Effects in high energy linear colliders due to particle fields

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Contents

- Compton scattering of electrons on wake field photons (produced by *coherent* beam field)

- Dark current due to collision of short wavelength photons with cavity irises (incoherent fields of relativistic particles with $\lambda \sim a/\gamma$)
- Conclusion

Compton scattering of electrons on wake field photons

Pre-history

In 1990 at the end of the summary session of LC2000 in KEK the chair of the workshop S. Kurokawa gave me 10 minites for a urgent talk about a new effect discovered during the night before this session, which looked as a possible stopper for linear colliders. The title of this talk was“ Compton scattering of electrons on wake fields”. Its conclusion was:

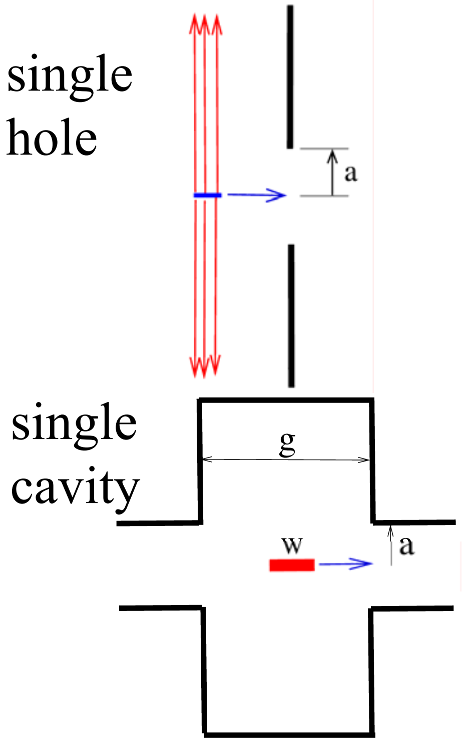
this effect can cause unacceptable beam energy spread (several % for high frequency linacs), which does not allow beam focusing.

After my talk R. Palmer has noticed that wake fields in multiple cavities differ very much from a single cavity therefore my considerations possibly overestimate the collision probability. In addition, on the next day I have realized that the transverse wake field (which cause Compton scattering) on the beam axis is zero. After that I asked S. Kurakawa to withdraw my talk and do not distribute copies of transparences.

Recently, thinking on one other effect connected with wake fields, I looked in my 24 years old transparences and found that my night estimates in fact coincide with Palmer's predictions for multiple cavity case within a factor of 2. In addition, cancelation of the field on the axis disappears after many scatterings on cavity walls due to imperfections. So, my estimates were almost correct.

Below I consider again this effects with account of present understanding of the wake field damping in real colliders.

Wake field energy losses by a bunch



$$\Delta U_0 \approx \frac{Q^2}{w} \ln \frac{r_{max}}{a} \qquad \text{w - bunch length} \qquad (1)$$

According to Palmer's simplified wake fields theory (Particle Accelerators, 1990, v 25, pp. 97-106) for the first cavity (a – iris radius, g – cavity length).

$$\Delta U_1 \approx \frac{Q^2}{a} \sqrt{\frac{g}{2w}} \qquad (2)$$

Multiple cavities

After passing many cavities $(n \geq a^2/2gw)$

the energy loss per cavity becomes constant

$$\Delta U = \frac{2Q^2}{a^2} g \qquad (3)$$

Compton scattering on wake field photons

When an electron bunch travels in a linac it is appropriate to use Eq. 3 for the multi-cavity case

$$\frac{dU}{dx} = \frac{\Delta U}{g} = \frac{2e^2 N^2}{a^2}$$

For the bunch with r.m.s. length σ_z the spectrum of wake field photons

$$dN_\gamma \propto \exp(-\omega^2/\omega_c^2), \qquad \omega_c = c/\sigma_z$$

Assuming that photons have uniform spectrum from 0 to ω_c we find the spectrum of photons per unit of length

$$\frac{dN_\gamma}{dx} = \frac{dU}{dx\,\hbar\omega} = \frac{2e^2 N^2}{a^2 \hbar\omega} \frac{d\omega}{\omega_c}$$

The wake photon travels initially along the beam axis and after reflection from the cavity follows towards the axis with impact distance ±λ. The density of photons on the axis (b- cavity radius)

$$n_\gamma \sim \frac{dN_\gamma}{dx}\frac{1}{2b2\lambda} = \int_0^{\omega_c} \frac{dN_\gamma}{dx}\frac{\omega}{8b\pi c} = \frac{\alpha N^2}{4\pi a^2 b}$$

The probability of Compton scattering on the length of a collider

$$p \sim \mathrm{n}_\gamma\, \sigma_T l = \frac{2\alpha N^2 r_e^2 l}{3a^2 b} \qquad \alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137};\ r_e = \frac{e^2}{mc^2} = 2.8\cdot 10^{-13}\,\mathrm{cm}$$

The average energy loss in one scattering (for collision angle 90º)

$$\bar{E}_\gamma = \int_0^{\gamma_0}\int_0^{\omega_c} 2\gamma^2 \hbar\omega \frac{d\omega}{\omega_c}\frac{d\gamma}{\gamma_0} = \frac{\hbar c}{3\sigma_z}\gamma_0^2$$

The maximum Compton scattered photon energy (for head-on collision)

$$E_{\gamma,\max} \approx 4\gamma_0^2 \hbar\omega_c = \frac{4\gamma_0^2 \hbar c}{\sigma_z} \sim 12\bar{E}_\gamma$$

The above consideration assumes that electron collides with photons created in the cavities by one preceding bunch. If damping time correspond to storage of photons from N_b bunches one should multiply the probability of collisions by N_b.

ILC,

For E_0=500 GeV, $N=2\cdot 10^{10}$, a~3.5 cm, b~10 cm, l=15 km, σ_z=0.03 cm and N_b~100 ? we get

$$p \sim 0.2 \qquad \frac{E_{\gamma,\max}}{E_0} \approx 0.005, \qquad \frac{\bar{E}_\gamma}{E_0} \approx 0.0005$$

CLIC

For E_0=1500 GeV, $N=3.8\cdot 10^{9}$, a~0.3 cm, b~1.5 cm, l=15 km, σ_z=0.0045 cm and N_b~1 ? we get

$$p \sim 0.05 \qquad \frac{E_{\gamma,\max}}{E_0} \approx 0.1, \qquad \frac{\bar{E}_\gamma}{E_0} \approx 0.01$$

CLIC has very strong damping of high modes and effective $N_b<1$

Discussion

1) Fortunately, due to special measures on damping of high frequency modes (for beam dynamics purposes) the considered effect is not catastrophic for linear colliders under consideration

2) We assumed an axial symmetry of cavity geometry which led to enhanced photon density (focusing) near the axis. Creation of some asymmetry (for example, in tubes between cavities) could help to spread photons around the cavity in order to decrease the photon density on the axis and thus to suppress substantially the probability of Compton scatterings.

Collision of short wavelength photons with cavity irises

Above we considered the coherent beam field which creates photons with the wavelength about $2\pi\sigma_z$.

In addition, there are fields of individual electrons with much shorter wavelength, about a/γ. For a=1 cm and $\gamma=10^6$ the energy of such photons is

$$E \sim \hbar c\gamma/a \sim 20 \text{ eV}$$

Such photons can knock out secondary electrons from irises with a rather high probability (up to 10%) These electrons will be accelerated in the cavity and then heat cavities. This effect is most important for SC cavities, where even a small rise of temperature is not acceptable (leads to the local decrease of Q and further break of superconductivity)

The energy loss of a bunch due to the cut of incoherent fields of individual electron passing through a hole in a single screen is given by (1) with w=a/γ

$$\Delta U_0 \approx \frac{\gamma N e^2}{a} \ln \frac{r_{\max}}{a}$$

The energy loss in a single cavity is given by (2)

$$\Delta U_1 \approx \frac{N e^2}{a} \sqrt{\frac{g\gamma}{2a}}$$

The energy loss per cavity in the multiple cavity case

$$\Delta U = \frac{2 N e^2}{a^2} g$$

We see that the later case the energy losses are smaller than for the single hole case by a factor of γ. The number of photons with the energy $\hbar c\gamma/a$ incident to the iris $N_\gamma \sim \alpha N g/\gamma a$. This is a small number, which could not lead to any dramatic effects.

Conclusion

- Compton scattering of electrons on wake field photons is very important effect for high energy linear colliders. Fortunately, special measures on suppression of wake fields for conservation of beam emittances also decrease the probability of Compton scattering down to acceptable levels.
- At high linac energies equivalent photons accompanying individual electrons can knock out electrons from irises that could lead to the breaking of superconductivity. Fortunately, most of such photons are cut at the entrance to the linac and the number of newly created photons at $r>a$ is negligibly small, proportional to $1/\gamma$.