GENERATION OF BUNCH TRAINS AND ITS APPLICATIONS

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Abstract

Trains of electron bunches produced with recently demonstrated masking technique has a wide range of application. Appropriate parameters for the resonant excitation of plasma wakefields, as well as for the probing of these wakefields with a witness bunch are the first application that motivated the research. Bunches in the train can be treated as "macroparticles" and therefore offer possibility for other type of Wakefield experiments: CSR and its shielding studies, accelerating Wakefield in dielectrics. X ray filming in the pump-probe ultra-fast studies with the 100fs frame rate can illustrate other possible application.

INTRODUCTION

We have demonstrated that trains of equidistant electron bunches with sub-picosecond separation can be produced using a masking technique [1]. With this method the bunch train parameters – number, spacing, individual length, and even charge - can be chosen by adjusting the mask pattern parameters as well as the beam parameters at the mask.

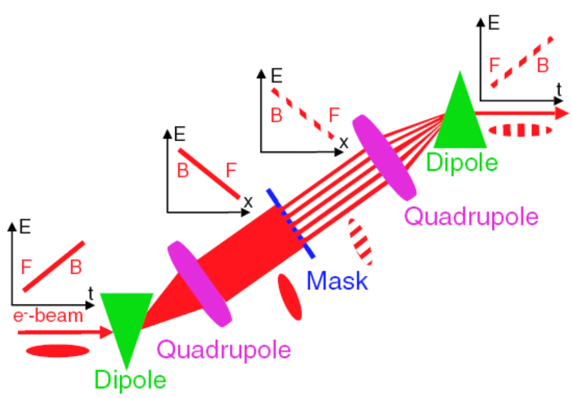

Figure 1: Simplified schematic of the mask principle. Only the dogleg section of the beam line is depicted (not to scale), and three quadrupole magnets are omitted. The side graphs represent the beam energy correlation with the beam front labeled by ''F'' and the back by ''B.''

We produce the microbunch train by imprinting the shadow of a periodic mask onto a bunch with a correlated energy spread (see cartoon in Fig. 1). The mask is placed in a region of the beam line where the beam transverse size is dominated by this correlated energy spread. The mask spoils the emittance of particles that strike its solid parts, and these particles are subsequently lost along the beam transport line. The shadow of the mask then is converted into a time pattern when entering the dispersion-free region of the beam line. We measure this time pattern using coherent transition radiation (CTR) interferometry. We have demonstrated the ability to produce trains with different numbers of microbunches and different spacings. Such a simple method can be implemented in any accelerator that includes a magnetic chicane or dogleg. It can be used in conjunction with magnetic compression to produce trains of ultrashort electron microbunches.

EXPERIMENTAL SETUP

At the ATF, the electron beam is produced in a 1.6 cell, S-band rf-photoinjector [2] and is followed by a 80 MeV S-band linac. The electron bunch with a normalized emittance of ~1 mm-mrad and ~500 pC can be sent to three different beam lines. For the present experiment, the beam is directed to ATF Beam Line #2 using two dipoles and five quadrupoles arranged in a dogleg.

For the present application the beam energy is E_0 = 59 MeV and the dogleg quadrupoles are adjusted to obtain a region of large dispersion and low beta function (in the plane of dispersion).

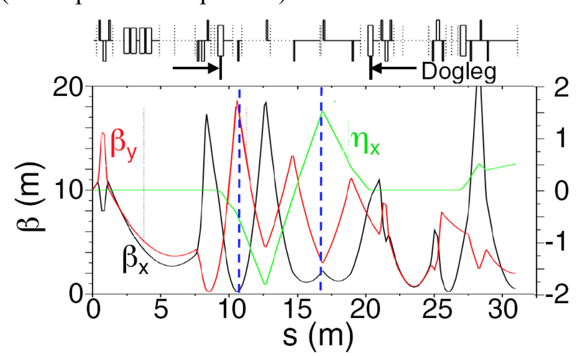

Figure 2: Beam beta functions (β_x black, β_y red line), and dispersion in the x plane η_x (green line), obtained using the MAD program. The dashed blue lines represent the location of the energy slit (left-hand side) and of the mask (right hand side). The beam line elements are shown in the figure above the graph. Quadrupoles focusing in the y (x), vertical (horizontal) plane are indicated by thin rectangles above (below) the middle line, dipoles by full rectangles across the line, and beam profile monitors by the dotted lines.

The beam is also accelerated off the crest of the rf wave in order to impart a correlated energy spread on the bunch (typically $\Delta E/E_0 \approx +1.5\%$). The beam line includes a limiting slit aperture located at a point in the dogleg where the dispersion is η~–0.5 m. This slit can be used to limit the energy spectrum of the bunch. After exiting the

dogleg, the beam propagates over a dispersion-free distance of 6.5 m before entering a magnetic spectrometer with a final dispersion of η = 1 m. Before the dogleg, the bunch is about 1500 µm-long (or ~5 ps, full width). The dogleg longitudinal dispersion function R_{56} is ~4 cm, which means that the effect of the dogleg is to either compress or stretch the bunch by ±400 µm (or ±1.3 ps, depending on the sign of the energy chirp) per percent of correlated energy spread.
In the dogleg, the time-correlated energy spread also corresponds to a correlation with position along the x-axis of dispersion.

BUNCH TRAIN FORMATION

The mask is placed in a region of the dogleg where the beam size is dominated by its energy spread. That is, its betatron size $\sigma_{\beta x}=(\varepsilon_N\beta_x/\gamma_0)^{1/2}$, where β_x is the beam beta-function, ε_N its normalized emittance, and γ_0 the electron relativistic factor satisfy: $\sigma_{\beta x}<<\eta_{mask}\Delta E/E_0$. η_{mask} is the magnetic dispersion at the mask location [1].

Figure 3: Picture of the wire mesh mask and frame. The wires are d=800 µm in diameter with a period of D=1650 µm. The red arrow indicated the two consecutive wires.

We have modified the mask to produce a train of equidistant (Δz) DBs followed by a WB separated from the last DB by $\Delta z'=1.5\Delta z$. The mask consists of circular stainless steel wires with diameter $d=800\ \mu m$ and stretched on metallic frame. On one side of the mask the wires are separated by $D=1560\ \mu m$. Then two wires are placed next to each other and the distance between the following wires is again D (see Fig. 1). The separation between bunches in the train is given by [1]:

$$\Delta z = D\frac{L_z + R_{56}\,\Delta E/E_0}{\eta_{mask}\,\Delta E/E_0} \qquad (1)$$

where R_{56} is the magnetic compaction factor of the dogleg, L_z is the incoming (long) bunch length. The bunch train spacing follows the mask pattern. A slit with variable width and position is placed at another location along the dogleg where β_x is small and the dispersion large. The slit determines the beam energy range that reaches the mask, and therefore also the number of bunches that are formed. In particular, it can select a number of DBs separated by Δz, followed by WB separated by $\Delta z'$. Figure 2 shows the shadow cast on the dispersed beam by the mask, a distance ≈286 cm downstream of the mask location.

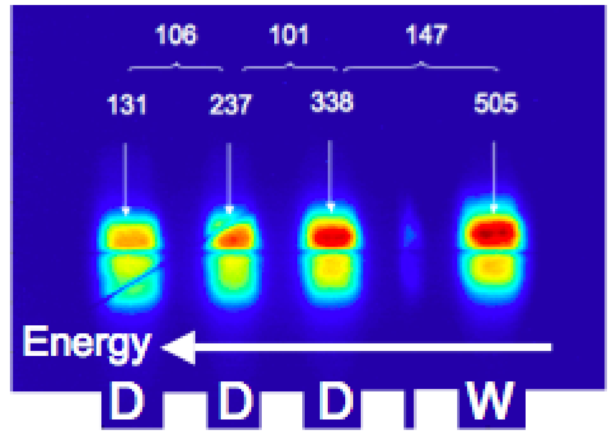

Figure 4: Shadow cast by the wire mesh captured 286 cm downstream from the mask, in the dogleg. Three DBs and one WB have been selected with the energy slit. The slit and the mask wires are schematically indicated by the white rectangles at the bottom of the image. The numbers indicate the bunch locations on the image, as well as their calculated separation (in pixels). The two lines across the image are caused by alignment wires on the screen.

The bunch train produces transition radiation (TR) when entering a copper mirror located after the dogleg. The TR is sent to a Michelson interferometer where the coherent components (CTR) interfere according to the path length difference between the interferometer two arms. The interference patter contains information about the bunch spacing and width.

APPLICATIONS

Multibunch Plasma Wakefield Acceleration

The next significant result in plasma wakefield accelerator (PWFA) experiments is likely to be the acceleration of a witness bunch with a large energy gain and a narrow (a few %) energy spread. Beam structure consisting of two or more short bunches (bunch train) is needed. Such a train consists of a number of DBs separated by a distance Δz, and have DBs have a length smaller than $\Delta z/2$. The drive train is followed by a WB distant by $\Delta z'=1.5\Delta z$ from the last DB. The plasma density can then in principle adjusted such that the wavelength of the relativistic plasma wave $\lambda_{pe}=2\pi c/\omega_{pe}$ ($\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$ is the plasma pulsation) is equal to the DB spacing. In this case, and in the linear theory of the PWFA, the wakefield driven by each bunch adds in phase with that driven by the other ones. The DB train therefore resonantly drives the plasma wake to a large amplitude. The witness with spacing $\Delta z'$ is then in the accelerating phase of the wake and can gain large amounts of energy. When the WB length is much shorter than λ_{pe} it exits the plasma with a narrow energy spread. Large amplitude wakefields and production of accelerated bunches with a narrow energy spread are essential characteristics for a future plasma-based linear collider or PWFA-LC.

The preliminary PWFA interaction results show for the first time the resonant excitation of plasma wakefields by a train of drive bunches. Large energy gain is observed, accompanied with possible energy gain. [3]

Coherent Synchrotron Radiation Studies

In the PWFA experiment discussed above, an increase in energy spread was observed for a square shape bunch passing through a bending magnet. The energy difference between individual beamlets in the train was also affected (Fig. 5.). Such an increase in energy spread is expected if CSR is not shielded.

Taking the following parameters: average beam energy E=58MeV, R=1.14m, L_b=0.4m, σ_s=0.16ps, l_b=0.4ps and peak current of 100A, one obtains that steady-state CSR after passing two bending magnets would result in an additional increase in relative energy spread of 5.8e-4 for a Gaussian bunch, which would comparable with the intrinsic relative energy spread of the bunch is of the order of 5e-4. On the other hand, for a square shaped bunch of similar intrinsic energy spread, the increase in rms energy spread due to CSR is dominating 1.7e-3. These numbers qualitatively reproduce the effects observed at ATF. The quantitative disagreement could be due to the fact that transient CSR effects can result in an additional enhancement of CSR power.

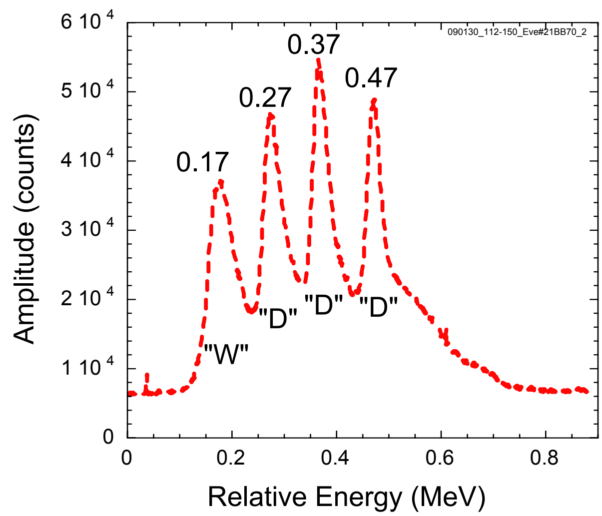

Figure 5: Projection at the energy spectrometer illustrates difference in energy change after passing through two dipoles for the last (W) and prior (D) bunches, when compared to Fig. 4.

A system of vertical plates with controllable distance between them can be installed inside the vacuum chamber of the bending magnet to test the suppression of CSR. By performing measurements for various distances between the plates one can systematically study shielding of CSR. Estimates suggest that the observed energy spread for bunches in the ATF can be suppressed with an appropriate choice of distance between the vertical plates.

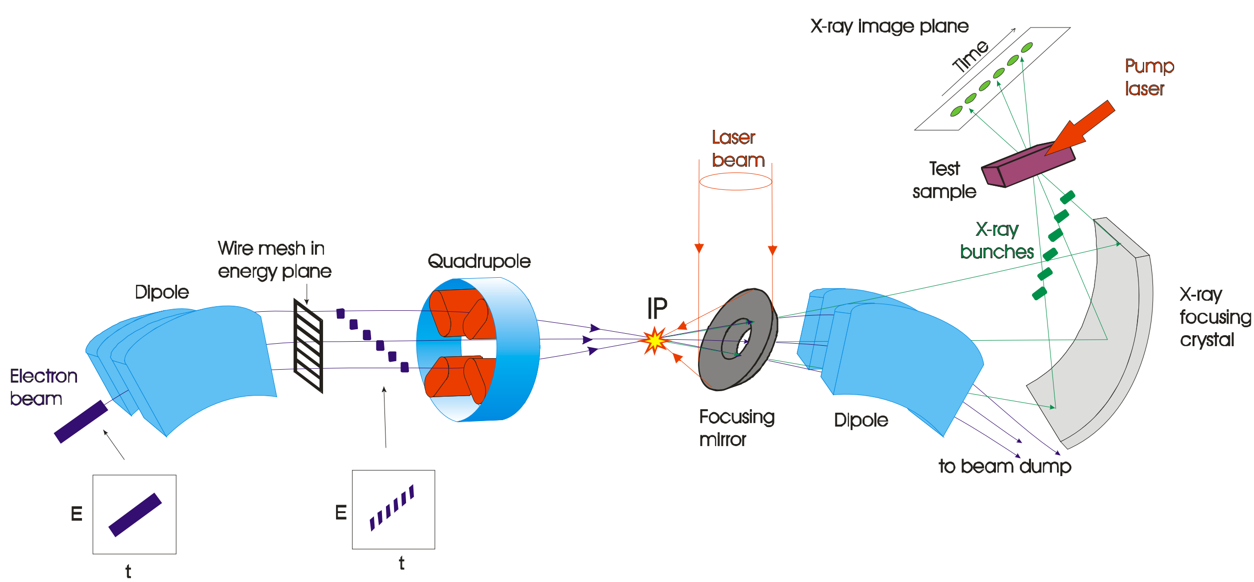

Figure 6: Simplified schematic of our proposed x-ray stroboscope.

X Ray Movie Camera with 100fs Frames

X-ray stroboscope is illustrated in Fig. 6. The first step is production of subpicosecond periodical microbunches sliced from the initial several-picosecond linac pulse using a periodical wire mesh placed in the energy plane. As the result the produced microbunches have a systematic shift in energy from the first to the last bunch in the train that, depending upon the initial chirp and the mesh density, may comprise up to 10 bunches. This energy variation is instrumental for building x-ray stroboscope because it allows angle separation between the microbunches after passing a dispersion magnet.

A fan of microbunches is refocused by a quadrupoles into a point where the electron beam interacts with counter-propagating intense laser beam. The ATF already demonstrated the record high x-ray yield produced via Thomson scattering from a laser interaction with a single electron bunch [6] that produced low-divergence, 7-keV x-rays in the proportion of one photon per electron, directed exactly along the e-beam axis, and with the pulse duration corresponding to the electron bunch length. A fan of microbunches separated by the $1/\gamma$ radian or bigger angle, where γ is the Lorentz factor of the electron (170 for 85 MeV), will produce a fan of 13-keV x-ray beamlets with the pulse duration and relative delays between individual beams exactly matching the time structure of the electron microbunches. These multi-beam x-rays will be transported through a hole at the center of the focusing laser mirror and separated from the electrons by a dipole magnet. Afterwards, the x-rays can be refocused onto a test sample with a curved crystal. After passing the focal point, the x-ray beamlets continue to spread until they are clearly separated and imaged individually by the appropriate x-ray detector or a set of detectors. 10^7 X-rays per beamlet are expected with 1% energy spread with 0.3 mrad divergence, 35μm source size and 100fs RMS duration. This correspond to peak brightness of 10^{23} ph/sec/mm^2/mrad^2/0.1%.

Similar to a conventional pulse-probe technique, the test sample will be irradiated by a short laser pulse that initiates the processes (e.g., melting, chemical reaction, etc.) to be probed by the x-rays.

An evident advantage of the x-ray “movie” produced by x-ray beamlets to compare with a conventional “still photo” is a new capability to explore an extended or full dynamics of the process in a single shot on the sample. This should be fully understood that the proposed approach is not aimed to merely speed up the data collection as far as the same purpose could be achieved by using a higher repetition rate pump and probe radiation sources. The x-ray stroboscope will allow to study the actual dynamics of individual processes that may not be exactly reproducible from shot-to-shot (such as electron filamentation in dense plasma) and from sample-to-sample (e.g., crystal shape, structure orientation, and impurities). This promises to revolutionize the experimental ultrafast research in physical, chemical, biological, material, and plasma sciences.

SUMMARY

We used the masking technique that we previously demonstrated [1] to produce a train of bunches appropriate to demonstrate for the first time the resonant excitation of plasma wakefields in plasmas with densities in the 10^{16}-10^{17} cm^{-3} range. The train consists of a variable number of equidistant drive bunches followed by a witness bunch. Preliminary PWFA results were obtained with the generated beam. Such a sub-picosecond separation bunch train can also be used for the study of coherent synchrotron radiation CSR in magnetic bends, and chicanes. The shape of the microbunches and therefore the amount of radiation they produce can be varied by changing the beam betatron size at the mask. Suppression of CSR is particularly important for the design of electro/proton colliders, such as the one planned at the Brookhaven National Laboratory. CSR results in an increase of the energy spread and of the emittance of the bunches in the train. CSR effects can also be studied at the picosecond scale as a function of the distance between the two bunches. In addition there trains are also useful to study the coherent emission of THz radiation in dielectric coated metallic tubes. Generation of 100 fs train of x rays with the generated beam offers exciting new possibility for filming fast transitional events with unprecedented frame speeds.

ACKNOWLEDGEMENTS

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