THE ACCEPTANCE AND PHOTON BEAM FORMATION IN SLS FEMTO

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Abstract

The FEMTO insertion at Swiss Light Source (SLS) produces sub-ps X-ray pulses by modulating the electron energy in a slice of the bunch through interaction with a fs-laser. The modulated electrons form a beam halo, which becomes a source of background noise at the experiment. We study the beam halo dynamics and calculate how the noise to signal ratio scales with the laser repetition rate.

INTRODUCTION

The FEMTO facility [1] in the SLS storage ring, as schematically shown in fig. 1, produces 140 fs (FWHM) pulses of X-rays in the energy range of 3–18 keV. Inside a wiggler magnet, a laser pulse of 50 fs (FWHM in power) resonantly modulates electrons of a correspondingly thin slice of the bunch in energy. A magnetic chicane bracketing the wiggler translates the energy modulation in a horizontal separation, so synchrotron radiation from thus created “satellite bunches”, emitted in a subsequent in-vacuum undulator, can be separated from the “core” bunch radiation by a suitable set of apertures (slits) in order to extract the short X-ray pulse.

In the turns following the laser beam interaction and the generation of short X-ray pulse, the satellite bunches form a beam halo due to filamentation, which then decays and merges back into the core beam due to radiation damping. Since the time between laser pulses is much shorter than the radiation damping time, the background halo will reach an equilibrium, which depends on the laser repetition rate. Depending on the signal to noise requirements of the experiments, this leads to a limitation of the maximum laser repetition rate.

The photon flux from radiator is proportional to [2], $flux \sim \eta_1 \cdot \eta_2 \cdot \eta_3$, where $\eta_1 = \sigma_S / \sigma_z$ is the ratio of satellite rms length to bunch rms length, $\eta_2 = f_L / f_B$ is the ratio of laser repetition rate to the bunch revolution frequency and $\eta_3 = N_{\text{mod}} / N_S$ is due to the fact that only a fraction of the electrons in the satellite acquires sufficient energy deviation for separation from core bunch. In order to increase the flux, an increase of the laser repetition rate (η_2) is most efficient, since the peak current in a storage ring is rather low (η_1) and the core beam needs to be blocked thoroughly (η_3). However this also increases the background noise from the beam halo.

In the following, we will study the formation and evolution of the beam halo and calculate the radiation background from many turns in order to obtain noise/signal ratio as a function of laser repetition rate.

We neglect diffraction and coherent effects, because for X-rays the diffraction phase space is small compared to the horizontal electron phase space, and coherent radiation is only relevant in the THz-range. Thus we assume that the photon distribution is identical to the electron distribution.

Using the energy modulation in the bunch after laser beam interaction in the modulator wiggler [3], the electron 4-dimensional phase space distribution is transformed to the radiator undulator, where the photons are emitted. The apertures (slits) of the photon beam line are back-transformed to the radiation point forming the radiation acceptance area in phase space that separates the sub-ps X-Ray satellite pulse from the core beam in “turn 0”, i.e. immediately after laser interaction. Initial energy distribution, local dispersions and beta functions determine the transverse phase space distribution in the radiator in subsequent turns. Integration of the distribution over the acceptance area provides the background from a particular turn. Summarizing over many laser interactions finally gives the total background as a function of laser repetition rate.

RADIATION DISTRIBUTION

To obtain the beam distribution in 4-dimensional phase space $\bar{x} = (x, x', s, \delta)$ in the radiator, we start from the beam distribution $\rho(\bar{x}_W)$ at the wiggler exit W taking into account the electron energy modulation $\delta_L(s)$ by laser-beam interaction [3].

With $\bar{x}_W = F(\bar{x}_R)$ the phase space coordinate transformation from wiggler to radiator, the distributions are related as

$$\rho_R(\bar{x}_R) = \mathrm{I}_R(\bar{x}_R) \cdot \rho_W[\bar{x}_W(\bar{x}_R)] \qquad (1)$$

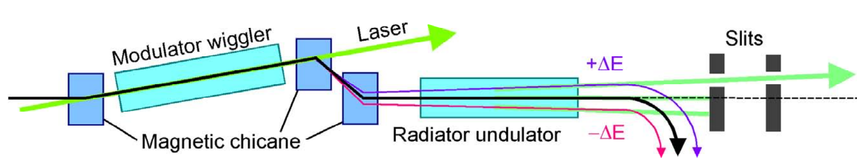

Figure 1: Schematic view of the SLS FEMTO beam line.

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where $I_R(\bar{x}_R) = \left|\partial x_{W\,i} / \partial x_{R\,j}\right|$ is the Jacobean of the transformation $\bar{x}_W = F(\bar{x}_R)$. For "turn 0" the motion is linear, since there are no sextupole magnets in this section, and the transformation is given by the transfer matrix M

$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_R = \begin{pmatrix} m_{11} & m_{12} & 0 & m_{14} \\ m_{21} & m_{22} & 0 & m_{24} \\ m_{31} & m_{32} & 1 & m_{34} \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_W \qquad (2)$$

and $\bar{x}_W = M^{-1}\bar{x}_R$ since the Jacobean is equal to 1.

In order to extract radiation only from one satellite and to suppress static (core beam, chicane magnet radiation) as well as dynamic (beam halo) backgrounds, several slits are used, where only 2 are shown in Fig.1, that form the radiation acceptance. Essentially only the first and the last slit form the acceptance: fig.2 shows the acceptance back-transformed to the radiation point and the photon/electron distribution for "turn 0".

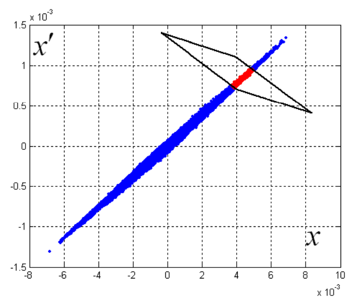

Figure 2: Particle phase space distribution during 0 turn and radiation acceptance at the point of radiation.

For convenience we use normalized phase space coordinates (X, X'). The radial distribution of satellite particles in $R = \sqrt{X^2 + X'^2}$ "turn 0", after laser-beam interaction (tracking simulations) and after radiation damping (equilibrium distribution) at the radiation point are presented in Fig.3.

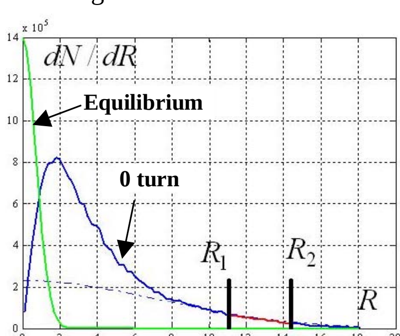

Figure 3: Radial distribution of photons emitted from the satellite bunch in "turn 0" immediately after laser interaction, and in equilibrium eventually reached through radiation damping.

Note that for equilibrium particle distribution $R_{rms} = 1$. The points $R_1 = 11.1$, $R_2 = 14.4$ correspond to the radiation acceptance which is basically determined by only one of slits (see fig.2).

RADIATION BACKGROUND

In subsequent turns after laser beam interaction, the satellite lengthens due to synchrotron oscillations (fig.4).

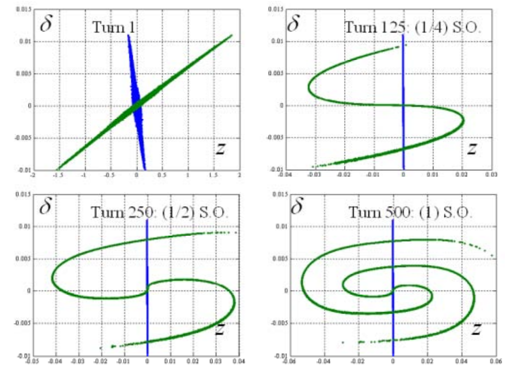

Figure 4: Longitudinal distribution of the beam halo in turn 1, 125, 250, 500 after laser interaction. For comparison the turn 0 distribution is shown in blue.

Note that 500 turns corresponds to one synchrotron oscillation period. As one can see after one turn the satellite lengthens by factor of ~50. Even after half a synchrotron period, the satellite bunch does not reproduce the initial shape (turn 0) due to strong nonlinearity introduced by third harmonic cavity in the ring.
While the satellite slowly filaments and lengthens in longitudinal phase space, it filaments rapidly in transverse phase space due to non-linear chromatic spread of betatron tunes and due to amplitude dependant tune shifts.

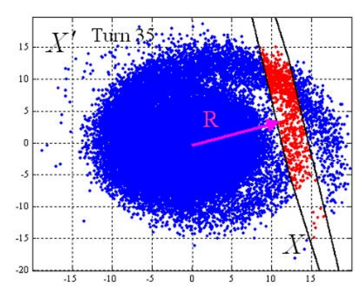

Figure 5: Phase-space distribution, slit and accepted particles in normalized (X, X') coordinates.

Fig. 5 showing the electron distribution in normalized phase space (X, X') at the radiation point after 35 turns proves that the beam halo is fully developed before the next laser interaction (10 kHz laser repetition rate correspond to the next interaction after 104 turns in SLS). Mainly one slit forms the acceptance. Two parallel lines located at the distances R_1, R_2 correspond to this slit.

To obtain radiation background we have to integrate the beam distribution over the acceptance area in subsequent turns and summarize over many particular turns. For multi laser-beam interaction the radiation background will be conditioned by the halo formed during the old laser flashes and radiation damping.

The rms bunch radius $\sigma_\perp$ in normalized phase space after zero turn will be conditioned by radiation damping

$$\sigma_\perp(t) = 1 + \sqrt{H/\varepsilon}\,\delta_{Lrms}\exp(-t/\tau_x) \qquad (3)$$

where H is the "dispersion's emittance" at the wiggler exit, $\delta_{L\,rms} = 0.0041$ is the rms modulated energy spread of the satellite and τ_x is the radiation damping time. Using $\delta_{L\,rms}$ implicitly assumed a Gaussian radial distribution in normalized phase plane for the tail particles (fig. 3). Then the number of particles in the acceptance at the moment of next laser shot can be calculated:

$$N_{ACC} = \frac{N_S}{2(R_1+R_2)\sqrt{\pi}}\left[erf\left(\frac{R_2}{\sigma_\perp}\right) - erf\left(\frac{R_1}{\sigma_\perp}\right)\right], \qquad (4)$$

with

$$\sigma_\perp(f_L) = 1 + \sqrt{H/\varepsilon}\cdot\delta_{Lrms}\cdot\exp\left(-\frac{1}{f_L\tau_x}\right) \qquad (5)$$

The total number of electrons inside the acceptance area from all previous interactions can be defined by summarizing the numbers of remaining halo particles from all previous interactions.

Fig.6 presents the dependence of the relative shot to shot noise signal from the number of laser shots for laser rates of 1, 2 and 10 kHz. For high laser repetition rates ($f_L \geq 10kHz$) the relative noise signal is constant $N^{n+1}_{ACC} / N^{n}_{ACC} = \alpha \approx const$, with

$$\alpha = \frac{erf\left[R_2/\sigma_\perp(N_L)\right] - erf\left[R_1/\sigma_\perp(N_L)\right]}{erf\left(R_2/\sigma_{\perp 0}\right) - erf\left(R_1/\sigma_{\perp 0}\right)}. \qquad (6)$$

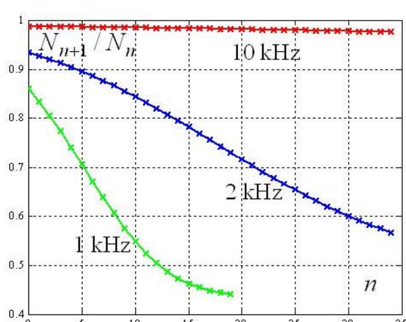

Figure 6: Ratio of background signals from subsequent laser shots as a function of laser shot number.

Then the noise signal can be evaluated analytically. At the end of first laser shot the number of particle in acceptance from the beam halo will be equal to $N_1 = \mu(f_L)\cdot N_S$, where $\mu(f_L)$ in general depends on laser repetition rate . For small laser frequency $\mu/\eta_3 << 1$ due to radiation damping. If n laser shots have passed, the number of electrons in the acceptance area (noise signal) after the last interaction is given by $N^n_{ACC} = \alpha^{n-1}N_1$. The total number of accepted particles from all previous shots gives the total noise signal and is given by

$$N^{noise}_{ACC} = N_1\left(1+\alpha+\alpha^2+...+\alpha^{n-1}\right) = N_1\frac{(1-\alpha^{n-1})}{1-\alpha} \qquad (7)$$

For a large number of laser shots we can take $n \to \infty$

$$N^{noise}_{AC} = \mu(f_L)\cdot N_S\,\frac{1}{1-\alpha} \qquad (8)$$

Finally, the background noise/signal ratio will be:

$$Noise/Signal = \frac{\mu(f_L)}{\eta_3\cdot[1-\alpha(f_L)]} \qquad (9)$$

For lower laser repetition frequency we can calculate the total noise/signal ratio by (9) taking the average laser pulse to pulse ratio $\alpha = \alpha_{av}$. Table 1 present the results of noise/signal ratio obtained by tracking simulations and analytical prediction (9) for laser frequency of 2 and 10 kHz. For laser frequency of 20 kHz the noise/signal ratio at the level of 14.3 is predicted.

Table 1

f_L (kHz)	Noise/Signal (Simulation)	Noise/Signal (Analytic)	Difference (%)
2	1.15	1.264	9.9
10	6.94	7.05	1.5

CONCLUSIONS

The noise/signal ratio for SLS femto beamline is studied. It is shown that for 10 kHz laser frequency the noise/signal ratio will increase by factor of about 6 with respect to current laser frequency of 2 kHz.

REFERENCES

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