Chapter 6

Electron Cooling at RHIC

6.1 Intra-Beam Scattering

The recent advances in nuclear physics experimental research demand high density particle beams with low emittances. Multiple small-angle Coulomb scattering or intra-beam scattering (IBS) is one of main limitations of luminosity and lifetime at the RHIC due to diffusion in both transverse and longitudinal planes. The presence of non-linear elements also results in the increase of the normalized emittance of the ion beam. Fig. 6.1 shows a typical RHIC store with Au-Au collisions at a top energy of 100 GeV/nucleon. Several analytical treatments have been developed to describe the effect of the IBS [58, 59, 60]. The growth rate due IBS either using a classical two body scattering or gas diffusion representation for round beams at high energies scales approximately as [61]

$$\frac{1}{\tau_{||}} \sim \frac{1}{(\beta_r\gamma_r)^3\epsilon_x^{3/2}\langle\beta_\perp^{1/2}\rangle} \tag{6.1}$$

where $\beta_r\gamma_r$ is the relativistic factor, ϵ_x is the transverse emittance, and $\beta_\perp$ is the average transverse beta function of the lattice. The transverse growth can be expressed as function of the longitudinal growth time as

$$\frac{1}{\tau_\perp} \sim \frac{1}{\epsilon_x}\left\langle\frac{D_x^2}{\beta_x}\right\rangle\frac{1}{\tau_{||}} \tag{6.2}$$

where, D_x and β_x are the average dispersion function and the beta function over the lattice. Note that the terms with derivatives of the dispersion and the β function have been neglected due to their weak contribution.

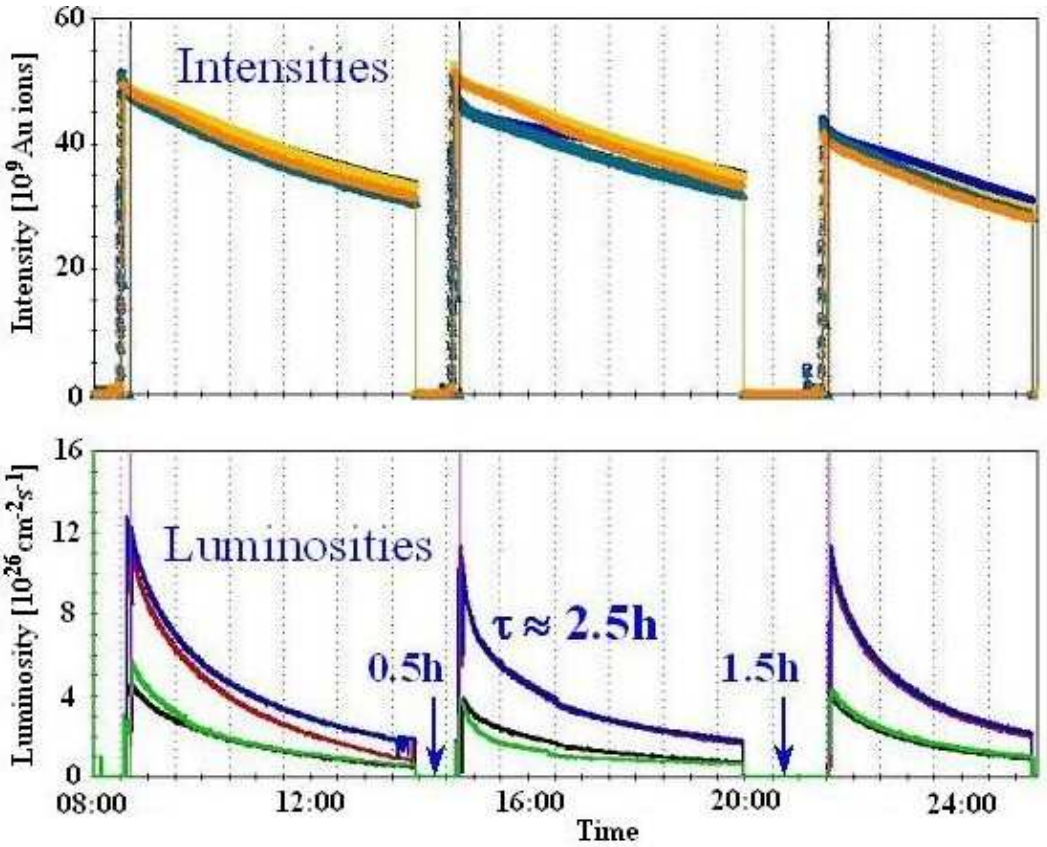

Figure 6.1: Typical RHIC stores and refill times with gold ions. The beam lifetime is limited by IBS leading to particle loss from the RF buckets. The luminosity lifetime is further reduced by transverse beam size growth from IBS. The luminosities are for the four RHIC experiments with β^*=1 m and β^*=3 m (courtesy W. Fischer).

6.2 Electron Cooling

Electron cooling is one of the key component in RHIC II, the next luminosity upgrade of RHIC aiming at a ten fold increase. Electron cooling, first proposed by G. I. Budker in 1965, is a technique to introduce low emittance electrons into the ion beam at the same average velocity (or $\langle\gamma\rangle$). Electron cooling can help increase the peak and average luminosity in several ways [62]:

- Energy exchange between ions to the electrons results in a decrease transverse emittance and momentum spread of the ion beam resulting in an increase in the luminosity.

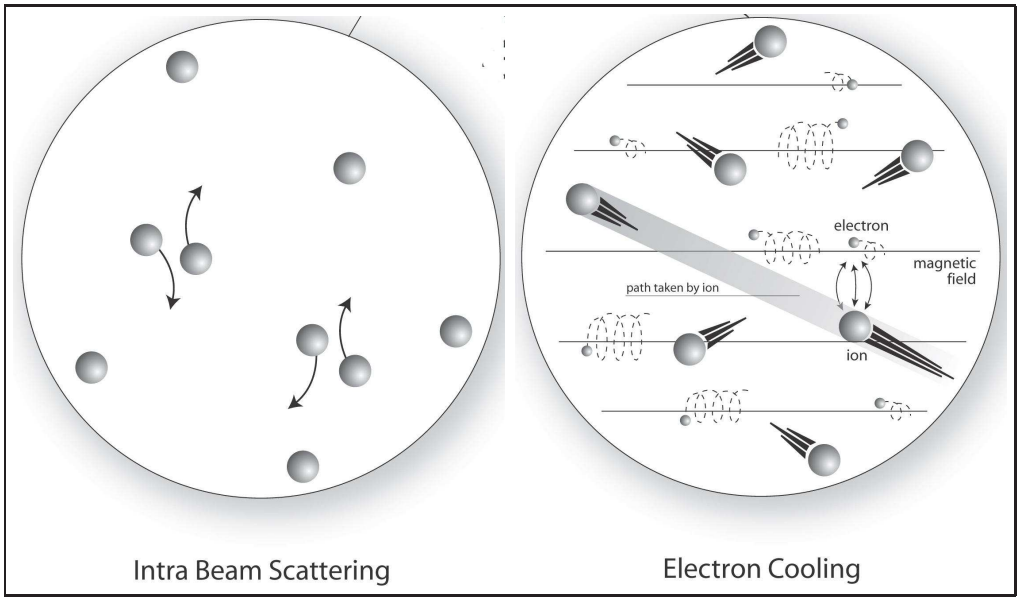

Figure 6.2: Graphical Representation of IBS with and without e^- cooling.

- The continuous cooling of ion beams may also help suppress non-linear resonances due to beam-beam interactions to achieve a higher beam-beam parameter and reduce emittance growth.
- The limitations imposed by the injectors to the high energy colliders can overcome accumulation of high intensity ion beams.
- Cooling of the large amplitude particles in the tail can result in a reduction of the experimental background.

The rate of cooling for a given transverse emittance scales as

$$\frac{1}{\tau_{cooling}} \sim \frac{Z^2 L_{cs}}{A\gamma^2}\left(\frac{\beta_x}{\gamma\epsilon_x}\right)^{3/2} \tag{6.3}$$

where Z and A are the ion charge and atomic number, L_{cs} is the length of the cooling section, and β_x beta function in the cooling section. For RHIC parameters with Au ions, the cooling time is estimated to be in the range of 15-30 min for a typical store of approximately 4 hrs. The ultimate goal of any collider is to reach particle burn-off limit which seems feasible at RHIC with e^- cooling.

Cooling Gold beams at 100 GeV/nucleon require an electron beam energy of approximately 54 MeV and a high average current in the range of 50-200 mA. The traditional e^- coolers are typically low energy DC accelerators. The energy of e^- beam for RHIC is quite high, and the only feasible option to generate high current high quality CW beam is via a superconducting energy-recovery linac (SC-ERL). Without energy-recovery, CW operation is prohibitive due to the large beam power. In this option, an e^- beam from the gun is accelerated using high gradient superconducting RF cavity ($\sim$ 15 MV/m) to match to the ion velocity and then injected into the colling section along with the ion beam for cooling. The e^-'s are returned back to the accelerating cavity with 180° phase shift to recover the energy back into the cavity before being dumped. A schematic of the proposed electron cooler with a $\sim$ 5 MeV SRF injector, a linac comprising of four five-cell SRF cavities, and a recirculation loop for energy recovery is shown in Fig. 6.3. Two variants of the e^- cooling, a non-magnetized version with a simple drift section, and a magnetized version with a 60 m solenoid are being considered as primary and secondary options for cooling sections respectively. Table 6.1 lists relevant beam parameters for both non-magnetized and magnetized versions. Future projects such as eRHIC (electron-ion collider) push the operational current to 300 mA-600 mA at 20 nC bunch charge or higher.

A prototype consisting of a $\frac{1}{2}$-cell SRF gun as an injector to a 20 MeV SRF linac comprised of a single five-cell SRF cavity, and a return loop back through the linac for energy recovery is being pursued as an initial R&D step towards the realization of high current e^- cooler and future SC-ERLs. Part II of thesis will focus on the design and development of SRF cavities in the ampere regime and their related challenges. The next section will introduce some relevant RF cavity basics, specifically related to SRF cavities. The following chapters will elaborate on the design of the five-cell SRF linac cavity followed by the $\frac{1}{2}$-cell SRF injector gun design for the SC-ERL prototype and some future developments.

Table 6.1: Parameters for the prototype SC-ERL used in simulations for optimization of the gun shape. A possible scenario with high charge and low repetition rate similar to the electron cooling case is also presented.

Parameter	Magnetized	Non-Magnetized
Injection energy [MeV]	5.2	5.2
Maximum energy [MeV]	20-40	20-40
Avg. beam current [mA]	200	50
Repetition rate [MHz]	9.4	9.4
Charge/Bunch [nC]	20	5
Norm. emittance [mm.mrad]	50	3
Bunch length [cm]	1.0	1.0
Energy recovery efficiency	> 99.95 %	> 99.95 %

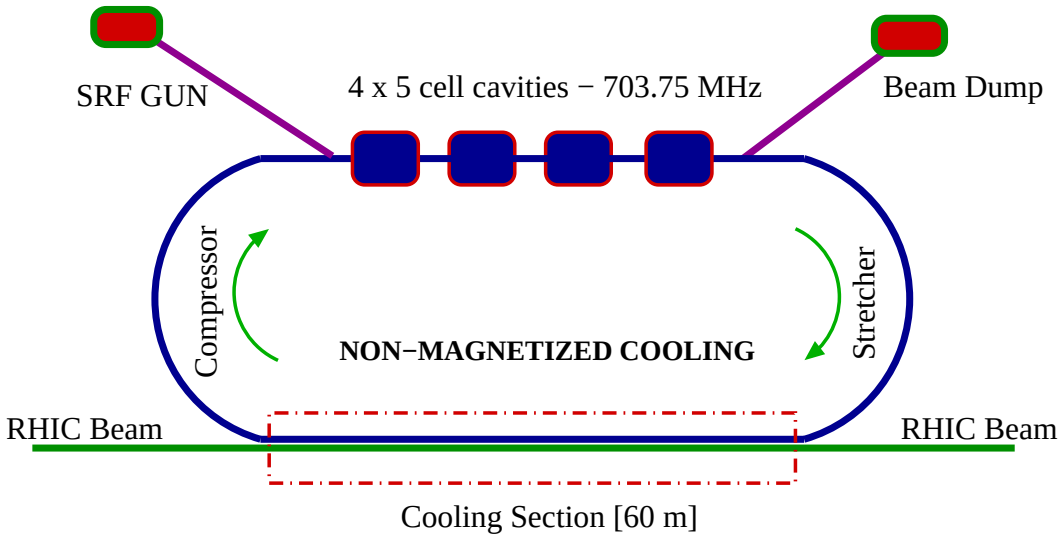

Figure 6.3: Electron cooling schematic for RHIC II upgrade (not to scale).