SUCCESSFUL MeV-RANGE ELECTRON BEAM RECIRCULATION

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Abstract

Electron cooling [1] of heavy particle beams with energies of some GeV per nucleon requires high-quality dc electron beams of MeV energies and ampere range currents. The enormous electron beam power dictates that the beam current be returned to the high voltage (HV) terminal which provides the accelerating potential. In this paper we describe the successful recirculation of a dc electron beam at energies 1-1.4 MeV and currents in excess of 300 mA with typical relative losses of $1\text{-}2\cdot10^{-5}$. Currents of 200 mA were maintained for the periods of one hour (typical) without a single breakdown, 300 mA for 20 minutes.

1 INTRODUCTION

Electron cooling of the 8 GeV antiprotons in the Fermilab Recycler ring [2] could permit faster stacking rates and larger antiproton stacks. In 1995 Fermilab started an R&D program in electron cooling that has two principal goals: (1) to determine the feasibility of electron cooling the 8 GeV antiprotons; and (2) to develop and demonstrate the necessary technology. The primary technical problem is to generate a high-quality, monochromatic, dc, multi-MeV electron beam of 200 mA or greater. The only technically feasible way to attain such high electron currents is through beam recirculation (charge recovery). High-efficiency recirculation of a 1 MeV, 1 A, dc electron beam was first demonstrated in 1987 [3] by INP, Novosibirsk using a continuous solenoidal field which provided beam focusing. Presence of a solenoid makes such a system cumbersome and not easily extendible to the several MeV range. Another approach, suggested and tested by a group from UCSB [4], is to utilize an electrostatic accelerator with discrete focusing elements. The UCSB group has demonstrated a recirculation of a pulsed (several microseconds) 1.25 A electron beam using a 3 MeV Pelletron® accelerator (Van de Graaff type) at National Electrostatics Corporation (NEC). The results of this demonstration became a basis for a Fermilab-led collaborative effort which attained recirculation of a 2 MeV, 105 mA beam with 11 μA losses sustainable for one to ten minutes [5]. Recirculation tests, described in the present paper, were performed on the same accelerator as described in Ref. [4] and [5] with shorter 2 MV acceleration and deceleration tubes, a new electron gun and collector [6], as well as a different beam line. Figure 1 shows the test beamline layout. Table 1 summarizes the important system parameters.

This system employs an electrostatic HV supply like a Van de Graaff with maximum charging current of a few hundred microamps. Electron gun can be operated in both emission and space charge limited regime with a control electrode being always negatively biased with respect to the cathode. Electron beam line consists of a 7.5 m long channel with discrete focusing elements (lenses and a bending magnet) flanked by small aperture (2.54 cm ID) acceleration and deceleration tubes.

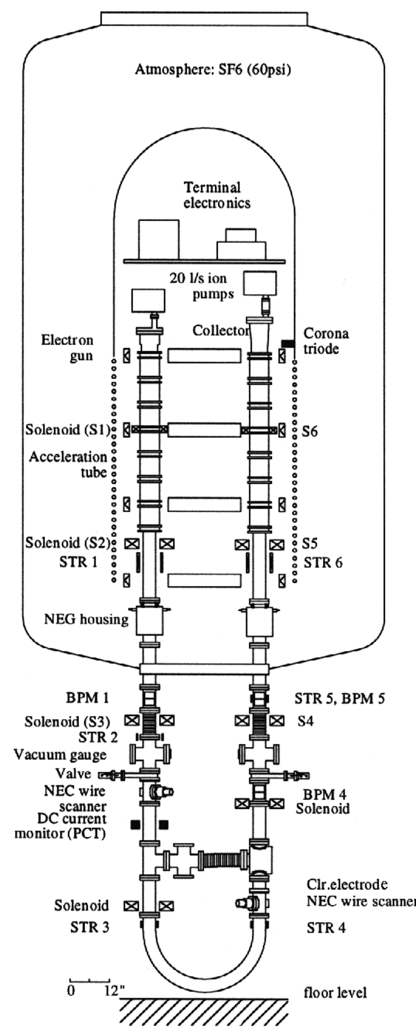

Figure 1: Recirculation system beamline layout.

[1] Fermilab operates under US DOE Contract with Universities Research Association, Inc.

Table 1: Recirculation System Parameters

Parameter	Symbol	Value	Units
Pelletron Voltage	U_o	1 - 1.4	MV
Max. Recirculated Beam Current	I_b	350	mA
Typical Vacuum	p	$1\cdot10^{-7}$	Torr
Relative Losses	$\Delta I/I_b$	$1\text{-}2\cdot10^{-5}$	
Electron Gun			
Cathode Radius	r_c	1.7	mm
Gun Perveance	P	0.07	μPerv
Anode Voltage	U_A	≤ 50	kV
Control Voltage	U_C		
beam off		$-U_A/13$	
beam on		$-U_A/100$	
Electron Collector			
Collector Voltage	U_{COL}	≤ 5	kV
Relative Losses (30 keV bench test)		$3\cdot10^{-6}$	

2 STABILITY

The specific attribute of this recirculaion test is relatively weak focusing: typical focal length of the beamline elements is about 1 m. Note, that in traditional low energy electron cooling systems this value is 1-10 mm and electron trajectories do not depend on the beam energy. The system, described in Ref. [3], had a typical focal length of 5 cm and this allowed it to sustain 3% energy fluctuations. One of the consequences of the weak focusing in our test system is that particle trajectories, as well as beam losses, strongly depend on the particle's energy (Fig. 2). In the event of an energy fluctuation that exceeds several kilovolts, the voltage on the Pelletron drops ("crashes") instantly to a very low level. If losses occur in the acceleration (deceleration) tube it takes only a couple of microamps to redistribute grading potentials on the tube and to crash the system. These crashes were of primary concern in our test since the final electron cooling system has to operate in a true dc mode 24 hours a day.

One of the most common mechanisms leading to large energy fluctuations is a partial or full tube breakdown. In our tests we have lowered the Pelletron voltage from a nominal 2 MV to 1-1.5 MV in order to both reduce the frequency of such breakdowns and to minimize the damage to the terminal electronics, caused by these breakdowns. Even with the lowered voltage it takes at least one week to condition the tube with the beam on after opening the tube to the atmosphere.

We found that the operation without crashes for the periods of one hour or longer is possible only when the beam boundary is far away from the apertures. In this mode of operation all the beamline settings can be varied (to some extent) without a significant current loss increase. Figure 2 illustrates the dependence of losses on the beam energy for such a regime. The best stability is achieved at the minimum of losses curve (33 - 34 kV for the conditions of Fig. 2).

The behavior of the system significantly differs for the operation below and above the most stable energy. Figure 2 shows that the energy increase above the stable point leads to higher losses, which reduces the mean time between crashes. On the other hand, the energy decrease below the stable range leads to an immediate crash: the increase of losses leads to further decrease of beam energy, which, in turn, increases losses, etc. This mechanism is valid on time scales shorter than the response time of a corona triode regulation circuit.

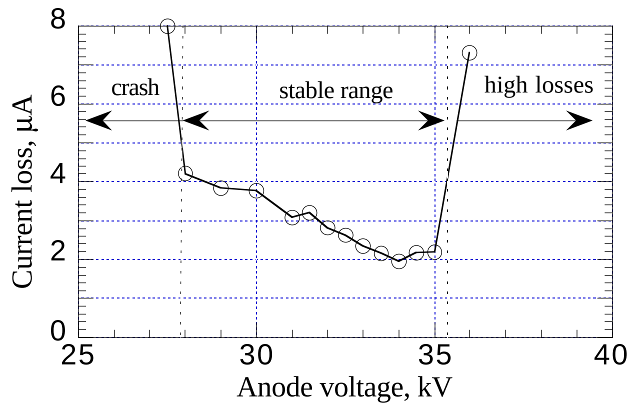

Figure 2: Measured dependence of losses on beam energy. Pelletron voltage was kept at 1.135 MV, beam current was 200 mA. Beam kinetic energy is $eU_o + eU_A$.

The time period between crashes decreases with beam current: typical time between crashes for 200 mA is one hour, 20 minutes for 300 mA, and seconds for 350 mA. The main reason is that the beam size generally increases with current. This reduces the range of sustainable fluctuations of various beamline settings and, consequently, the stability of the system. Also, the beam losses increase with the beam current (see Fig. 3), and we found that the best stability is achieved with the lowest level of losses.

Stability with respect to the beam position inside the collector is also very important because of the electron-induced gas desorption from the collector surface[7]. The coefficient of desorption from the collector surface initially lay between 1 and 10 molecules/electron. Even a small steering of a high current beam inside the collector onto a new "spot" can be accompanied by a burst of the desorbed gas and subsequent HV breakdown. After a long operation period and uniform exposure of the collector surface to the electron beam the coefficient of desorption fell to the level of 10^{-3} and this effect disappeared. Our estimate of the acquired dose by the collector surface is on order of 10 mA·hr/cm^2. This effect puts the limit on how fast one can establish a recirculating beam after letting the collector up to the atmosphere. Our best results were achieved with the collector being under vacuum for more than one year.

Thus, there are at least three necessary conditions for a stable recirculation: (1) losses in the tubes should be significantly lower than the tube resistive divider current (typically equal to 10-20 μA); (2) fluctuations of the beam energy and the bending magnetic fields should not exceed 0.2% (this requirement is less stringent than the requirement of 0.01% energy regulation for efficient electron cooling); and (3) the beam boundary should be far away from the apertures.

3 BEAM LOSSES

The typical dependence of current losses as a function of beam current is shown in Figure 3. This dependence has two reproducible parts: linear and exponential.

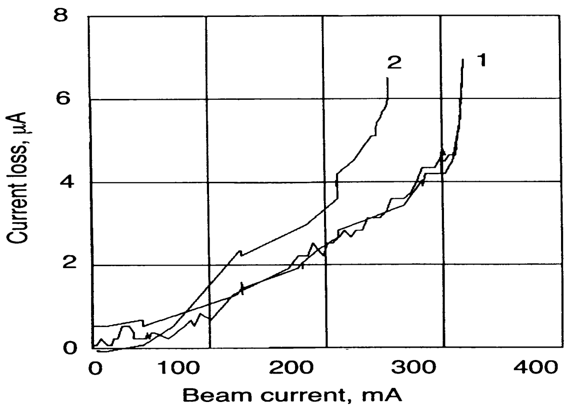

Figure 3: Measured current loss as a function of electron beam current. Curve (1) - p = 0.8-1.0·10^{-7} Torr, (2) - 2.3-3.3·10^{-7} Torr. U_o = 1.135 MV, and U_A = 39 kV for both curves. Two lines of curve (1) correspond to the increase and decrease of the beam current.

The exponential growth of losses is often observed because of beam scraping during initial beam steering as one tries to establish the recirculation. Exponential part in Fig. 3, most likely, also corresponds to the scraping of a primary beam. Figure 3 was obtained while operating the gun in a space-charge limited regime when the beam current is determined by the control electrode potential. We observed that the voltage on the control electrode that corresponds to the “knee” point in Fig. 3 increases linearly with U_A. This corresponds to a fixed beam size in the anode while the beam current scales as $U_A^{3/2}$.

The linear part of the losses in Fig. 3 might have three contributions: (1) collector losses, (2) residual gas scattering, and (3) beam halo, formed in the gun region. At observed level of losses 1-2·10^{-5} it is difficult to distinguish between these mechanisms. The collector losses, probably, do not play a major role because on a low energy test bench we were able to attain $\Delta I/I_b$ = 3·10^{-6} for the beam current of 600 mA[6].

We found that at high beam currents losses demonstrate approximately linear dependence on vacuum. Figure 3 shows the measured beam losses as a function of beam current for two different vacuum pressures. However, we do not believe that the residual gas scattering is a primary reason for beam losses. Typical scattering cross-sections for the electrons of MeV energy yield losses too low to support such a mechanism.

By a beam halo we imply particles with the longitudinal energy nearly equal to the primary beam energy and with the transverse energy orders of magnitude higher. The most understood source of this halo is an emission from the cathode edge and side surface. Such an emission in our electron gun is suppressed by employing a negatively biased control electrode, adjacent to the cathode. Voltage on this electrode (typically ranging from -400 V to -3 kV) determines the emitting area on the cathode’s face surface[6].

Possible halo mechanism that would give a linear dependence on vacuum is the secondary electron emission, produced by the backstreaming ion bombardment. This mechanism is supported by the fact that during the initial HV conditioning with a cold cathode we often observe a stable electron beam coming out of the accelerating tube. We have also observed that the losses do not depend on the vacuum in the gun and collector region but only on the vacuum in the beamline.

4 CONCLUSION

To attain stable recirculation of electron beams with currents of 200 mA and greater in a system with relatively weak focusing it is necessary to ensure small current losses (on the order of 10^{-5}). This requires a carefully designed gun with a small halo and a very efficient collector. Vacuum pressure should be kept preferably under 10^{-7} Torr. Electron beam size should be much smaller than the tube’s aperture. Energy and bending magnetic field stability should be better that 0.2%.

Based on the results of our tests we believe it is feasible to build a Pelletron-based dc recirculating system capable of producing hundreds of milliamps in the MeV energy range.

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