RF-GUN OPTIMIZATION FOR FEMTO-SECOND ELECTRON BUNCHES

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Abstract

The aim of this study is to optimize and construct an rf-gun to be a source of femto-second electron bunches to produce coherent far infrared (FIR) radiation or femto-second x-ray pulses. To produce ultra-short bunches we use an rf-gun with a magnetic bunch compression in the form of α-magnet. In this study we concentrate on the specific optimization of an rf-gun to produce femto-second electron bunches. The optimum geometric and electric rf-gun specifications have been investigated through numerical simulation with the particle-in-cell code PARMELA. The numerical simulation show that the electron bunches from this optimum rf-gun as short as a few fs rms can be expected.

1 INTRODUCTION

This study is part of the research and development for the project SURIYA which is presently under construction at the Fast Neutron Research Facility (FNRF) at the Chiang Mai University, Thailand. SURIYA is a facility that has the purpose to produce intense, coherent, polarized FIR radiation in the wavelength range of 10 μm to 1000 μm or femto-second x-ray pulses to be used for basic and applied research. An electron source and a beam transport system under construction at the SURIYA is similar to SUNSHINE facility at Stanford University [1,2,3], which can produce electron pulses as short as 100 fs rms. SURIYA will consist mainly of an rf-gun with a thermionic cathode, an α-magnet for bunch compression, post linear accelerator (linac) to accelerate electron beam to 25-30 MeV, and beamlines guiding the electron beam to experimental stations where intense FIR or femto-second X-ray pulses are generated. The details about the SURIYA project are discussed in another contribution to this conference [4]. A schematic outline of the SURIYA facility planed at the FNRF is shown in Fig. 1.

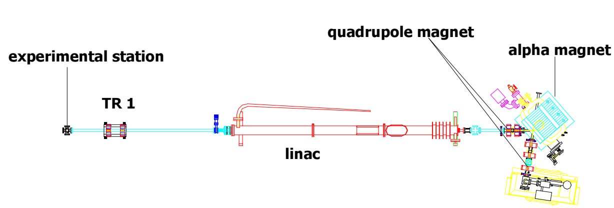

Figure 1: Layout of the proposed SURIYA source at FNRF, Chiang Mai University.

2 RF-GUN CHARACTERISTICS AND NUMERICAL SIMULATIONS

2.1 General Characteristics of Rf-Gun

A microwave or rf-gun is an electron source consisting of a cathode serving as an electron emitter, which emits electrons into the rf- fields inside a metal-walled cavity. Depending on the type of the cathode we distinguish between a thermionic cathode and a photocathode rf-gun. In our electron source, we use a thermionic cathode, which produces an electron beam by thermal emission of electrons from a material with a low workfunction [5]. The main advantages of an rf-gun are the higher current, lower emittance, and higher momentum electron beams compared to a conventional DC-gun. In addition, the rf-gun with thermionic cathode exhibits essential features for efficient bunch compression. First, high acceleration to near relativistic energy (2-3 MeV) within a short distance allow space charge effects little time to dilute the beam emittance. Second, the momentum-time phase space of the particle distribution is very well suited for a simple and efficient bunch compression in an α-magnet. Finally, the particle flux obtainable from a thermionic cathode can be increased to values at which space charge effects cannot be controlled anymore.

The rf-gun consists of one and a half standing wave structure rf-cavities with a thermionic cathode attached to the wall of the half-cell. All rf-cavity cells operate at 2856 MHz and are energized by a klystron through an rf-input rectangular waveguide port in the full-cell. The half-cell is coupled to the full cell by an external-coupling cavity as shown in Fig. 2.

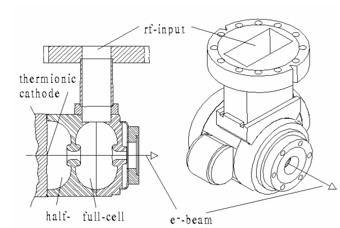

Figure 2: Cross section and 3D-view of the rf-gun [6].

The half-cell, full-cell, and side-coupling cavity, allow for three possible structure modes and operate in the π/2 mode. That means, there is a phase-shift of 90^o between the first half-cell and the side-coupling cell, and between the side coupling cell and the full-cell. Thus the rf-fields are 180^o out of phase between the half- and full-cell.

Electrons emerge from the cathode with thermal velocities, then travel through the half and full cell during the accelerating phase. The electron beam reaches a kinetic energy of about 2-3 MeV at the gun exit

2.2 Numerical Simulations

The electron dynamics inside the rf-gun is very complicated and must take space charge effects into account. Therefore, it is necessary to use a numerical computer program to simulate the details of the gun operation and evaluated the optimum geometric and electric rf-gun parameters.

In this study we use mainly PARMELA and SUPERFISH to simulate and optimize the specific parameters of the rf-gun. SUPERFISH is a well-established code from Los Alamos National Laboratory (LANL) that calculates the frequency and the electromagnetic field distribution for TM modes for resonant cavities in two dimensions. This code lets us to simulate rf-cavity shapes to the desired frequency. PARMELA is a particle-in-cell code, also developed by LANL, which can track many particles through the fields obtained from SUPERFISH. PARMELA' s results show both longitudinal and transverse particle phase space distributions at selected points along the beam line. This code includes space charge effects. In PARMELA simulations, we assume that the cathode emits a uniform stream of macroparticles comprising a cathode current of 3.4 A composed of 50,000 macroparticles per 2856 MHz rf-period. Therefore, the cathode emits 142.8 macroparticles per ps, and each macroparticle simulates 1.48 x 10^5 electrons.

3 RF-GUN OPTIMIZATION

3.1 Longitudinal Particle Distributions

Electrons emerge from the cathode during the rf-period phase from 180^o-540^o. During the accelerating half wave of the rf-fields these electrons gain almost relativistic energies in a very short distance. For the optimum field, the particles emerging from the cathode as the field turns accelerating reach the exit of the half-cell just when the field becomes decelerating again. Particles emerging from the cathode later will see some decelerating field at the exit of the half-cell and therefore gain less energy. The rf-fields inside the second rf-cell continue to accelerate the electrons to travel through the second rf-cell during the accelerating phase reaching velocities near the velocity of light ($v \approx 0.98$ c). By this dynamics the phase space distribution of the beam at the rf-gun exit is shown in Fig.3 for each 2856 MHz cycle.

We observe a thin monotonic distribution of particles and the histogram tells us that most particles are concentrated in the head of the bunch. It is this thin distribution that allows efficient bunch compression.

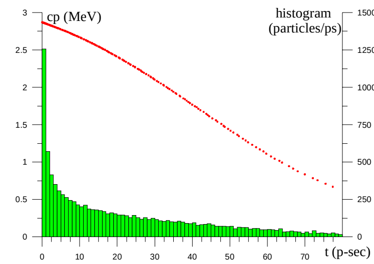

Figure 3: Momentum-time phase space distribution at the rf-gun exit with histogram.

As long as the rf power from the klystron is supplied to the rf-gun, this cycle is repeated every rf-period, resulting in a train of bunches separated by 350 ps at the 2856 MHz rf-period.

3.2 RF-Gun Fields and Ideal Phase Space Distribution

A critical parameter determining the limiting bunch is the electric accelerating field in the half-cell. The particle phase space distribution at the gun-exit shows a varying curvature for different electric fields as shown in Fig. 4.

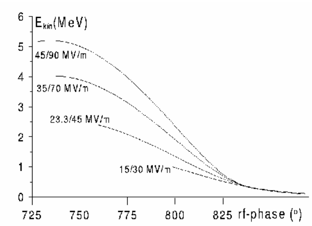

Figure 4: Energy-time phase space distributions for different accelerating fields in the rf-gun [6].

At very high fields, particles reach almost the same fields during a finite time interval in each bunch. Such a distribution cannot be compressed for lack of a monotonic energy-time correlation. The required monotonic energy-time variation of the particle distribution appears only for lower electric fields. Knowing the bunch compression system and the beam line to be used we may calculate an ideal phase space distribution that would result in a zero bunch length at a selected point downstream in the beam line.

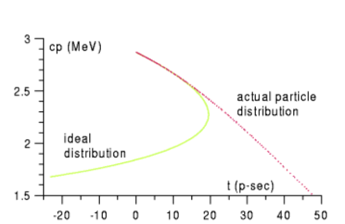

Figure 5: Ideal and actual phase space distribution at the rf-gun [6].

Such an ideal distribution is shown in Fig. 5 and we may adjust now the electric field in the rf-gun cells such that the actual particle distribution matches the ideal distribution. This is possible at least over the range of 10-20 ps where most of the particles are concentrated anyway.

3.3 Bunch Compression

To produce femto-second electron bunches we use an α-magnet [7]. The α-magnet has the shape of half a quadrupole magnet with two poles and a mirror plate to terminate the field across the vertical midplane (yz-plane). The electron beam enters an α-magnet in the xz-plane at an angle of 49.3^{o} with respect to the magnet axis. Particles travel along a closed loop similar to the letter α inside the α-magnet and exit again exactly at the entrance point but at a different angle (as indicated in the Fig. 6).

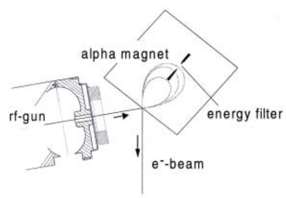

Figure 6: rf-gun and α-magnet layout.

The path length of the particle trajectory in the α-magnet depends on the particle momentum and magnetic field gradient scaling like $s \approx (cp/g)^{1/2}$ [5]. For a relativistic electron beam the effect of velocity dispersion is very small compared to the path length dispersion. Therefore, by adjusting the gradient of the α-magnet the bunch compression can be optimized. Since we perform experiments downstream from the α-magnet we must adjust the compression such that the shortest bunch length is obtained there and not at the α-magnet exit. Consequently, we overcompress the bunches such that lower energy particles exit α-magnet first followed by higher energy particles. While the particles travel through the beam transport line including linac, higher energy and faster particles will catch up with slower particles forming the shortest bunch at the experimental station.

The momentum-time phase space distribution after bunch compression and acceleration with respect to the initial distribution at the rf-gun exit (Fig. 3) is shown in Fig. 7 (left). It shows an extremely short spike of only about 2.8 fs-rms on top of a broader base of some 34 fs-rms. While it would be interesting to contemplate 2.8 fs bunches, at this time we cannot offer an efficient way to preserve such a short bunch length and we must therefore ignore this spike for the time being. However, the length of the base at 34 fs-rms together with a charge of 0.1 nC constitutes a peak current of 3 kA and is about three times shorter than the bunch lengths obtained at the SUNSHINE facility which can produce electron pulses as short as 100 fs rms (Fig. 7 right).

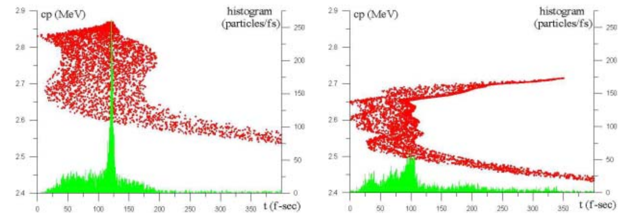

Figure 7: Momentum-time phase space distribution after bunch compression and acceleration with histogram of SURIYA (left) and SUNSHINE (right).

3.4 Transverse Particle Distributions

Ultra short bunches can be diluted again along the beam transport line by excessive focusing of beam divergence. This effect limits the bunches at SUNSHINE to about 100 fs-rms. The SURIYA rf-gun has been designed for much smaller beam divergence compared to the SUNSHINE gun as shown in Fig.8. Bunch lengthening due to a quadratic effect and is greatly reduced for the SURIYA rf-gun with only about 1 mrad of divergence beam [6].

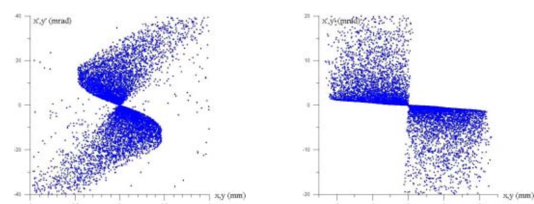

Figure 8: Transverse phase space distributions show 10 mrad divergence beam at the SUNSHINE gun-exit (left) and 1mrad divergence beam at the SURIYA gun-exit (right).

4 ACKNOWLEDGEMENTS

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