Compton ring with laser radiative cooling

Advance in Compton sources

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Outline

Method of fast laser radiative cooling in Compton storage rings

- Essence of radiative cooling
- Asymmetric ‘fast’ cooling
- Fast cooling in synchrotron–dominated rings
- Challenge of LHeC

Thermodynamics of Radiative Cooling

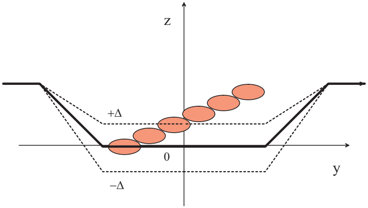
Necessary conditions: three ‘many’ in average

Each electron in bunch must undergone:

- Many betatron oscillations
- Many synchrotron oscillation
- Many photons scattered off (emitted)

Asymmetric Cooling: Problem setup

Model of Collision Points (CP)



Model setup

Laser radiation field exists at $z \geq 0$

- Theoretical model
  - Synchrotron motion: $p = \sqrt{2S}\cos\psi$
  - Betatron motion: $z = Dp + \sqrt{2\epsilon\beta_{\mathrm{cp}}}\sin\theta$
  - Scattering condition: $z > 0$
- Simulation
  - Synchrotron motion: drift + rf cavity
  - Betatron motion beyond CP: harmonic + synchrotron damping
  - Scattering: Compton recoils (Monte Carlo)
  - CP setup: array of 3D laser pulses; crossing in (x, y) plane at certain angle
  - Dispersion at CP induced by a chicane

Theory

Coupling of the Synchrotron and Betatron Emittances

With $\varepsilon = \epsilon/\beta_{\mathrm{CP}}$ normalized emittance, $S = \langle p^2 \rangle$ rms spread $[p = (\gamma - \gamma_{\mathrm{s}})/\gamma_{\mathrm{s}}]$, $g = D/\beta_{\mathrm{CP}}$ normalized dispersion at CP (β_{CP} the betatron function at CP), changes per the average interaction are:

$$\begin{aligned} \frac{\Delta\varepsilon}{\Delta\tau} &= -\frac{b}{2}\varepsilon + bg\sqrt{2\varepsilon}\, F_s\left(G\right) \\ &\quad + \frac{3b^2}{80\gamma^2}\left(1 + \frac{14}{3}g^2\gamma^2\right) ; \\ \frac{\Delta S}{\Delta\tau} &= -bS - b\sqrt{2S}\, F_c\left(G\right) + \frac{7b^2}{40} . \end{aligned}$$

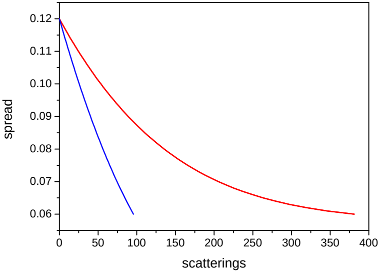
where $b \approx 4\gamma_{\mathrm{s}}\gamma_{\mathrm{las}}$ is the maximal recoil undergone by the electron scattered off the laser photon; $G \equiv g\sqrt{S/\varepsilon}$.

- Spread $\langle p^2 \rangle$
  - No dispersion: $\langle p^2 \rangle_* = 7\gamma_{\mathrm{s}}\gamma_{\mathrm{las}}/10$
  - Positive dispersion: $\langle p^2 \rangle < \langle p^2 \rangle_*$
- Emittance ε
  - No dispersion: $\varepsilon_* \approx 3\gamma_{\mathrm{las}}/10\gamma_{\mathrm{s}}$
  - Positive dispersion: $\varepsilon > \varepsilon_*$, exponential growth.

Negative dispersion decreases the emittance, but significantly increases the spread.

'Decrements:' Fast Damping.

Time scale in scattering events (the number of scattered off photons)



Theoretical damping of spread vs scatterings.

No dispersion, positive dispersion

- No dispersion at CP
  - Damping of the transversal emittance (initial ε_0, steady ε_*)

$$\varepsilon(\tau) - \varepsilon_* = (\varepsilon_0 - \varepsilon_*)\, \mathrm{e}^{-b\tau/2}$$

  - Damping of the squared spread – two times faster:

$$\langle p^2 \rangle - \langle p^2 \rangle_* = \left(\langle p^2 \rangle_0 - \langle p^2 \rangle_*\right) \mathrm{e}^{-b\tau}$$

- Positive dispersion
  - Both steady–state emittance and transition time increased
  - Both steady–state spread and transition time decreased

Regular Radiative Cooling

- Exponential decrease of the initial spread.
- *e*–fold reduction of the spread takes $t_e = \gamma/\dot{\gamma}$ time: the electron emitted full energy $\gamma m_0 c^2$ and restored it from RF system.
- Robinson's sum rule hold.

Asymmetric 'Fast' Radiative Cooling

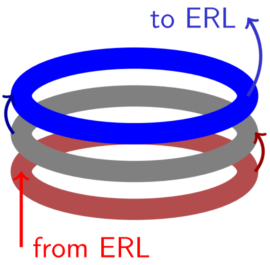
- Non–exponential decrease of the initial spread, depending on the initial spread and the transversal emittance.
- *e*–fold reduction of the spread takes shorter time $t_e < \gamma/\dot{\gamma}$: the electron emitted (and restored) smaller fraction of energy than $\gamma m_0 c^2$.
- Robinson's sum rule violated.

Importance and Application

- Intensive gamma–sources
    - Reduction of steady–state spread reduces the bunch length: enhance of the yield
    - RF voltage may be lower
- Regular synchrotron dominated x– and gamma–ray Compton sources
    - ‘Quantum losses’ reduce beam lifetime (efficiency)
    - Since particles diffuse out from bottom of the longitudinal separatrix, shift of CP into top should reduce the losses
- LHeC challenge: fast damping of continual positron beam

A Positron Recovery Scheme for LHeC
How to cool down continual beam (recall 3 'manys')

6 mA Positron Beam *Tri–Ring Scheme*



- Basic cycle
  - N–turn injection from ERL in accumulating ring
  - N–turn cooling in cooling ring (laser fast cooling may employed)
  - N–turn slow extraction from extracting ring into ERL
- 1–turn transfer from cooling ring into extracting ring
- 1–turn transfer from accumulating ring into cooling ring

Average current in the cooling ring is $N\times$average ERL current.

Laser cooling may generate positrons to compensate losses.

Laser Fast Cooling: Summary and Outlook

- Reduction of cooling time and increase of cooling efficiency
- Progress in Compton cooling directly connected with progress in laser techniques and development of short wave high voltage continuous rf sources
- Asymmetry in quantum losses may be used for fast cooling proof-of-principle

THANK YOU FOR ATTENTION !

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