Laser cooling of electron beams

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Contents

- Introduction, principle of laser cooling of electrons
- Minimum transverse normalized emittance
- Laser flash energy
- Energy spread
- Optimum laser wavelength
- Possible variant of the cooling system
- Discussion, conclusion

Motivation

First detail consideration of laser cooling of electrons was stimulated by necessity of small beam emittances for the photon collider

V.Telnov, Laser cooling of electrons for linear colliders,
Phys.Rev.Lett.78:4757-4760,1997, Erratum ibid.80:2747,1998;
Nucl.Instr.Meth.A 455;80,2000

Then the same idea was applied for low energy storage rings for X-ray generation

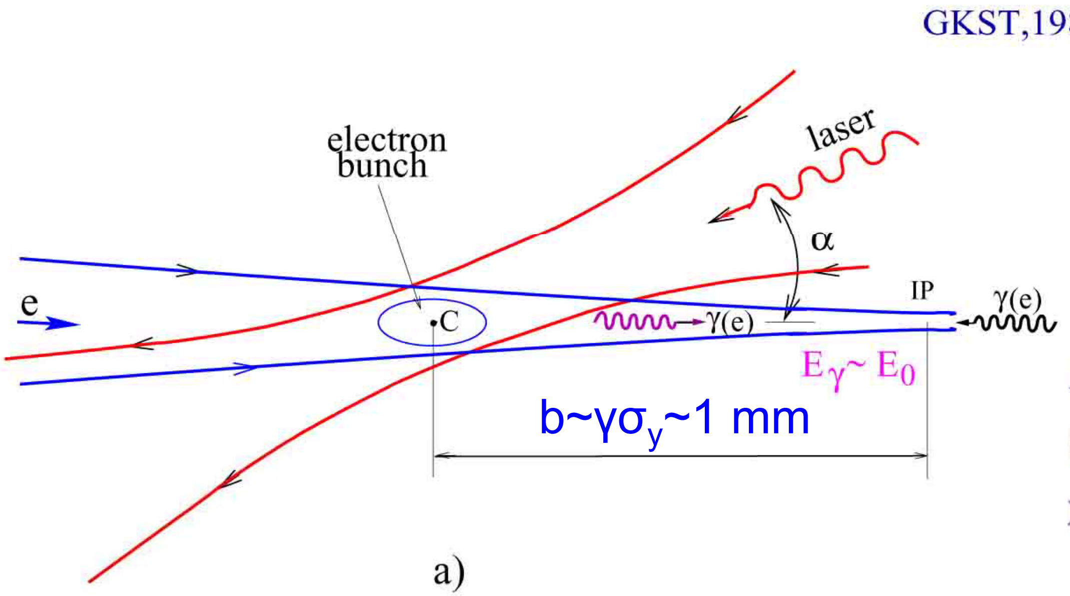
Z.Huang and R.Ruth, Laser-electron storage ring,
Phys.Rev.Lett. 80: 976, 1998.

At present, Compton ring is considered for production of polarized positrons for the linear collider.

S.Araki et al, physics/0509016, T.Omori, this workshop

Basic principles and technologies are quite similar. I will speak mainly about linear laser cooling (first item) which is adequate for the photon collider.

Scheme of $\gamma\gamma$, γe collider



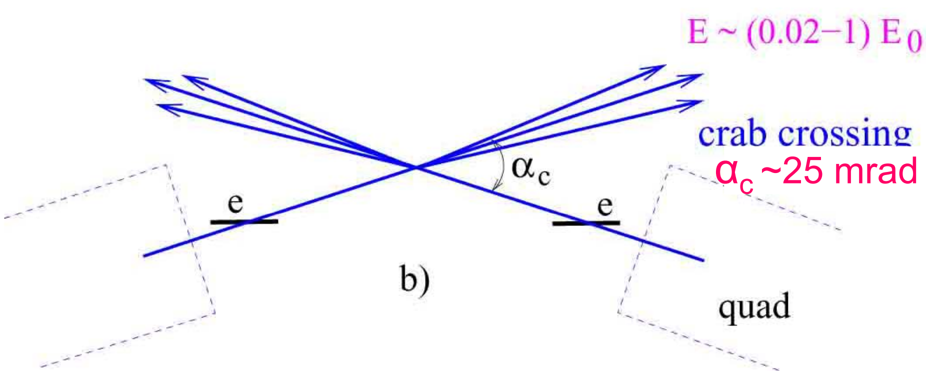
$$\omega_m = \frac{x}{x+1} E_0$$

$$x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\omega_0}{\text{eV}}\right]$$

($\omega = 4\gamma^2\omega_0$ at $\omega \ll E$)

$E_0 = 250$ GeV, $\omega_0 = 1.17$ eV ($\lambda = 1.06\ \mu$m) $\Rightarrow$

x=4.5, $\omega_m = 0.82 E_0 = 205$ GeV



$x = 4.8$ is the threshold for $\gamma\gamma_L \to e^+e^-$ at conv. reg.

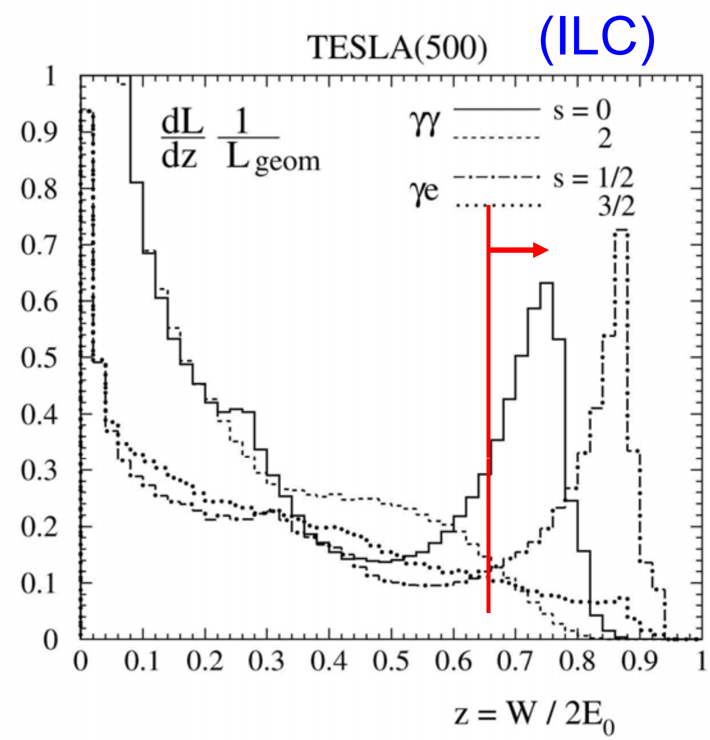
$\omega_{max} \sim 0.8\ E_0$

$W_{\gamma\gamma,\ max} \sim 0.8 \cdot 2E_0$

$W_{\gamma e,\ max} \sim 0.9 \cdot 2E_0$

Luminosity spectra ($\gamma\gamma$ and γe)

(with account of collision effects)



Usually a luminosity at the photon collider is defined as the luminosity in the high energy peak, $z>0.8z_m$.

For nominal ILC beam emittances and optimum focusing

$L_{\gamma\gamma}(z>0.8z_m) \sim 0.17\ L_{e+e-}$(nominal)
$\sim 0.35 \cdot 10^{34}\ cm^{-2}\ s^{-1}$

(but cross sections in $\gamma\gamma$ are larger by one order, and the number of events in e+e- and $\gamma\gamma$ will be similar)

Requirements to beam emittances

At the ILC, beams are produced in damping rings with C~6 km. Normalized emittances

$$\varepsilon_{nx}/\varepsilon_{ny}=10/0.04\ \mathrm{mm\cdot mrad}$$

satisfy e+e- requirements, where the luminosity is determined by collision effects (instability and beamstrahlung), for suppression of beamstrahlung the beam should be flat. For the ILC(500)

e^+e^- $\sigma_x/\sigma_y = 650\ /\ 5.5\ \mathrm{nm}$ ($\beta_x/\beta_y = 20\ /\ 0.4\ \mathrm{mm}$ at $\sigma_z = 0.3\ \mathrm{mm}$)

For $\gamma\gamma$ collisions one can reduce β_x only down to 5mm (limitation due to chromo-geometric aberrations). As result beam sizes at the IP

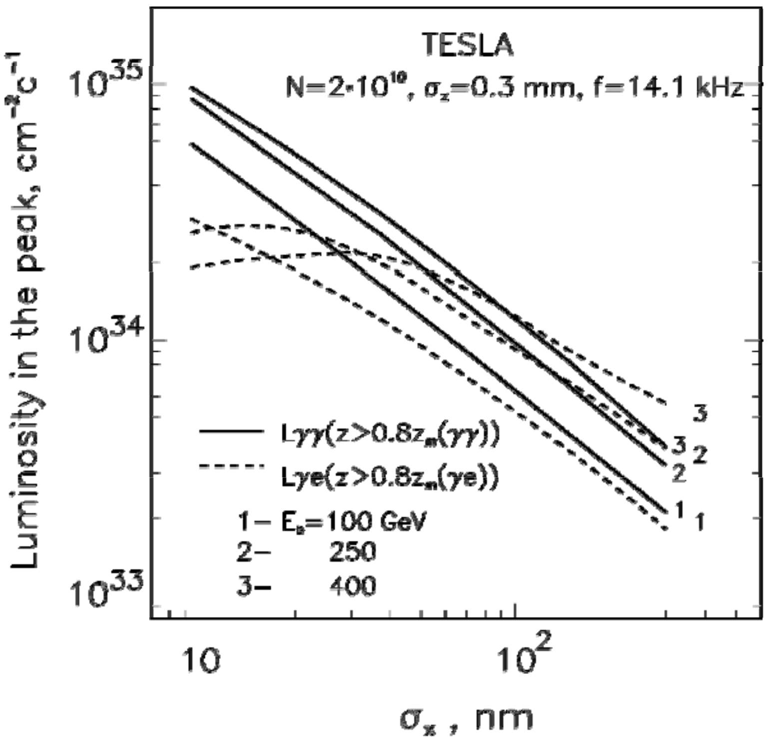
$\gamma\gamma$ $\sigma_x/\sigma_y \sim 300\ /\ 5\ \mathrm{nm}$

But what is the physical limit of beam sizes for the photon collider ?

Factors limiting γγ, γe luminosities

- Coherent e+e- pair production (in γγ, γe)
- Beamstrahlung (in γe)
- Beams repulsion (in γe)

Simulation (see Fig.) shows that for γγ collisions at 2E< 1 TeV one can use beams with horizontal beams sizes as small as 10-20 nm without beam collision effects.



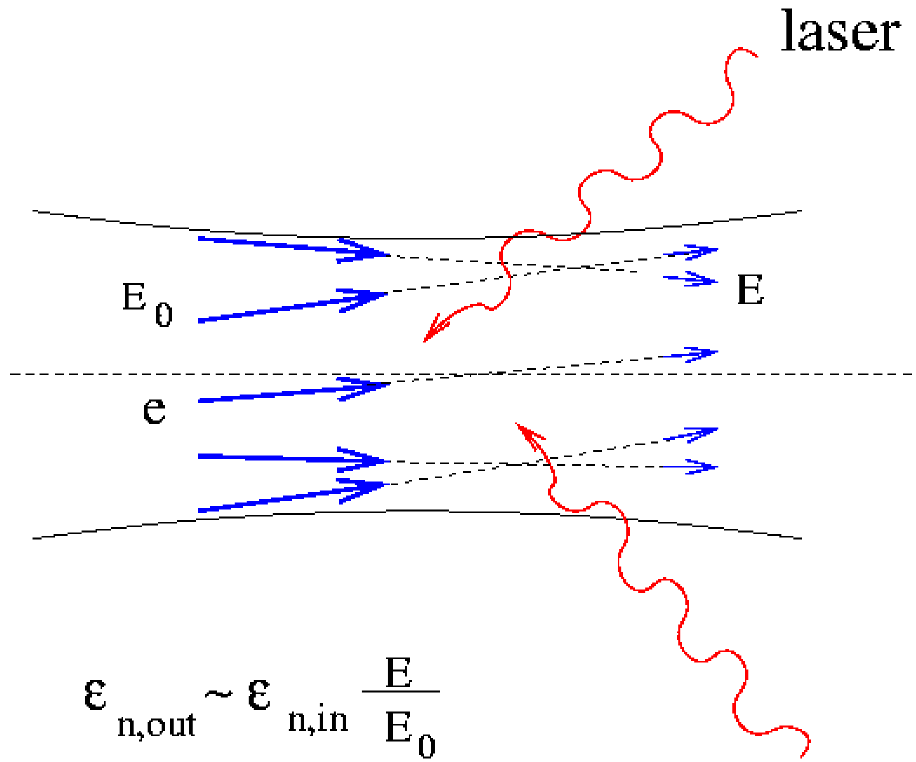
So, γγ luminosity is just proportional to the geometric e^-e^- luminosity (for 2E<~1 TeV). Having beams with smaller emittances one could get γγ luminosity larger by more than one order of magnitude than those attainable with damping rings (which give σ_x ~300 nm)

Limitting factors in damping rings

In damping rings emittances are determined by stochastic emission of photons in bending magnets, intra-beam scattering and beam space charge effects. Additional damping provide wigglers, but they help not very much: damping time is long enough and all effects give substantial contributions.

Much faster cooling can be done using laser wigglers. All is similar, but the range of parameters and technology are completely different.

Laser cooling of electrons



$$\varepsilon_{n,out} \sim \varepsilon_{n,in} \frac{E}{E_0}$$

During Compton scattering electrons loss longitudinal and transverse momenta, as result the normalized emittance $\varepsilon_n = \gamma\varepsilon = \sigma_x(\sigma_{pt}/mc)$ decreases.

Estimation of minimum emittance

The beam shape in the focal area $\sigma_i = \sqrt{\varepsilon_i \beta_i} \sqrt{1 + z^2 / \beta_i^2}$

In the electron rest system laser photon has the energy $\omega = \gamma\omega_0$.

In equilibrium, $p_t^2/m \sim \gamma\omega_0$. (1)

The angular spread $p_t/\gamma mc \equiv \mathrm{sqrt}(\varepsilon_n/\gamma\beta)$ (2)

From (1),(2) we obtain

$$\varepsilon_n \sim \frac{\omega_0}{mc^2}\beta \sim \frac{\lambda_c}{\lambda}\beta \qquad (\lambda_c = \hbar / mc)$$

Compared to an usual undulator with a period of several cm, the laser undulator needs smaller beta-functions for obtaining the same emittance.

Minimum emittances

More accurate consideration gives for the equilibrium normalized emittance

$$\varepsilon_{nx} \approx \frac{3\pi}{5}\frac{\lambda_c}{\lambda}\beta_x(1+3\xi^3) = \frac{7.2\cdot 10^{-9}\beta_x[cm]}{\lambda[\mu m]}(1+3\xi^3) \quad m\cdot rad \qquad (3)$$

$$\varepsilon_{ny} \approx \frac{3\pi}{5}\frac{\lambda_c}{\lambda}\beta_y(1+2.3\xi) = \frac{7.2\cdot 10^{-9}\beta_y[cm]}{\lambda[\mu m]}(1+2.3\xi) \quad m\cdot rad \qquad (4)$$

where $\xi^2 = \frac{e^2\langle B^2\rangle\hbar^2}{m^2\omega_0^2c^2} = \frac{2n_\gamma r_e^2\lambda}{\alpha}$ "undulator" parameter (5)

For example, λ=10 μm, β=10 cm => $\varepsilon_{n,min}$~$7\cdot10^{-9}$ m·rad

While at the ILC with DR $\varepsilon_x=10^{-5}$ m·rad, $\varepsilon_y=4\cdot10^{-8}$ m·rad.

The product of emittances with laser cooling is smaller by a factor 8000, the luminosity (1/sqrt($\varepsilon_x\varepsilon_y$)) will be smaller by two order of magnitude.

In reality, the term with ξ is also important and reduces the profit.

The question: why we need the laser undulator when in usual undulators ultimate emittances are even smaller.

The answer: the damping length

$$l_d = \frac{3\lambda^2}{2(2\pi)^2 r_e \xi^2 \gamma} = 650 \frac{\lambda^2[cm]}{\xi^2 \; E[GeV]} \quad km$$

($r_e = e^2/mc^2$)

At $\xi^2 < 1$ (undulator regime) and E=5 GeV,

l_d=13000 km at λ=10 cm

l_d=13 cm at λ=10 μm

For $\xi^2 > 1$ (wiggler regime,Eq.3) $\varepsilon_{nx} \propto \lambda^2 B^3 \beta \propto \lambda^2 \beta L^{-3/2}$

Calculations show that for a linear cooling section of several km length made of wigglers the resulting emittance is even larger than that in damping rings (because B is larger). Such linear wiggler cooling was considered by N.Dikansky, A.Mikhailichenko in 1988.

So, for linear cooling on reasonable length the wiggler period should be short, the field strong, the aperture large enough, that is the laser wiggler

Laser flash energy

The shape of he laser beam near the focus

$$r_\gamma = a_\gamma \sqrt{1 + z^2 / Z_R^2}, \quad Z_R = 2\pi a_\gamma^2 / \lambda$$

For $Z_R << l_e \approx l_\gamma$ the required flash energy (A)

$$\frac{\varepsilon_{n0}}{\varepsilon_n} \approx \frac{E_0}{E} = 1 + \frac{A}{A_0} \qquad A_0 = \frac{3mc^2 \lambda l_e}{64\pi^2 r_e^2 \gamma_0} = \frac{25\lambda\,[\mu m] l_e [mm]}{E_0 [GeV]} \; J$$

For λ=1 (10) μm, l_e=0.5 mm, E=5 GeV we get A_0=2.5 (25) J, respectively

For a continues cooling-acceleration $\varepsilon_n = \varepsilon_{n0} \exp(-A / A_0)$

For example, at λ=10 μm, $\varepsilon_{n0}/\varepsilon_n$=50 at A=4$A_0$=100 J.

This is the minimum total flash energy required for the cooling of one electron bunch. This is just an estimate. For non-head-on collision angle (laser optics without holes) it will be larger by a factor of 3.

The laser flash energy is smaller for shorter wavelength, but for the choice of the optimum wavelength other effects are also important.

The energy spread

The energy spread increases due to quantum-statistical nature of radiation.
On the other hand it decreases due to the fact that $dE/dx \sim E^2$.
The energy spread after the energy loss from E_0 to E

$$\frac{\sigma_E^2}{E^2} \approx \frac{\sigma_{E_0}^2 E^2}{E_0^2} + \frac{56\pi \lambda_c \gamma_0}{10\lambda} \frac{E}{E_0}\left(1 - \frac{E}{E_0}\right)(1 + 0.65\xi) \qquad \lambda_c = \frac{\hbar}{mc}$$

For continuous linear cooling

$$\frac{\sigma_E^2}{E^2} \approx \frac{7\pi \lambda_c \gamma}{5\lambda}(1 + 0.65\xi)$$

(For cooling in the damping ring it is somewhat large: 14 instead of 7).

For example, E_0=3 GeV, λ=10 μm and ξ^2=1 we obtain σ_E/E=0.04. After acceleration up to 100 GeV the energy spread will be 0.12%, that meets the LC requirements. Even λ=1 μm gives an acceptable energy spread at the IP of LC, however the energy spread during the cooling is ~13%, that makes problem for focusing to the cooling point with a small β-function.

Chromatic aberrations, the problem of small β at cooling points

Chromaticity problem is focusing is characterized by the parameter

$$C = \frac{F}{\beta}\frac{\sigma_E}{E}$$

From (4) follows that in order to have ε_{ny} about the half of the nominal ε_{ny} at ILC, for ξ=1 one needs

$$\beta_y[\text{cm}] \sim 0.8\ \lambda[\mu\text{m}]$$

For F=50 cm, λ=10 μm, σ_E/E=0.04, β_y = 8 cm -> C=0.25
For F=50 cm, λ=1 μm, σ_E/E=0.13, β_y = 0.8 cm -> C= 8
Note, at the IP of the ILC C = (400/0.04)0.002~20

In order to have ε_{nx} ~0.05 of the nominal ε_{nx} at ILC, for ξ=1 one needs

$$\beta_x[\text{cm}] \sim 17\ \lambda[\mu\text{m}] \sim 20\ \beta_y$$

So, the chromatic problem is much easier for λ=10 μm. For λ=1 μm the focusing is a problem, proper chromatic corrections should be done at many focusing points.

T.Ohgaki (1999) (see also K.Yokoya, 2000) has considered the focusing system for laser cooling and found that σ_E/E=0.13 is not acceptable. Further studies are needed.

Plasma focusing? Still exotics.

The number of the cooling points

To achieve minimum emittances the laser cooling should be done at $\xi^2<1$.
For longitudinally uniform laser beam and $l_\gamma=l_e$

$$\xi^2 = \frac{2r_e\lambda A_1}{\pi Z_R l_e mc^2}$$

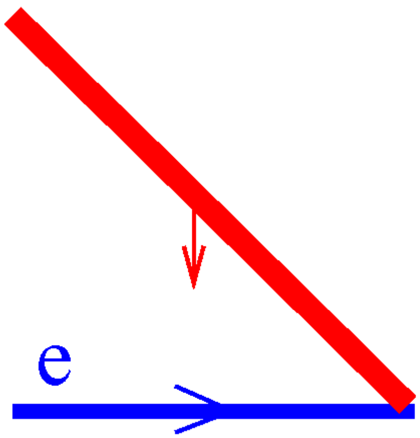
The number of cooling points for cooling by a factor of 2.71

$$n = \frac{A_0}{A_1} = \frac{3\lambda^2}{32\pi^3 r_e \gamma Z_R \xi^2} \approx \frac{0.5\lambda^2[\mu m]}{E_0[GeV]Z_R[mm]\xi^2}$$

For E_0=5 GeV, Z_R=1 mm and ξ^2=1 we get
n~1 for λ=1 μm and n=50 for λ=10 μm.

Each cooling region can have up to 4 cooling points. For good cooling (e^4) at λ=10 μm the total number of cooling sections should be about 50 (smaller for larger ξ^2).

The number of cooling sections which is necessary to provide $\xi^2<1$ can be decreased using tilted laser beams.



Such tilted beam for CO_2 laser can be obtained, for example, using Ge-plate with reflection-transmission controlled by several ps YLF laser pulses which make Ge conducting (technique used at BNL).

Depolarization

For continuous laser cooling relative decrease of longitudinal polarization

$$\frac{\Delta\varsigma}{\varsigma} = -7.5\,\frac{\lambda_c \gamma}{\lambda}(1+2.5\xi)\,\ln(\varepsilon_{n0}/\varepsilon_n)$$

For E=5 GeV, λ=10 μm, ξ=1, $\varepsilon_{n0}/\varepsilon_n$=20 => $\Delta\zeta/\zeta$~-0.03

For λ=1 μm it is -30%, that is not good, it is desirable to decrease ξ.

Long vs short wavelength

Advantages of shorter wavelength:

- required flash energy $\propto \lambda$;
- there are powerful lasers with $\lambda \sim 1\ \mu m$;
- the number of cooling points is smaller.

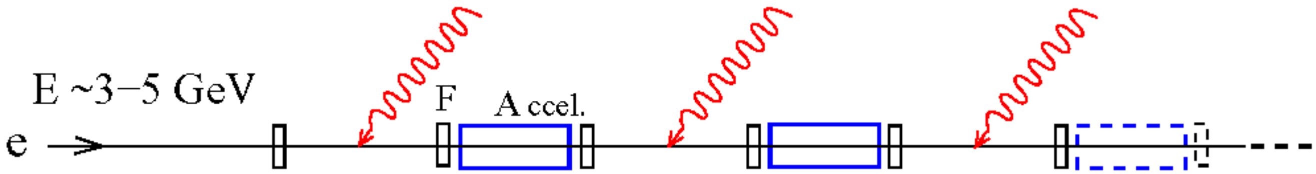
Advantages of longer wavelength:

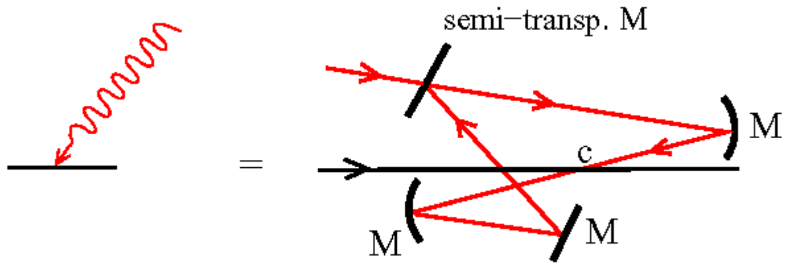
- $\varepsilon_n \propto 1/\lambda$;
- the energy spread $\sigma_E/E \propto 1/sqrt(\lambda)$;
- easier chromaticity problem in focusing;
- depolarization $\Delta\zeta/\zeta \propto 1/\lambda$.

Note, one can use a short wavelength laser (λ_0) and collided with the electron beam not head-on ($\theta=0$) but at the angle θ, then the effective wavelength is longer: $\lambda=2\lambda_0/(1+\cos\theta)$. This method may have advantages in some cases, if a laser with long wavelength is not available, for example.

Optimization of the wavelength depends first of all on results of detailed consideration of chromaticity problem of obtaining small β.

Laser system





The optical “external” cavity pumped via semitransparent mirror can have Q~1000 that reduces considerably the required laser power. Cooling should be done after the beam compression, just before the main linac. One can generate initial beam in damping rings or use electron beam directly from polarized photo-guns (at present there are only DC guns with large emittance, but may be in future polarized RF guns with smaller emittances will appear.)

Even with such cavities the laser system for laser cooling is very difficult.

I don’t like present detailed parameters of the system until the chromaticity problem in obtaining small β becomes more clear. In any case, it is a about 1-1.5 km long system.

Damping rings with laser cooling?

Usually I assume a straight laser cooling system for linear colliders because it allows to reach ultimately small emittances.

Laser cooling rings has one advantage:

- smaller number of cooling sections because the bunch cross each section several times.

However, they have many disadvantages (stoppers):

- increase of the emittance due to radiation in bending magnets, due to intrabeam scattering and the space charge;
- DR can not operate with short beams (σ=0.3 mm) needed for LC;
- bunch compression after the DR with laser cooling is not possible due to very large energy spread.

So, only linear laser cooling seems possible for the linear collider (for the photon collider)

At present there is very big activity on development of the laser pulse stacking cavities at Orsay, KEK, CERN, BNL, LLNL for

- ILC polarimetry
- Laser wire
- Laser source of polarized positrons(ILC,CLIC,Super-B)
  (talk by T.Omori at this workshop)
- X-ray sources

All these developments are very helpful for the photon collider and for the laser cooling.

Conclusion

- Laser cooling of electron beams for LC is very promising, but a difficult task.
- The technique for this method is well staged:

  Laser wires

  X-ray generation in small rings with laser cooling

  Polarized positron production for LC

  Photon collider
- The laser cooling would be nice for the second stage of the PLC: PLC-factory. But we should think about this already now.