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ELECTROMAGNETIC RADIATION FROM LOW ENERGY ELECTRON BEAMS

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Abstract

Injector particle beams can be used for a variety of applications in beam physics and radiation production. Some of such applications will be discussed together with their high potential for forefront graduate student research projects. Since beam time on main accelerator facilities is very scarce it seems prudent to utilize easier available storage ring injection systems for such research.

1 INTRODUCTION

Most operating synchrotron light facilities include an injector linear accelerator which is used only infrequently and only for short durations to fill the storage ring maybe once or twice a day. While not operating in the injection mode, this linear accelerator could be used for many other applications and research projects. Fitted with a special electron source, the linac beam characteristics can exhibit most desirable features like small emittance, high bunch charge and very short femtosecond pulse duration. This electron source can be a rather simple $1\frac{1}{2}-$cell rf-gun with a robust and reliable thermionic cathode [1,2,3]. Installation of such an electron source does not compromise storage ring injection capabilities because it serves also as an efficient and reliable injector into a synchrotron light facility [4]. An electron beam from a microwave gun at some tens of MeVs with small emittance and sub picosecond bunchduration [2,5] can be used to pursue research in a variety of areas.

In a typical setup, we would find a 20 to 30 MeV S-band linac generating electron pulses about 1 μs long and containing some 3000 micro-bunches at a pulse repetition rate of 10 - 20 Hz. From an rf-gun with thermionic cathode each of these micro-bunches can contain a charge of about 100 pC. Utilizing an α-magnet, the micro-bunches can be compressed to 120 fs-rms [2] or less [6]. Typical operating characteristics as obtained at SUNSHINE [3] are compiled in Table 1.

In this paper, some of the potential research applications shall be discussed shortly. Many of the phenomena to be discussed are well known, but so far insufficiently studied. In addition, new technologies appear which can be applied to advance in the study of electron interaction with dense media and to generate radiation sources in the far infrared (FIR) and X-ray region. We may
– use the electron beam directly
– use the subpicosecond property to produce coherent FIR
– generate X-rays by beam interaction with dense media

Table 1: Electron Beam Characteristics

Parameter		**units**
rf-gun energy	2.5 - 5.0	MeV
uncompressed bunch length	10 - 20	ps
energy	25-30	MeV
macro pulse current	300-400	mA
pulse rep rate	10-30	Hz
micro pulse duration	120	fs-rms
charge per micropulse	100	pC

2 DIRECT APPLICATION OF ELECTRON BEAM

Ultrashort intense electron pulses allow the study of detrimental beam dynamics effects. For future linear colliders and X-ray lasers it is important to preserve extreme beam characteristics over long distances. Specifically, the compression of electron bunches at higher energies can cause dilution of a carefully prepared small beam emittance [7]. Space charge forces or the emission of synchrotron radiation within an achromatic bunch compression system foil the properties of an achromat and result in a dilution of the beam emittance. Space charge induced emittance dilution scales like $\Delta\epsilon \propto \hat{I}/\gamma^2$ which is well suited for studies with lower energy beams and sub picosecond bunch lengths.

Analysis of transition radiation serves for the diagnostics of electron beam emittance and ultra short pulse length [8,5,9]. Understanding of beam characteristics is essential to allow the study of limitations in achievable bunch length and bunch compression as well as preservation of critical beam parameters in sometimes long beam transport lines.

3 COHERENT FIR RADIATION

The most obvious application of high intensity, sub-picosecond electron bunches is to generate coherent radiation. Such beams are well suited to drive infrared (IR) or FIR [10] free electron laser or to generate high intensity FIR pulses by way of the SASE principle [11]. Given sub picosecond electron pulses, very high intensity coherent FIR radiation can be produced by the SASE process (Fig. 1).

Femtosecond electron pulses can also be converted into broadband, Fourier transform limited coherent FIR radiation in form of Synchrotron [12], Transition-[13,2,14] or Cherenkov radiation. With presently available technology, electron bunches as short as 120 fs-rms can be produced [2,14]. From such bunches, coherent FIR radiation in the

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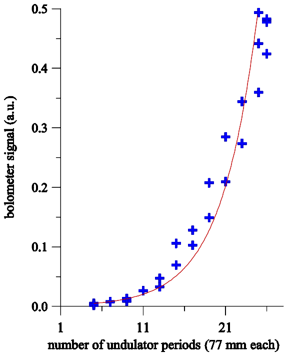

Figure 1: Exponential growth of 54 μm radiation along an undulator [11]

regime from microwaves up to wavenumbers of some 100 cm^{-1} can be derived as shown in Fig. 2

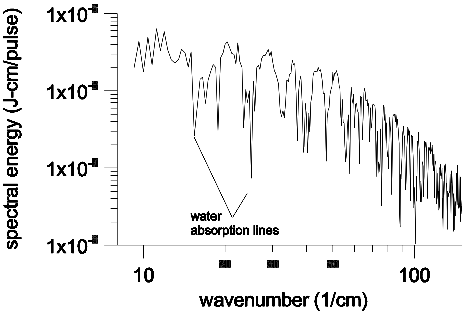

Figure 2: Measured coherent FIR spectrum obtained from sub picosecond electron bunches at SUNSHINE. The structure in the spectrum is due to water absorption and thin film interference effects in the detector.

The FIR radiation intensity is given by

$$P(\lambda) = p(\lambda)\ [N_\mathrm{e} + N_\mathrm{e}\,(N_\mathrm{e}-1)\ f\,(\lambda,\sigma_\mathrm{b})]\,, \qquad (1)$$

where $p(\lambda)$ is the radiation power from a single electron and for a particular radiation process, N_e the number of electrons per bunch, and $f\ (\lambda,\sigma_\mathrm{b})$ the bunch form factor, which is equal to unity for $\lambda \gg \sigma_\mathrm{b}$ (σ_b bunch length) and drops to zero for wavelengths shorter than the bunch length. With bunch populations $N_\mathrm{e} \approx 10^8 - 10^9$ and the radiation scaling like N_e^2, broadband FIR radiation becomes available at intensities exceeding that from black body or synchrotron radiation by up to eight orders of magnitudes. Figure 3 shows the comparison of the source brightness, $\mathcal{B}$ (ph/s/mm^2/mr^2/100%BW), from 30μm (SUNSHINE) or 10μm [6] electron bunches with that available from a black body radiator or a 1 GeV synchrotron radiation source. Transition radiation can also be used in an optical cavity to generate even more radiation. The status of this effort is discussed in [9].

The broadband FIR spectrum covers well a spectral region where only a few FEL's or low intensity laser sources

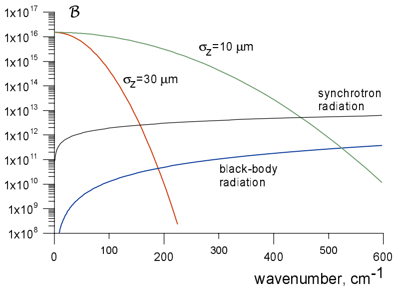

Figure 3: Comparison of FIR source brightnesses, $\mathcal{B}$ (ph/s/mm^2/mr^2/100%BW)

are available. The radiation is, for example, well suited for dispersive Fourier Transform Spectroscopy [15,16,17] of chemical and biological substances or to study high T$_\mathrm{c}$ materials.

4 SOFT X-RAYS BY THOMSON BACKSCATTERING

The ultrashort duration of the electron bunches can be converted to equally short X-ray pulses. Most efficiently, the electron beam is made to collide head-on with either a laser beam or the reflected coherent radiation emitted by this same beam. Since the electron bunches are very short, one can use a long laser pulse to generate a long interaction region and thereby high intensity. The backscattered photons are then all bunched into the same length as the electron bunch independent of the laser pulse length and their energy is shifted into the soft and hard X-ray regime to

$$\varepsilon_\mathrm{ph}(eV) = 4.959\,\frac{\gamma^2}{\lambda_\mathrm{L}(\mu m)}. \qquad (2)$$

Table 2 shows a few examples for backscattered radiation from a 25 MeV electron beam and different incoming radiation wavelengths.

incoming radiation	**backscattered radiation**
coherent FIR, 100 - 1000 μm	12-120 eV
CO$_2$ Laser, 10μm	1200 eV
Yag Laser, 1μm	12.0 keV

Table 2: Backscattered Radiation from 25 MeV Electrons

The intensity of the backscattered radiation or number of photons per unit time can be estimated from $\dot{N} = \sigma_\mathrm{Th}\,\mathcal{L}$, where σ_Th is the Thomson scattering cross section, and $\mathcal{L}$ is the luminosity defined by

$$\mathcal{L} = \frac{N_\mathrm{e}}{2\pi\sigma_x\sigma_y} n_\mathrm{b} \frac{P_\mathrm{L}\ell_\mathrm{I}/c}{\hbar\omega}\,\nu_\mathrm{rep}. \qquad (3)$$

Here, N_e is the number of electrons per bunch, n_b the number of electron bunches per pulse, $2\pi\sigma_x\sigma_y$ the average beam cross section along the interaction length ℓ_I assumed to be the same for both the electron and laser beam, P_L the laser power, $\hbar\omega$ the laser photon energy, and ν_rep the laser and electron beam pulse repetition rate.

5 ELECTRON-PHOTON INTERACTION IN DENSE MEDIA

Interaction of relativistic electrons passing through dense media is the focus of intense research since many years [18] and was the subject of a recent workshop in Armenia [19]. Progress in electron beam technology combined with other high tech developments make it more and more interesting to research this field on a broader basis. One of the driving forces behind this activity is the potential for more compact radiation sources, especially in the X-ray regime. It is impossible within this limited space to give the appropriate attention to the issues and prospects involved. Areas of present research interests shall be covered only briefly and the interested reader is referred for more information to available literature like [19].

Channeling radiation is known since a long time but has attracted considerable interest lately as a source of quasi monochromatic X-rays for a variety of applications like protein crystallography or medical applications. At present research is focused to determine limitations on electron charge and optimum crystal thickness for a 10 MeV electron beam (Genz in [19]).

Progress in the manufacturing of crystallite structures like nanotubes, nanoropes and Fullerites allow the expansion of the channeling radiation concept to such materials generating radiation in the soft x-ray regime. It is possible now to grow Fullerene crystals with volumes as large as 10-100 mm^3 which allows the application as radiators ([Zhevago in [19]).

Periodic deformations of crystals are proposed to serve as mirco-undulators. Conventional micro-undulators suffer from a steep drop-off of the radiation intensity for low values of the strength parameter $K \propto$ field·periodlength. In periodically bent crystals the reduction of the periodlength is greatly compensated by the high fields present in crystalline structures. Deformation can be considered in a dynamic or static fashion. Dynamically one would subject the crystal to acoustic waves at very short wavelength ([20], and Krause et.al. in [19]). A static periodic deformation has been suggested by graded composition of strained layers in supperlattices like in $\mathrm{Ge}_x\mathrm{Si}_{1-x}$ crystals [21].

Parametric X-rays, PXR, are emitted when the electrostatic field of an electron passing through a crystal gets Bragg- or Laue-diffracted at the crystal planes (see Backe, Potylitsin or Shchagin in [19]). Presently, PXR is expected to hold the greatest promise as a high intensity X-ray source.

Transition radiation is used since a long time for diagnostics of beam parameters ([Fiorito in [19]) or in high energy physics to determine the particle energy. To make TR a source of higher intensity X-rays stacks of radiator foils are used. It has been proposed to expand this concept by manufacturing stratified radiators composed alternately of sub-micrometer thick layers of high and low-Z materials, (e.g. $Ni-C$ layers) ([22] or Ispirian in [19]).

6 SUMMARY

Fitting medium energy linacs with a mircrowave electron source opens up a rich field of research in beam physics and radiation production. Such linacs may be available as separate installation [23] or are part of injector systems into synchrotron radiation facilities and are used only once or twice a day and are available most of the time for the kind of research discussed in this paper. The research subject offers broad basic physics, rich opportunities for graduate student education, challenging physics problems and the prospect of developing small scale but competitive X-ray sources.

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