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High Efficiency Charge Recuperation for Electron Beams of MeV Energies

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Abstract

Electron cooling of ion beams with energies of some GeV per nucleon requires high-quality electron beams of MeV energies and currents as high as several amperes. The enormous beam power dictates that the beam current be returned to the high voltage terminal which provides the accelerating potential. The beam is returned to a carefully designed collector within the terminal and biased a few kV positive with respect to it. Thus the load on the HV supply is only the accelerating potential times the sum of the beam current loss and the current used to maintain a graded potential on the accelerating structure. If one employs an electrostatic HV supply like a Van de Graaff with maximum charging current of a few hundred μA , the permissible fractional loss is $\sim 10^{-4}$. During the fifteen years or so the concept of medium energy electron cooling has been evolving, the need to demonstrate the practicability of such high efficiency beam recovery has been recognized. This paper will review some experimental tests and further experiments which have been proposed. The design and status are presented for a new re-circulation experiment at 2 MV being carried out by Fermilab at National Electrostatics Corp.

Introduction

In the electron cooling technique an ion beam circulating in a storage ring interacts with a high current electron beam of the same mean velocity in a ring straight section. The high quality dc electron beam makes a single pass from a thermionic gun at high potential through the straight section at ground potential and is decelerated and then collected on an electrode just a few kV positive with respect to the gun cathode. The cooling rate depends in part on the electron beam current density, and several existing facilities use electron beams of 2 A or more at energy as high as 500 keV to cool ion beams for experiments in nuclear and atomic physics.^[1] High efficiency capture of the electron beam makes the technique economically feasible by reducing not only the running costs but also, of course, the capital cost of the

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Figure 1: Typical low energy electron cooling system (installed in the LEAR ring at CERN)

high voltage power supply as well. In current practice the HV supplies are usually Cockroft-Walton voltage multiplier chains, and beam losses are $\leq 0.01\%$. A typical low energy electron cooling installation is shown in Fig. 1. Characteristic of all such is the use of a longitudinal magnetic guide field continuous from gun cathode to collector. From the beginning of plans for proton-antiproton colliding beams for high energy physics there has been a desire to extend electron cooling to medium energy antiproton beams.^{[2],1} Most suggestions for the realization of medium energy electron cooling call for an electrostatic HV supply and focusing with discrete optical elements for both the beam transport and the cooling straight section. Fig. 2 is a schematic representation of a facility of this sort as it would be installed in the tunnel of the Fermilab Main Injector (MI), a 150 GeV synchrotron now being built. The proposed 8 GeV antiproton storage ring in the MI tunnel is called the Recycler; it is a permanent magnet ring now being designed for installation more or less concurrent with the end of MI installation. It will provide approximately a factor of four gain in Tevatron collider luminosity by providing a second stage of antiproton cooling to accumulate larger stacks and to recycle antiprotons remaining at the end of stores. The baseline design of the Recycler incorporates stochastic cooling; complementing that design with electron cooling is expected to provide an additional factor of five in performance, providing the antiproton supply required for Tevatron luminosity $\mathcal{L} \gtrsim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Electron cooling is a crucial element in Fermilab's plans to reach the $\mathcal{L} \sim 10^{33}$ region early in the next decade. These plans and the necessary development efforts are being called TeV33. An R & D project in medium energy electron cooling was started in the Fermilab Accelerator Division in April 1995. A major technical challenge to the project is to develop and demonstrate the capability

¹The interest in a possible \bar{p} - p collider goes back to the early days at INP. Certainly the development of electron cooling by Budker^[3] in 1966 was a response to the problem of how \bar{p} 's should be accumulated.

Figure 2: Schematic layout of an electron cooling system for the 8 GeV Recycler antiproton storage ring

of sustaining a high quality 4.3 MeV electron beam of 2 A or more.²

Overview of charge recuperation experiments

Although Fermilab put aside electron cooling as a candidate for accumulating \bar{p} 's from a production target after its generally successful tests of cooling 200 MeV protons,^[4] the idea of stochastic pre-cooling followed by electron cooling at the 8 GeV production energy clearly held promise of improving upon the results that could be obtained by stochastic cooling alone. During the construction of the Antiproton Source an experiment was initiated at National Electrostatics Corporation (NEC) to explore the practicability of MeV level dc electron beams of high quality at currents of an ampere or more.^[5] This effort coincided with, and cooperated with, the development of beam with similar requirements being pursued by UCSB for a free electron laser.^[6] The experimental proposal set a goal of 2 – 5 A dc beam of quality suitable for electron cooling in a short U-shaped beamline as shown in Fig. 3. The HV supply was a 3 MV NEC Pelletron with 2 MV of accelerating and decelerating column installed. Using this same beamline the UCSB group had circulated 1.25 A at 2.5 MeV with a recovery of 99.4 % of the beam. The loss was too much for dc operation but adequate for free electron laser operation with about a 20 μ s pulse. The WI/Fermilab/NEC group was able to sustain only 100 mA dc for any significant time, but the desired 10^{-4} fractional beam

²To be precise, the Accelerator Division R & D project was chartered with an initial electron beam current goal of 200 mA thought to be sufficient for a lesser luminosity goal associated with the label TeV*; the long range aim for electron cooling is more ambitious than this interim goal.

Figure 3: Recirculation test beamline used at NEC by both UCSB and Fermilab/U. Wisconsin in the 1980's

loss ($11 \mu\text{A}$) was obtained.^[7] The experimenters attributed their inability to circulate more current to ionization of the SF_6 insulator in the Pelletron tank by loss induced x-rays.

An approach somewhat more like the standard low energy arrangement shown in Fig. 1 was tried by a Budker Institute group.^[8] They placed the acceleration and deceleration columns in separate insulating vessels hung from the top of a modified 1 MV industrial accelerator made by BINP (model ELV-6) as indicated in Fig. 4. The HV supply has at least one hundred times the current capability of a Pelletron, but the BINP experimenters appeared to have had problems with voltage regulation and perhaps magnetic field regulation also. Their best results are reported as 1 A of beam circulated at 1 MeV sustainable for about one half hour with fractional beam loss of $5 \cdot 10^{-4}$. There is also a statement of having attained minimum loss of 10^{-4} for some unspecified operating parameters.

A group working at the Indiana University Cyclotron Facility (IUCF) proposed to the SSC to develop medium energy electron cooling for the Medium Energy Booster.^[9] The earlier results showed that the 2 A at 6 MeV which they proposed would require a development effort. They proposed to repeat the earlier experiment at NEC with improvements in gun, collector, transport optics, instrumentation, and x-ray shielding of the Pelletron.^[10] The beamline is shown in Fig. 5. A significant fraction of this hardware was built and new shielding was installed at the base of the Pelletron. However, the end of funding for the SSC also brought this work to a halt. The end of SSC funding also brought about a rapid re-assessment of the Fermilab high energy physics program and caused the lab to renew its interest in medium energy electron cooling.

The Fermilab recirculation experiment

Notwithstanding its early contributions to the development of electron cooling, Fermilab was making a completely fresh start when it initiated its R & D in April 1995. It is borrowing both ideas and equipment from IUCF to benefit as much as possible from the work done for the SSC. Like the IUCF group, Fermilab has decided that a first goal is to produce a suitable beam in a short beamline designed solely to achieve the charge recuperation. The general plan and many of the components come from IUCF or are built according to their intentions. IUCF never built the gun and collector they had planned for, and more study was needed to validate the design. Therefore, Fermilab has chosen to begin using the improved beamline developed by IUCF with the original gun and collector from the 1984 WI/Fermilab/NEC test. This first phase will presumably indicate whether the difficulties of that experiment were primarily the result of these critical components or of more general problems with beam optics, instrumentation, or shielding. Another important object is to develop the Pelletron controls to be easily integrated with the Fermilab accelerator control system. The tests at NEC are being carried out from the beginning with a stand-alone version of the Fermilab system informally known as "ACNET in a box". At this time the Pelletron at NEC is being set up to run with 2 MV of accelerating column into a short, straight line with two solenoids, a wire scanner, and a faraday cup. This commissioning test will provide a first check of accelerator and controls operation and test the radiation interlocks. Because the beam current will $\sim 10^{-3}$ of the expected circulating current, it will

Figure 4: 1 MeV charge recovery test performed at Budker Institute in the late 1980's using a modification of the ELV-6 industrial accelerator which they produce commercially

Figure 5: Recirculation test beamline designed by IU CF for a second experiment at NEC

be possible to learn rather little about the beam until the recirculation line is installed over the next few months. It is planned to have good data from the existing gun and collector by October 1996. At that time the measurements will be interrupted to install a new gun and collector being designed and built by Budker Institute.

The gun and collector for this second phase experiment will differ considerably from both the existing ones and the IUCF design. One of the reasons for the difference is that the goal for beam current has been set at about 500 mA. There were three considerations favoring this value. First, a cooling facility working reliably with this much beam can make a major contribution to collider luminosity. Second, given the difficulties experienced in previous work, a reliable half ampere represents a worthy challenge for the short term. Finally, beam envelope calculations for the NEC columns show that space charge defocusing and electrostatic focusing should be about in balance for 500 mA beam of somewhat less than 1 cm radius. Therefore, the beam optics should be somewhat more simple and the risk of excessive losses in the column is minimized. Having the gun and collector matched to the NEC columns at this reasonably conservative current improves the chances for a modest success. Because even the smallest commercial cathode of which we are aware will provide much more current than this in space charge limited operation, the gun is designed to be emission limited. Therefore, it will not employ the typical Pierce configuration.

There is a minimum goal of 200 mA set for this test, but, according to calculations with EGUN^[11] and beam envelope codes, much higher current should be possible. The calculated beam envelope in the first part of the column (EGUN output) is shown in Fig. 6, and the horizontal and vertical beam envelopes through the rest of the line (TRACE3D output) are shown in Fig. 7 for 500 mA.

A major function of the test will be to find what limits in practice the approach to current levels possible in principle. Reaching the programmatic goal for Tevatron luminosity will probably require understanding and circumventing a number of technical obstacles over the next few years in addition to developing a fundamentally sound system design. Many of these difficulties should make their first appearance over the next few months of recirculation tests.

Acknowledgements

The work on the Fermilab recirculation experiment to date is primarily that of A. Curtis Crawford and Sergei Nagaitsev, who was also a major contributor to the IUCF medium energy electron cooling project.

Figure 6: Ray-trace output from the EGUN program for the gun and first half of a NEC accelerating tube section in the Fermilab recirculation experiment

Figure 7: Horizontal plane and vertical plane beam envelopes calculated with TRACE3D for the NEC accelerating column through the symmetry point at the center of the achromatic bend – 500 mA

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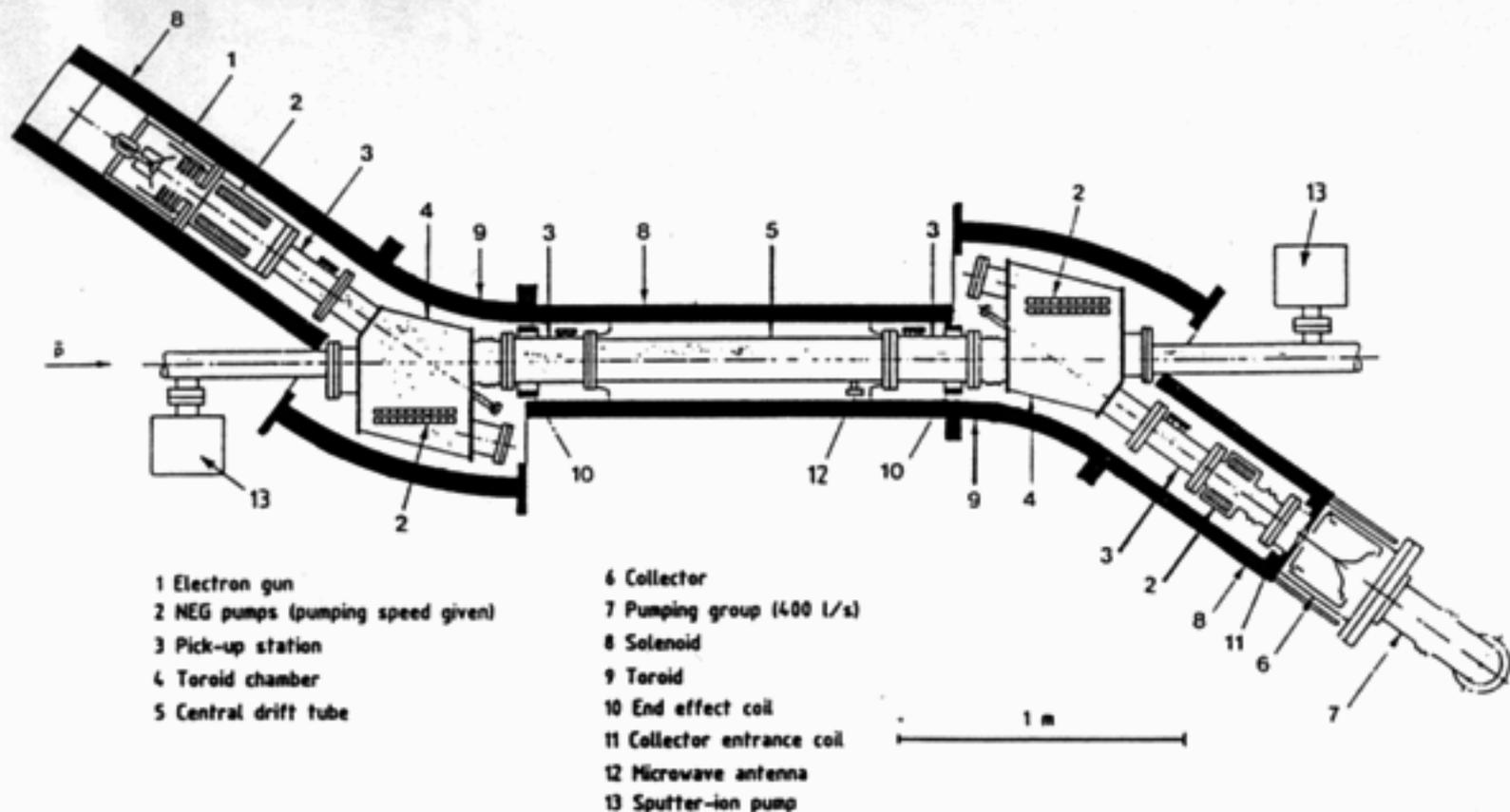


Figure 1: Typical low energy electron cooling system (installed in the LEAR ring at CERN)

Electron Cooling System Schematic

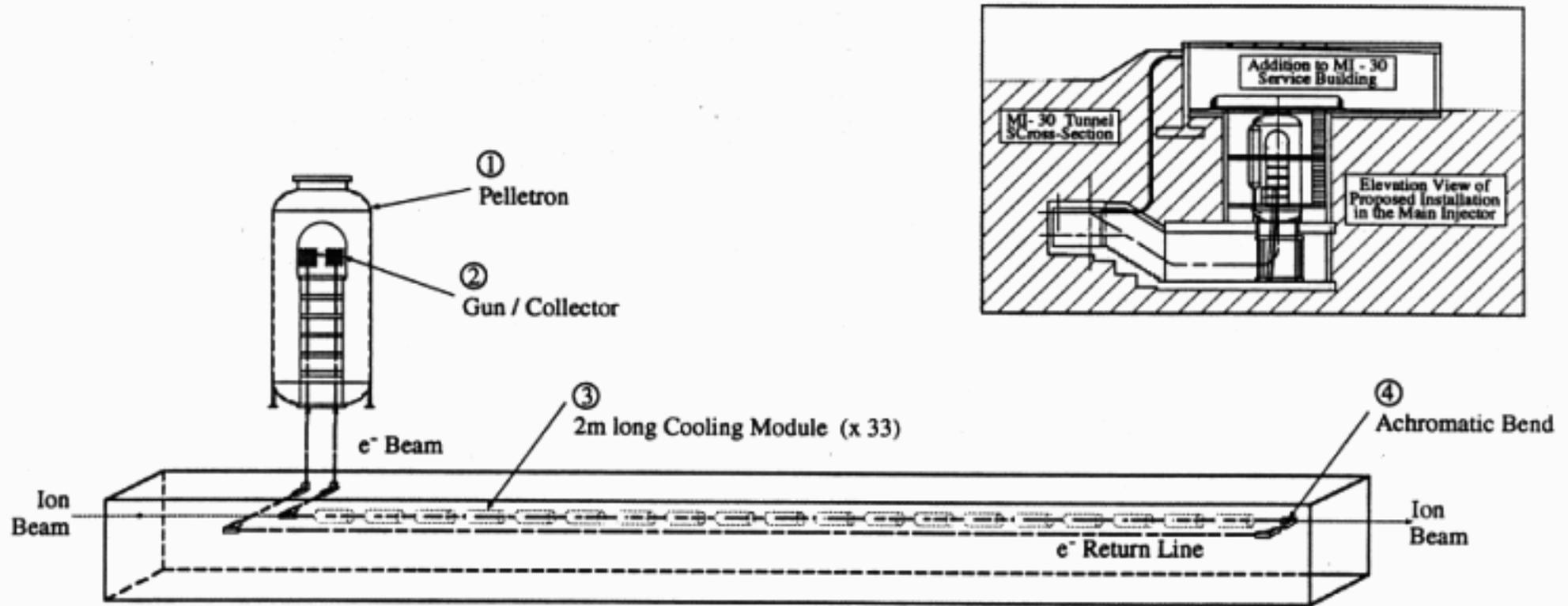
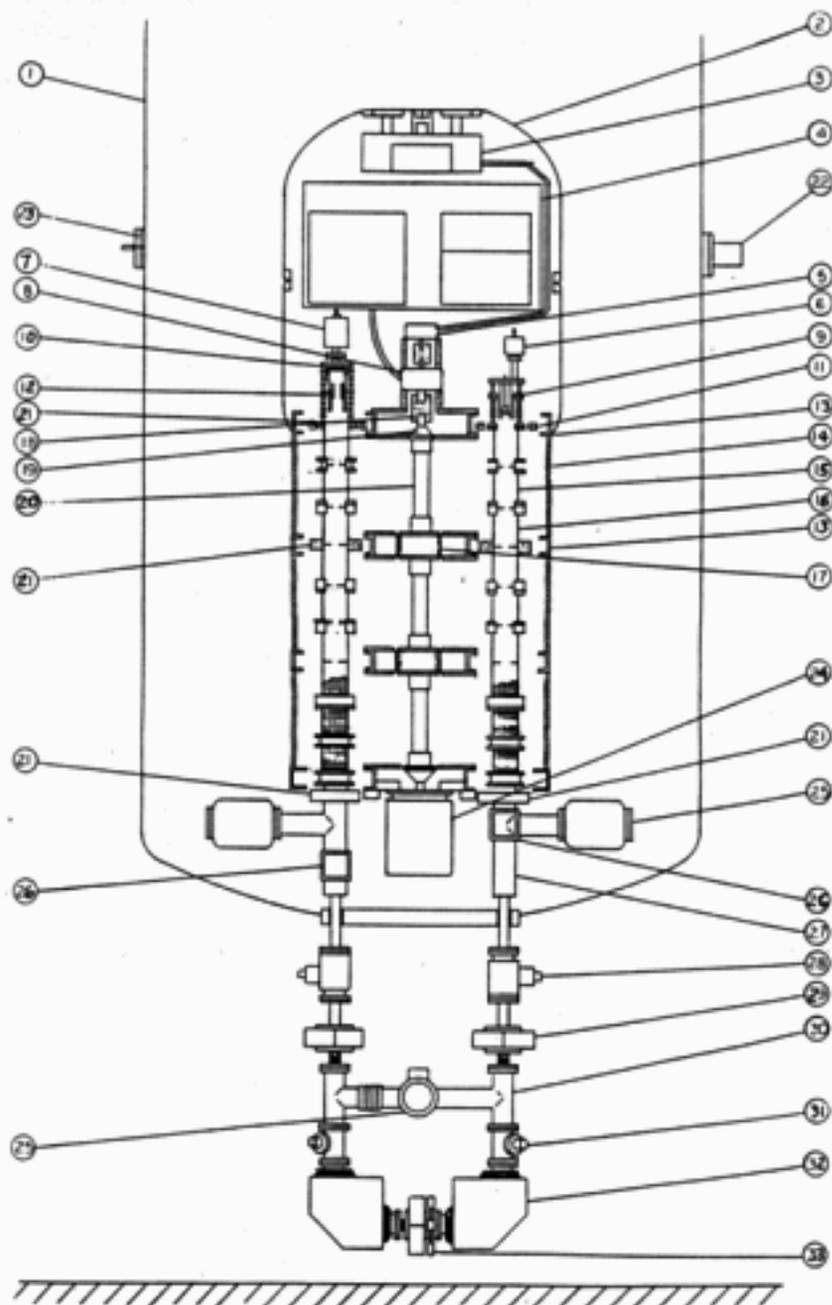


Figure 2: Schematic layout of an electron cooling system for the 8 GeV Recycler antiproton storage ring



Beam Line Layout: (1) Tank, (2) Terminal, (3) Terminal potential (-3MV) electronics, (4) Cathode potential (-3.05 MV) electronics, (5, 8, 17) 400 Hz generators, (9, 6) Electron gun with ion pump, (11, 21) Solenoid lenses, (26) Magnetic steerers, (15, 16) Accelerating tubes, (20, 24) Rotating shaft and motor, (25) Ion pumps, (31) Beam Profile Monitor, (29) Quadrupole Singlets, (32) Bending magnets, (28) Faraday cups, (10, 12, 7) Collector with ion pump, (22) Generating voltmeter, (23) Capacitive pick-up.

Figure 3: Recirculation test beamline used at NEC by both UCSB and Fermilab/U. Wisconsin in the 1980's

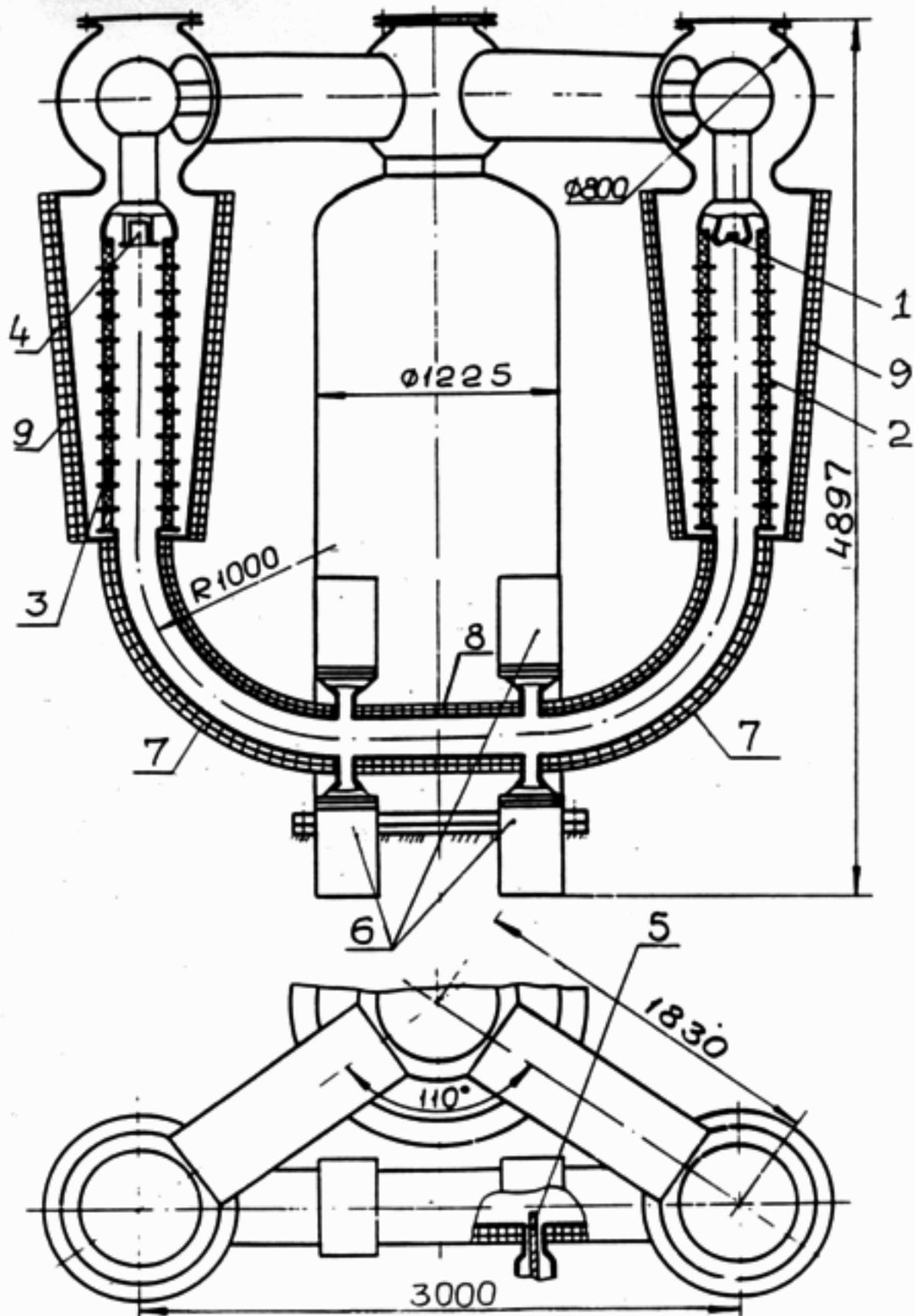


Figure 4: 1 MeV charge recovery test performed at Budker Institute in the late 1980's using a modification of the ELV-6 industrial accelerator which they produce commercially

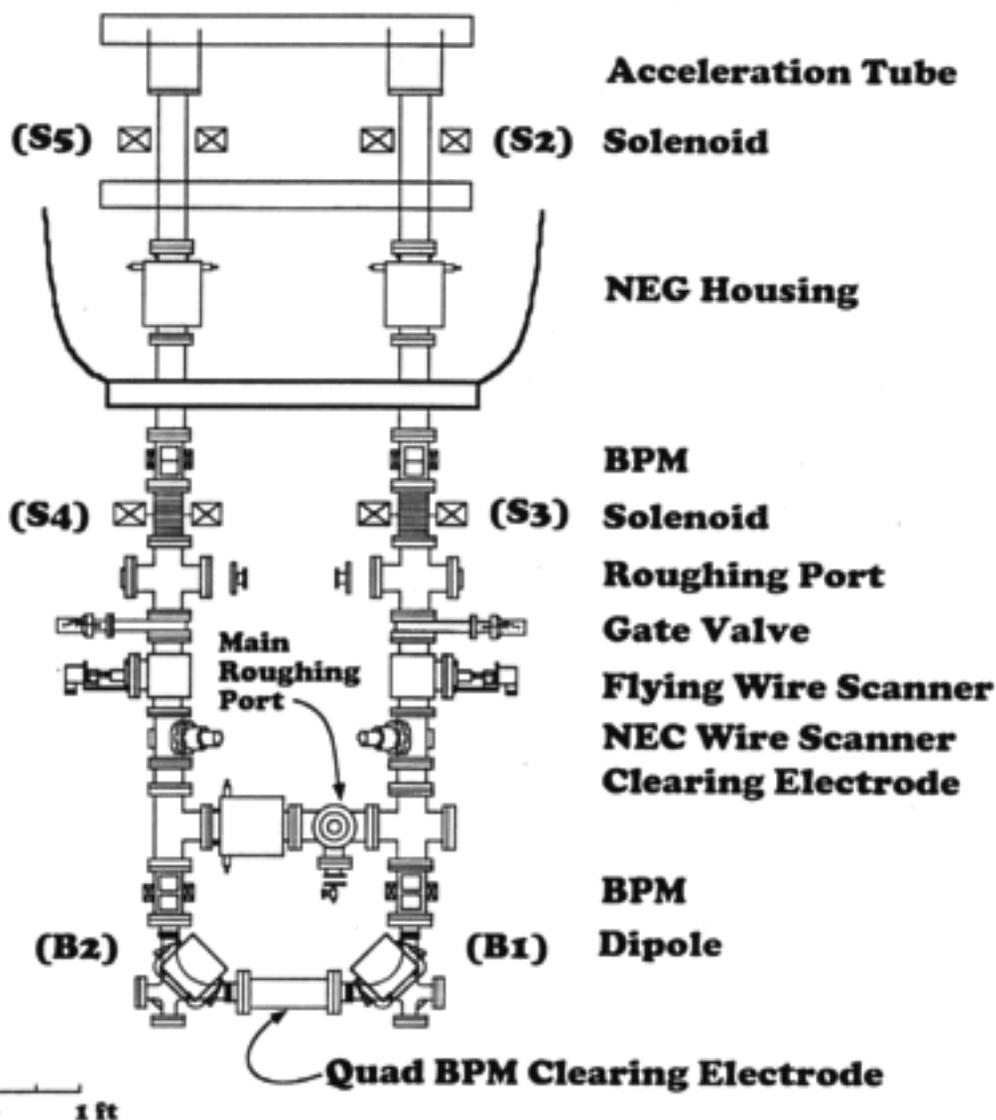


Figure 5: Recirculation test beamline designed by IUCF for a second experiment at NEC

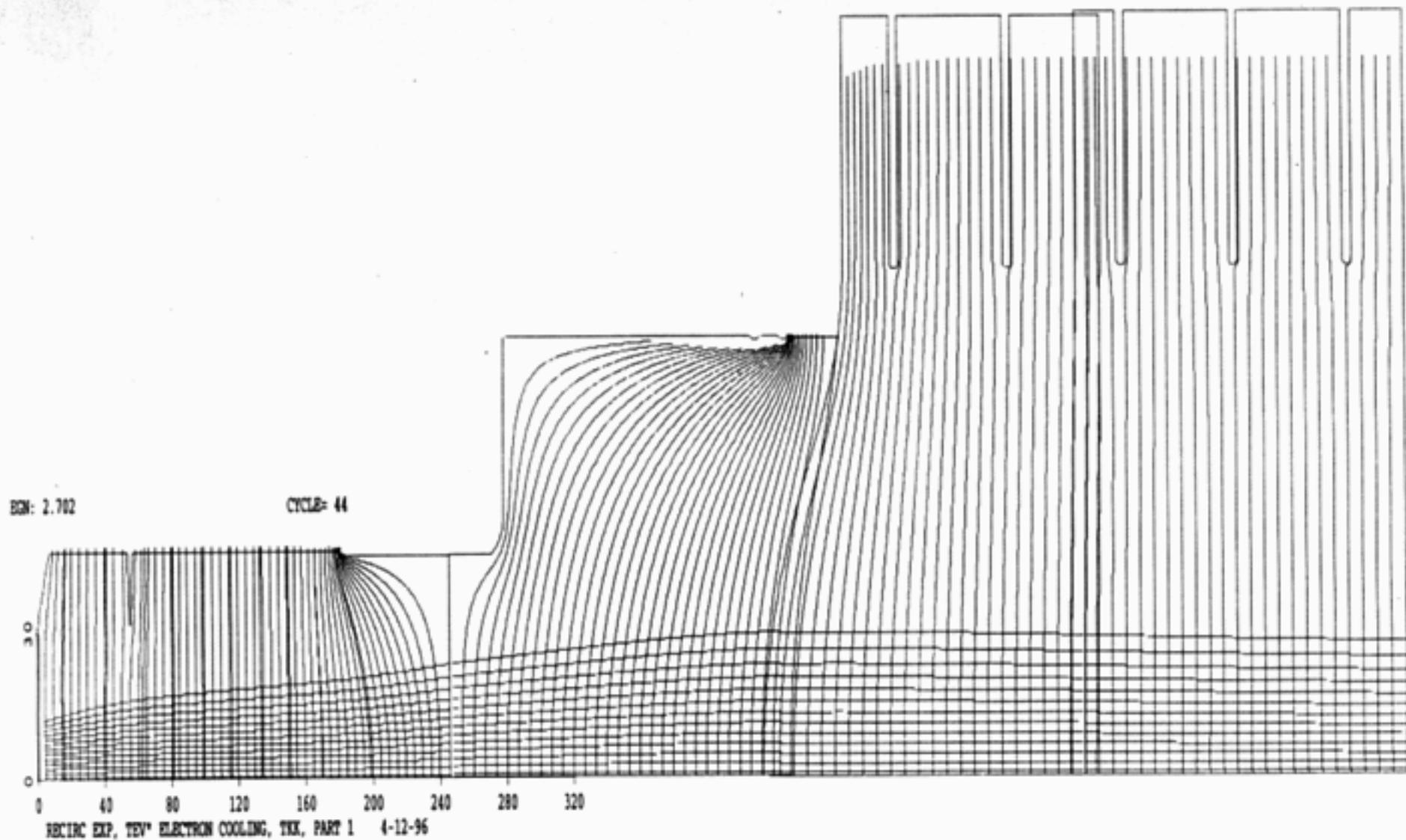


Figure 6: Ray-trace output from the EGUN program for the gun and first half of a NEC accelerating tube section in the Fermilab recirculation experiment

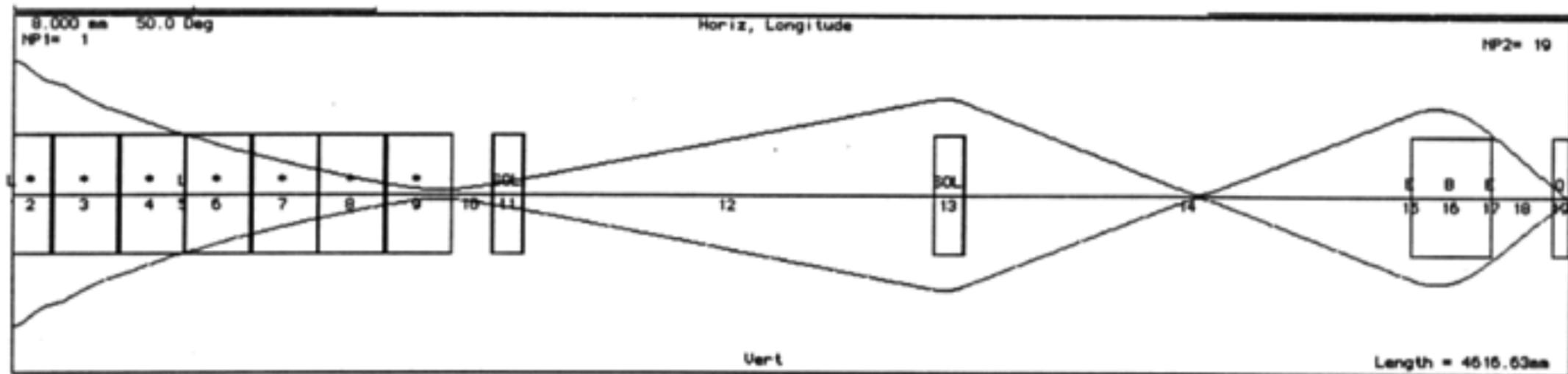


Figure 7: Horizontal plane and vertical plane beam envelopes calculated with TRACE3D for the NEC accelerating column through the symmetry point at the center of the achromatic bend – 500 mA