Chapter 1
Introduction

In accelerator and beam physics technology, experimental opportunities based on particle beam brightness are determined by the particles' distribution in 6-dimensional phase space. Reduction of the transverse phase space has been attempted in several laboratories around the world, especially in pursuit of high brightness third generation synchrotron light sources. In the last decade, reduction of the longitudinal phase space distribution became possible. Electron short pulses of 80 fs can be generated by large high-energy linear accelerator system with magnetic bunch compression in form of magnetic chicanes [1]. Production of intense electron pulses of very short duration on the order of a hundred femtosecond without relying on high-energy accelerators and extensive bunch compression was achieved for the first time at the Stanford University Short Intense Electron Source (SUNSHINE) [2][3].

Sub-picosecond electron bunches can be generated from an RF-gun with a thermionic cathode and an alpha-magnet for bunch compression at low electron energies. This system has been developed at the SUNSHINE facility and produced electron bunches as short as 120 fs (rms) at a bunch charge of 100 pCb [2][4]. At SUNSHINE, a train of 2000 to 3000 microbunches separated by 350 ps was produced at a pulse repetition rate of 10 Hz [5][6]. Observing the coherent spectrum in an autocorrelation method [7] permits the determination of the bunch length in the sub-picosecond regime by purely optical methods and independent of limiting features of electronic systems operating in the time domain. A Michelson interferometer for far-infrared (FIR) radiation has been developed and installed for measurements of the bunch length of the order of 100 fs [2][4] or less. Similar facilities called SURIYA have been built and presently attempt to produce electron bunches in femtosecond range [8].

Femtosecond electron bunches can become a tool for many research opportunities, which is available at only very few other facilities. A variety of possible applications can be pursued with femtosecond electron pulses. Sub-picosecond electron pulses at low energies of a few tens of MeV are desired for use in direct applications on physical, chemical and biological materials [9][10][11]. A direct application of femtosecond electron pulses at low energies has been used by the Nobel Price Winner A. Zeweil to study the dynamics of chemical transitions [11]. Femtosecond electron pulses can be used as a source of femtosecond photon pulses, which provide many opportunities for research to study dynamic processes in chemical reaction, biological molecule and in time-resolved experiments. Transformation of the electron pulses into photon pulses can be obtained by, for example, single pass free electron laser (SASE) [12], Compton scattering [13], Parametric and other methods to produce femtosecond x-ray pulses [14], or for the generation of coherent far-infrared (FIR) radiation [2][15][16] with a photon brightness far exceeding that available from conventional and synchrotron radiation sources.

1.1 Femtosecond Electron Pulses as a Source of FIR Radiation

The properties of electromagnetic radiation from charged particles depend greatly on the actual particle density profile. For example, synchrotron radiation is known to be incoherent in existing electron storage rings. This is not a fundamental property but is only a consequence of the long electron bunches compared to the observed radiation wavelength and to the dimensions of the vacuum chamber. The radiation from an electron bunch becomes coherent and highly intense at wavelength about or longer than the bunch length. The possibility of generating coherent radiation from electron bunches was predicted first by H. Motz [17] in 1951 and was first observed for coherent synchrotron radiation by T. Nakazato in 1989 and later by E.B. Blum in 1991 [15][16]. The radiation from these short bunches has a continuous spectrum at submillimeter to millimeter wavelengths. The radiation spectrum is the Fourier transform of the particle distribution, and if the particle bunch duration is less than one picosecond, the radiation emitted is in the far-infrared (FIR) regime. The intensity of coherent FIR radiation exceeds greatly that of incoherent synchrotron radiation at the same wavelength. The origin of this great enhancement is that the radiation fields of all electrons adding coherently and that the radiation intensity being proportional to the square of the field therefore scales like the square of the number of radiating electrons. This works only if the radiation field from all electrons are in phase, e.g. if all electrons are concentrated over a short distance compared to the radiated wavelength. The actual enhancement factor over incoherent radiation depends on the particle distribution, and a form factor describing the enhancement for arbitrary particle distribution, can be derived. Since the coherent radiation from the electron bunches is proportional to the number of electrons squared the typical number of electrons is some 10^8-10^9 per bunch provides very intense coherent radiation is generated. According to the fact that radiation fields add up coherently at wavelength much longer than the bunch length, short bunch length is desired for production of broadband radiation spectrum. Electron pulses with a bunch length in order of a hundred femtosecond will produce broadband radiation in the wavelength range from 50 μm to a few 1000 μm with an intensity far in excess to that available from black body radiators or synchrotron light sources.

At the SUNSHINE facility, coherent radiation has been observed in the form of transition radiation from sub-picosecond electron bunches spanning a wavelength range from about 50 μm up to microwaves. In Fig.1.1 the calculated radiation brightness of coherent transition radiation (CTR) from a 30 μm rms (100 fs) electron bunch, which was available at the SUNSHINE facility, is compared with that available from a synchrotron light source (SR) and black body radiation (BB). The electron bunch length measured at the SUNSHINE facility is approximately 120 fs with electron energies of 26 MeV [18]. Autocorrelation measurement based on a Michelson interferometer can be used to determine the radiation and electron bunch lengths. Figure 1.2 shows a measured coherent transition radiation spectrum obtained at SUNSHINE. The radiation is broadband and its detectable spectrum reaches from microwaves to 120 cm^{-1} wavenumber.

Due to its broadband intense coherent characteristics, the far-infrared radiation from femtosecond electron bunches can be used for basic and applied research on, for example, biological macromolecules, polymers and material at THz frequencies [19][20][21]. The high intensity far-infrared radiation produced at SUNSHINE allows the probing of chemical and biological samples in dilute watery solutions. The effectiveness of this radiation together with Dispersive Fourier Transform Spectroscopy to study, for example, hydrogen-bond-stretching-modes in DNA has been demonstrated in the last experiments performed by K. Woods at the SUNSHINE facility before the system was disassembled [22]. This was the first time that DNA molecules could be studied in dilute solutions rather than in crystalline or dry form. The success of this experiment stimulated the desire to continue along this line to achieve more understanding how the low-frequency vibrations function in biological molecules. These vibrations are biologically important since they involve motions of large groups of atoms relative to each other. These motions can be important for conformational transitions associated with biological functions, for example, the local melting or the separation of the two strands of DNA during the transcription and the transport of molecules and ions through the cellular membrane by membrane transport proteins.

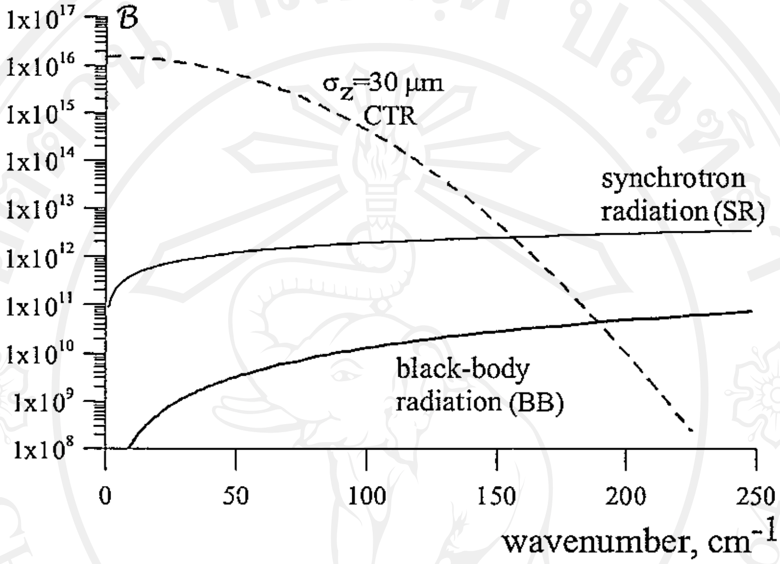

Figure 1.1. Calculated radiation brightness B (ph/s/mm^2/100%BW) vs. wave number for CTR, SR, and BB.

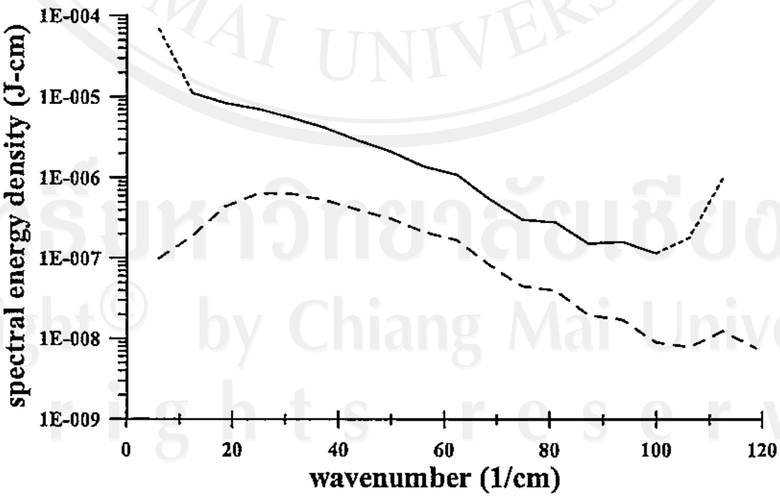

Figure 1.2. Coherent transition raw-spectrum (dashed-line) and the corrected spectrum (solid-line) after applying the correction for beam splitter (BS) efficiency. The dotted-section occupy region near singularities of the BS efficiency [18].

1.2 Femtosecond Electron Pulses as a Source of Femtosecond X-ray

Femtosecond x-ray pulses become an interesting probe for the study of extremely fast chemical and biological reactions (pump-probe experiment) since atomic reactions occur at time scales of less than a picosecond. Femtosecond electron pulses can be converted into equivalent x-ray pulses by different ways, for example, Bremsstrahlung, synchrotron radiation, channeling radiation, Smith-Purcell radiation, Compton scattering and parametric x-radiation. Parametric x-ray are generated when electron pulses pass through a crystal slab. Since the output photon energy of parametric x-ray is independent of the electron energy, thus it is a suitable way for x-ray production from electron beams with low energies of a few tens MeV [14][23][24].

1.3 Generation of Femtosecond Electron Bunches at SURIYA Facility

A femtosecond electron source has been established at the Fast Neutron Research Facility (FNRF) as the SURIYA project since 2000. The SURIYA system was developed from the Stanford SUNSHINE facility and consists of an RF-gun with thermionic cathode, an alpha-magnet (α-magnet) as a magnetic bunch compressor [25], a SLAC-type linear accelerator (linac) serving as a post accelerator, beam steering and focusing elements, beam diagnostic instruments, RF system, and control units. Figure 1.3 illustrates the schematic layout of the SURIYA system. The RF-gun is an S-band 1-1/2 cell resonant cavities. The thermionic cathode is attached to one wall of the first half-cell emitting electrons constantly to a high accelerating field. The dimensions and fields in the RF-gun are designed and specially optimized to generate short electron bunches. The electromagnetic field is transported through an RF-rectangular waveguide into the full-cell and coupled into the half-cell through the side coupling cavity. Electrons are emitted from the cathode with thermal energies and are accelerated or decelerated from the electromagnetic fields depending on the oscillating field cycle. The first electrons emitted when the field becomes accelerating reach the end of the half-cell just before the accelerating field inside the half-cell becomes decelerating again. These electrons, thus, experience maximum acceleration. Later electrons feel some decelerating fields and gain less and less overall energy. This phenomenon results in a correlation between energy and time of electrons at the

RF-gun exit. The maximum kinetic energy is about 2-2.5 MeV depending on the external RF-power. This fast acceleration to relativistic energies diminishes emittance-diluting effects of space-charge forces.

The electron beam emerging from the RF-gun is then guided to an α-magnet. Faster electrons travel with longer path length than the slower ones. The characteristics of the α-magnet allow the lower energy electrons to catch up with the higher energy electrons resulting in electron bunch compression. Since the electron energy distribution in the bunch is time-dependance, the desired fraction of about 10-20 percent of high energy electrons in the bunch is selected by energy slits inside the α-magnet vacuum chamber. Hence, this desired part of the electron bunch is compressed to within a few picoseconds. After bunch compression, the electron beam is guided through an S-band SLAC type linear accelerator (linac) for further acceleration. Experimental stations and related beam transport line components are located downstream of the linac. At the end of the beam transport line, a dipole magnet serves both as the beam dump and energy spectrometer. Although, the electron beam is considered to be a relativistic beam but the variation of individual electron velocity is not negligible. After the bunch compression inside the α-magnet, the bunch will spread due to this velocity variation as the beam travels through the beamline. Hence, an overcompression of the bunch is desired, by optimizing α-magnet field, in order to compensate the effect and to achieve a minimum bunch length at the desired experimental station.

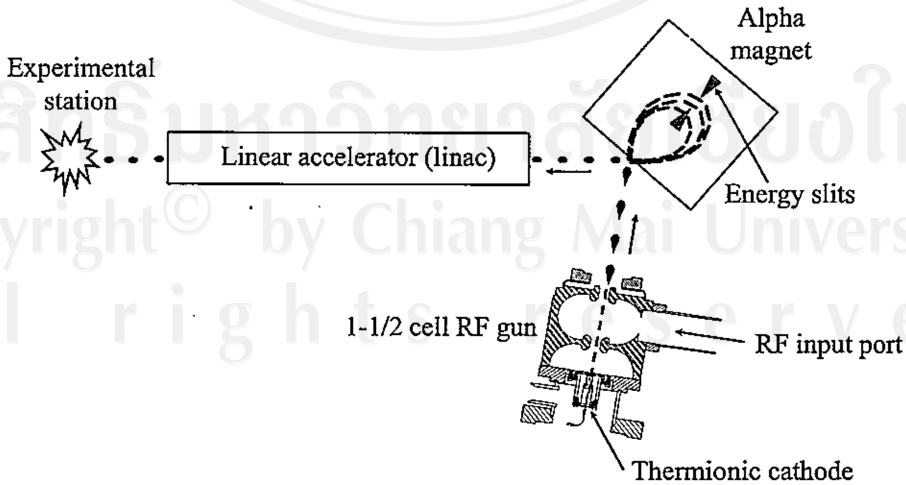

Figure 1.3. Schematic diagram of SURIYA system, which consists of the S-band RF-gun, the α-magnet and the post linear accelerator.

The main components of the SURIYA system have been designed and developed in house at FNRF. The SURIYA facility is designed to reach even shorter electron bunches than the SUNSHINE facility. This is mainly due to the new improved version of an RF-gun design, which has been optimized for most efficient bunch compression reaching an ideal shortest bunch length of about 53 fs at experimental station. This is two times shorter than those obtained at the SUNSHINE facility and therefore promises to give a radiation spectrum twice as broad. All major parts of the newly designed RF-gun have been machined based on the simulation results in Thailand. RF-evaluation and fine-tuning have been done in 2002 and this RF-gun has been installed at the SURIYA beamline in March 2003. A 2856 MHz microwave system including klystron and modulator system for energizing the RF-gun was obtained from Sirirat Hospital. This system was used in a medical-radiation therapy linear accelerator. The control electronics has been fully updated to remove therapy related interlocks and replace them with a system matched research requirements. The α-magnet has been designed and constructed based on the bunch compression requirements.

The Stanford SUNSHINE facility was terminated and disassembled by the end of 2002. The 30 MeV SLAC-type linear accelerator (linac) and some vacuum components have been transferred to the SURIYA facility. This linac is now powered from a second klystron independent of the RF-gun system. This klystron and modulator with related necessary components was obtained from the Chiang Mai hospital by donation. To minimize the transverse dimension of the electron beam, some beam focusing and steering elements are needed. There are several quadrupole and steering magnets placed along the beam transport line. The quadrupole magnets are used mainly for beam focusing and can also be used for beam emittance measurement. Combination of an electromagnetic dipole magnet and a Faraday cup are placed at the end of the beam transport line serving as an energy spectrometer and a charge collector. The spectrometer has been designed and modified from a beam dump magnet of the Chiang Mai Hospital linac system. All personnel and machine protection systems have been installed. An international standard security and safety protocol has been incorporated into the operation of the machine, which includes access door interlocks and panic buttons for automatic beam shut-off in case of personnel access to a restricted area. Beam-on warning lights, high voltage signs and audible sirens are implemented and appropriate locations to notify machine operating status and radiation hazards.

The whole facility is installed in a below ground area which became available from an earlier neutron beam activity. The final floor plan of the SURIYA facility is shown in Fig.1.4.

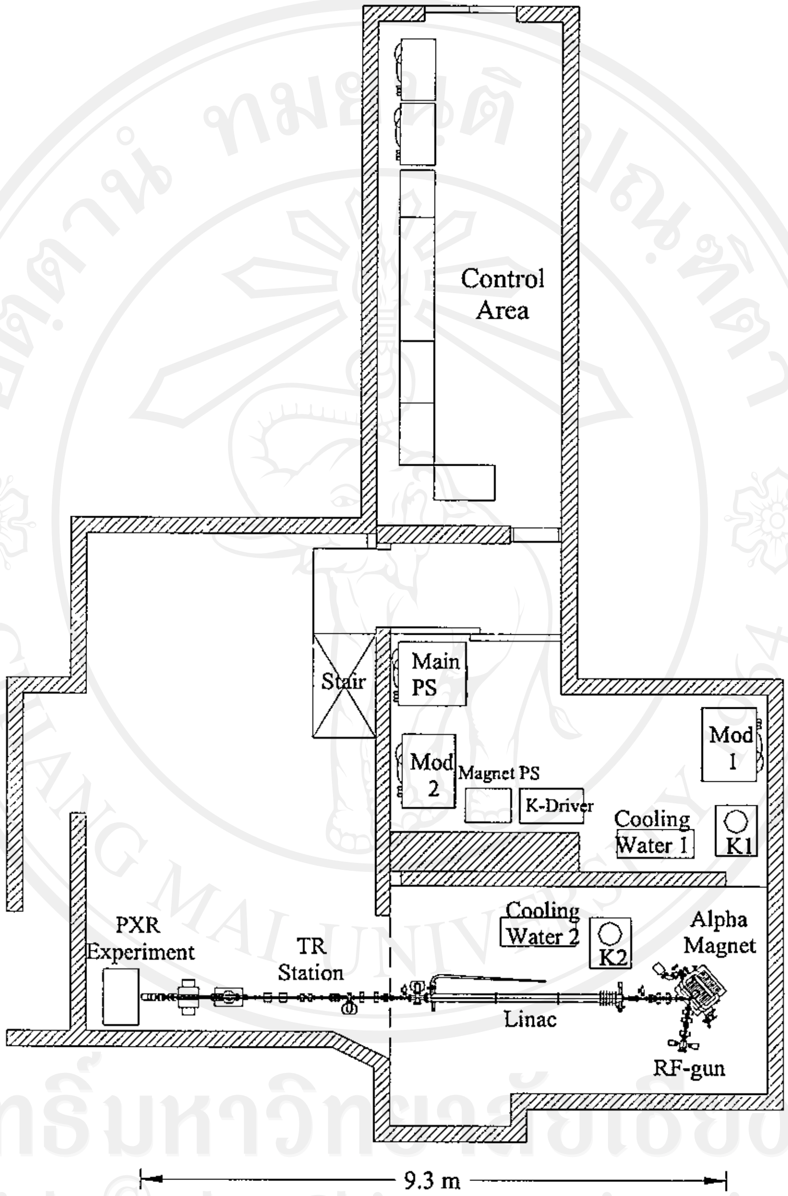

Figure 1.4. Schematic diagram of SURIYA floor plan.

At SURIYA facility, coherent FIR radiation is generated at the experimental station as transition radiation (TR) which is emitted when electrons pass through an interface between two media with different dielectric constants. In our case, an Al-foil is used for the radiator, which represents the transition between vacuum and metal. Rotating the foil by 45^o with respect to the electron path generates the backward transition radiation emitted at 90^o with respect to the beam exits through a polyethylene window into open air. This polarized coherent FIR radiation will be measured with a Michelson Interferometer and a room temperature pyroelectric detector.

1.4 Overview of Thesis

The research objective of this thesis is to investigate the generation of femtosecond electron bunches as a source of coherent far-infrared radiation both numerically and experimentally. The intensive studies include fundamental and practical limits to reduce the bunch length of electron pulses in longitudinal phase space. This has never been done in a systematic way and the results are expected to give greater insight into possible improvements to reach coherent radiation at short wavelength. Shorter wavelengths can be generated from shorter electron bunches. The main improvement to produce short electron pulses is the RF-gun optimization. The fundamental theory for the RF-cavity and particle beam physics corresponding to the electron beam generation and acceleration will be reviewed in Chapter 2.

Investigation of limits and possible cures in achieving shortest electron bunches by optimizing the RF-gun design with the beam dynamics study throughout the beam transport system is discussed in Chapter 3. The computer codes which were used in the RF-gun design and beam dynamics study will be introduced as well as the the overview of the RF-gun characteristics. The RF-gun optimization started from the existing designs of the SUNSHINE RF-gun and the compression system. The studies included a systematic investigation of design parameters of the RF-gun and their impact on bunch length. The RF-gun construction as well as the cathode installation and test is presented in Chapter 4. Low-power RF-measurements of the RF-gun both theoretical and experimental will also be described in this chapter.

In Chapter 5, the actual SURIYA setup will be introduced. Characteristics of the SURIYA components downstream of the RF-gun including α-magnet, linac, quadrupole magnets for beam focusing, steering magnets for beam guiding and dipole magnet as beam dump and energy spectrometer as well as the experimental instrumentations will be discussed. The generation of the electron pulses from the RF-gun at the SURIYA facility has been studied and the results are presented in Chapter 6. Experimental characterizations of electron beams generated from the RF-gun and the linac acceleration will also be described in this chapter. The characterization covers electron beam loading, beam current, beam energy, energy spectrum from RF-gun and the beam output after the linac acceleration. These studies are important in order to optimize the electron beam generation in the RF-gun. Studies of effects due to the gun temperature, cathode temperature, RF-power characteristics are included in this chapter.

Chapter 7 describes theoretical aspects of the coherent radiation from electron bunches and reviews the theory of far-infrared radiation production as transition radiation. A transition radiation station was installed in the SURIYA beam line to produce far-infrared radiation. Preliminary experimental results obtained presently at SURIYA will be presented. However, while the results of the bunch length optimization cannot be implemented during the duration of this thesis, a future plan for bunch length measurements as well as possible future experiments and system developments will be suggested in Chapter 8.