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FEMTO - Preliminary studies of effects of background electron pulses

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When a short laser pulse (50fs) interacts with an electron bunch in a wiggler or an undulator, a small part of the electron bunch (50 fs) undergoes an energy change of 13 MeV resulting in two femto pulses. The energy of one of these is higher than the beam energy by 13 MeV and that of the other lower by the same amount. This energy change is exploited to transversely separate these pulses from the main beam to produce FEMTO photon pulses. Normally, the FEMTO photon pulse produced by the electron pulse having higher energy is tapped for experimental purposes The electron beam is exposed to the laser beam at a certain repetition rate which, in our case, will be 5-10 kHz. In each exposure, a new FEMTO electron pulse is produced and this produces a FEMTO photon pulse in an undulator.

During interaction with the laser beam, there is a sudden change in the energy of electrons. The part of electron bunch which experiences a change of energy undergoes betatron oscillations and consequently, the emittance of this part of the beam or the phase space area of the ellipse in which these electrons moves increases. The electron beam is exposed to the laser beam at a repetition rate of 10kHz. In each exposure, a new FEMTO electron pulse is created, whereas the earlier created electron pulses (or background electron pulses) are still there in the ring. The earlier FEMTO electron pulses may increase the pulse length or add to the background noise, if they arrive at the radiator alongwith the freshly created pulse. In order to understand the effect of the earlier pulses on the quality of FEMTO photon pulses, it is necessary to calculate parameters such as change in the beam emittance of the affected part of the electron bunch, synchrotron frequency, bunch length, fraction of electrons affected by the laser pulse during each interaction with the laser pulse.

Change in emittance of the affected part

$$= (\gamma_z \eta_z^{\,2} + 2\alpha_z \eta_z \eta_z' + \beta_z \eta_z'^2) \cdot (\Delta E/E)^2$$

$$= 1.73\cdot 10^{-10} \text{ m.rad} \qquad (1)$$

(β_z=3m, α_z= 0.022, η_z=12mm, η_z'= -2mrad & $\Delta E/E$= $5.4\cdot 10^{-3}$ in the modulator section)

Synchrotron frequency = 7.03 kHz (Momentum Comp.= $6.74\cdot 10^{-4}$, Energy loss/ turn = 520 keV, Cavity voltage = 2.2 MeV) (2)

Bunch length = $1.3\cdot 10^{-11}$s (Taking energy spread = $8.58 \cdot 10^{-4}$) (3)

Amplitude of time deviation due to synchrotron oscillations after the energy change of 13MeV

$$= 8.23\cdot 10^{-11}\text{s} \quad (\Delta E/E = 5.4\cdot 10^{-3}) \qquad (4)$$

(4) being much greater than (3) implies that the electrons affected by the laser pulse will be at the tail of the bunch.

Fraction of electrons contained in a 50 fs electron pulse

$$= 1.53 \cdot 10^{-3} \text{ (Assuming Gaussian distribution)} \qquad (5)$$

Schoenlein et.al. show that only 20% of these electrons will undergo the required energy change. Therefore, fraction of electrons undergoing enegry change of 13MeV

$$=2.\ 0.2.\ 1.53 \cdot 10^{-3} = 6.12 \cdot 10^{-4} \qquad (6)$$

The multification factor 2 is due to the fact that two electron pulses are created in one exposure.

Multi-bunch Mode:

Here we note that a small fraction of electrons of the bunch are affected by the laser pulse at a time. Since the repetition rate of the laser pulse is 10kHz, in order that the equilibrium emittance of the electron beam does not deteriorate, it is desirable that all electron bunches are exposed uniformly in a systematic way to the laser pulse. If this scheme is followed, each bunch will face the laser pulse after $400 \cdot 10^{-4}$ s or 40ms.

The emittance of the affected part of the bunch after 40ms & just before next injection

$$= 1.73 \cdot 10^{-10} \cdot e^{-40/(2x9)} \text{ m.rad (Damping time = 9ms)}$$

$$= 1.87 \cdot\cdot 10^{-11} \text{m.rad (Vertical emittance} = 2.51 \cdot 10^{-11} \text{m.rad)} \qquad (7)$$

After 40ms, the emittance of this part is nearly the same as the vertical emittance and immediately after the injection it will again be given by (1).

Amplitude of oscillations (on time scale)of these electrons w.r.t the centre of the bunch after 40 ms (before injection)

$$= 8.23 \cdot 10^{-11} \cdot e^{-40/4.5} \text{s (Longitudinal damping time = 4.5ms)}$$

$$=1.11 \cdot 10^{-14} \text{s} \qquad (8)$$

After 40ms, the affected electrons will be nearly at the centre of the bunch.

Above estimates give an indication that after 40ms, betatron and synchrotron oscillations excited in the earlier exposure to the laser beam will be almost completely damped. We can, therefore, conclude that the emittance and energy spread of the circulating beam will not be affected if all bunches are exposed sequentially to the laser beam.

Single bunch mode :

With uniform filling and beam current of 400 mA, the current per bunch will be 1mA which is one fifth of the current in the single bunch mode. In order to increase the intensity of the FEMTO pulse, it will be desirable to operate the FEMTO pulse generation facility in the single bunch mode of the storage ring. To decide whether it should be done or not will depend on whether there will be a degradation in the quality of the photon pulse due to exposure of the same bunch at 10 kHz.

To investigate this problem, we have to determine where the femto electron pulses, will appear later on the time scale after every 0.1ms which is the time interval between the two successive laser pulses. If any of them is close to the freshly created part, it may affect the intensity depending on its transverse co-ordinates. Let us try to make some estimates about the longitudinal location of a FEMTO electron pulse after every 0.1ms assuming the synchrotron frequency to be 7kHz. The synchrotron frequency is considered to be constant because the maximum energy deviation through electrons undergo is small. In the following discussion, we consider the behaviour of the femto electron pulse of higher energy i.e. the electron pulse, the femto photon pulse of which is tapped for experiments. The behaviour exhibited by the other pulse will be similar to it.

In the first 0.1ms, the femto electron pulse which has higher energy will complete around three quarters of a synchrotron oscillation. At the moment, when the fresh FEMTO part is in the radiator, the pulse under consideration will be far way from it in time (nearly $8 \cdot 10^{-11}$s) as well as space.

After 0.2ms, this pulse will have completed 1.4 synchrotron oscillations and developed the energy deviation opposite to that of the freshly created pulse. Since the synchrotron frequency is 7kHZ, it will still be far away (nearly$1.25 \cdot 10^{-11}$s) from the freshly created pulse. Under such conditions, it will not be able to influence the intensity of the freshly created pulse. If the frequency of synchrotron oscillation is 7.5kHz, it will complete 1.5 synchrotron oscillations and will be at the radiator at the same time when the freshly created pulse reaches there. Its transverse co-ordinates at the radiator can be calculated by using the following expressions for dispersion and its derivative[2].

$$h_{2eff} = h_2 - \left(\sqrt{b_1 b_2}\, h'_1 + a_1 \sqrt{\frac{b_2}{b_1}}\, h_1\right) \sin m_{12} - \sqrt{\frac{b_2}{b_1}}\, h_1 \cos m_{12} \qquad (9)$$

$$h'_{2eff} = h'_2 - \left(\sqrt{\frac{b_1}{b_2}}\, h'_1 + \frac{a_1 - a_2}{\sqrt{b_1 b_2}}\, h_1\right) \cos m_{12} + \left(\frac{1 + a_1 a_2}{\sqrt{b_1 b_2}}\, h_1 + a_2 h'_1 \sqrt{\frac{b_1}{b_2}}\right) \sin m_{12} \qquad (10)$$

Here, the symbols have their usual meanings. The subscript 1 denotes the centre of the modulator and 2, the centre of the radiator. While making use of these expressions for calculations of transverse displacement due to betatron oscillations, the ΔE/E has to be always the same as that of the initial FEMTO pulse. These expressions give only a rough estimate of maximum oscillations because the frequency of betatron oscillations is considered independent of energy This assumption can lead to a considerable error in the above estimates where the number of turns involved are large. However, the pessimistic view can be formed by using them. In this case, it is envisaged that the electrons of the earlier pulse can reach the radiator at the same time and at the same place where the freshly created FEMTO pulse will be. If this happens, the earlier pulse will add to the unwanted background of the radiation produced by the new FEMTO pulse. According to this logic, the other FEMTO electron pulse can also reach the radiator in coincidence with the freshly created pulse.

Obviously, such a situation must be avoided. For how many 0.1ms intervals such a situation should be avoided is governed by the damping time of betatron oscillations. The damping time of betatron oscillations in the SLS is 9ms, therefore for 90 subsequent 0.1ms intervals, the used FEMTO electron pulse should not be allowed to overlap the freshly created FEMTO pulse. Such a situation can be avoided if the repetition frequency of the FEMTO pulse is chosen such that it is not exactly equal to 4/3 times of synchrotron frequency and difference between the two frequencies should be such that for 100 intervals, the overlap of the used pulses with all fresh FEMTO pulses is avoided. For achieving such a condition, the synchrotron frequency can also be adjusted by adjusting the RF voltage. It may be noted that the gap between a used pulse and the freshly created pulses will progressively reduce with number of intervals due radiation damping of synchrotron oscillation.

The other issue of relevance is the effect on the equilibrium emittance. The fraction of the beam which is affected by the laser beam in one damping time which is 90 times the number given by eq(6) is 5.6×10^{-2} still a small fraction of the beam. The overall emittance of the beam will not be increased much and other experiments will not be adversely affected due to the simultaneous operation of the FEMTO facility. The analysis of both these effects leads us to the conclusion that it should be possible to operate the FEMTO pulse generation facility in the single bunch mode operation of the SLS without sacrificing much the quality of the FEMTO photon pulses.

In order to know accurately whether the background pulses will impair the quality of the FEMTO pulses or not, electron tracking simulation studies involving the dependence of synchrotron and betatron oscillations on energy are required to be carried. out. There may be some fliamentation of background electron pulses in lingitudinal and transverse direction due to the variation of frequencies of these oscillations on beam energy.

Conclusions:

In a nutshell, the quality of the FEMTO pulse will not be affected by the background electron pulses if the storage ring is operated in the multibunch mode with a uniform filling pattern and bunches are exposed sequentially to the laser beam. It should also be possible to generate FEMTO photon without a significant deterioration in their quality pulses in the single bunch mode by making proper choice of the laser repetition frequency or by adjusting the synchrotron frequency.

References:
1.R W Schoenlein et.al, Applied Physics B 71, 2000, 1-10
2.G Singh , A Streun, SLS-TME-2001-0179