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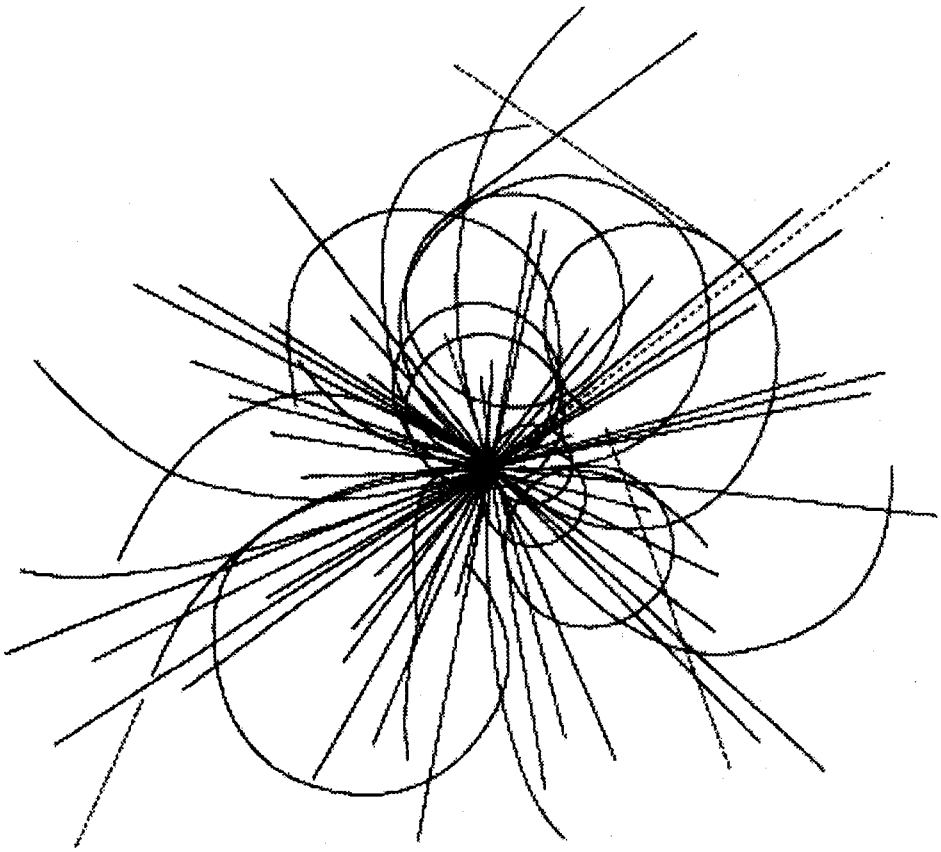

Superconducting Super Collider Laboratory

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Electron Cooling of Electron Beams*

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ELECTRON COOLING OF ELECTRON BEAMS

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ABSTRACT
Electron cooling of electron (and positron) sources may be important for future linear collider applications. In order to cool electrons with electrons, an intermediary positron beam must be employed, since it is impossible to merge two beams of identical particles into the cooling straight. By adjusting the beta functions of the electron and positron lattices appropriately, the final emittance of the stored electron beam can be made less than the emittance of the cooling electron beam. This paper will discuss accelerator physics issues relating to an electron-cooled electron beam source.

1. INTRODUCTION

Electron cooling was originally proposed by Budker in 1966 [1]. The basis for his proposal came from work done by Spitzer [2] (1956), who showed that warm ions come to equilibrium with cooler electrons in a plasma. Due to the much larger mass of the ion, the final rms speed of the ions is much less than that of the electrons. Budker realized that an electron beam is simply a moving electron plasma. By superimposing an ion beam on a co-moving electron beam, warmer ions are cooled by the electron beam.

In the 1970s electron cooling was demonstrated to be an extremely good way of increasing the phase space density of proton beams. Cooling times of 1−5 s were reported by experiments at Novosibirsk [3], CERN [4], and Fermilab [5]. Recent experiments at the Indiana University [6] and at the Low Energy Antiproton Particle Ring (LEAR) at CERN [7] have made progress in extending the use of electron cooling to ion and antiproton beams, respectively. Electron cooling of positrons has also been suggested [8,9]. This paper will propose extending the use of electron cooling to electron beams.

Since electron cooling relies on a merging of beams that have identical average beam velocity, it is not possible to directly merge an electron cooling beam on a hot electron beam. An intermediate beam must be used to transfer heat from the hot electron beam to the cooling beam. The best choice for the intermediate beam is to use positrons. Positrons do not decay, and their light rest mass is the best for cooling. Figure 1 shows the proposed electron cooling scenario. A cooling electron beam is formed in an electrostatic accelerator (not shown) and merged with a positron beam in the first cooling straight. The positron beam is then transported around to a second long straight section, where it is merged with the hot electron beam. The hot electron beam transfers heat to the positron beam, which in turn transfers heat to the cooling electron beam. The cooling electron beam is recirculated to the terminal of the electrostatic accelerator, where it is collected. The cooling electron beam is thus continuously regenerated at the cathode, and the heat is dumped into the electron beam collector.

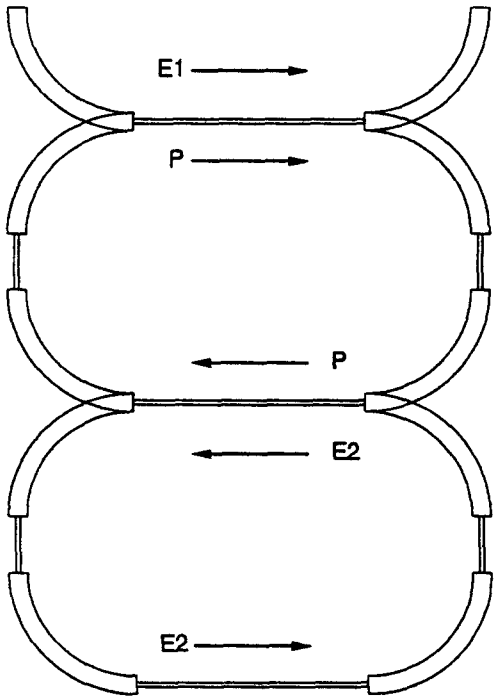

Figure 1. Schematic for electron cooling of electrons. Stored electron beam (E2) transfers heat to a stored positron beam (P), which transfers heat to the single pass cooling electron beam (E1).

2. EQUILIBRIUM OPERATION OF THE POSITRON HEAT TRANSFER RING

An earlier study of electron cooling of electrons was presented at the 1992 SPIE Conference [10]. That work was able to present a much more detailed study than the present work, due to the present page limit requirement. The earlier work derived the usual formula for the electron cooling of positrons,

$$dv_{p*}/dt = 60IL_c r_e^2 c^3/\beta\gamma^2 a^2 eCv_{p*}^2 \quad \text{(lab frame)} \quad , \tag{1}$$

where v_{p*} is the positron velocity in the moving frame, t is the time, I is the electron beam current, L_c is the length of the cooling straight, r_e is the classical radius of the electron, c is the speed of light in vacuum, β is the beam velocity divided by c, $\gamma = (1-\beta^2)^{-1/2}$, a is the beam radius, e is the charge on the electron, and C is the circumference of the positron ring. The earlier study went on to compare the electron cooling rate to the intrabeam scattering rate within the electron-cooled positron storage ring in order to determine where equilibrium operation of the positron storage ring would occur.

Figure 2 presents the equilibrium positron beam size within a possible positron heat transfer ring. The equilibrium vertical emittance is 0.2 π mm-mr, and the equilibrium horizontal emittance is 0.05 π mm-mr. These values compare favorably with what is desired for the next linear collider [11]. Table 1 presents parameters for the possible electron cooling system.

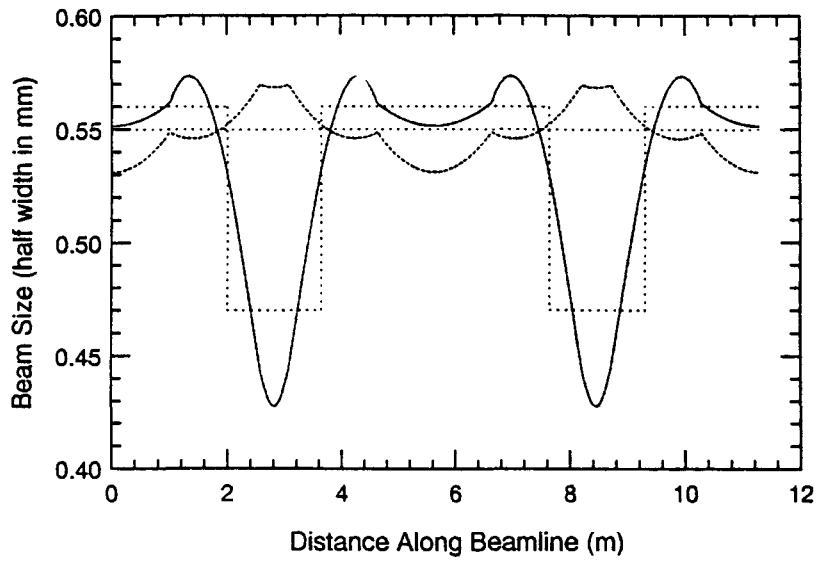

Figure 2. Equilibrium beam size in the positron heat transfer ring. Solid trace shows horizontal beam profile. Dashed trace shows horizontal beam profile. Dotted traces show beam size approximation for calculating IBS heating rates.

3. OPERATION OF THE ELECTRON COOLING RING

3.1. Determination of Cooling Time

The electron cooling time can be determined by including the minus sign and rearranging Eq. (1) as

$$-v_*^2 dv_* = dt 60 I L_c r_e^2 c^3 / \beta\gamma^2 a^2 e C \ . \tag{2}$$

Integrating from the initial time and velocity to the final time and velocity leaves:

$$[(v_{*i} - v_{*f})^3]/3 = (t_f - t_i) 60 I L_c r_e^2 c^3 / \beta\gamma^2 a^2 e C \ . \tag{3}$$

Linear collider designs typically use 10^{10} particles per bunch, which here corresponds to a current of 43 mA. The hot electron beam will likely be supplied by acceleration from a thermionic gun. Thermionic guns can produce such currents with transverse emittances of 0.5 π mm-mr. This emittance is a factor of ten larger than the value of the positron horizontal emittance; therefore, the electron horizontal beam size and divergence due to emittance will each be about a factor of three greater than the equilibrium positron beam values. Therefore $(v_{*i} - v_{*f}) \approx 10^{-3}$. In this case the cooling beam is the positron beam, and I = 43 mA and a = 0.55 mm. But the effective cooling current will be reduced by a factor of six due to the overlap of the positron beam with the hot electron beam. (Since the area of the positron beam is six times less than the area of the electron beam, 5/6 of the electron beam will not be in contact with the positron beam on any given pass.) So the effective cooling current is 7 mA. Substituting the appropriate values into Eq. (3) leads to an expected cooling time of

$$(t_f - t_i) = 1.9 \text{ ms.} \tag{4}$$

The value of cooling time indicates that electrons could be cooled and delivered to a linear collider at a rate of 500 Hz.

Table 1. Parameters of Electron and Positron Storage Rings	
Beam Kinetic Energy (MeV)	3.0
Relativistic Factors, β, γ	0.99, 6.87
Ring Circumference (m)	11.3
Entrance and Exit Dipole Pole Face Rotations (deg)	5
Length of Cooling Straight (m)	2
Average Value of Dispersion Function, D (m)	1.1
Transition Gamma, γ_T	1.265
Z/n Instability Limit (Ω)	20
Betatron Tunes Including Space Charge, ν_x, ν_z	1.135, 0.176
Betatron Tunes Excluding Space Charge, ν_x, ν_z	1.249, 0.452
Space Charge Tune Shift, $\Delta\nu_x$, $\Delta\nu_z$	0.114, 0.276
Electron Cooling Current (A)	0.1
Electron Cooling Beam Radius in Cooling Straight (mm)	3.2
Positron Beam Current (mA)	43
Equilibrium Positron Beam Radius in Cooling Straight (mm)	0.55
Equilibrium Normalized Positron Emittances ε_{nx}, ε_{nz} (π mm-mr)	0.05, 0.2
Equilibrium Positron Momentum Spread, $\Delta p/p$	3.65×10^{-4}
Stored Electron Beam Current (mA)	43
Initial Stored Electron Beam Size in Cooling Straight (mm × mm)	1.61 × 1.1
Equil. Stored Electron Beam Size in Cooling Straight (mm × mm)	0.55 × 0.55
Initial Norm. Stored Electron Emittances ε_{nx}, ε_{nz} (π mm-mr)	0.5, 0.5
Equil. Norm. Stored Electron Emittances ε_{nx}, ε_{nz} (π mm-mr)	0.05, 0.2
Initial Stored Electron Beam Momentum Spread, $\Delta p/p$	0.001
Equil. Stored Electron Beam Momentum Spread, $\Delta p/p$	3.65×10^{-4}
Cooling Time (ms)	1.9

3.2. Equilibrium in the Electron Cooling Ring

If the electron cooling ring has a lattice identical to the positron transfer ring, the IBS heating rate within the electron cooling ring is the same as the IBS heating rate for the positron transfer ring. But the cooling force will be much greater than the cooling force in the positron beam, since now the entire 43 mA positron beam is in contact with the electron beam. For this reason equilibrium in the electron cooling ring will be established thermally; the equilibrium emittance of the electron beam will equal that of the positron transfer beam.

The equilibrium emittances of the electron-cooled electron beam will be 0.2 π mm-mr vertically and 0.05 π mm-mr horizontally. The momentum spread will be $\Delta p/p = 3.65\times10^{-4}$.

4. POSSIBLE INSTABILITIES

Particle beams can become unstable if they are cooled too far. If all beam particles have the same momentum, image charges generated by the particles onto the surrounding environment (such as pipes) will all be in synchronization with each other. This can lead to a field large enough to destroy the beam (the Z/n instability). Neil and Sessler [12] originally derived the criterion for onset of the Z/n instability,

$$|Z/n| = Fmc^2 \beta^2 \gamma \eta (\Delta p/p)^2 (eI)^{-1} . \tag{5}$$

In Eq. (5) I is the stored particle beam current and η is the absolute value of the momentum compaction of the storage ring, $\eta = |(1/\gamma_t^2) - (1/\gamma^2)|$, where γ_t is the transition energy of the storage ring, here 1.265. F is a form factor of about 3. For both the electron and positron storage rings discussed here, the onset of the Z/n instability will occur for

$$Z/n = 20\,\Omega \quad . \tag{6}$$

Small beam sizes lead to an increase in the relative contribution of space-charge forces to the beam optics, causing a large tune spread that can cross destructive resonances, leading to beam loss. For the electron and positron lattices discussed here, the horizontal tune including space charge is 1.135 and the horizontal tune excluding space charge is 1.249. The vertical tune including space charge is 0.176 and the vertical tune excluding space charge is 0.452. This region of tune space avoids the destructive integer and half-integer resonances, but the vertical tune does cross the third integer resonance. It may be desirable to investigate different lattices to avoid this resonance as well.

5. CONCLUSION

This paper has presented the concept of electron cooling of electron beams. The necessary electrostatic accelerator technology for this concept has already been demonstrated [13]. The final emittance and rep rate capability of electron-cooled electron sources are a fine match to future linear collider needs.

6. ACKNOWLEDGEMENTS

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