TIME CORRELATION STUDIES OF SECONDARY EMISSION PROCESSES

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Abstract

In the framework of the CRYSTAL proposal for the production and studies of ordered beams, a direct imaging diagnostics of longitudinal structures of ordered ions is now under development. The fundamental elements of the diagnostics device are a thin foil, an accelerating grid, an RF camera and an imaging detector. The thin carbon foil is responsible for the direct production of time correlated electrons upon the arrival of ordered ions. The accelerating grid ($10 \div 15$ kV) is used to enhance the time correlation of the electrons against the angular spread of emission. The accelerating grid is followed by the RF camera, working at 2.465 GHz, for the transverse deflection of the correlated electrons. A detector with spatial resolution around 50 μm is foreseen after a drift length of 30 cm. The time response of the thin carbon foil was investigated with a Monte Carlo method with particular emphasis to electrons with kinetic energies smaller than few hundreds eV. According to the adopted model, the time lags originated by the transport of the primary electrons through the thin foil are limited at few tens of femto-seconds.

KEYWORDS: heavy-ion, diagnostics, radio-frequency, instrumentation, Monte Carlo.

1 INTRODUCTION

Starting from 1988 different groups devoted a particular attention to the possibility of producing ordered beams, i. e. a sequence of accelerated ions which move at a well defined relative positions of equilibrium under the counteracting forces originated by the space charge of the particles themselves and the external guiding fields of a storage ring [1, 2, 3]. Such a kind of beams are also indicated as crystalline beams. Actually, in a certain sens, these beams behave like a new state of matter.

In the last years experimental evidences of ordered ions in RF traps were reported [4]. The ions at rest in the RF traps show exactly the predicted patterns in transverse and longitudinal space. Following these ideas and the work carried out in different laboratories a proposal for a storage ring (CRYSTAL) optimized for producing ordered beams was presented at Legnaro [5, 6, 7].

In the framework of the CRYSTAL proposal different techniques for detecting the order of the stored ions was studied and are now under development. One of these techniques concerns the direct imaging of the longitudinal ordering of the beam by fast transverse deflecting devices (streak cameras).

Unfortunately, the need of detecting ions separated by distances of the order of 100 μm with velocity of the order of some per cent of the speed of light means that the time separation between two subsequent ions is of the order of tens of picoseconds. The decay time of the fastest scintillator is about 800 ps (BaF) and therefore it is not possible to convert ions in photons to be sent on a photocathode of a classical streak camera.

An alternative choice can be the direct conversion of ions to electrons which have to be sent to an open (without photocathode) deflecting device.

The secondary emission processes of electrons in thin foils can be the proper mechanism of producing bunches of electrons correlated in time to the incoming ordered ions. The time correlation between the ions and the electrons is a function of many parameters (secondary emission coefficient, thickness of the foil, angle of emission, ion velocity, extraction voltage). In order to understand the different contributions to the time lag a Monte Carlo code was developed.

2 THE RF DEFLECTING CAMERA

Short laser pulses are normally investigated in time domain with streak cameras. i.e. deflecting devices which reproduce in transverse space the longitudinal structure of the incoming pulse. The same analysis can be done on short bunches of low energetic electrons on open version of streak cameras. The usual time resolution of commercial streak cameras is in the range of few pico-seconds. The main limitations towards smaller time resolutions is due to the technological limit on fast discharges, preserving linearity, which nowdays are limited to few tens of kV in $10 \div 20$ ns.

Recently an RF device has been developed to overcome the limitations coming from fast discharges [8, 9]. The RF device is made of a cavity in cylindrical geometry which sustains a TM_{110} mode. The cavity is supplied by two RF inputs of the same power taken apart in angle of 90°. The RF inputs are also shifted in phase by 90°. On the axis of the cavity, the magnetic field originated by the configuration described above is constant in module and it rotates with an angular frequency equal to 2π times the resonance frequency ν of the cavity. As a results of the rotating magnetic field, the linear momenta of the incoming electrons

vary as (Lorentz force):

$$\begin{aligned} P_x &= \quad e\,H_0\beta_z \cdot sin(\omega t) \\ P_y &= \quad e\,H_0\beta_z \cdot cos(\omega t) \end{aligned} \tag{1}$$

After a drift of length L the bunch of electrons describes on a plane perpendicular to initial trajectory a circumference with radius R_e determined by the cavity frequency ν and the relativistic factor γ:

$$R_e = \frac{e\,H_0\,\lambda L}{\pi\gamma m_e c^2} = \frac{e\,H_0 L}{\pi\gamma m_e c\nu} \tag{2}$$

With a resonance frequency ν = 2.46 GHz, a magnetic field H_0 = 30 Gauss and a length L = 30 cm the radius of the circumference comes out to be about 15 mm. With a detector on the focal plane with a spatial resolution of about 50 μm the time resolution comes out to be of the order of 200 fs. The RF device has been already checked with a coarse focal plane detector (3 mm spatial resolution) and a time resolution of 13 ps was obtained.

The high potentiality of the RF camera can be well put in evidence if the electrons produced by the ion on the conversion foil will be time correlated, within a fraction of pico-seconds, with the ion itself.

3 SECONDARY EMISSION PROCESSES

The emission of electrons from a thin foil upon the transit of an ion is a well known and studied problem. In particular, the energy distribution of the emitted electrons has been extensively studied by a variety of authors [10, 11]. The energy spectra, at different angles of emission, extend from few eV up to thousands of eV (up to 5 keV). In this range the production probability decreases of two orders of magnitude at 0 degrees and of about three orders of magnitude at 135 degrees. Therefore, even if the energy spectra is very large, actually the majority of electrons is emitted at energies below 300 eV. Furthermore at 0 degrees two distinct phenomena take place. The first one is the production of electrons due to the Auger effect in the atoms of the medium. The Auger electrons have kinetic energies around few hundreds of eV. At higher energies the convoy electrons emitted from high Rydberg states of the ion projectiles can be found with the same velocity of the parents ion. The described energy spectra suggests that particular attention must be devoted to the very low energy electrons. In other words, the physical model which have to be introduced in the Monte Carlo simulation must be able to describe in a correct way the great majority of the slow energy electrons.

4 PHYSICAL MODEL FOR THE MONTE CARLO SIMULATION

The differential cross section for ionization of atoms of the medium is the result of three different contributions, namely the soft (small angles) collisions, the hard collisions and the capture to the continuum [10, 11]. At very low kinetic energies (hundreds of eV) of the emitted electrons (the great majority), when the projectile ions have total kinetic energies of few MeV or greater, the main contribution to the cross section comes from the soft collisions. Furthermore the cross section for soft collisions with low emission energies has a $cos^2(\theta)$ behaviour has shown in equation (3):

$$\frac{d^2\sigma_s}{d\Omega dE}(E,\theta) = d_2 Z_P^2 \Delta E^{-(2.9+I_B^{0.08})} \cdot [2 - \frac{1}{2}(3cos^2\theta - 1)]. \tag{3}$$

where E is the energy of the emitted primary electron and $I_B = 284\,eV$ is the binding energy of the K-shell in carbon atom. The parameter d_2 has the value of $\sim \ 1.76 \cdot 10^{-14}$ and it is an average of a very slow varying function of the angle θ, the energy of the generated primary electron and the energy of the projectile ion. Experimental data are in good agreement with the described parametrization for a large variety of angle of emission, ion species and final energies of the emitted electrons. Therefore, the above expression was taken as the fundamental relationship for the implementation of the ionization section of the Monte Carlo code.

The excitation cross section for the atoms of the medium was not taken into account. The energy loss of the impinging ions across the small thickness of the foil was also neglected.

As anticipated above, the study of the transport of primary electrons through the foil is the first goal of this work. In particular the Monte Carlo simulation was devoloped to follow the primary electrons and evaluate the time lag between the incoming ion and the primary electrons coming out from the surface of the foil. To describe the motion of primary electrons the classical SELAS approximation of separating the energy loss from the angular scattering was adopted [10, 11].

The energy loss of electrons in a medium is described by the Bethe formula [12]:

$$-\frac{dE}{ds}(E) = \frac{2\pi e^4 NZ}{E} ln \frac{1.166E}{J} \tag{4}$$

which unfortunately loses its validity for energies of the same order of the average ionization potential J when the argument of the natural logarithm become smaller than unity.

- $J = 9.76Z + 58.5Z^{-0.19}$ (eV) =100.18 (eV) in carbon, following the Berger and Selzer relationship [13]

Because of this loss of validity, the energy loss of the electrons was then evaluated by a modified Bethe formula due to RaoSahib and Wittry [14] which maintains its validity also for energies below few hundreds of eV where most of primary electrons are found.

$$-\frac{dE}{ds}(E) = \frac{2\pi e^4 NZ}{1.26(JE)^{1/2}} \tag{5}$$

Equation (5) with the numerical values of the atomic density N and atomic number (Z=6) of carbon becomes:

$$-\frac{dE}{ds}(E) = \frac{6.15 \cdot 10^9}{\sqrt{E}} \text{ if } E < 85.9\, eV \qquad (6)$$

The elastic scattering of the primary electrons from the atoms of the foil should be evaluated by the non-relativistic Mott phase shift formula which refers to the scattering of non-relativistic electrons from a point-like nucleus with arbitrary screening [15]. Furthermore the atomic potential responsible for the phase shifts of the partial waves could be described by the Hartree formula and the phase shifts themselves could obtained by an asymptotic solution of a differential equation.

For this preliminary evaluation of the time spread due to the transport of the electrons trhough the foil a more simpler approximation was instead adopted. The phase shifts are calculated from a three dimensional potential well with a depth equal to difference between the ionization potential and the work function of the bulk material. The radius of the well is taken equal to half the distance (1.42 $\mathring{A}$) between two neighbouring atoms in the sp^2 hybrid of graphite. The phase shifts obtained from the three dimensional potential well are then introduced in a classical partial wave expansion to obtain the differential cross section to be used in the Monte Carlo steps. The partial wave expansion was truncated at the 20th term of angular momentum which corresponds to a maximum kinetic energy of the electrons of about 3 keV.

5 RESULTS OF THE MC SIMULATION

The energy distribution of the primary electrons put in evidence that the model foresees an average value of about 200 eV with a FWHM also around 200 eV and a short tail up to about 600 eV. The energy distribution derived by the model is in good agreement with experimental and numerical results found in literature.

With the adopted model, the time distribution generated with a 15 μg/cm^2 carbon foil has a mean value of about 30 fs. The same kind of simulations with foil thickness ranging from 100 $\mathring{A}$ to 1000 $\mathring{A}$ show a saturation value around 35 fs starting from 20 fs at 100 $\mathring{A}$.

6 CONCLUSIONS

The preliminary results obtained with the physical model adopted for the Monte Carlo simulation seems to support the idea of using a thin foil as fast converter able to produce electrons in good time correlation, within fraction of picoseconds, with the incident ions of an ordered beam. Further investigations will be carry out in the next future with an experimental apparatus which is now under development.

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