resolved observation of atomic processes, electron beams shorter than 100 fs (fwhm) with small divergence are required. In this paper, a conceptual design of an L-band gun system is proposed with beam parameters optimisation for electron diffraction experiments.

INTRODUCTION

Ultrashort electron beams generated by RF guns have potential usages to investigate ultrafast dynamics in many areas [1-5]. Up to now, such sources have been studied with S-band photocathode guns due to their ability to increase the RF field up to 100 MV/m or higher. However, the repetition rate is limited far below 500 Hz. In this study, we consider an L-band copper gun because the repetition rate of this gun can be increased up to 1 kHz [6] or higher if we operate the gun with a low RF field. This L-band gun was originally designed [7] as an injector for the UK's New Light Source (NLS) facility [8]. By using this L-band gun, the ultrashort electron pulse may be generated with the same repetition rate as FEL photons from superconducting linacs like NLS, FLASH, or European XFEL.

For high energy electron beams with about 5 MeV, the scattering angle is small. To have a clear diffraction pattern, the pattern should be collected a few metre downstream of the target and therefore the electron beam must have small geometric divergence about 0.05 mrad not to spoil the diffraction pattern [3]. When the electron bunch length decreases shorter than 100 fs, many new physics would be discovered [5].

In this study, we propose an experimental setup as shown in Fig. 1 to generate electron beams suitable for ultrafast electron diffraction (UED) experiments. In this setup, a target is located at 1 m from cathode and a screen for the measurement of diffraction patterns is located at 5 m downstream of the target. Before the target, collimators will be installed to select the beam size and cut out the dark current from the gun. For beam divergence measurement, one slit will be located at the same location as the collimators. At the location, another mirror for a pump laser will be installed (not shown in Fig. 1). The bunch charge will be measured with a Faraday cup. An RF deflector is considered to be used for electron bunch length measurement. A bending magnet will be used for beam energy and energy spread measurements.

We numerically optimise electron beams for ultrafast electron diffraction experiments for two bunch charge cases; 0.16 pC (10^6 electrons) and 1.6 pC (10^7 electrons). The laser beam size and pulse length, the gun RF field and phase, and the focusing solenoid location and field strength were used as optimisation parameters. When the RF field increases, the beam quality, i.e. the bunch length and divergence, becomes better. However, field emission would be significant for a high field case [9]. Here, we limit the field to 44 MV/m at cathode as a compromise between the high beam quality and the suppression of the dark current from the gun. The dark current issue will be discussed in the last section.

ELCTRON BEAM GENERATION

For the generation of ultrashort electron beams, the pulse length of the cathode laser should be in the same order of magnitude as the beam. Ti:Sapphire laser which has a wide band width would be a good candidate as

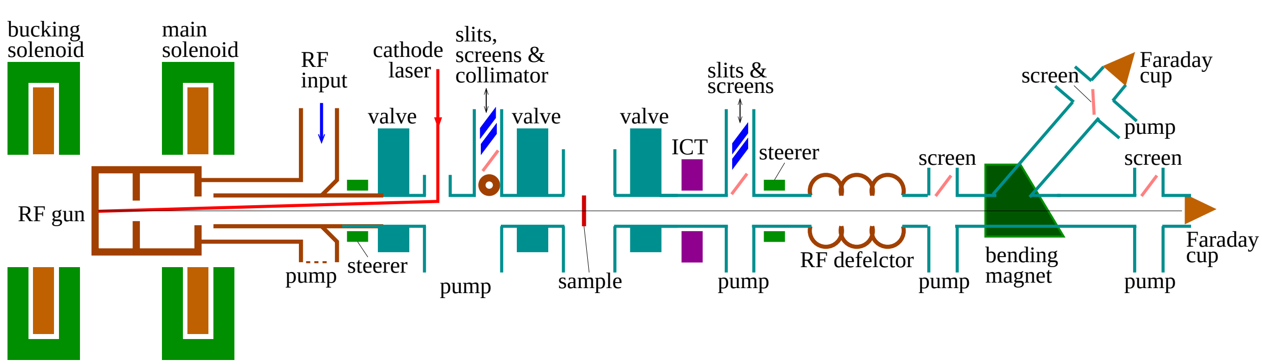

Figure 1: Proposed layout of an ultrafast electron diffraction system with an L-band photocathode gun.

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cathode laser. Conventionally available Ti:Sapphire lasers provide a pulse length shorter than 100 fs with 1 kHz repetition rate. This laser system can be used as cathode laser as well as pump laser of the sample.

The response time between the impact of a laser pulse to the cathode and an electron beam generation from the cathode should be much shorter than the pulse length. Typically, semiconductor cathodes like Cs_2Te or GaAs have high quantum efficiency (QE). However, the response time ranges 0.1 ps or more [10]. On the other hand, metal cathodes like Cu, Mo and Pb have a low QE, of an order of 10^{-5}. Nevertheless, a metal cathode should be used for a UED source because they have a fast response time, an order of femto-second [10]. Since an electron diffraction source does not require high bunch charge beam, a metal cathode would generate enough bunch charge with a conventional laser.

FOCUSING OF AN ELECTRON BEAM

Due to the very short bunch length of an electron beam, space charge force is strong enough to deteriorate the beam even if the beam has a small bunch charge like 0.16 or 1.6 pC. The brightness of the beam is defined as $B = \eta I / \pi^2 \varepsilon_x \varepsilon_y$, where η is a form factor which is 2 for a K-V distribution [11]. Electron beams discussed here have high peak current of several ampere and small transverse emittance of about 0.2 mm mrad. This brightness is comparable to electron beams in FEL injectors. Because the ultrashort electron beam is space charge dominated, the electron beam size and length become larger during the propagation to the target. A focusing solenoid was applied to focus the beam. Another solenoid was put behind the cathode to compensate the solenoid field tail at cathode (see Fig.1).

The beam dynamics was numerically calculated with a space charge tracking code, ASTRA [12]. 50,000 macro-particles were generated with "generator" program in ASTRA to have a Gaussian temporal distribution. The radial distribution was assumed to be uniform. Numerical optimisation was done to generate electron beams with small divergence, short pulse length and small beam size at the target. The result is summarised in Table. 1. The solenoid field is optimised for lowest divergence at the sample location, 1m. The solenoid location is adjusted to 255 mm instead of 235 mm as optimised in Ref. [7].

Table 1: Machine and Beam Parameters.

	Parameters	0.16 pC	1.6 pC
Laser	length (fs), fwhm	47	520
	radius (mm)	0.52	0.40
Gun	max E (MV/m)	44	44
	emission phase* (deg)	3	3
Solenoid	location (m)	0.255	0.255
	max field (T)	0.140	0.160
Beam	number of electrons	10^6	10^7
	size (mm), rms	0.43	0.46
	length (fs), fwhm	94	680
	divergence (mrad)	0.051	0.045
	kinetic energy (MeV)	4.49	4.49
	energy spread (keV)	1.97	6.54
	normalised emittance (mm mrad)	0.20	0.20

*Defined from the phase for maximum beam energy condition.

The beam divergence depends strongly on the focusing solenoid field as shown in Fig. 3. About 1% drift of the solenoid field may produce 10% increase of beam divergence and 3% change of beam size. This means that the divergence should be monitored and optimised during experiments. On the other hand, the other parameters like

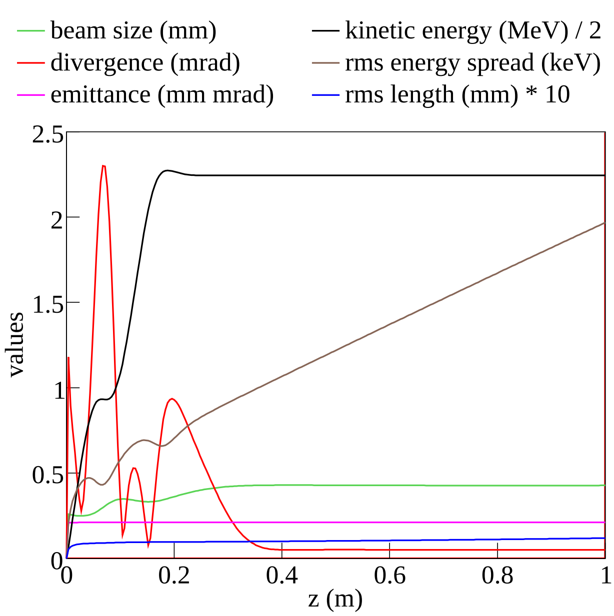

Figure 2: Beam parameter evolution as a function of distance for the 0.16 pC case.

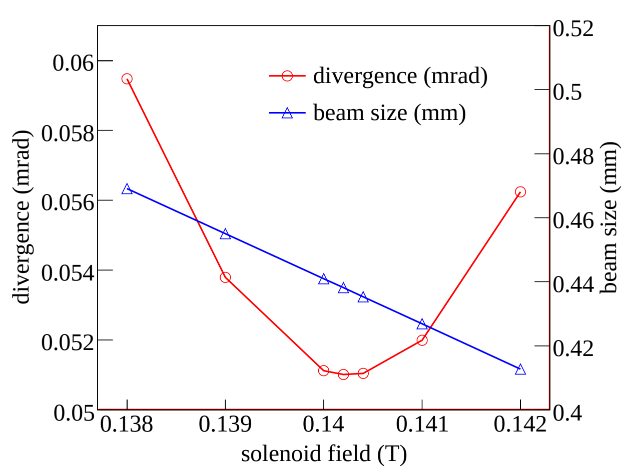

Figure 3: Beam parameter variation as a function of focusing solenoid field for the 0.16 pC case.

bunch length and energy spread vary far less than 1% for 1% focusing field drift.

DARK CURRENT EFFECT

In RF guns, a high RF field for fast beam acceleration should be applied. This high RF field generates dark current from the cathode and the cavity inner surface. The dark current increases with applied RF field strength as $I_{DC} \sim E_0^{2.5} \exp(-C/E_0)$, where I_{DC} generated dark current, E_0 RF field amplitude, and C is a constant [13]. The generation of dark current should be suppressed especially in UED source because the bunch charge for UED is very small. According to the measurement at PITZ and FLASH [9], the dark current becomes a level of a few hundreds µA when the RF amplitude is higher than 40 MV/m.

In the model shown in Fig. 4, the RF field is assumed to increase up to 46.5 MV/m after 20 µs RF pulse. Because of the finite rise time of the RF field, the field strength reaches about 44 V/m after 8 µs. Here, we launch the cathode laser to generate electron beams. At the time, dark current is about 0.16 mA. If we quit the RF feed to the cavity at 8 µs, the dark current during one RF pulse will be about 400 pC. The electron charge of dark current is higher than that of a beam because only one bunch of beam will be generated per RF pulse. However, most of the dark current has much lower kinetic energy compared to the beam energy and is over-focused before the target. Furthermore, the dark current has much larger beam size and divergence at the target so that the diffracted electron pattern to be monitored at a screen far downstream is not affected. Nevertheless, such a high level of dark current may damage the sample and therefore should be minimised.

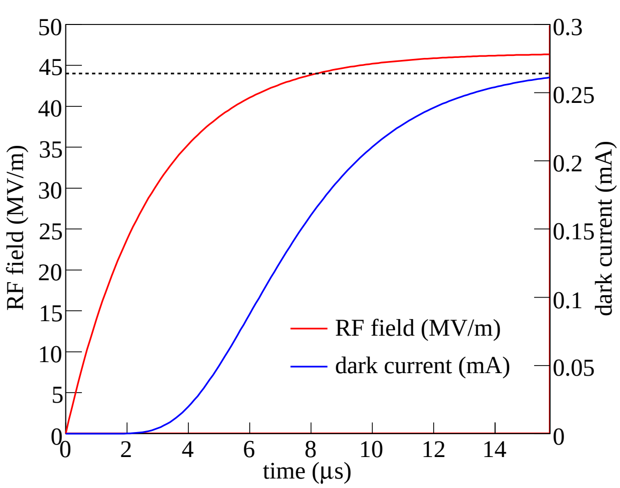

Figure 4: RF field and dark current increases with time during an RF pulse. For the dark current model, a field enhancement factor of 220 and a field emission effective area of 3×10^{-16} m^2 are assumed [9].

SUMMARY

An ultrafast electron diffraction system was designed with an L-band photocathode gun. This system may provide an electron beam shorter than 100 fs for 0.16 pC bunch charge. This bunch may have a divergence of 0.051 mrad at the target. With 1.6 pC bunch, the pulse length would increase to about 700 fs but the divergence may be below 0.05 mrad.

Dark current issue was reviewed. The charge of dark current per RF pulse is much more than that of electron beam. However, the energy of the dark current would be much lower than that of an electron beam and most of dark current will be over-focused before the target.

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