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Micro-bunching Diagnostics for the ICA by Coherent Transition Radiation*

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Abstract

Here, we propose an effective method to detect micro-bunching effects ($10fs$ bunch length), produced by the ICA interaction, by using the CTR spectrum. The re-bunching of initialy energy modulated $e-$beam passing through a Hydrogen gas cell (ICA interaction) is studied via a Monte Carlo simulation code (STI), as well as in a space-charge dominated region by a multi-particle time domain tracking code (PARMELA). The results show that even in a strong space-charge dominated region the re-bunching effect is still very pronounced. The 'erosion' of bunching due to the space-charge defocusing 'washes out' the final bunching peak only by about 10% (FWHM). The longitudinal distribution of a micro-bunched beam is Fourier analyzed to find the dominant harmornics contributing to the CTR. The CTR spectrum is calculated analytically for the ICA situation. A schematic of the experimental set up is also proposed.

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1. Introduction

With the success of the Inverse Cherenkov Acceleration (ICA) experiment[1] at the Acceleration Test Facility (ATF) of Brookhaven National Laboratory, a proposed $100MeV/m$ acceleration gradient – demonstration experiment[2] is the next step towards developing the ICA scheme into practical technique that may eventually lead to a high gradient linear accelerator. Our basic approach is to send $e-$beam into a laser-driven prebuncher, whose output feeds directly into a magnetic compressor. Following the compressor, a free space is placed, where magnetic focusing and steering elements re-focus the pre-bunched $e-$beam into the laser accelerator. Both the prebuncher and a laser accelerator are the ICA based devices. The prebuncher is needed to maximize the number of electrons maintaining specific phase relationship with the optical mode, required for optimum acceleration.

A radially polarized laser beam is focused by an axicon mirror onto the e-beam traveling through a gas-filled interaction region[1]. The electrons are accelerated when the oblique incident laser beam and the e-beam meet the following Cherenkov condition in the gas cell,

$$n\beta cos(\theta_c) = 1. \qquad (1)$$

Here, θ_c is the crossing angle between the two beams(e-beam and laser beam), β charcterizes velocity of the $e-$beam and n is the index of refraction for Hydrogen gas at a given pressure. A prelimiary test was preformed a year ago. Then, a typical absolute acceleration of about 0.7 MeV was observed by delivering $\sim 34MW$ laser peak power (at $\sim 10ns$ pulse length). Furthermore, for higher laser peak power (at $\sim 1GW$, $\sim 200ps$ pulse length) a net acceleration of about 3.7 MeV was observed. These results imply that the $e-$beam is energy modulated by the axicon mode, while passing through the interaction region. Therefore, formation of micro-bunches may be possible after modulated e-beam propagates through a specific length of a drift space.

In this paper the ICA self-bunching process (with and without the space-charge effects) has been simulated by PARMELA-time domain tracking code. A photon production from the coherent transition radiation (CTR) is estimated according to current ICA setup at the ATF. Furthermore, a feasible CTR diagnostic system to detect and measure micro-bunching is proposed.

2. Self-bunching with the Space-charge PARMELA Simulation

The e-beam passing through the gas cell and interacting with the axicon (optical) mode leaves the interaction region with a distinct velocity distribution pattern, which propagated over a certain distance results in self-bunching of the $e-$beam. In our bunching experiment, this characteristic distance is optimized to be about 30 cm and we expect to observe a strong bunching on a scale of several micron. Since, there is no external electromagnetic field present in the drift space, the effects of the space-charge within the e-beam will dominate and they should be considered. Here, we use PARMELA to simulate phase-space evolution in the drift space. We start with a 6-dim phase-space configuration, obtained from the STI Monte Carlo simulation[3] at the exit window from the gas cell. We assume a total beam intensity of 1 nC. In our simulation (PARMELA), the step size in the longitudinal direction is chosen so that it takes 100 simulation steps during one period of the plasma oscillation (for this intensity) – a characteristic time scale for the space-charge induced re-configuration of electrons to take place. Energy is measured in MeV, while the phase is expressed in degrees of 1.3 GHz rf system. Figures 1 and 2 illustrate results of PARMELA simulation without and with the space-charge forces, respectively. They show the energy - phase distribution at the end of the drift (z = 30 cm). As predicted, a strong self-bunching due to previously introduced velocity distribution occurs. A histogram on Figure 1 shows about 30% of the electrons tightly bunched in 1 micron region. Figure 2 illustrates defocusing effects due to the space-charge forces. Using a simple physical picture of the space-charge effects, particles at the head of the bunch tend to gain energy, while particles from the tail are decelerated. In effect, the energy-phase space is rotated in the counter clockwise direction. The amount of this local rotation is weighted by the longitudinal charge distribution gradient. Therefore, the strongest effect occurs near the center of the distribution (smearing). Figure 2 shows that even under strong space-charge condition (1 nC bunch) the effect of self-bunching is still present. The bunching peak illustrated by a histogram in Figure 2 is slightly 'washed out' by the space-charge defocusing and smearing – at about 10% level (FWHM).

3. Coherent Transition Radiation

When a particle crosses the interface of the two media at oblique angle, θ, its backward transition radiation is charcterized by the following distribution[4]

$$\frac{d^2U}{d\omega d\Omega} = \frac{e^2\beta^2}{4\pi^2 c}\frac{|r|^2 sin^2\theta}{(1-\beta cos\theta)^2}, \tag{2}$$

where r is the Fresnel reflection coefficient for the mirror. Coherent transition radiation(CTR) is a collective effect produced by a large ensemble of electrons being in phase with each other. The total number of photons radiated is highly enhanced. The coherent photon flux scales like N^2 compare to the incoherent part, which scales linearly with the $e-$beam intensity, N. The forward emission was estimated by Rosenzweig, *et al.* for the UCLA IR FEL and for some others applications.[5,6,7]

To estimate the backward CTR coming from a 45^0 mirror for the ICA experiment, we assume the following set of conditions describing the experimental setup at the ATF. (1) The initial $e-$beam distribution (before entering the ICA gas cell, where the electrons are modulated by the CO_2 laser) is assumed to be a smooth bi-Gaussian in r and z. (2) The energy modulation imposed in the interaction region is significant and the affected electrons should self-bunch at a certain distance ($z = 30cm$). Under such assumptions we should expect, that the modulated electron distribution evolves in a drift space (z) according to the following formula[8]

$$f(r,z) = N_b g(r)h(z) = N_b[\frac{exp(-\frac{r^2}{2\sigma_r^2})}{2\pi\sigma_r^2}][\frac{exp(-\frac{z^2}{2\sigma_z^2})}{(2\pi)^{1/2}\sigma_z^2}[1+\sum_{n=1}^{\infty} b_n cos(nk_r z)]], \tag{3}$$

where N_b is the number of electrons per bunch, k_r is the wave-number of the CO_2 laser modulation and b_n are the Fourier coefficients of the longitudinal electron density distribution.

Furthermore, we notice that the difference between the forward and the backward emissions is just a factor of $|r|^2$. Based on the above similarities, it is possible to follow the treatment of ref. 8 to calculate the coherent transition radiation in a straightforward manner.

The differential spectrum of radiation energy due to multiparticle effects is represented by the following formula

$$\frac{d^2U}{d\omega d\Omega} \approx N_b^2 F(\omega,\theta)\frac{d^2U}{d\omega d\Omega}|_{singlee^-}, \quad (4)$$

where

$$F(\omega,\theta) = |f(\omega,\theta)|^2 = |\int\int\int g(r)h(z)exp(-i\vec{k}\cdot\vec{x})d^3x|^2. \quad (5)$$

One can notice, that the term $F(\omega,\theta)$ can be factorized into two form-factors; the transverse and the longitudinal one: $F(\omega,\theta) = F_T F_L$.

The transverse part F_T is given by the following expression

$$\begin{aligned} F_T(\omega,\theta) &= |\int\int g(r)exp(-ikrsin\theta cos\phi)rdrd\phi|^2 \\ &= exp(-(k\sigma_r sin\theta)^2). \end{aligned} \quad (6)$$

Similarly, the longitudinal part, F_L, is obtained by integrating over the micro-bunch distribution according to the following formula

$$\begin{aligned} F_L(\omega,\theta) &= |\int h(z)exp(-ikzcos\theta)dz|^2 \\ &= |exp(-\frac{(k\sigma_z cos\theta)^2}{2}) + \\ &\sum_{n=1}^{\infty}(\frac{b_n}{2})[exp(-\frac{\sigma_z^2}{2}[kcos\theta - nk_r]^2) + exp(-\frac{\sigma_z^2}{2}[kcos\theta + nk_r]^2)]|^2. \end{aligned} \quad (7)$$

Since the micro-bunch peaks are narrow compared to their separation distance ($k_r\sigma_z \gg 1$), and the strongest modulation will occur at the CO_2 laser fundamental frequency($\lambda = 10.6\mu m$), where in vacuum ($n = 1$), therefore, we can simplify Eq.(7) as follows

$$F_L(\omega,\theta) \approx (\frac{b_n}{2})^2[exp(-\sigma_z^2(kcos\theta - k_r)^2]. \quad (8)$$

The total number of CTR photons in the narrow band around the fundamental frequency is given by the following expression

$$\frac{d^2N}{dkd\theta} \approx \frac{\alpha|r|^2}{2\pi}(\frac{N_b b_1}{2})^2\frac{sin^3\theta}{(1-\beta cos\theta)^2}\frac{1}{k}exp[-(k\sigma_r sin\theta)^2 - \sigma_z^2(kcos\theta - k_r)^2], \quad (9)$$

where $\alpha = \frac{2\pi e^2}{\hbar c}$. To find the angular distribution of the CTR photons in the narrow band (approximately one percent width) around this frequency, we should integrate Eq.(9) over described frequency range. Due to a very narrow frequency band, the value of k, in the fourth term of Eq.(9), could be set to k_r and the integration limits could be extended from $-\infty$ to ∞. Finally, we get the angular distribution of the CTR photons around the modulation frequency, in the following compact form

$$\frac{dN}{d\theta} \approx \frac{\alpha|r|^2}{2\pi}(\frac{N_b b_1}{2})^2\frac{1}{k_r\sigma_z}\frac{sin^3\theta}{(1-\beta cos\theta)^2}[\frac{\pi}{(\frac{\sigma_r}{\sigma_z}sin\theta)^2 + cos^2\theta}]^{1/2}exp[-\frac{(k_r\sigma_r sin\theta)^2}{(\frac{\sigma_r}{\sigma_z}sin\theta)^2 + cos^2\theta}]. \quad (10)$$

In general $\sigma_r \ll \sigma_z$ and $\theta \ll 1$. Using this approximation, Eq.(10) reduces to the following simple formula

$$\frac{dN}{d\theta} \approx \frac{\alpha|r|^2}{8\sqrt{\pi^3}}(\frac{k_r\sigma_z}{\pi})(\pi\frac{N_b b_1}{k_r\sigma_z})^2\frac{sin^3\theta}{(1-\beta cos\theta)^2}exp[-(k_r\sigma_r sin\theta)^2]. \quad (11)$$

The physical meaning of Eq.(11) is quite clear. The second term in Eq.(11) represents the full length of the macro-bunch in units of the modulation wavelength λ_r. The third term in Eq.(11) is the square of the total number electrons within the micro-bunch (the laser modulation 'chops' the macro-bunch into number of micro-bunches). The fourth term in Eq.(11) describes the contribution of the single electron transition radiation (incoherent part) and the last term in Eq.(11) reflects the transverse distribution of electrons. By Fourier analysis of the CTR spectrum at the optimum bunching distance the coefficients b_n are easily found. Since the micro-bunches are very narrow the contribution from the second and the third harmornic components may not be negligible. Here, we estimate the number of photons generated by each harmornic separately.

For the ICA experimental conditions, a $40MeV$ e-beam pulse ($2\sigma_z \sim 3000\mu m$) is about $10ps$ long. Its diameter at the focal waist is about $100\mu m$. After passing through $30cm$ of the dirft space the beam size will grow; it will reach the transverse size given by $2\sigma_r \sim 200\mu m$ (at optimum bunching distance). Total number of electrons in a single macro-bunch is assumed to be $N_b \sim 3.1 \times 10^9$, which is equivalent to $0.5nC$ of the total charge. From the spectrum analysis the Fourier coefficients are evaluted as follows: $b_1 = 0.04$, $b_2 = 0.24$ and $b_3 = 0.15$. The higher terms are negligible, therefore, we confine our consideration to the first three harmonics only. The total number photons at these frequencies are evaluated as follows: $N_1 \sim 1.7 \times 10^{13}$, $N_2 \sim 6.1 \times 10^{12}$ and $N_3 \sim 2.4 \times 10^{12}$. Those values imply that the ICA CTR signal is very strong. A possibility of detecting the first, the second, or the third harmonic frequencies with a narrow bandwith detector, gives more flexibility to our measurement. Theoretically predicted angular distributions for all three harmonics are shown in Figure 3.

4. Proposed Diagnostic Setup for the ICA

At the ATF, the beam-line number 1 is provided for ICA experiment. The basic experimental setup downstream of the gas cell exit window can be described as follows. There is a $1.2m$ long drift space followed by a strip-line detector, then a beam position monitor, followed by a dipole and a spectrometer. The most efficient way to detect the CTR is to insert a 45^0 mirror and measure the backward CTR. The mirror can be moved in and out easily. The light will be focused by the IR lens and then it will be sent to a cool detector. The disadvantage of measuring the backward CTR is the fact that the intensity may be a slightly weaker than for the forward CTR, diminished to the factor of $|r|^2$. Upstream of the CTR mirror a strip-line detector is required to measure the e-beam current information. The schematic of the complete detection system is shown in Figure 4.

The acceleration process in the presence of gas scattering have been carefully investigated by using the STI Monte Carlo code. We concluded that, a longer interaction length may not enhance re-bunching of the electrons due to the phase slipage and large multiple scattering emittance growth. Considering the optical damage limit, an optimized interaction length is found to be about $4cm$ (for a $40-65MeV$ e-beams). A lower energy beam may provide a shorter bunching distance under the same energy modulation conditions. However, the scattering effects will be more significant at lower energy, which may lead to a large beam emittance growth. In the CTR setup the mirror, which generates the CTR is held by a bellows type 4-way holder, which can be moved along the e-beam direction back and forth to a maximum distance of about $30cm$ without disturbing the vacumm environment. This motion will be driven by a digitized remote control stepping motor. By moving the mirror back and forth the optimum bunching distance could be identified by looking at the micro-bunching effect variation. The adjustment of the input laser power at the fixed e-beam energy is an alternative way of finding the optimum re-bunching distance. However, it may affect the bunching characteristics significantly, which will lead to a complex calibration procedure. The CTR light will be delivered to the ATF FEL table next to the experiment hall by a transport line. The cool detector and the data collection devices (including a PC) will be configured in the FEL room. The above setup could significantly reduce the background effects. The original ICA gas cell is modified by equipping it with window extensions to shorten the $e-$beam path in the gas cell and to reduce the gas scattering effects.

The diagnostic procedure will be done in two steps. First, in order to find the optimum bunching distance, the CTR light should be collected at all posisble wavelengths depending on the cool detector detection range. Second, a spectrometer should be added to select a specific wavelength in order to quantify (measure) the bunching effect. The micro-bunch shape (longitudinal distribution) measurement would be the final step of this procedure.

5. Acknowledgment

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Figure Captions

Figure 1. Snapshot of interesting phase-space prejections at the optimum re-bunching distance (z = 30 cm) – no space-charge considered.

Figure 2. Snapshot of relevant phase-space prejections at the optimum re-bunching distance (z = 30 cm) – full space-charge simulation (1 nC).

Figure 3. Angular distribution of the CTR photons within 1% bandwidth. (a) First harmonic frequency, (b) second harmonic frequency, (c) third harmonic frequency.

Figure 4. Schematic of the CTR diagnostic setup for the ICA experiment.

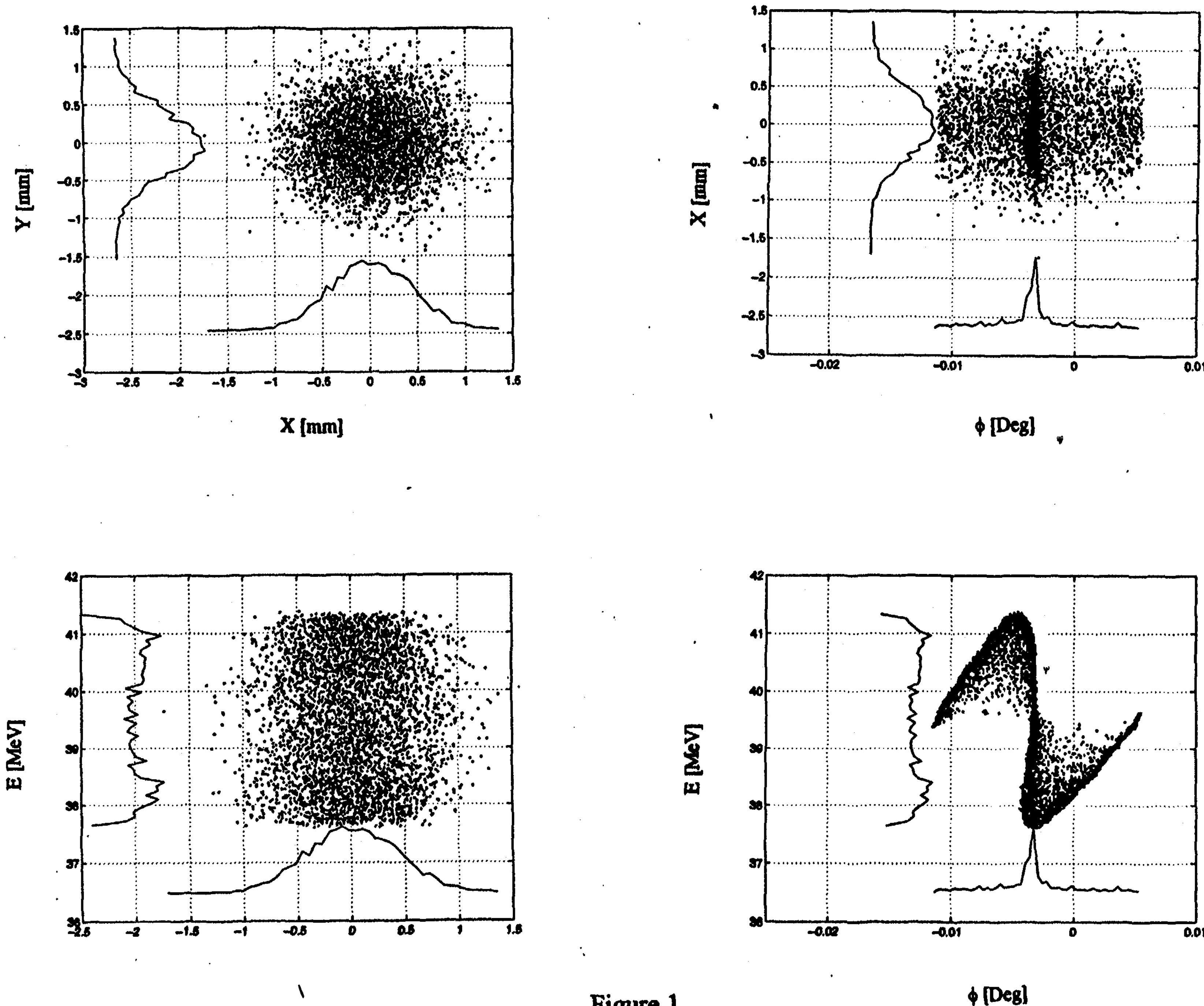

Figure 1

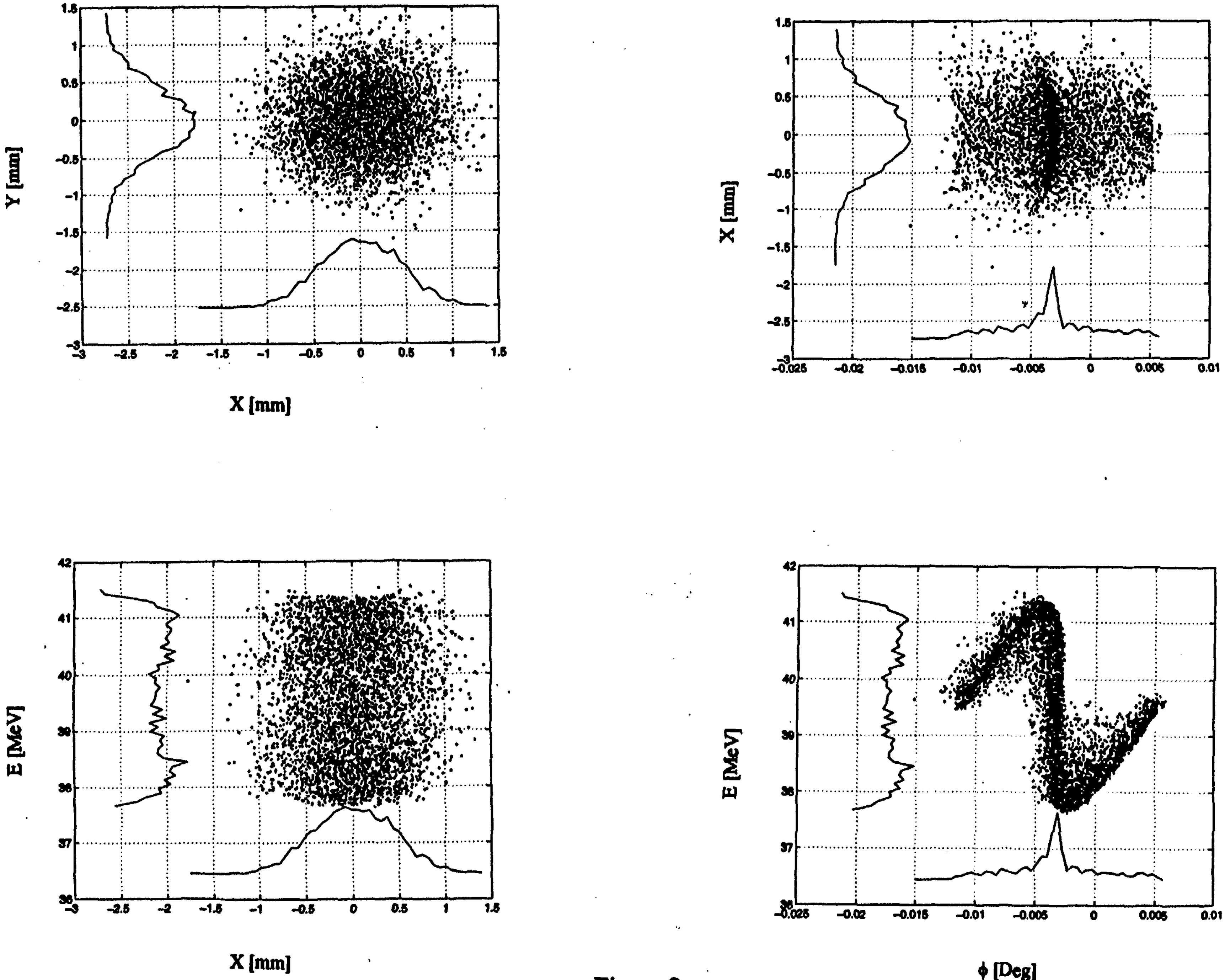

Figure 2

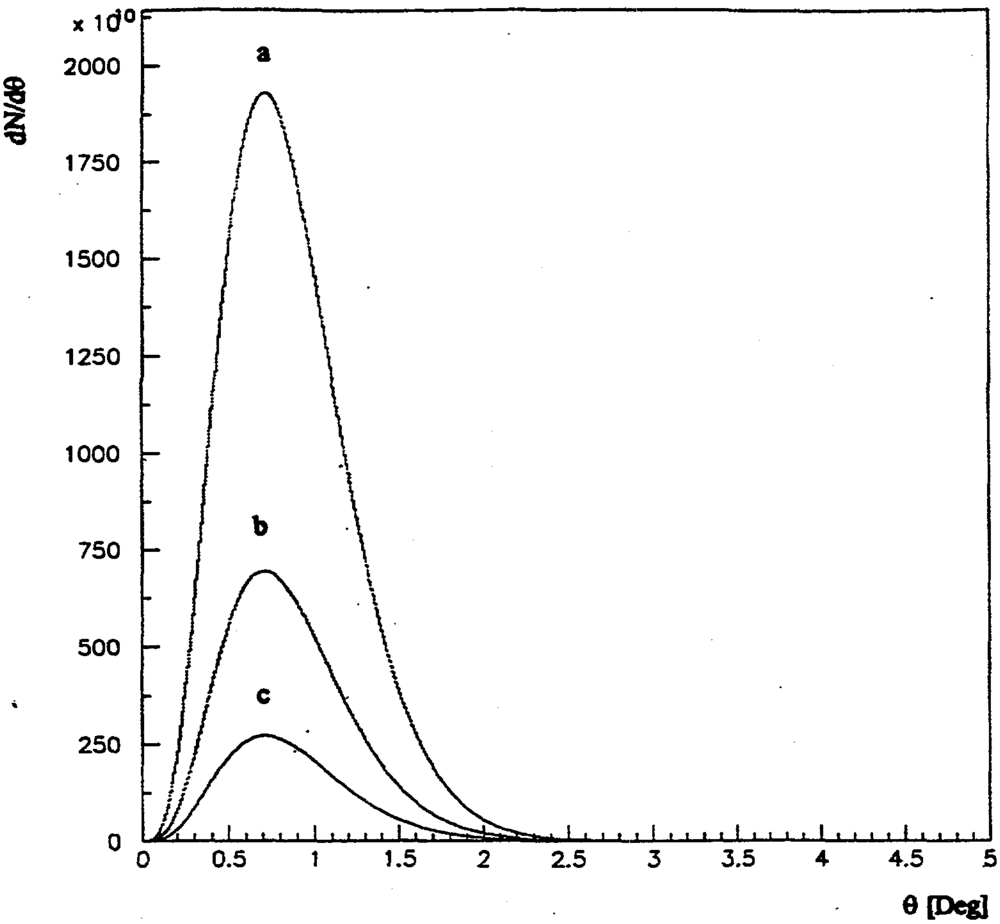

Figure 3

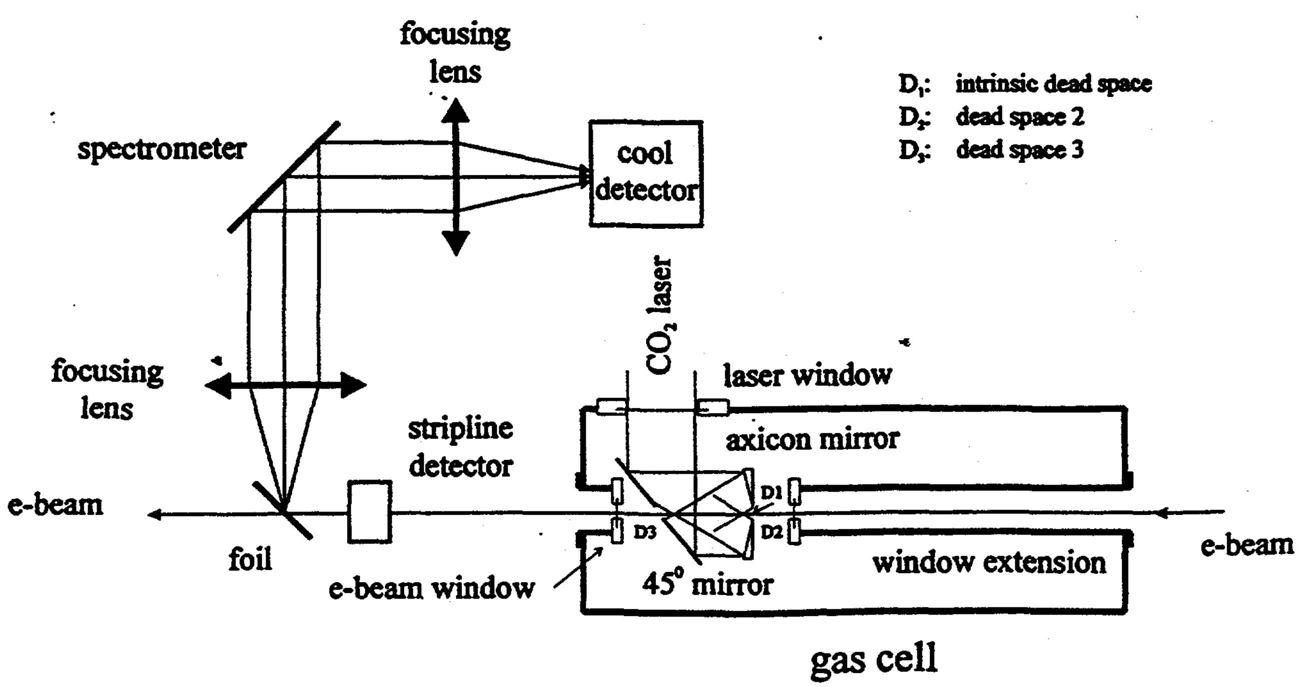

Figure 4