Two Laser-Plasma Methods for Conditioning Beams

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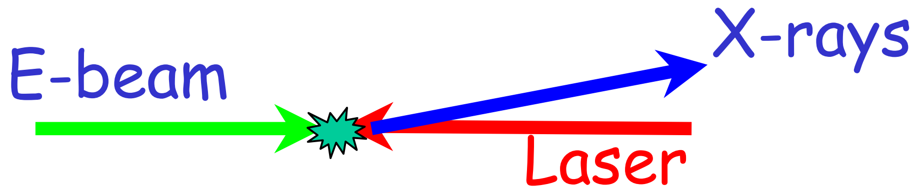
1. Laser Backscattering Conditioner



- The laser photons are backscattered, Compton scattered, off the moving electrons and thus cause the electron to loose energy. The up shift in energy is $4\gamma^2$.It is easy to tailor the laser pulse so that the electrons near the axis loose more energy than those at larger radii. It is necessary to choose the conditioning energy, $\gamma m_e c^2$, to be sufficiently low that there are a good number, N, of photons, of energy $h\nu$ required to give the necessary conditioning energy shift $\Delta\gamma_c m_e c^2$. We have:

$$N = \frac{\Delta\gamma_c m_e c^2}{h\nu 4\gamma^2}$$

1. Laser Backscattering(Continued)

- The Compton cross section is:

$$\sigma = \frac{8}{3}\pi r_0^2$$

The rate of collision is:

$$R(\#/\text{sec}) = F(\#/\text{cm}^2\text{sec})\sigma$$

Let the laser pulse length be τ. We require $R\tau=N$ or $F=N/\tau\sigma$.

The Rayleigh Length, $Z_R=\pi r_L^2/\lambda$, where λ is the laser photon wavelength and r_L the spot size. The pulse length is τc and this can't be shorter than the Rayleigh Length.

1. Laser Backscattering(Continued)

$$\# = F(\# / cm^2 \sec) r_L^2 (cm) \tau (\sec)$$

$$\text{Laser Energy} = \# h\nu = F r_L^2 \tau h\nu = \frac{Nc\,\tau\lambda h\nu}{\pi\sigma}$$

We can insert some numbers: $\Delta\gamma_c$= 5 MeV

λ= 1μ

γ= 200 (100 MeV)

$h\nu$= 1 eV

τ = 1 picosec

1. Laser Backscattering (Continued)

- We find that the energy is 5 J. (N comes out to be 30 and r_L is 10 microns.) The laser at LBNL is 2 J, >40 fs, and has a rep rate of 10 Hz. We would want a few 1 J lasers spread out over a few betatron periods.
- Multi-J, short pulse lasers exist at 10 Hz and there is rapid progress on laser technology. (Easier, but similar to the need for gamma-gamma colliders.)
- Andy Wolski's code can be readily modified to replace rf cavities with lasers and design a beam line.

1. Laser Backscattering(Continued)

- Of course one can insert different numbers into the formula. However, one must be careful to always keep N>>1. So, for example, increasing gamma and thus decreasing the required laser energy, is not good (but one could go a little way).
- Pump depletion is not a problem, in a typical case the number of electrons in a bunch is 1×10^{10} and there are 3×10^{19} photons, so only one in 10^{8} does anything. Or, equivalently, the energy used is only 5×10^{-8} J out of 5 J.
- Backscattering is an incoherent process and will lead to emittance growth

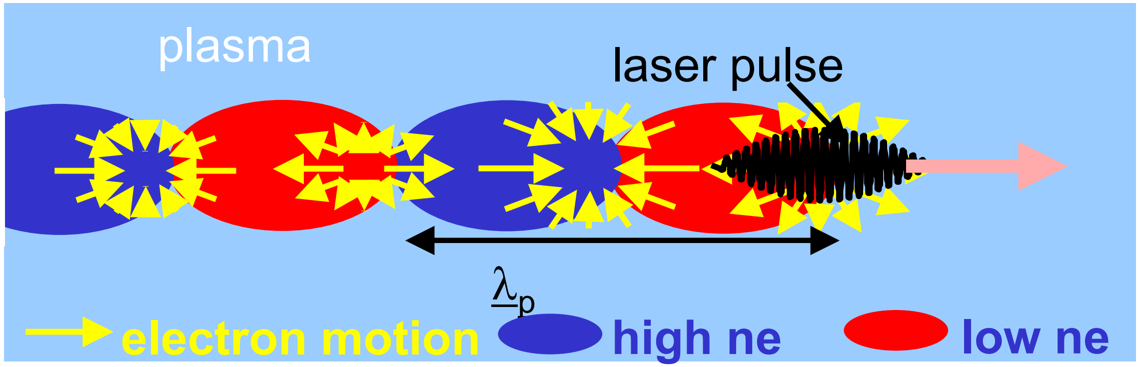
1. Laser Backscattering: Emittance Growth

- Transverse momentum kick from emission of single photon:
  - $\Delta p_x \approx E_{ph}/\gamma$
- Transverse kick from N photons
  - $\Delta p_x \approx (E_{ph}/\gamma)\ N^{1/2} \approx (E_{ph}/\gamma)\ N^{1/2} \approx \gamma\ mc\ \Delta\theta$
  - $\Delta\theta \approx (NE_{ph}/\gamma\ mc^2\ )/(\gamma\ N^{1/2}) \approx (\Delta\gamma\ /\gamma)/(\gamma\ N^{1/2})$
- Growth of emittance
  - $\Delta\varepsilon_N \approx \gamma\ r_b \Delta\theta \approx (\Delta\gamma\ /\gamma)(r_b/N^{1/2})$
- For fixed $\Delta\gamma\ /\gamma$ and $N^{1/2}$, reducing $\Delta\varepsilon_N$ requires enhanced focusing (smaller r_b)
- Example: $\Delta\gamma$=10, γ=200, N=30, r_b = 30 μm (rather than its natural size of ≈ 300 μm)
  - $\Delta\varepsilon_N \approx 0.3$ mm-mrad

2. Laser-Plasma Wakefield Conditioner

- Conditioning can, of course, be accomplished by having a shaped absorber so there is more energy loss on axis than at large radii. An absorber of this type is considered for longitudinal muon cooling. However, even with the best of material (liquid hydrogen) the scattering of electrons would lead to an excessive growth of emittance for the fine beams we are considering.
- However, in a plasma, the energy loss can be coherent and, therefore, rather large even while the scattering remains small. Thus it is interesting to consider a plasma wake-field conditioner with the wake generated by a laser pulse.

2. LWFA Conditioner (Cont'd)



- Laser Wakefield Accelerator (LWFA) basics:
- Plasma wave wake driven by laser ponderomotive force
  - $F_{pond} \sim \nabla I$ (I = laser intensity)
- Radial profile of accelerating wakefield proportional to that of the laser intensity profile (linear regime):
  - $E_z(r) \sim I(r) \sim \exp(-2r^2/r_L^2)$ (r_L= laser spot size)
  - $E_z(r) = E_{max} \exp(-2r^2/r_L^2) \sin k_p(z\text{-}ct)$
- Wake max. when laser pulse length ≈ plasma wavelength:
  - Plasma wavelength: $\lambda_p \sim n^{-1/2}$ (n = plasma density)
- Lifetime of wake typically many λ_p (many ps)

2. LWFA Conditioner (Cont'd)

- LWFA scaling laws:
- Plasma wavelength: $\lambda_p \sim n^{-1/2}$
- Plasma density: n
  - For uniform acceleration: $\lambda_p \gg z_{bunch}$
  - Let: $\lambda_p = 10\ z_{bunch} = 230\ \mu m \Rightarrow n = 2.1\times10^{16}\ cm^{-3}$
- Laser pulse length: τ
  - Max. wake excitation: $c\tau = 0.37\ \lambda_p = 85\ \mu m$ (280 fs)
- Laser spot size: r_L
  - Reduce acceleration at beam edge: $r_L = r_{bunch} = 28\ \mu m$
- Interaction length $\approx 2\ Z_R$ (Z_R =Rayleigh length):
  - $2Z_R = 2\pi\ r_L^2/\lambda = 0.62$ cm (for $\lambda = 0.8\ \mu m$)

2. LWFA Conditioner (Cont'd)

- LWFA scaling laws (cont'd):

- Wake axial electric field: $E_{max} \sim n^{1/2} a_L^{\,2}$ $(a_L^{\,2} \ll 1)$

  - $E_{max}\,[V/m] = 36\,(n[cm^{-3}])^{1/2}\, a_L^{\,2} = 5.3\times10^{9}\, a_L^{\,2}$

- Laser strength parameter: a_L
  - $a_L = 8.5\times10^{-10}\,\lambda[\mu m](I[W/cm^2])^{1/2}$
- Laser power: P
  - $P[GW] = 21.5(a_L r_L/\,\lambda)^2 = 26\times10^{3}\, a_L^{\,2}$

2. LWFA Conditioner (Cont'd)

- Radial wakefield produces head to tail variations in focusing
- Radial wakefield:
  - $E_r = (2r\, \lambda_p/\pi\, r_L^{\,2}) E_{max} \exp(-2r^2/\, r_L^{\,2}) \cos k_p(z\text{-}ct)$
- At beam end and edge ($r=r_b$ and $z=L_b/2$):
  - $E_r \approx 0.22\ E_{max}$
- This can be handled using the lattice methods developed by A. Wolski et al. (But the radial field is *very* large.)
- The radial field also produces a change in focusing and that must be considered.

2. LWFA Conditioner (Cont'd)

- Example: $\lambda = 0.8$ μm, $c\tau = 85$ μm, $r_L = 28$ μm, $2Z_R = 0.62$ cm, $\lambda_p = 230$ μm, $n = 2.1\times10^{16}$ cm^{-3}
- a_L=0.2 (I= 8.7×10^{16} W/cm^2, P= 1.1 TW, 0.29 J)
- Accelerating field on-axis and at beam edge
  - $E_z(r=0) = 210$ MV/m
  - $E_z(r=r_L) = 29$ MV/m
- Distance required for a 1 MeV energy difference:
  - $Z = 0.55$ cm ($\approx 2Z_R$)
- Beam conditioning requires (perhaps) five laser pulses interacting at different betatron phases (within A. Wolski's lattice) for a 5 MeV energy difference
- Plasma length (per interaction) $\geq 2Z_R = 0.62$ cm

3. Laser and Plasma Conditioners: General Comments

- Compton method requires a much higher energy laser (few J) versus that for the wakefield method (few tenths of J).
- Wake method requires a properly designed lattice so as to remove the kick effect of E_r. Compton method requires only a tight focus.
- Wake method can condition at high beam energy (conditioning does not need to be preserved through accelerator) , whereas Compton method requires low energy.
- Compton method's physics is straightforward (laser only), whereas wake method requires the generation of a plasma and understanding of laser-plasma dynamics.
- Compton method is an incoherent process and leads to emittance growth; wakefield is coherent.

4. Current Status of Compton Scattering and Laser Accelerators

- High Power Lasers: Examples (0.8 micron, Ti:sapphire)
  - LBNL: 2 J, > 50 fs, <20 TW at 10 Hz (upgrade to 100 TW at 10 Hz underway)
  - Michigan: 20 mJ, >20 fs, <1TW at 1 kHz
- Laser wakefield accelerators (many labs, e.g., LBNL):
  - Gradients: 1-100 GeV
  - Electron energies: > 100 MeV
- Compton backscattering (many labs, e.g., LBNL)
  - BNL (ATF): Electron beam: 3×10^9 e^-, 60 MeV, 5 ps; Laser: 17 GW CO_2, interaction length $2Z_R$=1.4 mm (4.7 ps), effective laser energy 78 mJ.
    - X-ray photons at 6.8 keV, 2×10^8 ph/pulse