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Abstract

Electron cooling has been applied in many accelerators. All of them operate at low energies where cooling times are short. Electron cooling is now considered for RHIC where gold ions are stored at 100 GeV/u. The corresponding electron energy is 55 MeV. This energy cannot be reached with a DC source like a Fermilab's pelletron. The cooling time is proportional to the square of the energy. In order to have a cooling time of of less than one hour it is necessary to maintain a transverse normalized emittance of 50 mm mrad and an energy spread with a charge of 20 nC per bunch. Such beam quality cannot be achieved with a storage ring. Only a Photocathode Energy Recovery LINAC (PERL) promises success [1].

A special super-conducting cavity was developed for the RHIC electron cooler. It is optimized for high current operation and uses ferrite beam pipes outside the cryostat for higher order mode damping. First simulations with the TBBU computer code [2] show a beam breakup threshold of 3 Amperes.

A strong longitudinal field in the cooling section enhances the cooling process. A solenoid magnet with a field of 1Tesla and a field error of less than is being developed. For a minimum transverse temperature inside the solenoid it is necessary to have a "magnetized beam", i.e. a beam from a cathode immersed in a longitudinal magnetic field. The usual emittance compensation scheme needed to be adapted so that the magnetization does not lead to strong emittance growth.

The RF gun is super-conducting, providing high accelerating fields to minimize the effects of space charge. A cathode insert with a diamond window uses secondary electrons to produce the high charge and avoids a breakdown of superconductivity through surface contamination by the cathode material and the magnetic field required for the magnetization.

Finally, the bunch is lengthened and the energy spread in the cooling section is reduced by bunch rotation in the longitudinal phase space. This also reduces the space charge effect between electrons and ions. The original bunch length must be restored by a second rotation before deceleration and energy recovery.

INTRODUCTION

Electron cooling has been known for many years and is practiced in many machines around the world. The physics of cooling takes place in the reference frame of the ions (and electrons) bunch, which is independent of the energy of the machine. However, there are a number of differences between this electron cooler and any other built so far:

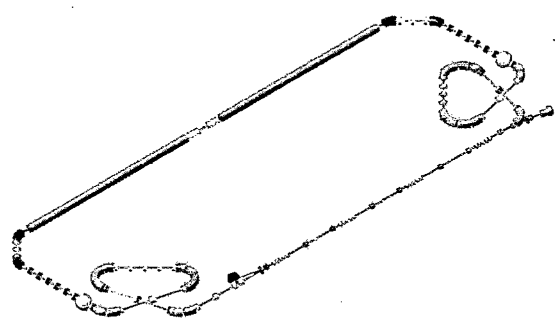

Figure 1: Electron bunches are produced in the gun and accelerated in the super-conducting linac. A beam-transport loop stretches the bunch length and a debunching cavity reduces the energy spread before the electrons are merged with the ion beams. A strong solenoid must be installed in the cooling section to enhance the cooling effect [10]. The electron bunches are then shortened by a combination of a second cavity / transport loop, and then decelerated in the linac before they are dumped. The start of operation is planned for January 2010.

- The RHIC cooler will be by far the highest energy cooler, requiring electron energy of over 50 MeV as compared to the few hundred KeV of any previously built cooler (the only exception is the recycler cooler of FNAL, which is under construction and will have 4.3 MeV electron energy).
- The RHIC cooler is the only machine planned for cooling with bunched electron beams.
- The RHIC II will be the first instance of a directly cooled collider.
- The RHIC cooler will operate with electrons that are much "hotter" than in previous coolers.
- The RHIC cooler will use a very long, high-field, ultra-high precision solenoid.

The electron beam technology of this cooler will be different than any other, requiring high-energy, high-current and low-emittance (temperature) electron beams. In order to reach the goals R&D is taken along the following fronts:

* Work performed under the auspices of the U.S. Department of Energy

ELECTRON SOURCE

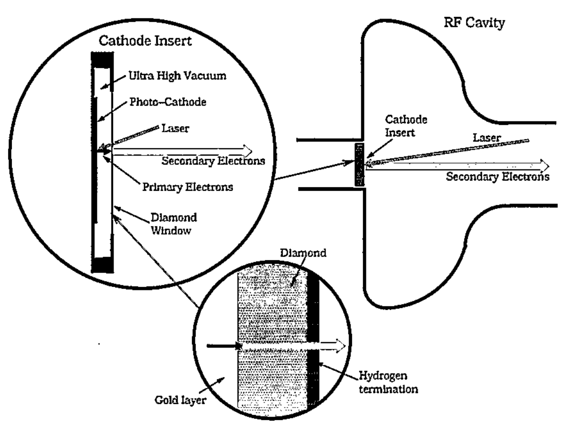

Figure 2: Schematic diagram of a secondary emission enhanced photoinjector. Please note that the figure is not to scale. The figure on top right shows the cathode insert in the gun cavity. The figure on top-left is a magnified view of the cathode insert. The gap between the diamond window and the photocathode is typically some fraction of a millimeter. The bottom figure is a blow-up of the diamond, showing (very schematically) a gold coating on the photocathode side of the diamond and hydrogen termination of the diamond's dangling bonds on the gun side of the diamond. The gold is very thin, about 10 nm or less, while the diamond may be as much as 10 microns thick, while the hydrogen is a monolayer.

An electron source based on a 703.75 MHz laser-photocathode RF gun (photo injector) must be developed. This research may be broken down to the following R&D components:

- High quantum-efficiency, long-lived photocathode. Fig. 2 shows the principle of a secondary emission enhanced photoinjector [3]. The secondary emission is produced in a diamond window which also shield the superconductive gun cavity from the photo-cathode material and the photo-cathode material from the cavity vacuum.
- High average-power, 9.4 MHz repetition frequency laser.
- A high electric field, CW operation RF gun.

ACCELERATING CAVITY

A five cell superconductive cavity (shown in Fig. 3) was developed which is optimized for high current operation. The large bore (17 cm iris radius, 24 cm beam pipe) allows HOMs to be damped in ferrite absorbers outside the cryostat. Fig. 4 shows the result of TDBBU calculations. The higher order modes differ in frequency from cavity to cavity due to manufacturing tolerances. A higher frequency spread allows higher beam current. The breakup current is above requirements.

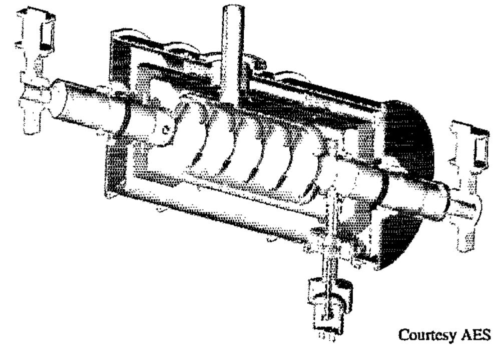

Figure 3: Superconductive cavity for high current operation.

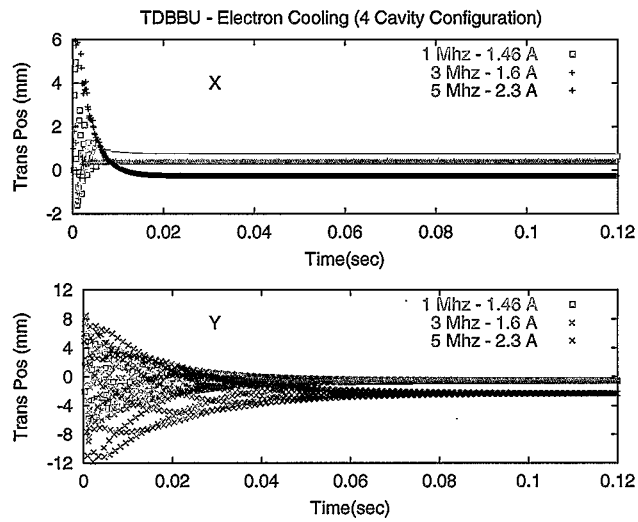

Figure 4: Beam breakup calculations with TDBBU.

ENERGY RECOVERY LINAC TEST FACILITY

In order to verify the energy recovery and beam breakup thresholds an energy recovery linac with a single cavity and variable optics will be build. The layout is shown in fig. 5. Injection energy will be 3-5 Mev, the maximum beam energy 15-20 MeV. Average beam current will be up to 200 mA, We expect a current recovery efficiency $> 99.95\%$. The ERL will operate in two modes: The high charge mode with a Bunch repetition rate 9.4 MHz, Charge per bunch $>= 10$ nC, Normalized emittance $\tilde{3}0$ mm mrad. The low charge mode with a Bunch repetition rate 9.4-700 MHz, Charge per bunch 0.3-1 nC, Normalized emittance $\tilde{1}$-3 mm mrad. Start of installation in September 06, commissioning in March 07.

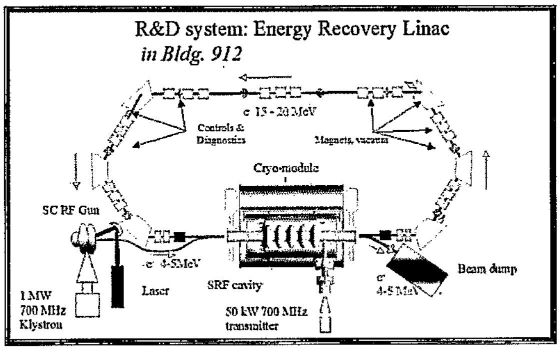

Figure 5: Energy recovery linac test facility.

COOLING SOLENOID

The friction force is proportional to $\frac{v_{ion}^2}{(v_{ion}^2+v_{longitudinal}^2+v_{tranverse}^2)^{3/2}}$ where $v_{tranverse}^2$ for a magnetized beam is given by the transverse field components of the solenoid. The relative field error must be less than $8 \cdot 10^{-6}$. The transverse field is measured using a magnetic mirror and corrected with dipole corrector.

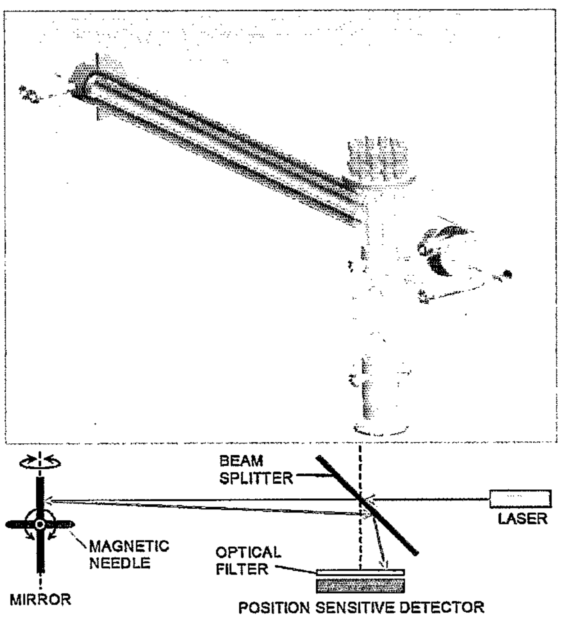

Figure 6: Cooling solenoid and field measuring setup.

BEAM DYNAMICS AT LOW ENERGIES

The fringe field of the cooling solenoid causes a rotation of the beam around the longitudinal axis. In order to minimize the transverse temperature of the electrons inside the solenoid they should enter the solenoid with the opposite rotation. Such beam can only be created through a magnetic field on the cathode and is therfore called a "magnetized" beam.

Traditional emittance compensation uses the space charge force to align the phase ellipses for different longitudinal slices of the bunch. The Bunch is then accelerated so that space charge forces can be neglected . For a magnetized beam Busch's Theorem must be taken into consideration. The rotation speed of a slice depends on its radius:

$$r^2\theta' + r^2 \frac{e}{m_e\gamma\beta c} B = r_o^2 \frac{e}{m_e\gamma\beta c} B_o$$

Therefore, in addition to the phase advance, the relative change of radius must be made equal for all longitudinal slices. Fig. 7 illustrates the effect of a radius change caused by space charge effects. On the cathode all slices have the same radius. As the bunch traverses the gun cavity the radii of the center slices increases more than those of the head and tail slices. In a frame that rotates with the average rotation of the bunch slices with larger radius rotate clockwise, slices with smaller radius rotate counterclockwise.

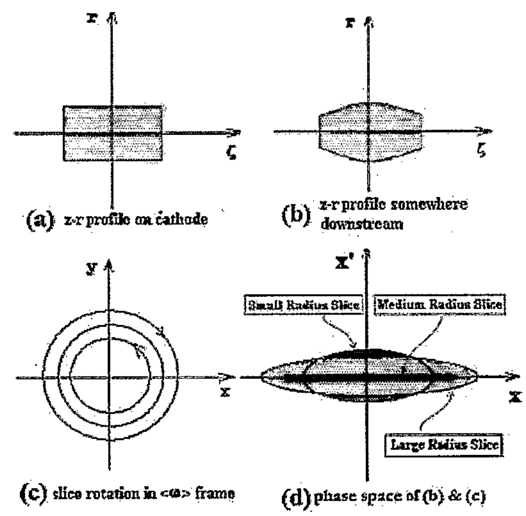

Figure 7: Emittance compensation for a magnetized beam.

CONCLUSION

The RHIC electron cooler is a challenging project. The limits of existing technology are pushed by orders of magnitude. R&D is in progress on many fronts to reach this goal.

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